

URBAN TRANSIT SYSTEMS AND TECHNOLOGY

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Vukan R. Vuchic



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PREFACE

Many cities and metropolitan areas face the problems of chronic traffic congestion and its serious negative side effects. They also suffer from excessive auto dependency, which reduces mobility and sustainability. To solve these problems, cities are making efforts to implement intermodal transportation systems that minimize negative side effects and enhance their economic viability and quality of life. In these efforts, city governments recognize urban public transportation, popularly known as transit, as the critical element in achieving balanced transportation system.

These trends and experiences have led to introduction of policies favorable to transit system development and innovations. The support for urban transit provided by federal/national and other levels of government have played a major role in its upgrading through research and development, financing of new systems, new modes, and applied research for solving technical, operational, and planning problems. Consequently, the need for greater expertise in technology, operations, and planning of transit systems is now more obvious than it has ever been since the introduction of wide use of private cars.

This author's first book, *Urban Public Transportation Systems and Technology* (Prentice-Hall, 1981), contained systematic definitions and evaluation of basic concepts in urban transportation, descriptions of transit modes, their design and analysis. Its focus was on engineering aspects of transit systems. That book was followed by *Transportation for Livable Cities* (Center for Urban Policy Research at Rutgers, 1999), covering the roles of transit and its interaction with city character and quality of life. It presented explanations of the basic characteristics and relationships of differ-

ent modes, including pedestrians, private automobiles, and different transit modes. His third book, completing a sequence named "Transit Trilogy," was *Urban Transit Operations, Planning and Economics* (Wiley 2005). It covered a broad range of topics on transit system operations, scheduling, lines and networks, economic and organizational aspects, planning procedures, and mode selection.

This book, *Urban Transit Systems and Technology*, is an updated and revised version of the first book, focusing on systems and engineering aspects of transit. The intent here is again to present the fundamental classification of transit modes and their physical components, as well as descriptions of state-of-the-art transit technologies. Thus, parts of the first book which describe the basic elements of transit modes and their dynamic characteristics are retained. However, all descriptions of transit systems and their operations have been updated, including numerous developments and innovations from the last 25 years.

To illustrate the changes during this period, in 1981 metro systems existed in 55 cities in the world; today there are over 100. In 1981 there was only one new light rail transit system in North America (Edmonton); in 2006 there are more than 20. Bus rapid transit existed as a special type of bus operations in São Paulo and a few other cities, while in recent years it has been recognized as an established mode in many countries. Automated systems have also had a strong development.

This book starts with an updated Chapter 1 covering historic development of transit and its impacts. Chapter 2 presents classification and description of transit systems—the family of transit modes, guiding the reader

to the grouping of modes into several categories which are covered in later chapters.

Chapter 3 covers theory of traction and describes particularly internal combustion engine and electric traction. The latter has recorded revolutionary developments in recent decades (choppers and inverters, then AC motors, both resulting in great increases in energy efficiency). Travel time computations and energy consumption are also covered.

Transit system performance and measures of its capacity, efficiency, utilization, etc., are presented in Chapter 4. Material covers considerable theoretical analyses, as well as practical methods for performance and efficiency computations.

Chapters 5 through 9 describe different categories of transit modes. Chapter 5 has extensive material on bus systems, including bus rapid transit in a separate section. Rail systems, including the four major modes, are the subject of Chapter 6. This is the largest chapter because of the technical complexity, diversity, as well as increasing use of rail modes in many countries. Chapters 5 and 6 discuss the recent introduction of low-floor vehicles, which have significantly increased the convenience and efficiency of bus, LRT, and RGR services in pedestrian-oriented urban areas.

Unconventional modes, particularly automated guided systems, are the subject of Chapter 7. Increasing use of these modes as people mover shuttles and as regular transit lines are described. Chapter 8 covers specialized modes, such as cog railways, funiculars, and ferryboats, all of which have had increasing applications in many cities in recent years. A variety of paratransit modes and their numerous applications in industrialized and in developing countries are described in Chapter 9.

Finally, Chapter 10 presents a review and comparisons of different modes presented in the preceding five chapters. Some material from preceding chapters is summarized to facilitate this review and comparisons

of modes in different categories: medium-capacity, automated, rail transit modes, and others. Common errors and biased arguments frequently used in mode comparisons are also critically discussed.

Each chapter has a set of exercises and a list of references. A list of most relevant references for the entire book follows Chapter 10.

Like the preceding books of the “Transit Trilogy,” this one is intended for use as a textbook, and as a reference book for professionals such as transit operators, traffic engineers, consultants, and planners. It therefore attempts to “bridge” the separations between research, teaching, and applications in practice. The international coverage and extensive references to leading transit systems in different countries is also followed again. Both of these features—bridging theory and practice and international orientation—have found very positive responses with the users of previous books. This was obvious from considerable acceptance of these books in many countries, as well as its several translations.

This book utilizes SI units in a few instances where it was logical to add English traditional measures. A very convenient set of tables for conversion of units between the SI and English systems is presented as Appendix I. Other appendices present a list of abbreviations (II), definitions of transit terms (III), and solutions to selected exercise problems (IV). Two indexes—general and names of cities—are at the end of the book.

With extensive development and diversity of urban transit systems, it is increasingly difficult to cover the broad field of transit technology in one book. The author has tried to select the material that will be most useful for increasing knowledge about transit and for assisting in its planning, operations, and analysis in cities with a variety of conditions. If that has been achieved, the main goal of writing this “Transit Trilogy” will have been realized.

ACKNOWLEDGMENTS

The author wants to express his gratitude to many persons—colleagues and students at universities, transportation engineers and planners in transit agencies, government organizations, and consulting firms—who contributed information and materials, assisted in preparation, or reviewed manuscript for this book. Many materials and contributions were produced over a period of several years, but the most intensive cooperation has been done “under pressure,” during the rather short period of about one and a half years that it took to write this book.

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I want to point out that Wolfgang Homburger and Hans Leopold, my colleague since our joint work in Hamburg in the early 1960s, have actually reviewed manuscripts for all four books I have published and therefore share any credit that my “Transit Trilogy” may obtain.

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Professors Shinya Kikuchi, Virginia Tech University and Antonio Musso, Università di Roma provided valuable experiences from their use of my first book in their teaching over the years.

I also want to recognize several persons who have always readily provided me with information, data, photographs, and other materials during the writing of this book and other research I have performed. John Schumann of LTK Engineering provided data on transit in different cities, particularly light rail transit systems. William Vigrass supplied information and numerous photographs, some of which are in this book. Others who provided materials include Andrew Bata, Harry Hondius, Srecko Kahvedzic, Tom Matoff, Angel Molinero, Dr. Francesca Pagliara, Tom Parkinson, Takis Salpeas, and Gradimir Stefanovic.

Contributors of substantial materials used directly for this book include several persons. Norman Vutz of LTK Engineering Services structured and wrote major parts of the section on electric propulsion. Nathan Maak, as my student, prepared a paper which has been used for the tables and diagrams on rail rolling stock. Christopher Wallgren and Paul Christener provided many technical materials and photographs.

Among transit agencies, I want to recognize cooperation of the American Public Transportation Association and its President William Millar, Bay Area Rapid Transit, Municipal Railway in San Francisco, New York City Transit, New Jersey Transit, South-

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This and my other books could not have such international breadth without my frequent contacts with numerous colleagues in many countries. Most valuable cooperation I have enjoyed over several decades and which have been directly useful for this book has been with Dr. Günter Girnau, honorary Director of Verband Deutscher Verkehrsunternehmen—VDV in Germany; Dr. Adolf Müller-Hellmann, VDV present Director; Dr. Wolfgang Meyer, honorary President of the International Union of Public Transport—UITP; Manfred Bonz and Peter Höfflinger, Directors of the Stuttgarter Strassenbahnen. Discussions, materials, publications, and visits that we have exchanged have provided the highest professional and intellectual experience with respect to transit and urban transportation that I have had in my career. Other similar contacts I have had have been with colleagues in Japan, several other European and Latin American countries, South Africa, Canada, and Australia.

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Vukan R. Vuchic

University of Pennsylvania

1

HISTORY AND ROLE OF PUBLIC TRANSPORTATION IN URBAN DEVELOPMENT¹

The founding, shaping, and growth of human agglomerations throughout history have been products of complex interactions of many forces. One major force has always been transportation. A review of historic developments will show how long-distance transportation had a major role in determining the *locations* of cities; how their *size* has been influenced by both long-distance as well as local, intraurban travel and transportation systems; and how the latter have affected the *urban form* (shape of urban area and its basic transportation network) and *urban structure* (distribution of land uses and population densities).

1.1 EARLY DEVELOPMENT OF CITIES

A brief description and analysis of urban development through history, focusing particularly on periods when relationships among different influences were relatively simple, is helpful in understanding the impacts of various technological and organizational changes that have taken place in modern times. Consequently, such an understanding may be helpful in selecting the transportation policies that have an impact on the creation of desirable urban development patterns. In particular, the role of public transportation in cities is

better understood with the perspective that such a background provides.

1.1.1 Transportation and Locations of Cities

It is considered that the first significant civilian transportation began with exchange of goods. The exchange started when either a surplus of production was created, allowing producers to trade their surplus commodities for other goods, or when there was deficiency of some resources that existed at other locations. With intensification of exchange, it became possible to introduce specialization of work, which led to increased productivity, a greater surplus of goods, and a further increase of exchange. The process thus developed and accelerated itself.

The intensification of goods exchange led to the formation of trading routes and markets. At locations along the routes where tradesmen or caravans exchanged supplies or stayed overnight, stores, inns, and other services began to develop. Most frequently, these locations were at the points where goods had to be transloaded from one transportation mode to another or where trading routes intersected. Crossings of natural obstacles, such as rivers or hills, also created clustering of facilities and services.

1.1.1.1 Transloading Points and Route Crossings. Typically, ports and harbors on seacoasts and lakes or along rivers became the most common deter-

¹ Substantial parts of this chapter were written by Mark Horn as a part of the requirements for the author's graduate course, Urban Public Transportation, at the University of Pennsylvania in 1977.

minants of locations of cities. This is obvious from the present distribution of cities throughout the world. Istanbul, Naples, Lisbon, Rotterdam, Hamburg, and Oslo are harbor cities. The Atlantic Coast of the United States—with Boston, New York, Philadelphia, Baltimore, and many other ports—represents the largest concentration of cities and population in the country. Seattle, San Francisco, Los Angeles, and San Diego are prime harbor locations on the Pacific Coast. Regensburg, capital of the Holy Roman Empire of the German nation, Vienna, Budapest, Novi Sad, Belgrade (originally the Roman city of Singidunum), and a number of smaller cities are located along the Danube, the largest waterway in that part of Europe. Zürich, Chicago, Detroit, and Toronto are harbor cities on lakes, and so on.

Although for some cities—such as Berlin, Paris, and Moscow—it is difficult to discover today any special geographic reason for the choice of their particular locations, it is considered that route intersections and river crossings caused their initial development. Thus transloading points and route intersections were in most cases determining factors in the selection of city locations. Other factors that influenced urban locations can be grouped into the following four categories.

1.1.1.2 Mining Locations. Construction of a mine usually caused development of service industries and other components of future cities. Typical examples of cities that grew around mines are the densely developed areas of the Ruhr in Germany and the Midlands region in England; both represent agglomerations consisting of a number of large cities.

1.1.1.3 Strategic Considerations. In contrast to cities located along transportation routes (i.e., at accessible points), some cities were founded at locations that were easy to defend. Often, they were built close to transportation routes, where topography or water bodies provided good defense lines on one or more sides. Although some of these cities declined or were even abandoned (particularly those developed on hill-tops), others—such as Copenhagen, Heidelberg, and Belgrade—were later opened up and grew into modern cities. Most towns that developed far from transportation routes could not prosper for long periods.

1.1.1.4 Resorts. Natural beauty, a pleasant climate, hot springs, and seacoasts attracting tourists, often represent a major force in the founding and growth of cities. With increasing affluence, these factors have become particularly important. Honolulu, Acapulco, Odessa, Nice, Innsbruck, and many Swiss cities owe much of their growth and prosperity to their natural attractions.

1.1.1.5 Political or “Representative” Reasons. Some cities have been founded at certain locations by a government decision. The reasons have usually been economic or political: to stimulate development of a particular part of the country, to utilize remote resources, to provide a representative capital. Good examples are Washington, DC (1780s), Ankara and Canberra (1920s), Brasilia (1950s), and Islamabad (1990s).

Only the first of the five major factors influencing the locations of cities—transloading and route-crossing points—is a direct function of transportation, but it is by far the most prevalent. Moreover, cities at mine locations were indirectly influenced by transportation: to reduce transport of bulky ores, extractive industries were developed in the vicinities of mines. It can therefore be said that transportation has had a major role in the determination of urban locations, although it did not always continue to be a dominant activity in later stages of a city’s development. In all large cities, the growth of supporting services led to diversification of activities and eventually to the strong development of the tertiary sector (administrative, cultural, financial activities, etc.), which is not directly dependent on transloading of freight. Consequently, even closings of major transloading facilities that took place in some cities (e.g., relocation of most port activities from New York to New Jersey and from San Francisco to Oakland) had negative but not fatal effects on the city.

1.1.2 Transportation and City Size

Transportation technology and organization have in many periods of history had a major impact on the size of city and its population. Having influenced the locations of many cities, transportation continued to

stimulate growth of cities that had easy access from many areas and by different modes. Good mobility within cities also influenced their growth. This was the case in many cities when construction of a bridge or tunnel resulted in the development of new areas with commercial, industrial, and residential activities, leading to economic growth and population increases in the entire urban area.

However, transportation has sometimes also acted as a constraint on urban growth in two ways, particularly prior to the invention of mechanized vehicles. First, the capacity of the system to supply the city with food and other material needs was limited. The transportation of supplies was slow, expensive, and often physically impossible beyond certain volumes and distances. Theorizing about the maximum possible size of cities, British statistician Petty stated in 1686 that all supplies for a city must be produced within a radius of 50 km. He computed that the production from an area of that size could support at most 600,000 houses and concluded that the maximum population of a city (in his study, London) would be 5 million. The second constraint was personal travel. When internal passenger circulation was slow, it was not possible to develop a city that would operate coherently over a large area. All major activities involving contacts among people had to be located within distances that permitted walking or the use of horses.

In addition to transportation, urban growth has always been influenced by other forces. In his monumental study of the development and growth of cities, A. F. Weber (1899) estimates that several ancient cities—among them Thebes, Memphis, Babylon, and Nineveh—had populations probably well in excess of 100,000; that Carthage probably had as many as 700,000, that Alexandria was somewhat smaller, and that Rome was somewhat larger (800,000 to 1 million). On the other hand, it is conjectured that in the Middle Ages, probably only Constantinople reached a population of 1 million (data from both periods are not very reliable). Western cities (London and Paris being most notable) did not reach the figure of 1 million until early in the nineteenth century. Since transportation technology in ancient times was not significantly different from that in the Middle Ages, Weber concludes that economic, political, and social factors in the two pe-

riods were different and they, acting collectively with transportation, caused different rates of growth and sizes of cities.

Schaffer and Sclar (1980) describe interaction of cities and transportation at a further level: they show how the basic mode of travel—such as walking, use of public transit, and driving a car—influences the size and type of life in cities.

1.1.3 Form and Structure of Cities

The ancient city of Miletus in Asia Minor is often mentioned as one of the first systematically planned cities (about 450 B.C.). It had a regular grid pattern of streets, indicating the attention given to transportation within the city. In the Middle Ages, the dominant role of market activities in the creation of the city influenced the formation of its core; typically, markets remained the central places, and the church, city hall, and other religious and secular central facilities were located immediately around them. The fact that internal circulation was performed mostly by walking and the requirement that the city be surrounded by massive defense walls dictated that cities be built with a very compact structure, like the example in Photo 1.1; this resulted in high population densities. Such cities typically had irregular street patterns because the basic modes of transportation (walking, riding, using animal-drawn carts) did not require any special roadway geometry.

With the passing of the Middle Ages, the need for defense walls gradually decreased and new patterns of urban development appeared. Political, functional, and often aesthetic factors began to influence urban form and street patterns. For example, the cities of Karlsruhe in Germany and Versailles in France were laid out with distinct radial/circumferential (section of a ring) street networks. Moscow has a ring and radial network. Royal palaces and government seats were usually focal points in cities with radial networks.

A grid pattern of streets, although used in several ancient cities (e.g., Miletus) and in some European ones (Mannheim is a good example), became extremely popular in North American cities. William Penn's plan for Philadelphia, founded in 1682, and



Photo 1.1 A typical European city laid out in the Middle Ages: narrow streets and protective wall.

street layouts in all five boroughs of New York City as well as in Chicago, Toronto, San Francisco (two grids with different block sizes and geometric orientations), and most other cities in North America utilized this pattern. Examples of cities with different street patterns are given in Table 1.1.

Consequently, the role of transportation in determining street networks has varied with times and conditions. Transportation had little influence on the

layout of the irregular streets in medieval cities, but it has been a major factor in the designs of most regular networks. Grid street patterns provide for regular-size lots and easy travel along their two axes, although they are poorly suited to diagonal and radial travel toward areas with concentrations of offices, commercial and other activities, which are major traffic generators. To facilitate diagonal travel as well as to achieve aesthetic effects, L'Enfant designed Washington as a grid with

Table 1.1 Examples of street network patterns

<i>Grid</i>	<i>Radial/ Circumferential</i>	<i>Combinations</i>	<i>Irregular</i>
Philadelphia	Moscow	Mexico, Milan (grid-irregular)	Boston
Chicago	Cologne		Lisbon
Mannheim	Copenhagen	Paris, St. Petersburg (diagonal-radial-irregular)	Bremen
New York	Karlsruhe		London
San Francisco	Amsterdam	Washington (grid and diagonal)	Manchester
Toronto	Versailles		Regensburg

superimposed diagonal arterials. These broke up the monotony of the grid but created many extremely complex intersections. The boulevards of Paris, built by Haussmann mostly for other reasons (to control civil disorders), also had a major impact on the city's transportation.

Public transportation has usually been given inadequate attention in street network designs. In cities with farsighted planning, central medians were provided for separate streetcar rights-of-way, which had increasing importance when street congestion intensified. In most cities, however, transit vehicles, especially buses, were considered as one of the user categories on regular streets; no special facilities were provided for them. Metro systems did get better treatment in most cities: their stations were used as focal points for street networks and for feeder transit convergence. Various commercial and office complexes and other intensive land uses have often been built around metro stations.

1.1.4 The Industrial Revolution, Urbanization, and the Growth of Cities

Cities have always been centers of human activity. In addition to being seats of government, they have been central locations for manufacturing, trade, educational, cultural, and other activities. However, before the development of large-scale industrial processes, most people resided in rural areas and were employed in the agricultural sector of the economy. This pattern was completely changed by the industrial revolution, which was initiated and sustained by many institutional, economic, and technological developments in the course of the eighteenth and nineteenth centuries.

The invention of the steam engine by James Watt around 1765 is often mentioned as symbolizing the beginning of the industrial era. Although that invention was by no means the single cause of the far-reaching economic and social developments that subsequently occurred, it did represent a significant technological breakthrough: it created a practical means of obtaining mechanical energy for application in mining, manufacturing, and, somewhat later, in transportation.

With an energy source many times more powerful than those available earlier and the introduction of the division of labor in industrial processes, labor productivity grew rapidly. Increased industrial production created a much greater surplus of goods than had been available previously. Trade intensified and locally autonomous economies were gradually replaced by economies based on distant supplies of resources and wide distribution of products. Agricultural and manufacturing production were reorganized toward an increased volume of production and consumption. The impact of these changes upon urban patterns was first evident in the rapid growth of the centers of international trade and commerce that began at the end of the eighteenth century. These centers—London, Paris, Berlin, New York, and others—grew throughout the century, and in most countries this growth has continued to the present.

New jobs in cities offered employment opportunities and attracted the rural population with the prospect of higher wages. The major shift proceeded from the primary sector of the economy (agriculture) to the secondary (manufacturing industry) and tertiary (government, administration, banking, trade, education, culture, etc.) sectors. While it is estimated that during the Middle Ages in European countries over 80% of the population was in the primary sector, with the secondary and tertiary sectors having some 10% each, these ratios have drastically changed since the industrial revolution. In highly developed countries, the primary sector now employs the smallest segment of the population.

The employment shifts that occurred during the process of industrialization are shown schematically in Figure 1.1: the curves showing the shift of population among the three sectors are typical for most countries, but the time periods in which they occurred and exact percentages vary with local conditions. Table 1.2, which gives estimates of present population distributions among the three sectors in several countries, shows that the tertiary sector is now predominant in the developed countries. It is therefore sometimes said that these countries have "tertiary economies."

Because the secondary and tertiary sectors are concentrated primarily in towns and cities, these employ-

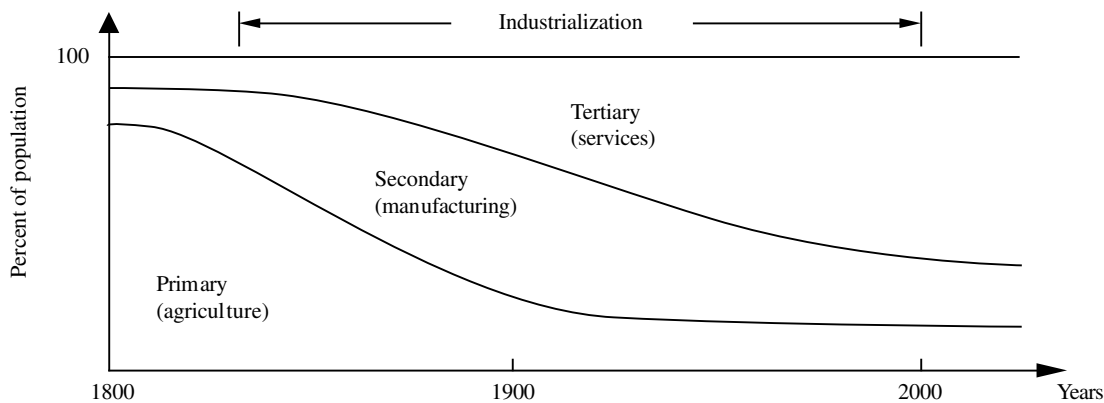


Figure 1.1 Population shifts among sectors of the economy in the United States

ment shifts among the sectors were accompanied by a massive movement of population from rural to urban areas, the process called *urbanization*. The scale of this process can be measured by changes in the proportions of the population living in urban areas on the one hand and in rural areas on the other. Before the nineteenth century, rural population was dominant, amounting typically to some 70% to 90% of the total population; following the period of intensive urbanization, which in most countries is still continuing, this share has now fallen to approximately 30%. The approximate trend of urbanization in the United States is shown in Figure 1.2; the estimated present distribution of population between rural and urban areas in different countries is given in Table 1.3.

Table 1.2 Estimated population distribution (%) among the three economic sectors for selected countries (1990)

Country	Economic Sector		
	Primary	Secondary	Tertiary
United States	2.8	26.0	71.2
United Kingdom	2.2	29.1	68.7
The Netherlands	4.6	25.6	69.8
Norway	6.3	25.3	68.4
France	5.5	28.8	65.7
Japan	7.3	34.2	58.5
Germany	4.0	38.1	57.9
Italy	8.6	31.4	60.0

Source: ILO, *Economically Active Population 1950–2010*, 4th edition, Geneva 1997.

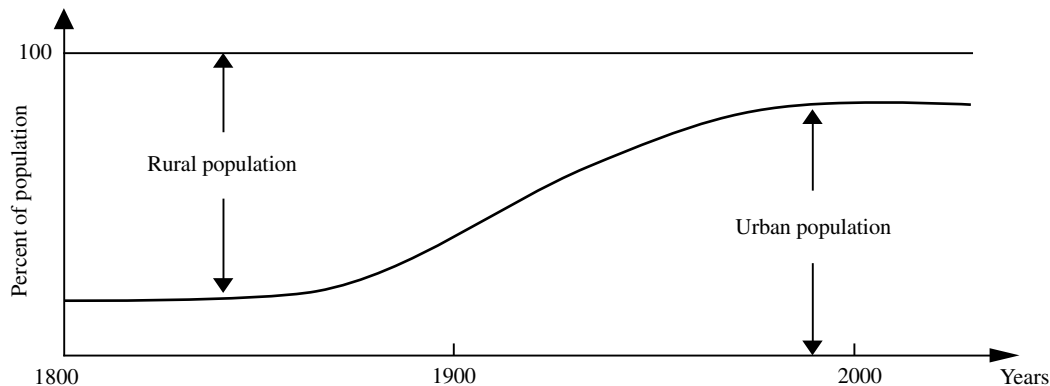


Figure 1.2 The trend of urbanization in the United States

Table 1.3 Changes in shares of urban population in different countries due to the urbanization process^a

Country	Percent of Population in Urban Areas ^b				
	1800	1850	1890	1970	2003 ^e
Germany ^c	7.3	10.6	30.0	79.6	88.1
The Netherlands	29.5	29.0	43.0	55.9	65.8
England/Wales	21.3	39.5	61.7	(U.K.)77.1	(U.K.)89.1
Canada	—	8.5	17.1	75.6	80.4
United States	3.8	12.0	27.6	73.6	80.1
France	9.5	14.4	25.9	71.1	76.3
Belgium	13.5(1820)	20.8	34.8	93.8	97.2
Russia	3.7	5.3	9.3	62.5	73.3
Brazil	6.7	7.4	10.2	55.8	83.1
Mexico	5.8	5.9	13.0	59.0	75.5
Japan	—	—	13.1	53.2	65.4
Italy	4.4 ^d	6.0 ^d	20.6	64.3	67.4

^a The data for 1800, 1850, and 1890 are from Weber (1899), Table CXII; they include cities with populations greater than 10,000. For 1970 from the United Nations, Common Database (UN Population Division).

^b Data are for the closest census to the quoted years.

^c The first two columns refer to Prussia, the third to Germany, the fourth to West Germany, and the fifth to present-day Germany.

^d Includes only cities with populations greater than 100,000.

^e *Urban and Rural Area 2003*, Population Division, United Nations.

Table 1.4 Number of cities with population over 100,000 by continent^a

Continent	Year							
	1700	1800	1850	1900	1930	1950	1970	2002
Europe	10	23	48	147	245	348	567 ^b	796
Asia	30	40	55	90	172	290	702 ^b	1962
Africa	1	1	2	7	16	39	123	322
Americas	—	1	9	51	142	192	440	919
Australasia	—	—	—	4	10	10	15	27
Total	41	65	114	199	585	879	1847	4026

^a The data are from Weber, A. F. (1899), Lehner F. (1969); and the United Nations, *Demographic Yearbook*, 1972 and 2002. Considerable variations exist in definitions of cities and reporting dates among sources and countries.

^b An estimated 238 USSR cities were distributed as follows: 167 to Europe and 71 to Asia, based on approximate shares of the country's population between the two continents (7:3). The two numbers are therefore approximate.

Coincident with the industrial revolution, food production also intensified and its supplies increased. Eventually, general living conditions improved and medical care progressed. These developments were major causes of the rapid population growth that has occurred since the eighteenth century. It is estimated that for many centuries world population fluctuated at a level between 300 and 500 million. This figure began to increase in about 1800 and grew to 1.2 billion in 1850, 1.6 billion in 1900, 2.5 billion in 1950, 3.6 billion in 1970, and 6.3 billion in 2003.

The process of urbanization, compounded by the population increases, resulted in explosive increases in urban populations. This phenomenon has been worldwide, as can be seen from the rapidly rising number of cities with populations over 100,000 on each continent since 1700, given in Table 1.4.

A particular event in transportation played a significant role in making the growth of cities possible. The invention of the first railway by George Stephenson (1781–1848) in England in 1825 represented a major milestone in the development of transportation, which

accelerated the industrial era and stimulated the growth of cities. This new mode of transportation possessed speed, capacity, comfort, and reliability many times greater than those provided by any mode previously known. The improved quality and decreased cost of the transportation by rail resulted in increased travel, intensified communications, and a broadening of markets for low-value (bulk) resource materials and products for which transportation costs had previously been prohibitive. Thus the limit on city size imposed by the capacity of transportation systems to supply materials and goods was virtually eliminated. The benefits from railroads were so great that, following their introduction in the western countries around 1830 to 1840, construction of their networks proceeded rapidly; by the end of the nineteenth century, virtually all European and North American cities depended on railroad services for their economic functioning and growth.

1.2 BEGINNINGS OF PUBLIC TRANSPORTATION

With one limitation on city size (supplies) removed, the pressure for resolving the other (internal travel) became increasingly important for the growing cities and led to many efforts toward inventing new urban passenger transport modes. Numerous attempts failed, but the successful ones had direct and very significant impacts on cities. Before proceeding to these new modes, however, it will be useful to briefly review their somewhat scattered antecedents.

1.2.1 Public Transportation before the Nineteenth Century²

The Greek myth of Chiron, ferryman of the Styx, attests to the ancient provenance of the *boat* as a public conveyance. *Ferries* were again used extensively in late-medieval commercial centers such as Venice and London. Several organized forms of interurban public

transportation appeared during the sixteenth century. Under the *posting* system, horses and horse-drawn post chaises were hired out for travel between posting points along major roads and highways. *Stage wagons*, used primarily for the transportation of goods, were operated on fixed routes to regular schedules from the beginning of the sixteenth century; faster *stagecoach* services, carrying only mail and passengers, appeared soon afterward.

During the seventeenth century, these methods of transport organization were adapted to intraurban conditions. Three of the new urban modes deserve special mention.

1. *Coaches*, hired out for intraurban trips, first appeared in London around 1600. In 1634, the proprietors of these hackney coaches obtained permission to ply the streets for hire, and by 1694 there were 700 licensed hackney coaches in London. This form of transport, the ancestor of the modern taxicab, was introduced in Paris as the *fiacre* in 1612.
2. The *sedan chair*, mounted on wooden poles and carried through the streets by a pair of "chairmen," was a significant form of urban public transportation in large European cities during the seventeenth and eighteenth centuries. Public-hire sedan chairs first appeared in Paris in 1617. They were introduced in London in 1634 and were still being used there as late as 1821.
3. In 1662, a *public coach* service operating on fixed routes was introduced in Paris. Blaise Pascal was one of the instigators of the scheme. Each vehicle had seating for eight passengers and services were provided on five routes. This early predecessor of modern forms of urban transit continued in operation for approximately 20 years.

These modes, however, were "public" only in the narrow sense of the word. Only the wealthy could afford them; their character is well illustrated by the official regulation, which excluded all but "bourgeoisie and people of merit" from Pascal's coaches. Conditions that would favor the development of large-scale

²The principal sources for this section are Causse (1972), Hart (1962), and Pratt (1912).

public transport systems available to large sections of the public did not arise until the nineteenth century.

1.2.2 Horse-Drawn Omnibuses³

The horse-drawn omnibus was, in effect, a long box on wheels, distinguished from its immediate antecedent, the stagecoach, by its higher passenger capacity. Such vehicles (known as “long stagecoaches”) were operating around London as early as 1798, but it was in France that they acquired the name by which they were to become generally known, and it was in France that they were first used in inner-city areas. Stanislaus Baudry established the first “omnibus” service in Nantes in 1826; omnibuses appeared in Bordeaux in 1827; and in 1828 Baudry obtained official permission to run 100 of the new vehicles on 10 fixed routes in Paris.

In 1829, George Shillibeer introduced an omnibus service in London. His vehicles were larger than those operating in Paris, carrying 20 passengers as against 14 in Paris, and drawn by three horses instead of two. Initially, Shillibeer was not permitted to stop for passengers in the inner streets of London, where the hackney coaches had a monopoly and his omnibuses were in direct competition with the “short stages,” which had capacities of only four or six seats. In his advertising he emphasized the speed and punctuality of the service, which was well patronized from the start and soon imitated by other entrepreneurs. The lifting of the London hackney coach monopoly in 1832 enabled the omnibus proprietors to run the high-capacity mode of operation for which their vehicles were best suited.

The first omnibus type of service in the United States was in New York City, where in 1827 Abraham Brower commenced operation on Broadway with a 12-passenger open-sided vehicle called *The Accommodation*. Within eight years the city had more than 100 omnibuses. In New York, as in London at the same time, rivalry between competing omnibus proprietors

was fierce, and recklessly driven omnibuses were a notorious hazard to pedestrians.

Within 20 years there were regular omnibus services in the other leading ports of the eastern seaboard: Philadelphia (omnibus introduced in 1831), Boston (1835), and Baltimore (1844) as well as in many European cities, such as Prague (1829), Liverpool (1831), Budapest (1832), Birmingham (1834), St. Petersburg (1835), Lyon (1837), and Leeds (1839). The omnibuses arrived somewhat later in Germany than in other parts of Europe: for example, in Berlin (1837), Dresden (1838), Hannover (1852), Leipzig (1860), and Munich (1861). Photo 1.2 shows several omnibuses from that era in Paris.

The great strength of the omnibus was its operating flexibility, and this—combined with gradual improvement in the condition of city streets—gave it a commanding position in urban transit during the middle third of the nineteenth century. Indeed, omnibuses continued to operate successfully in some European cities in the face of competition from rail modes of higher performance until they were finally superseded by motor buses in the first decade of the twentieth century.

Omnibus design varied considerably from place to place. The London omnibus in its final form was the model for its successor, the well-known double-decker motorbus; its evolution on London’s narrow streets is therefore of special interest. The first omnibuses in London were very cramped inside, as small as 4 ft 6 in. (1.40 m) high and 4 ft 6 in. wide, with wooden seats running down the side walls and entrance through a door at the rear. During the 1830s some passengers began to sit beside the driver on his seat, and after changes were made to the licensing provisions, they began to sit behind the driver on the roof. By 1847, “knifeboard” seating had been introduced; with this system the “outside” passengers sat back-to-back along the main axis of the roof. In 1856, ceiling heights were raised, ventilation was improved, and steps were added to give better access to the roof. In 1880, a new bus design incorporated lateral “garden seats” in place of the longitudinal knifeboard; other improvements included a swiveling front axle and upholstered seats inside the vehicle. But it appears that no roofing for the upper deck was provided until after

³The principal sources for this section are Barker (1963), Carter (1973), Miller (1941), and Risch (1957).



Photo 1.2 Horse-drawn omnibuses in Paris (Courtesy of RATP, Paris)

the conversion to mechanical traction, in the early years of the twentieth century.

1.2.3 Horse-Drawn Tramways⁴

In its earliest form, the horse tram, or horsecar (as it was called in the United States),⁵ was simply an omnibus running on rails. Here the technology of rail

guidance found its first specifically urban application. The horsecar's low rolling resistance gave it several marked advantages over the omnibus: more efficient use of horsepower, higher passenger capacity, and improved comfort. Moreover, since the horsecar ran on smooth rails instead of irregular cobblestones, the size of the wheels had little effect on the vehicle's riding characteristics, and with small wheels the car body could be built conveniently low and wide. These basic vehicle characteristics were carried over in the mechanized rail modes which superseded the horsecar toward the end of the nineteenth century.

The first horse-drawn "street railway" opened in New York in 1832. This first use of rail vehicles for urban transit was a line that ran from Harlem to lower Manhattan and was intended as a feeder to the proposed Harlem-Albany railroad. The vehicles initially used were like oversized stagecoaches. They had three

⁴In addition to the sources for the preceding section, material in this section is also based on Klapper (1961) and McKay (1976).

⁵The terms "horse-drawn trams," "horse trams," and "horsecars" all refer to rail vehicles towed by horses. "Horse tramway" or "horse-drawn street railway" refers to the lines served by these vehicles. These terms are used here interchangeably, according to the local terminology in the country or area under discussion.

compartments, each seating 10 passengers, plus 30 more on the roof.

The New York line flourished, and a horsecar line was built in New Orleans during the 1830s, but it was not until the 1850s that horsecars began to appear in other American cities: in Boston in 1856, and (within the next four years) in Baltimore, Chicago, Cincinnati, Philadelphia, and Pittsburgh. Probably an important reason for the widespread acceptance of horsecars in America at that time was the introduction of grooved rails, laid flush with the surface of the street, instead of step rails, which protruded above the pavement and so presented a hindrance to street traffic. Alphonse Loubat, a French engineer, built the first grooved-rail horsecar line in 1852 in New York.

In 1853, Loubat opened a horse tramway in Paris; but this line, *Le Chemin de Fer Americain*, the first of its kind in Europe, was so conditioned by official restrictions that it can hardly have been a fair demonstration for the new mode. Horse tramway development in Europe did not really get under way until the late 1860s. The first tramway in St. Petersburg opened in 1863, followed by Berlin (1865), Vienna (1865), and Budapest (1866). By 1869, tramways had been introduced in Hamburg, Stuttgart, Brussels, Geneva, and Copenhagen.

In Great Britain, the institutional factors that initially delayed the development of horse tramways were particularly severe. An engineer named William Curtis built the first horse tramway in Britain, at Liverpool in 1860; and George Francis Train, an American entrepreneur, built a line at Birkenhead in 1860. Train built two lines in London, in 1861 and 1862, but local residents forced their closure soon afterward, and permanent tramway services were not established in London until 1870. Subsequent legislation banned horse tramways from central London and gave local authorities the right to acquire tramways after 20 years of private operation. These regulations inhibited private tramway construction and established an institutional environment that would foster the “municipalization movement” some 25 years later. Tramway legislation in other European countries was more favorable to private entrepreneurs: for example, concessions were usually granted for periods of 40 to 50 years.

Horse tramway development in Europe proceeded very rapidly during the 1870s; for example, tramway networks were built in more than 16 German cities during that period. Because of their higher efficiency, the tramways could sustain lower fare schedules than the omnibuses, so that they supplanted omnibus services in some middle-class neighborhoods. They also attracted many working-class people who previously could not afford any kind of urban transportation. Two double-decker horse tramways in Paris are shown in Photo 1.3.

Nevertheless, the impact of the horse tramways on city life was more pronounced in the United States than in Europe. American cities, large and small, had tramway lines on all their major streets, and at least in the North, the tramways were a significant element of the post-Civil War boom in suburban housing. Tramway development was subject to fewer official restrictions in America than in Europe, and there were also important differences in physical conditions. In Europe, trams and omnibuses could complement each other, for in most of the old European cities there was a roughly two-level hierarchy of streets: narrow, winding medieval streets, where the omnibuses had the upper hand, and broad boulevards, built in the eighteenth and nineteenth centuries, where the trams had the advantage. On the other hand, the regular grid of broad, straight streets characteristic of American cities tended to minimize the omnibuses' competitive advantage, and for this reason trams tended to replace rather than complement omnibuses in the United States.

1.2.4 Mechanized Street Transit Technologies before 1880⁶

Omnibus and street railway operations were severely restricted in scope as long as they depended on horses for traction. The costs involved in purchasing, feeding, and stabling horses were large and constituted a large proportion of the overall cost of transit operations. Horses were quickly worn out by street work, and their

⁶The primary sources for this section are Barker (1963), Hilton (1982), Klapper (1961), McKay (1976), and Miller (1941).

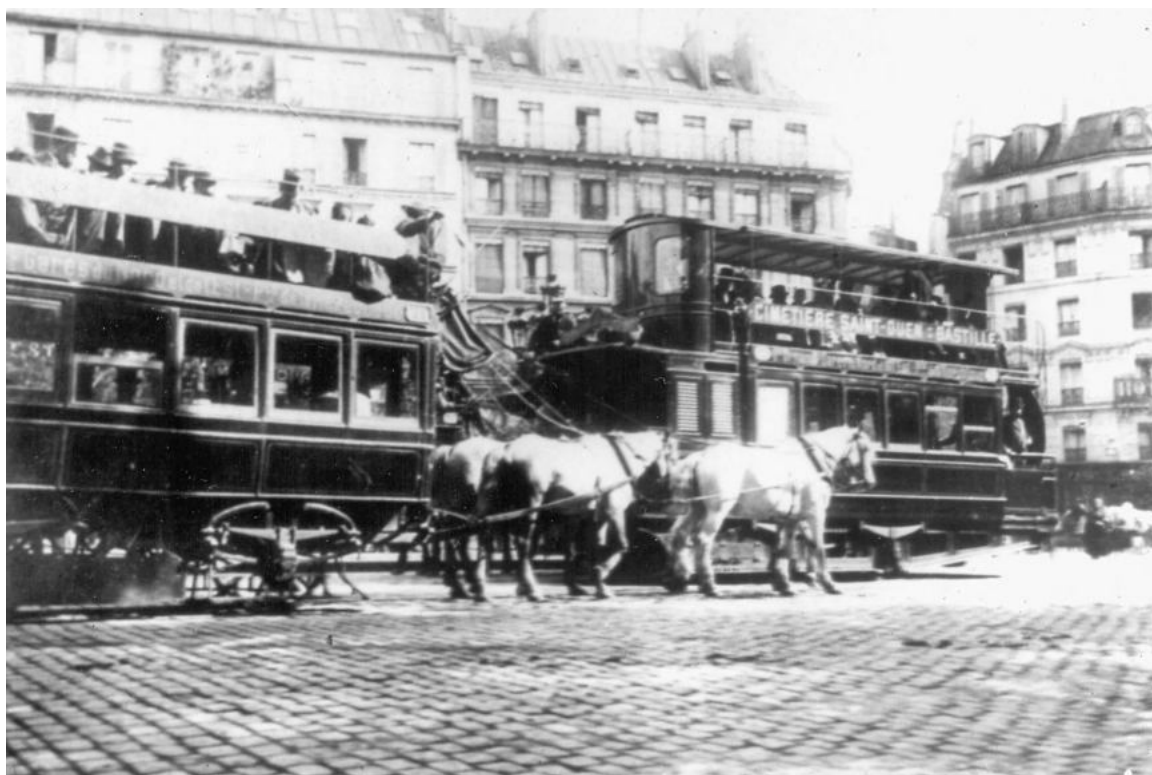


Photo 1.3 Horse-drawn tramways (Courtesy of RATP, Paris)

vulnerability to disease was demonstrated dramatically in 1872, when thousands of horses in the eastern United States died in the Great Epizootic, an equine influenza epidemic.

The search for a mechanical replacement for horses was concentrated initially upon the proven source of power, the steam engine. Between 1821 and 1840 a number of steam carriages were built in England. These vehicles were heavy, slow, noisy, and cumbersome; of the few that developed beyond the stage of technical experiment, none achieved sufficient success to attract further investment. For example, between 1833 and 1836, Walter Hancock operated regular services with 14- and 22-seat *steam-driven omnibuses* in London, but the vehicles attracted few passengers from the horse-drawn omnibuses working the same route,

and the venture was a commercial failure. Improvements in steam engine technology later in the century led to renewed interest in steam as a source of power for street vehicles, and during the 1870s several models of steam trams went into commercial production. In some cases a small rail-guided steam locomotive drew an ordinary unpowered tram; otherwise, the engine was incorporated in the passenger vehicle itself. It has been estimated that at various times there may have been as many as 2500 steam trams on the Continent, 700 in the United States, and 500 in Great Britain, but only a fraction of them were used as transit vehicles (most were operated as “light railways” in sparsely populated rural areas). The steam trams were noisy and dirty and were therefore unpopular with the public and with municipal authorities. Devices fitted to reduce

noise and smoke emission to acceptable levels rendered the vehicles too heavy for use on tracks laid for horsecars and less profitable than horsecars.

An ingenious solution to these problems was found in the *fireless steam engine*, which used pressurized steam generated in a stationary boiler at a central depot. No boiler was required for the locomotive itself; smoke, sparks, and cinders were eliminated; the dead weight of the locomotive was reduced; and the on-board fireman was dispensed with. This system was first tried in New Orleans in 1873 and was perfected by Leon Francq, a French engineer. Francq's fireless locomotives were adopted on several lines in the Paris suburbs and in a number of French provincial cities during the late 1870s and early 1880s; they were hauling tramways in Lyon until as late as 1905. But they were beset with one major problem: their ordinary operating range (15 km) could be sharply reduced by unusual events such as street congestion or blockage of tracks, leaving them stranded without steam anywhere along the line.

The Mekarski *compressed-air* system, developed in the same period, was similar in principle to the fireless steam engine and had similar weaknesses. Mekarski's tramcars were equipped with piston motors; the motors were driven by air compressed at a central plant and stored on board. They first gained official approval in Nantes (France), where they were in regular service from 1878 until 1913; as late as 1910, there were six compressed-air tramway lines in Paris. But the system was rather unreliable—one of the Paris lines was known popularly as *Reste en Panne* ("breakdown")—and the stationary air compressors consumed inordinately large quantities of fuel. Tests of compressed-air locomotives carried out in England in 1880 showed a rate of coal consumption five times that of ordinary steam locomotives. Several compressed-air trams were tried in British cities during the 1880s, but none went into permanent operation.

The investigation of *electric traction* for rail-guided vehicles commenced during the 1830s, soon after Faraday's invention of a rudimentary electric motor (1831). Thomas Davenport, a blacksmith of Green Mountain, Massachusetts, exhibited a miniature elec-

tric railway in 1837, and in the following year an engineer named Robert Davidson ran a locomotive powered by electric batteries on the Scottish railway lines, achieving speeds of over 6 km/h. Various experiments of a similar nature were carried out during the 1840s and 1850s, but they all depended on storage batteries for electricity supply, and none offered a serious challenge to the established modes of traction. Power supplied by electric batteries was "fully 20 times as costly as equivalent power supplied by a steam engine," and economical methods of supplying large quantities of electricity did not become available until the late 1870s (see Section 1.3).

Tests were also made with trams powered by *large springs* wound by stationary steam engines (London, 1875; Philadelphia, 1876); during the 1890s *oil and gas motors* seemed to offer some promise of success. Actually, trams driven by town gas fired in Crossley-Holt gas engines were running on a few English lines until as late as 1920.

The *cable car* was the first mechanized mixed-traffic mode to attain widespread commercial success and public approval. Its main mechanical features can be traced to a system of ropes, pulleys, and stationary steam engines developed during the eighteenth century for the hauling of rail-guided wagons on steep inclines in the British mines. Cable traction was used on a suburban railway line in London during the 1840s and on New York's first elevated railway, opened in 1868; but in both cases the cable system was found to be unsatisfactory and was replaced by conventional steam locomotion. The world's first cable-operated street tramway opened in 1873 on San Francisco's Clay Street Hill. Andrew Hallidie, a manufacturer of ropes and cables for the California gold fields, was the inventor and instigator of the project. The system comprised an endless wire-hemp cable driven by a stationary steam engine, a cable car running on rails with a gripping device mounted on board, and a driver or "gripman." By operating the "grip," the gripman could attach the car to the moving cable; to stop, he would release the grip and apply a wheel brake. The cable, guided by rollers and pulleys, ran in a slotted conduit built into the pavement between the rails; in

the engine house there was a movable counterbalanced pulley system to maintain cable tension.

In several respects Hallidie's system was clearly superior to the horse tramway: it was clean, running costs were very low, and high running speeds (up to 15 km/h) could be reached even with full passenger loading. Steep hills could be negotiated without difficulty and actually more safely than in most other traction technologies: gripping the cable, the car would travel uphill or downhill at a constant speed without the possibility of skidding or running away. An interesting feature of the system is that the cars traveling downhill when attached to the cable assist the traction of other cars—a simple and effective method of energy regeneration.

These advantages seemed to justify the large capital investments involved, and during the 1880s cable tramways were installed on many high-volume city routes, especially in the United States. By 1893, there were approximately 800 km of cable tramway in 16 American cities; the largest network was in Chicago, with 135 km of track, 496 grip cars, and perhaps 1000 trailer cars. Cable car systems were also built in large cities in England, Scotland, France, Portugal, Australia, and New Zealand. The first in Europe was London's High Gate Hill line, opened in 1884; the largest network in the world was in Melbourne: 153 km of track, built between 1884 and 1891.

But by 1890 the electric tramway (trolley) system already offered a cheap and practical alternative to cable traction. The simplicity of the trolley system offered a means of avoiding the imperfections and dangers of cable haulage. For example, negotiation of the giant pulleys installed at line crossings and bends often involved safety problems, and when the grip snagged in a frayed strand or loose cable, the cable car would be dragged along city streets, out of control until the depot engineers were notified and the driving engines halted. Consequently, most cable car systems were converted to electric traction or abandoned by 1905.

Nevertheless, on very steep gradients, cable traction has certain advantages over other modes, even today. Cable cars still provide effective service on steep hills in San Francisco. Other technologies with cable trac-

tion, such as *funiculars* (inclines) and *aerial tramways*, remain in extensive use in mountainous terrains and in many cities with special geographic conditions (e.g., Pittsburgh, Hong Kong, Salzburg, and New York's Roosevelt Island), as discussed in Chapter 9.

1.3 INVENTION OF ELECTRIC STREETCARS/TRAMWAYS⁷

The development of the dynamo and electric motor during the 1870s, through the inventions of Werner von Siemens (1816–1892), Z. T. Gramme, C. F. Brush, Pacinotti, and others formed the basis of a new industry associated with the generation and distribution of electricity for arc lighting and (after 1879) incandescent lighting. As early as 1855, several European inventors had conceived the idea of using continuous conductors to convey centrally produced electricity to rail-guided vehicles, and the new electrical industry provided the means for the realization of such a scheme.

In 1879, Siemens' firm, Siemens & Halske, built a demonstration electric railway for the Berlin Trade Fair, and two years later the world's first electric streetcar line, developed by the same firm, opened at Lichterfelde near Berlin. For both lines the running rails were used as positive and negative conductors; a similar railway opened at Brighton (England) in 1883.

The use of exposed conductors on a public street was obviously unsatisfactory, and it was clear that fencing off the line for safety (as was done at Lichterfelde) would severely restrict the range of places in which the new invention might be put to work. Electrification of tramway lines therefore proceeded very hesitantly at first, with much effort being spent in the search for a safe and reliable method of current collection. Siemens & Halske took a leading part in this work. For the Paris Exposition of 1880, they equipped a line with an overhead copper-wire conductor, which was set inside a slotted pipe. Current was collected by

⁷The principal sources for this section are Cudahy (1982, 1990), Hering (1892), Klapper (1961), Singer (1960), McKay (1976), Risch (1957), and Sprague (1931–32).

lugs running inside the pipe, taken down to the motor via a cable, and returned to the generator along the running rails. In the same year Siemens & Halske tried small contact carriages running on grooved wheels along a pair of overhead wires on an experimental line at Charlottenburg. But it was in America that the really fruitful technical development—the “breakthrough” in streetcar technology—was to occur.

1.3.1 Beginnings of Electric Streetcars in the United States

Thomas Edison built an experimental rail conductor tramway at his Menlo Park factory in 1880. The first regular electric streetcar service in the United States commenced operation in Cleveland in 1884; for this line its designers, Bentley and Knight, used a small “plough” to draw current from a pair of copper wires, which were laid in a slotted underground conduit between the rails. This system was found to be unreliable, and service on the Cleveland line was discontinued in 1885. Systems employing overhead wires and overrunning “trollers” (similar to those used by Siemens at Charlottenburg) appeared in several American cities during the middle 1880s. The underrunning spring-loaded trolley pole was first used in Montgomery (Alabama) in 1886, but Charles Van Depoele, the author of this scheme, went back to trollers in his subsequent electrification projects. All the electric lines built during this period encountered serious technical problems and few continued in operation for more than a few years.

While Siemens, with his inventions, made the first operational streetcar in Germany, another genius of electric traction in the United States made numerous inventions that eliminated the initial problems and made the streetcar a practical and efficient vehicle. Frank Sprague (1857–1934), a former officer in the American Navy who had worked with Edison on some of his electric railway experiments, set up the Sprague Electric Railway and Motor Company in 1884. In May 1887, he was awarded his first major contract, for the supply of electrical equipment and vehicles on 19 km of line in Richmond (Virginia). This was larger than

any other electric tramway network in the world and twice as large as any then built in the United States. Steep hills and poorly laid track presented a severe test to the performance and durability of Sprague’s equipment; but through a process of “patient experimentation, hard work, and attention to detail” (Klapper 1961), Sprague and his assistants found satisfactory solutions to most of the problems confronting them. They designed a power generation and distribution system that could meet peak demand conditions, and they perfected the underrunning trolley pole. To drive the streetcars, they used Sprague’s heavy-duty motors, which were capable of withstanding sudden surges of current; to minimize wear and tear on the drive gears, the motors were hung in “wheelbarrow fashion” between axle and sprung frame; speed control was by series/parallel switching and heavy-duty rheostats. This work established a sound technical basis for the streetcar industry in America.

The Richmond network opened in February 1888 and immediately attracted the attention of American street railway officials. Because operation by electricity was very much less costly than horse traction, street railway proprietors were able to reduce fares and so attract more passengers; with a larger market, they were able to build streetcar lines on routes that would have been unprofitable with horse traction. The dramatic impact of this technology can be seen from several statistical figures. It is estimated that in 1880 the total length of “street railway” networks (line lengths) in U.S. cities was 3300 km (2050 mi), virtually all of it with horse traction. By 1890 the length had increased to 9305 km (5783 mi), of which approximately 800 km was with cable and 1900 km with electric traction. San Francisco’s Market Street already had four tracks at that time (Photo 1.4). By 1902, virtually all of the total length of 26,782 km (16,645 mi) of lines was equipped with electric traction, and by 1912 the total length of lines had increased to 48,975 km (30,438 mi). Intensive streetcar traffic in Philadelphia around 1900 can be seen in Photo 1.5.

This development was closely linked with the rapid growth of urban population, which was evident both in the expanding industrial metropolises of the Northeast and in the booming farm produce and railroad



Photo 1.4 Cable car with trailer of the Clay Street Hill Railroad Co., San Francisco, ca. 1878 (Courtesy of San Francisco Cable Car Museum)

capitals of the Midwest. By virtue of their range and speed, the electric streetcars greatly increased the capacity of urban centers to accommodate population growth.

The introduction of cable and then electric streetcars was interrelated with some important changes in transit organizations. The original horsecar services were typically provided by many different operators, some of whom had only a single line. Coordination among them was poor, causing serious inconvenience to the public. For trips involving travel on more than

one route, passengers had inconvenient transfers and paid double fares. Since cable, and particularly electric traction, required substantial investment, its introduction accelerated the trend toward mergers of many small operators into larger companies. These consolidations led to greater efficiencies of operations and to improved transit service for the public through better schedules and information, integrated fares, and easier transfers. Increased ridership, attracted through better service, generated additional revenue.

The rapid growth of cities and industries resulted in increasing demand for travel in cities. Transit companies, facing rapid expansion and foreseeing the likelihood of imminent replacement of thousands of horses by mechanical traction, were interested to work on technical inventions as well as organizational improvements. It was thus logical that an initiative of H. H. Littell, of St. Louis, to form a national association of transit companies was widely accepted. At the meeting in Boston in 1882, the American Street Railway Association, predecessor of the present American Public Transportation Association (APTA), was founded. At that time, there were 415 street railway companies operating 18,000 streetcars and 100,000 horses. Cudahy



Photo 1.5 Streetcar terminal on Market Street at Delaware Avenue in Philadelphia, 1900

(1982, 1990) presents an extremely detailed and lively description of that event as well as the history of transit development since that time.

International development of transit systems led to the founding of the Union Internationale des Transports Publics (UITP) in Brussels in 1885. That organization, the International Association of Public Transport, continues today to be the world's leading organization of urban public transport.

In some U.S. cities, few official restrictions hindered street railway development during this period. Many municipalities granted perpetual franchises to streetcar entrepreneurs. The entrepreneurs were able to plan their routes to ensure the profitability of their investments, often without much concern for community and environmental impacts. For example, overhead wiring and supporting structures were erected with little or no consideration of their visual quality, a major concern in many European cities during the same period. The fact that the entrepreneurs' activities generally happened to be beneficial to the general public was in such cases of secondary importance in the minds of urban politicians steeped in the ideology of "free enterprise" and material progress. However, in the older, established cities—such as Boston, New York, Philadelphia, and Washington—awareness of the possible impacts of transportation facilities on the environment was much greater. As in Europe, city authorities often demanded the construction of tunnels instead of elevated steel structures. Regulation was sometimes excessive. In Washington and some parts of New York, transit companies had to provide an underground power supply for streetcars instead of overhead wires, while the transit company in Philadelphia had to maintain the entire pavement on all the streets on which its streetcars ran.

1.3.2 Introduction of Electric Tramways in Europe

In Europe, governments and influential sections of the public tended to regard the planning of tramway services as a public responsibility. This attitude, combined with systems of stringent government regulations established for the horse tramways, had substantial ef-

fects upon the development of electric tramways in Europe.

In 1890, the total length of electric tramway lines in Europe was only 96 km. Tramway electrification proceeded more slowly than in the United States until the last few years of the nineteenth century. This initial delay was due largely to the importance attached to aesthetic aspects of urban development in European city politics. Influential members of European city governments felt that streets and squares should not be wrapped in an untidy web of overhead wires and believed that further technical work would yield a feasible and visually unobtrusive alternative to the American overhead trolley system. Consequently, manufacturers of electrical equipment were forced to devote much effort to the search for safe, reliable, and efficient systems of power distribution and power pickup that would not require overhead wires. Three main alternatives were explored: battery traction, continuous-contact conductors in underground conduit, and surface contact systems.

Battery propulsion entailed the use of large storage batteries, charged at a central power station and carried on board the tramways. The chief advantages of this method were safety, low infrastructure costs, and freedom from the technical problems associated with continuous conductors. Battery-powered streetcars were given extensive trials in France, Belgium, Germany, and Britain during the 1880s and 1890s, but with very limited success. The problems encountered with battery traction were quite similar to those associated with traction by fireless steam engines and compressed air: running costs were high, and the battery cars lacked reserves to meet the demands of peak traffic loadings. In addition, the batteries were expensive to purchase, and they added about 2½ tons to the weight of each car.

Conduit and surface-contact systems were based on the use of continuous underground conductors. In the former systems, power was picked up by means of a plough moving in an underground slotted conduit.⁸ With the surface-contact systems, power was provided

⁸ A similar system was used on the streetcar system in Washington until its closure in 1962.

by contact between a long skate mounted under the tramway and iron plates or studs set between the running rails at intervals somewhat less than the length of the skate; each plate was connected to the underground conductor through a switch activated by the skate, so that the plates would be “live” only when a tramway was passing over them. These systems were used quite extensively in a number of European cities between 1890 and 1910, notably the surface-contact system in Paris and the conduit system in Budapest. But both systems were expensive to install and both were unreliable in operation: underground conduits easily became clogged with mud, and surface-contact plates remaining “live” on the open streets presented a lethal hazard to iron-shod horses.

The pace of tramway electrification in the industrial nations of central Europe quickened after 1895: successfully constructed networks served to demonstrate the merits of the new technology and to break down official resistance. Strong competition among tramway promoters placed municipalities in a favorable bargaining position, enabling them to make the best of the available systems. The range of choice encompassed the three nonoverhead systems described above, plus the overhead conductor system, for which power pickup was either by Sprague’s underrunning trolley or by the *Bügel* or “bow” (first used commercially by Siemens’ firm to equip lines in Hannover and Dresden in 1893). Nonoverhead systems were used quite frequently for inner-city routes, and (in “mixed” systems) for portions of routes in squares and streets of high symbolic importance. These “aesthetically pure” lines were so plagued with operating difficulties that, by 1900, the search for alternatives had lost its impetus and the overhead system was being adopted on almost all new tramway projects. The main aesthetic issue now was mitigating the visual impact of the overhead system, and on this point the tramway entrepreneurs went to considerable lengths to satisfy the municipalities. Heavy feeder cables were laid underground; elegant cast-iron poles and wall brackets, carefully set out, supported the wires; and in many cities the poles incorporated streetlighting fixtures.

European municipalities were willing to accept the overhead system because they recognized the fact that the electric tramway offered positive social benefits, resulting primarily from greatly increased travel speed and reduced fares. Cheap transportation would enable laborers and factory workers to travel considerable distances between their places of residence and places of employment; thus suburban housing would also become available to the lower economic classes, and the crime, disease, and “moral degeneracy” characteristic of the overcrowded inner-city slums could be alleviated. Fares and tramway lines therefore became important issues in negotiations between municipalities and tramway entrepreneurs. Fare rates—and, in many cities, special “workmen’s fares” for early-morning and late-afternoon travel on weekdays—were specified in franchise agreements; and tramway companies were often compelled to build initially unprofitable suburban lines, sometimes extending beyond existing built-up areas, in return for lucrative concessions on more heavily traveled routes. There is evidence indicating that the low fares made transit available to all but the very poorest sections of urban society, and although the construction of new lines in suburban and semirural areas tended to push up rents and property values in those areas, it did facilitate a gradual diffusion of residential population outward from the crowded central city areas.

In 1900, tramway electrification was at its height in Belgium, France, and Germany. In Great Britain, the tramways legislation of the 1870s, which limited tramway companies’ tenure of their lines to periods of 21 years, was such a strong deterrent to private investment that large-scale electrification did not commence until the late 1890s, and then generally under municipal ownership and operation. Glasgow was the pioneer in tramway “municipalization.” The Glasgow (Municipal) Corporation took over the city’s horse tramways in 1894, on the expiration of the operating company’s lease, and in 1899 commenced conversion to electric traction. By 1911, four-fifths of the tramway passengers in Britain were being carried on networks owned and operated by local authorities. At least in its early, constructive stages, the British institutional innovation

was eminently successful, and municipal enterprise became an important factor in tramway development on the Continent, especially in Germany, after 1900. In the United States, municipalization “was studied with interest and even awe” (McKay 1976), but was followed only several decades later.

The magnitude of what is sometimes referred to as the “tramway revolution” in Europe is illustrated by the threefold increase in tramway track length that occurred from 1890 to 1910. A typical European tramway with trailer from that period is illustrated in Photo 1.6. During the same period, the number of annual rides per capita (“riding habit”) in the four largest U.S. cities increased from 195 to 293; in the four largest British cities, from 56 to 226; and in the four largest German cities, from 56 to 203. Although portions of these increases were due to the new rapid transit systems opened at that time, the rate of increase was very similar in cities with streetcars only. These statistics also reflect the fact that in the beginning of this “revolution,” horsecar networks were more extensively developed in America than in Europe; thus the impact of electric traction was relatively greater in some European countries than it was in the United States.

1.4 STREET TRANSIT DEVELOPMENT SINCE 1900

At the beginning of the twentieth century, the basic breakthrough in transit—invention of an operational mechanized technology—had been achieved, and streetcar systems were in use in most large and medium-sized cities. Yet, that was only the beginning of the progress that was to follow in subsequent decades. Streetcar vehicles and infrastructure were further improved and new modes—notably the motorbus and trolleybus—were invented and made operational; the motorbus eventually became the dominant street transit mode.

1.4.1 Streetcars/Tramways⁹

The typical electric streetcar, from its introduction in the late 1880s up to World War I, was a short, two-

⁹The text in this section is based on APTA (2004), Cudahy (1982), FERC (1920), Klapper (1961), Miller (1941) and Smerk (1968).

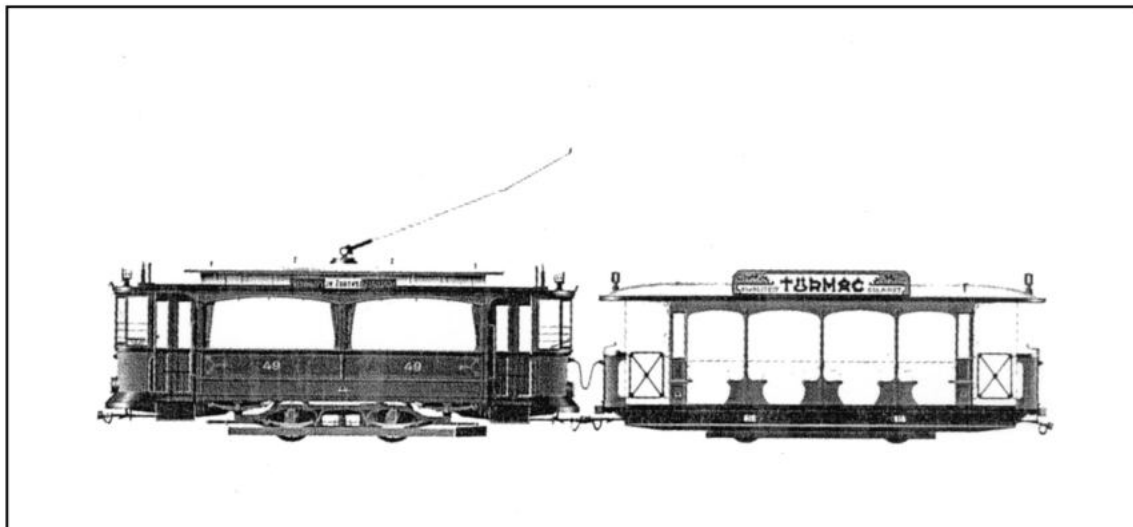


Photo 1.6 Amsterdam’s two-axle tramway with an open trailer in 1900 (Courtesy of Gemeentevervoerbedrijf, Amsterdam)

axle, wooden-body vehicle operated by a driver and conductor. In many respects it resembled its immediate predecessors, the horse tram and cable car. Somewhat enlarged (up to about 10 m in length) and often towing one or two trailers (Photo 1.7), this type of vehicle was still widely used in many European cities as late as the 1960s.

Four-axle vehicles, 12 to 16 m long, made their first appearance during the 1890s, mainly on American interurban lines; however, their introduction into urban transit systems was slower. Most U.S. cities operated two-axle cars around 1900; only during the following three decades were most of them replaced by four-axle ones. The change was gradual; still, in 1916, a new two-axle lightweight car designed for one-person operation, the Birney "Safety Car," was introduced and extensively used on lightly traveled routes. By the 1920s, four-axle cars already dominated most transit systems in large cities. Some transit systems used motor cars with trailers on heavily traveled routes, but this practice was far less common in American than in European cities.

Early streetcar fleets in many cities included special summer cars with open sides and peripheral footboards instead of central aisles. Designed for pleasure, these cars were very popular and in some cities were retained through World War II (Photo 1.8). A few cities

also had convertible cars. Both types were, however, gradually replaced by enclosed cars (Photos 1.9 and 1.10 show some typical models). Most of the cars up to about 1930s were still operated with two-person crews but had fare payments at entry or exit, providing directional passenger flow inside the vehicles.

In spite of their vital role in cities and increasing ridership, transit companies in U.S. cities were far from continuous financial success or even operation with reasonable fiscal stability. Competition among different streetcar companies on parallel lines prevented the achievement of economies of scale in operations. In some cities, jitneys and later buses "skimmed the profitable cream" of transit ridership. Moreover, the costs of labor and other operating costs were rising, but regulatory bodies did not allow corresponding increases of fares. For example, the traditional 5-cent fare was retained in some cities even through World War II, although long before that time such a fare could not cover operating and maintenance costs. Since transit companies had no other financial assistance, these conditions resulted in many bankruptcies.

An early widespread financial crisis in the transit industry occurred at the time of World War I. In 1919, President Woodrow Wilson appointed the Federal Electric Railway Commission to study the problem. The Commission's report, submitted in 1920, con-

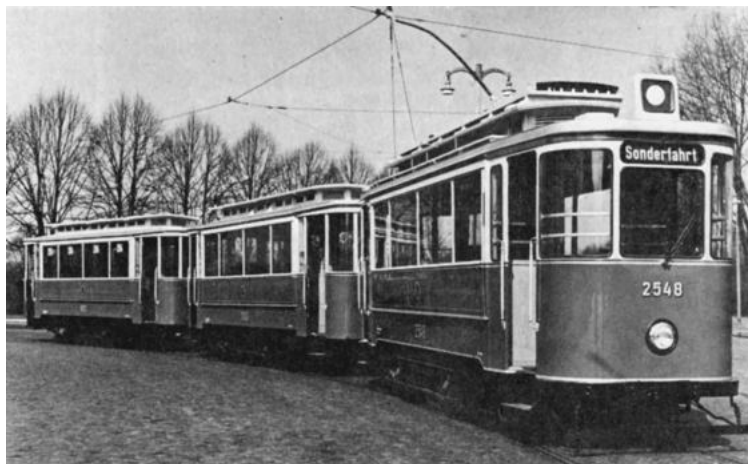


Photo 1.7 A typical European two-axle car with two trailers in Hamburg, operating between the 1920s and 1960s

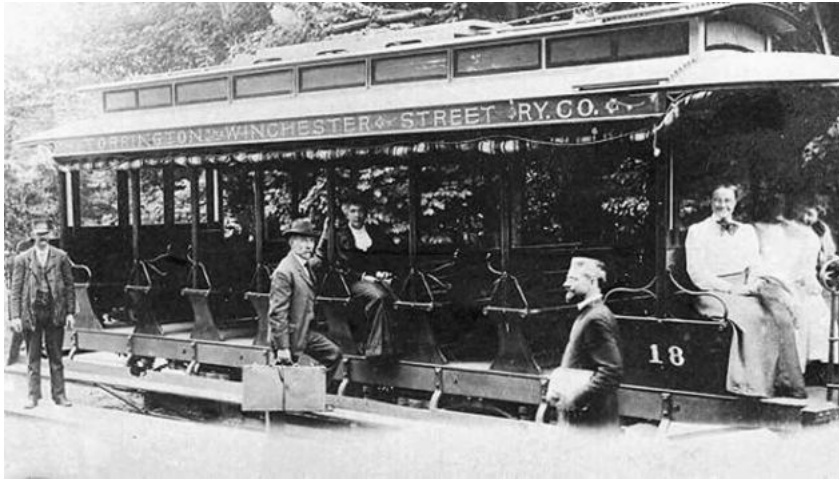


Photo 1.8 Open four-axle streetcar in New Haven, operated until the late 1940s (Courtesy of William D. Volkmer collection)



Photo 1.9 Large four-axle motorcar in Newark, New Jersey in 1935 (From the collection of Jeffrey Marinoff)



Photo 1.10 Articulated streetcar (over 30 m in length) in the Public Square, the main transit junction in Cleveland, ca. 1946 (From the collection of J. W. Vigrass)

tained some extremely progressive statements about the role and nature of public transportation (see Section 1.6) and a set of recommendations for improvements of its condition. Only a few of these recommendations, however, were implemented. Fare increases allowed financial recovery of some transit companies, but the continuing precarious financial condition of others was reflected in inadequate maintenance of tracks and other infrastructure and in the operation of obsolete rolling stock. This condition was a major obstacle to the provision of efficient transit services and later contributed to conversion from streetcars to buses.

During the 1920s and early 1930s, competition from the private automobile began to have a significant impact on streetcar ridership in the United States. In addition to diverting passengers, the automobiles created congestion, which impeded streetcar operations. The old cars, which had low acceleration, were poorly suited to running in mixed traffic. To improve operation in congested streets and avoid the investment required for track maintenance, transit operators began to convert streetcar lines to bus operation.

The problems of streetcar decline in the U.S. cities in the late 1920s were seriously discussed by the transit

industry. The American Electric Railway Association (AERA) at its 1929 conference concluded that if the streetcar was to retain its important role, it would have to match the performance, comfort and modern image of its competitors: the bus, trolleybus, and private automobile. The conference gave Thomas Conway of the University of Pennsylvania the task to organize a project that would develop an entirely new streetcar design that would use state-of-the-art technology to achieve these goals.

At its 1930 conference, AERA followed Conway's recommendation that a special committee be founded to perform this research and development task as a joint venture of transit companies and vehicle manufacturers, designated the Presidents' Conference Committee (PCC). This project, led by Clarence F. Hirschfield of the Detroit Edison Company, was one of the most thorough and efficiently organized development ventures in the history of transit technology. Its product, the PCC car (Photo 1.11) was in many respects far more advanced than any of its predecessors. An extremely quiet vehicle with soft suspension, it was able to accelerate and brake rapidly thanks to sophisticated indirect motor control (Cudahy 2003).



Photo 1.11 PCC car, circa 1950 (From the collection of J. W. Vigrass)

The first commercial application of the PCC car was in Brooklyn in 1936. Acceptance of this model was slow at first: by 1940 only about 1100 vehicles had been purchased. Later the orders accelerated, so that by 1952 about 6000 PCC cars had been produced in the United States by St. Louis Car Company, and Pullman-Standard Car Manufacturing Company and in Canada by Canadian Car and Foundry. At that time production of surface rail transit vehicles in the United States ceased, and it was resumed only about 20 years later. Modified versions of PCC cars continued to be produced in Europe (Belgium and Czechoslovakia), however.

The PCC car did help to improve the competitive position of transit systems vis-à-vis the private automobile and to slow down the conversion of streetcars to buses; but in the absence of other improvements—particularly provision of separate rights-of-way for which support from city authorities was not available—the PCC car was not able to secure long-term stability for the streetcar mode or for transit's role in cities in general. About 1950, many U.S. cities still had

extensive streetcar networks, but they would not last long.

In many cities it was considered desirable to “mix” transit with auto traffic rather than provide it with priority treatment and maximum possible separation. The conversion of streetcars to bus and trolleybus operations, which began on a large scale during the 1930s, was discontinued by the increased demand for transit services during World War II; it resumed in the late 1940s. By 1960, streetcar systems remained in only about a dozen U.S. cities.

The change from rail to road transit modes in small cities and on lightly traveled lines in large cities was a logical consequence of the improved technology and economics of buses and trolleybuses. But for numerous major transit systems with heavy passenger volumes, many of which even had fast lines on separate rights-of-way, the change from rail to road modes represented a degradation of service and contributed greatly to a further decrease of transit ridership. The change was a result of the absence of any significant public assistance to transit, either financial or in securing reliable

transit operations on city streets. Transit operators were thus forced to adopt the lowest-cost mode in the short run, regardless of long-term costs and impacts on ridership.

Another major force in this elimination of streetcars even where they offered superior services on exclusive rights-of-way (Los Angeles, Detroit, Cleveland, and many other cities) was the National City Lines consortium. As researched and reported in a congressional testimony by Snell (1974), The National City Lines was organized by General Motors Corporation (GMC), Firestone, and Esso Oil Company, which had the common goal of replacing electrified rail systems by the highway vehicles (buses and automobiles) that purchased their products—buses, cars, rubber tires, and oil. National City Lines purchased transit companies in many cities. To eliminate the often very popular streetcars, their maintenance and modernization were decreased, and then it was proclaimed that “streetcars are an obsolete transit mode.” Buses were presented as “modern” and “flexible” vehicles with many advantages. Their disadvantages—such as the facts that they were smaller, less comfortable vehicles with inferior dynamic and environmental characteristics—were ignored. The virtual elimination of streetcars resulted in a massive loss of ridership and weakening of the image and role of transit in U.S. cities. Black (2006) gives extensive documentation of this destructive development.

In Great Britain and France, transit operators faced many of the problems that appeared in U.S. cities: labor and equipment costs were rising, transit companies were required to perform construction and maintenance of tracks, while bus operators usually had no responsibility for maintaining roads and streets. Cities often took over track rights-of-way for roadway widening. While many French cities had never acquired modern rail vehicles, a number of British operators attempted to modernize their systems and increase labor productivity through the introduction of high-capacity double-decker cars. As late as after World War II, there were several serious attempts to modernize tramway systems. For example, Fitzpayne proposed in 1948 an innovative plan for an upgraded “light railways” sys-

tem for Glasgow (Skelsey 1976), which contained many ideas used in developing light rail transit systems initiated in the 1960s and 1970s. But public policies and governmental attitudes toward transportation in these countries did not provide adequate support for tramway modernization or for public transportation improvements in general. Similar to the events in the U.S., conversion of tramway rights-of-way into street lanes downgraded transit to operation in mixed traffic. Thus, tramways gradually disappeared from most British and French cities.

In several other European countries, on the other hand, attitudes toward tramways were much more positive. The organizational and financial situation of transit agencies were more stable, since transit systems were usually consolidated into single, municipally owned agencies. Separate tramway rights-of-way in many German, Dutch, Swiss, Austrian, and other central European cities were preserved, upgraded, and in many cases extended.

European tramway technology was initially less developed than that in the United States. Although four-axle cars were produced between the two world wars in Germany, Italy, Czechoslovakia, Great Britain, and elsewhere, most fleets were largely composed of simpler and slower two-axle cars. Some Italian (Breda) cars of the late 1930s, however, were quite advanced, matching or exceeding PCC cars in their body design and riding comfort. The decisive progress of tramway/streetcar technology and applications came during the 1950s when German manufacturer DÜWAG produced a new model of articulated cars (Photo 1.12) far superior to all earlier articulated cars, including European and U.S. models. The wide application of these cars and subsequent upgrading of tramway networks—through the provision of separate rights-of-way, priority treatments, and other technological and organizational advances—resulted in the creation during the period of the 1960s and '70s of light rail transit (LRT), a rail system that is, by its performance, more similar to rapid transit than to streetcars operating in mixed street traffic.

Following the lead by most German cities, the development of LRT since the 1970s resulted in contin-



Photo 1.12 The first model of DÜWAG's articulated cars, produced for many cities between 1956 and 1970, shown in Jan Wellem Platz, Düsseldorf, in 1972

uous innovations: the introduction of two- to four-car trains on lines that use separate rights-of-way in streets, tunnels, and aerial structures; construction of low-floor vehicles to better serve pedestrian zones and enhance their livability; operation on intercity railway lines, etc. With this diversity, LRT has acquired the central role of a high-quality, attractive transit mode in cities of different sizes in many countries world over.

In retrospect, the twentieth century saw the development of streetcars from small, noisy, low-speed vehicles in 1900 to the spacious, high-speed, quiet, comfortable units of today. The mode lost its dominant position to other technologies (mostly buses) in many cities, but it then evolved into the LRT that has become the dominant medium-capacity high-quality transit

mode in many of the cities that had abandoned streetcars as well as in many new, growing cities in industrialized as well as developing countries.

1.4.2 Motorbuses¹⁰

In the course of the nineteenth century, numerous attempts were made to equip omnibuses with mechanical propulsion; but for technical and economic reasons or because of legal restrictions, these ventures were un-

¹⁰The primary sources for this section are Klapper (1961), Miller (1941), and Singer (1960).

successful. At about the turn of the century, the first successful applications of the internal combustion engine (ICE) to highway vehicles were achieved, providing the technological basis for a new vehicle, the motorbus, which would soon replace the horse omnibus.

An ICE developed by Etienne Lenoir in 1859 was modeled upon stationary steam engines of the time: it was a double-acting two-stroke engine running on a gas-air mixture. Far more important, however, was the invention of the German engineer Nikolaus Otto in 1876. He built the first operational four-stroke ICE running on gas-air or oil-air mixtures. The new "Otto cycle" engines were soon finding extensive industrial uses. Realizing that many applications, particularly for vehicle propulsion, require a rather light power unit, Gottlieb Daimler (1834–1900) designed a lightweight high-speed motor in 1883. Three years later came the most important event in the development of modern highway transportation: Carl Benz (1844–1929), of Mannheim in Germany, constructed the first automobile. By the late 1890s, gasoline-powered vehicles were being manufactured in substantial numbers in Germany, France, and Great Britain; but the first ICE-powered transit vehicles, buses, were developed only about 1900; the first operation in Great Britain was in 1899, and in Germany in 1903.

Another invention that later had a great significance for buses took place during the 1890s: Rudolf Diesel (1858–1913), also a German engineer, developed a high-speed compression-ignition engine. This engine, named after its inventor, was initially very heavy and had no immediate influence on motorbus development. But after numerous design changes over some four decades, its efficiency was greatly improved, and the diesel motor gradually became nearly the exclusive propulsion unit for buses.

The introduction of motorbuses in Great Britain was facilitated by the Locomotives on Highways Act of 1896, which relaxed repressive provisions against motor vehicles. After 1899, the first gasoline-powered buses were introduced in England, and by 1911, all of the London's omnibus proprietors had replaced their horse buses with motorbuses.

In 1910, under pressure of police regulations issued in the previous year, several British manufacturers

commenced production of new-model buses whose light weight, reliability, and low cost represented a significant improvement upon their predecessors. Reliability was further improved later by the introduction of preventive maintenance procedures evolved during World War I. Vehicle safety was increased by the adoption of four-wheel braking systems. A bus from that period is shown in Photo 1.13. Pneumatic tires, first used for bicycles in 1888 and for automobiles in 1900, were first used for heavy vehicles, including buses, around 1920. Soon afterward, British engineers consolidated these improvements by giving their attention to the overall design of the bus chassis, which at that time still retained many features of the freight truck chassis. The new type of bus chassis had a low center of gravity and suspension designed for improved passenger comfort.

In the United States, the first city to begin conversion from horse bus to motorbus operation was New York. Between 1905 and 1908, the Fifth Avenue Coach Company (by then the only remaining omnibus proprietor in the city) replaced its entire fleet of horse-drawn vehicles with 35 double-decker motorbuses. These vehicles, like most of the early buses, were hybrids: each had a chassis built by the French DeDion-Bouton company and a body built by Brill of Philadelphia, the famous streetcar building firm.

The appearance of jitneys in many cities around 1914 gave a further impetus to motorbus development in the United States. The jitneys were private automobiles plying the main traffic routes for hire; at first they were not subject to any official regulation, and they represented a serious threat to the profitability of established streetcar systems. The first jitney bus—a makeshift, box-like body mounted on a light truck chassis—appeared in Los Angeles in 1914, and for 5 years jitneys and jitney buses flourished in many American cities, competing chaotically not only with streetcars but also among themselves. As some of the jitney operators realized that the use of buses instead of small vehicles offered economic and operational advantages for their major lines of service, they converted jitney operations to regular bus lines.

Regulation of jitney and bus transportation was gradually introduced during the 1910s and 1920s, reducing or eliminating their uncontrolled operations on



Photo 1.13 Double-decker bus in Paris, ca. 1920 (Courtesy of RATP, Paris)

major routes already served by streetcars. In the meantime, the streetcar companies began to perceive the potential of motorbuses for some services, particularly on lightly traveled routes. Thus buses were introduced for services coordinated with streetcar lines rather than competing with them. In 1920, only 10 streetcar companies in the United States were operating buses, but soon afterward their number began to increase quickly.

Many of the improvements in bus design introduced by European engineers were paralleled by the Fageol brothers, Frank and William, who produced their first gasoline bus in 1920 at Oakland, California. The advantages of the Fageol Safety Coach (Photo 1.14) over previous bus types—with respect to acceleration and braking, suspension, larger body, and others—were soon recognized, and its principal features became almost standard in buses produced in the United States.

Further mechanical innovations in bus design appeared during the 1920s. Gas-electric propulsion, introduced in 1924 in Philadelphia and Buffalo, con-

sisted of a drive system comprising a gasoline motor/electric generator/electric motor. Elimination of the gearbox from the drive train made possible a significant reduction in wear and tear and an increase in riding comfort. After a study showed that the useful life of buses was on average no more than 5 years (compared with 20 to 30 years for rail vehicles), many other U.S. cities introduced this propulsion system. Photo 1.15 depicts a typical bus from the 1920s.

Another innovation, of more permanent value, was the introduction of the diesel motor for bus propulsion. Use of lower-cost fuel and high operating efficiency were the chief attractions of the diesel motor. Its initial commercial development was in Germany and other European countries where fuel prices were especially high. The first British use of diesel buses was in Nottinghamshire in the late 1920s. In 1929, a New Jersey transit company began to import Mercedes-Benz diesel buses, providing them with electric transmissions. The use of diesel propulsion for buses spread rapidly during

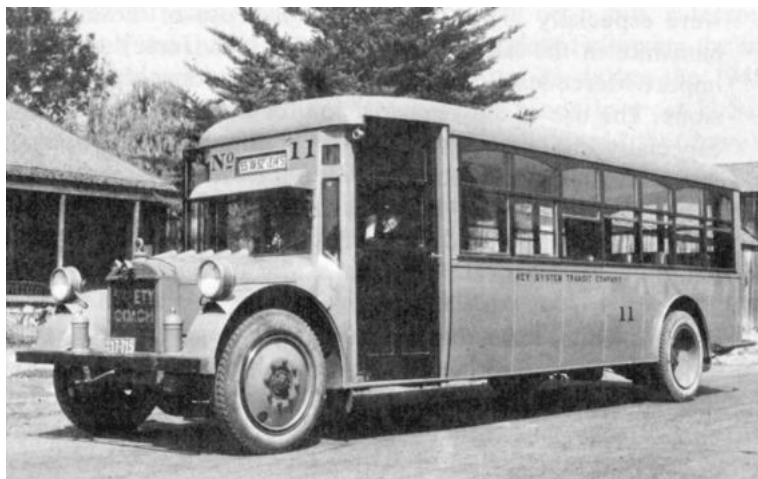


Photo 1.14 Fageol's "Safety Coach" in Oakland, mid-1920s (Courtesy of APTA, Washington)

the 1930s, especially in Great Britain, where attention was focused on hydraulic transmission rather than electric drive; but it was in America, at the Yellow Coach Factory, that the last major technical problem with this system, achieving interlock at high speed, was effectively overcome. The first American buses equipped with hydraulic transmission were introduced in New York City in 1939.

Meanwhile, buses had become much larger. Seating capacities common in 1912 had been 16 for single-deckers and 34 for double-deckers; by 1939, capacities had approximately doubled. In 1938, the Fageols introduced an articulated single-decker bus with a seating capacity of 58 passengers, but this model did not find wide use.

Following the stagnation of developments due to World War II (see Photo 1.16), the European bus manufacturers took a definite lead in vehicle design innovations, and they have retained the lead ever since. The articulated buses developed in Europe since the 1950s have found extensive use in many countries around the world. The European manufacturers have also made substantial improvements in vehicle suspension, body design (large windows, wide doors, etc.), and low-noise motors. In the United States, on the other hand, bus production was for many years dominated by a single manufacturer (GMC), and efforts to utilize or

catch up with the European innovations came only under the stimulus of federal research and development programs during the 1970s.

With the conversions from streetcars to buses and trolleybuses described in the preceding section, the role of buses grew rapidly. In the United States, the number of buses in transit service in 1940 was about 35,000, slightly less than the number of streetcars and rapid transit cars; bus ridership was approximately half the ridership of the two rail modes. Following the massive conversions from streetcars and trolleybuses to buses during the 1945–1965 period, buses became the dominant street transit mode in most U.S. cities.

Buses are presently used in nearly all cities in the world that have transit services, alone or in combination with rail modes and paratransit services. The increasing need for higher-quality transit services since 1960 has led to improvements in bus operations through various priority treatments and to their substitution by modern rail transit modes (rapid transit and light rail); in the latter cases, buses continue to play a significant role as suburban feeders.

Many bus improvements have been successful. The variety of vehicle designs has increased by the introduction of double-articulated and low-floor buses. Bus lanes and busways have been successful in some cases, while others have failed when they were converted into

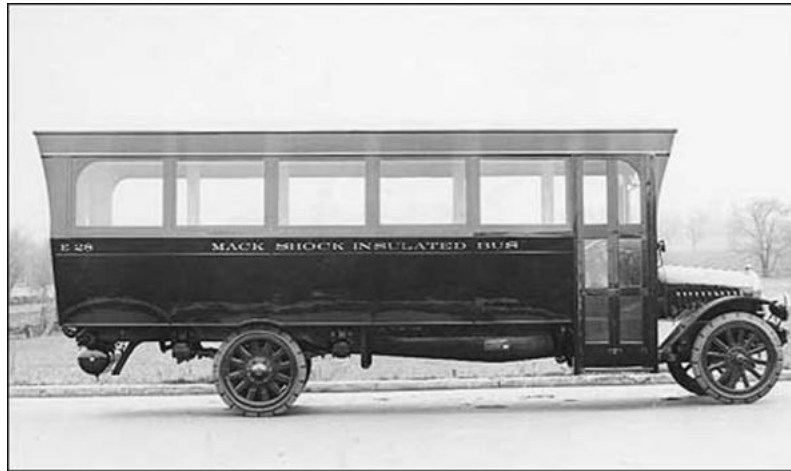


Photo 1.15 Mack senior tour bus, ca. 1910 (Courtesy of Mack Trucks, Inc.)



Photo 1.16 Transit bus of the Pacific Electric in Los Angeles, produced by Yellow Coach, ca. 1947 (From the collection of Jim Stubchaer)

high-occupancy vehicle (HOV) facilities. Guided buses have also had only limited application. However, the most significant change was the organized effort in many cities to coordinate many improvements so as to achieve a high-quality bus transit, named bus rapid transit (BRT). With separate busways, fixed lines with frequent service, and clear information, copying the features of the LRT mode, BRT systems have become a higher-quality mode than regular buses. As a medium-capacity system, BRT generally requires a

lower investment, but it also offers lower quality of service, capacity, and positive impacts than the LRT mode.

1.4.3 Trolleybuses¹¹

In 1882, Siemens & Halske made experiments at Halensee, near Berlin, with a small electrically powered road vehicle, the *Elektromote*. Current was collected by means of an eight-wheel trolley, which ran on a pair of overhead wires and was towed behind the vehicle by cable. The results were unsatisfactory, however, and the lack of an adequate solution to the problem of power pickup held back trolleybus development for many years. Except for a few isolated experiments, no further progress was made until the beginning of the twentieth century.

Lombard-Gerin built what was probably the world's first working trolleybus line for the Paris Exhibition of 1900. In 1901, he opened a trolleybus line between Fontainebleau and Samois (a distance of 8 km), but this was abandoned soon afterward owing to frequent

¹¹ The principal sources for this section are Klapper (1961) and Miller (1941).



Photo 1.17 An early trolleybus: Toronto, 1920s (From the collection of Jeffrey Marinoff)

derailments of the overrunning trolley. German engineer Max Schiemann was responsible for the first really successful trolleybus installation, at Bielatal, in 1902. Here Schiemann used a spring-loaded pole with a forked connection to trolleys underrunning a pair of wires, which were mounted one above the other. Over the next few years trolleybus lines were opened in various parts of Europe: in Denmark, Switzerland, and especially Germany and Italy. By this time electric tramway technology was well developed and tramways were being operated or under construction in most European cities.

In the United States, only limited interest was shown in trolleybuses before the 1920s. In 1903, A. B. Upham, president of the American Trackless Trolley Company, demonstrated a trolleybus on short lines in New Haven, Connecticut, and Scranton, Pennsylvania; power pickup was by means of pairs of trolley wheels sprung against the overhead wires. In 1910, a converted motorbus provided regular service for a few months in Laurel Canyon, California, and a specially

built trolleybus seating 18 passengers operated in Merrill, Wisconsin, in 1913 and 1914. In the early 1920s, several American streetcar and motor-truck manufacturers developed trolleybus designs, and by 1925, trolleybus services were established in Baltimore, Minneapolis, Philadelphia, Rochester, and Staten Island as well as in Toronto (Photo 1.17) and Windsor in Canada.

Trolleybuses were not used for large transit networks anywhere until after 1926. In that year, the first of a series of new models came into service. Guy Motors developed for Wolverhampton (England) new model demonstrating that the trolleybus possessed characteristics which, taken together, would give it a distinct advantage over other modes in many circumstances: fast, quiet, and comfortable running; smooth accelerating and braking; and low operating costs. Consequently, trolleybuses were introduced in many British towns (often as replacements for trams) during the period between 1926 and 1940. In 1931, trolleybuses were introduced in London; by the outbreak of

World War II, London's stock of trams had been reduced from 2600 to 900, while the trolleybus fleet—1764 vehicles—was the largest in the world. Innovations introduced in London during the 1930s included chassisless monocoque construction (body structure supports itself rather than lying on a chassis) and skids lined with carbon inserts in place of trolley wheels. Clearly, Britain, London in particular, was at the forefront of trolleybus development during the 1930s. At the end of the decade, the number of trolleybuses operating in Britain was approximately 2600.

During the 1930s, many American transit proprietors came to see the trolleybus as a viable “modern” alternative to the aging streetcar: by 1940, about 2800 trolleybuses were operating in some 60 cities and large towns in the United States. At the time of their greatest use, in 1950, more than 6500 trolleybuses with numerous advanced technological features were operated in U.S. cities (APTA 2004). For example, a trolleybus from that period shown in Photo 1.18 had a dual propulsion: electric and a propane gas ICE, which would propel a generator to provide electric power for the



Photo 1.18 Dual-mode electric-ICE bus with automated trolley pole raising, Public Service in New Jersey in 1935 (From the collection of Jeffrey Marinoff)

motor on nonelectrified sections of lines. Trolley pole control was automated. A few cities also operated articulated trolleybuses (Photo 1.19).

The use of trolleybuses was also increasing in many other countries from the 1930s until the mid-1950s. Extensive trolleybus systems existed in Brazil, Mexico, Spain, France, Italy (55 cities), Yugoslavia, Greece, several countries in eastern Europe, the USSR, and Switzerland. During the 1950s, however, expansion of trolleybus networks ceased and many cities began to replace them with buses. This conversion later accelerated, so that by 1970 in many countries only fractions of former trolleybus networks remained. In Great Britain, one of the greatest users of trolleybuses, this mode actually became extinct. In the United States, only five cities retained it.

Several factors caused the decline of trolleybuses. During the period of maximum efforts to accommodate

the automobile, the trolleybus was considered insufficiently “flexible” to operate in mixed traffic. Costs of trolleybuses increased faster than those of buses, and funds for the maintenance of overhead wires were often unavailable, while the advantages of trolleybuses over buses—in passenger comfort and environmental characteristics—did not bring any direct revenue to transit operators.

The changes in attitudes toward urban transportation that occurred in the late 1960s and early 1970s had a direct and positive influence on the position of trolleybuses. Increased attention given to the environmental aspects of transportation systems, greater emphasis on the attraction of passengers to transit, and the increased availability of public funds, particularly for capital improvements, generated a revival of positive attitudes toward trolleybuses. This change resulted in the retention of the remaining lines and even their extension in some cases.



Photo 1.19 Articulated trolleybus built by Twin Coach in 1940, in Cleveland, ca. 1949 (From the collection of J. W. Vigrass)

The position of trolleybuses has always remained strong in several countries, however. Their networks have been retained and modernized in Swiss and many cities in eastern Europe, while the USSR became by far the largest user of this mode: in 1960, a total of 58 Soviet cities utilized trolleybuses; by 1975, the number of such cities grew to 142 (U.S. DOT 1978). The beginning of the twenty-first century finds cities in many countries utilizing and modernizing trolleybus systems. Leading examples in this development are numerous Russian and other former Soviet cities (particularly Moscow and St. Petersburg), Swiss and Chinese cities, Athens, Belgrade, Vancouver, Seattle, San Francisco, and others.

1.5 DEVELOPMENT OF HIGH-SPEED RAIL TRANSIT MODES

Parallel with the beginnings of local transit services, large cities began to utilize rail technology for higher-speed services on lines with partially or fully separated rights-of-way. Three different modes providing such services emerged.

Suburban railways originated as local services on the main intercity railroad lines. *Interurbans*, large streetcar-type vehicles operating mostly on private rights-of-way between adjacent cities and towns, were developed after the invention of electric traction. *Rapid transit*, intraurban transit on fully separated rights-of-way, eventually became the most important high-speed urban transit mode. Although its first line (1863) was built for steam traction, rapid transit began to be widely utilized only when the invention of electric traction made underground operation efficient and attractive.

Major events in the developments of these three modes are briefly reviewed here.

1.5.1 Suburban Railways/Regional Rail¹²

Although they were initially designed and built for long-distance transportation, the intercity steam rail-

way lines also provided fast and reliable transportation between center-city stations and adjacent suburbs and towns. With growing populations and expansion of cities, passenger volumes on these intraregional sections of railway lines increased, which led to the introduction of special, more frequent local services representing the beginnings of suburban railways.

Because of their similarity with regular railway services, it is difficult to state precisely when suburban railway services commenced. It is known, however, that the first large-scale development of this mode occurred in London. Its first suburban railway line opened in 1838, and most of London's present extensive suburban railway network, covering a circular area with a radius of some 15 km, was built between 1840 and 1875. In addition to serving the middle-class suburbs that were being developed around existing villages and towns in the region, London's railways also gave working people living in the inner parts of the city access to the countryside, to pleasure gardens and racetracks, so that special excursion fares were introduced on suburban lines as early as the 1840s.

As Lehner (1961) points out, the lack of mechanized modes for local travel within cities forced the population to live in the immediate vicinity of factories, commercial centers, and railway stations. Thus the period between the introduction of railways and the invention of the first mechanized transit (electric streetcars) saw the development of very high residential densities and often very poor living conditions in inner-city areas.

London, with its large population and early development of industries, attempted to cope with these problems through the described utilization of railways for intraregional travel and the construction of steam-powered subway lines. The national government also wanted to encourage the relocation of middle- and lower-income people into less crowded suburban areas. Thus, in 1883, the British Parliament passed the "Cheap Trains Act" (Weber 1899), which provided financial aid of \$2 million per year to allow suburban railroads to maintain low fares, so that middle- and low-income families could afford commuting expenses. Governments of several other countries also began to provide financial support for suburban rail-

¹²Most of the historical data for this section are taken from Barker (1963), Kellett (1969), Taylor (1951), and Yeates (1976).



Photo 1.20 A Brooklyn Bath and West End RR at Bensonhurst Station on Long Island, 1880s (Courtesy of APTA, Washington)

ways during the same period. Other European cities started operating suburban railways somewhat later: Hamburg in 1866, Berlin in 1882, Liverpool in 1886, and Glasgow in 1887.

In the United States, suburban services on the main intercity railroad lines began with the practice of providing special “commuted” fares for morning and afternoon travel between city terminals and outlying residential areas. Probably the first American “commuter railroad” was the Boston and West Worcester Railroad, which introduced annual commuter tickets in 1838 and in 1843 instituted regular commuter trains on its line between Boston and West Worcester. By the mid-1850s, this railroad reported carrying nearly half a million passengers annually between Boston and stations no farther than Auburndale (16 km). The first commuter service in Chicago started in 1856.

The early patrons of commuter railroads were relatively wealthy people who could afford the luxury of suburban living. The “exurban” communities they inhabited were clustered fairly closely around commuter railroad stations. As a consequence, many commuter rail lines in Chicago, New York, Philadelphia, and other cities today connect a “string” of towns around their stations. As the older “exurbs” became swamped

by “streetcar suburbs,” there was a continuing demand for housing beyond the edges of existing built-up areas. For this reason, commuter lines—offering service with high speed, comfort, and reliability—continued to extend well beyond the expanding streetcar suburbs, serving satellite communities increasingly distant from city centers. An early suburban train is pictured in Photo 1.20.

Electrification of suburban railways began about 1900; during the subsequent three decades, many cities opened their first suburban rail lines designed specifically for electric traction. Electrification intensified after World War II particularly in Europe and Japan, so that most suburban and regional rail systems are now electrically powered. There are, however, some important exceptions, mostly in the countries that have little or no electrification on their railroad systems. For example, only a small part of Chicago’s extensive suburban rail system is electrified, and entire systems in Boston, Toronto, San Francisco, Los Angeles, and several Latin American cities are still diesel-powered.

The period from 1930 to 1960 was one of stagnation for many suburban railways, and a number of lines, particularly in U.S. cities, were forced to close down. The main problems operating agencies faced

were obsolete labor and operating practices, increasing wages, and lack of governmental support in terms of policies and financial assistance. Since 1960, however, suburban growth and highway congestion have resulted in a revival of interest in this mode. Lines and rolling stock have been modernized, services improved, and networks expanded. These developments began in Europe (e.g., Paris, Munich, Hamburg, Copenhagen); more recently, U.S. cities have begun to follow the same trend. Los Angeles, Miami, San Diego, Seattle, Dallas, Albuquerque, and several other cities have reintroduced passenger services on lines on which, for many years, only freight trains had operated; Boston, Chicago, New York, and Philadelphia have modernized their extensive networks of lines.

The initial layouts of railroad networks have influenced the character and role of suburban and regional railways in different cities. Two main types of networks can be defined, each with a characteristic set of functions.

The first type is the radial network, consisting of lines running from stub-end-type city terminals outward into the suburbs. Its main customers are usually commuters traveling into and out of city center. Rapid transit often provides the downtown connections between the suburban terminals and serves as the distributor for these lines. Examples of this type of system include London (where ten terminals at the periphery of the central city are connected by the Underground Circle Line, New York (Grand Central Terminal), and Boston.

The second type of urban railway service has been developed in cities that have lines passing through central areas, usually connecting suburbs on different sides of the center city. When this type of network has several stations in the central area, it offers a much more extensive area coverage than the radial network with its stub-end terminals. By its character and function, the latter type is rather similar to rapid transit: it serves many different types of trips throughout the region rather than mostly radial commuting trips. Its major distinctions from rapid transit are somewhat greater station spacings, higher speed, and operation by railroad instead of transit agency.

Based on their character and function, systems of this type have been given a more appropriate name,

“regional rail,” instead of the more limited term “suburban railways.” Examples of regional rail system are found in Berlin, Hamburg, Vienna, Copenhagen, Osaka, and—by far the largest—in Tokyo.

A number of cities have made great efforts to change the suburban-type networks into regional rail. By connecting stub-end terminals, they have provided important coverage and created truly regional lines between different suburbs. Examples of this type of system modification—and, usually, concomitant upgrading of service—are found in Brussels, Munich (S-Bahn), Oslo, Paris (R.E.R.), and Philadelphia. Thus the trend is clearly away from the traditional commuter-oriented suburban railways and toward multifunctional regional rail systems, which are better suited to the present more decentralized, multifocal cities than are their nineteenth-century predecessors.

1.5.2 Electric Interurban Railways¹³

At the end of the nineteenth century, electric streetcar technology found an important new field of application in *electric interurban railways*. This mode consists of large, high-speed single cars or short trains operating on electrified lines, mostly on separate rights-of-way. A typical interurban network connects a group of cities and towns at distances of 15 to 80 km (10 to 50 mi). In some cases freight is carried on the same tracks, but passenger service generally has precedence.

A line fitting this definition was built in Northern Ireland in 1883. The commencement of large-scale development of this mode, known in the United States as “interurbans,” was marked by two lines built in the United States in 1893: one in Oregon (Portland to Oregon City), and one in Ohio (the Sandusky Milan and Norwalk Electric Railway). Between that year and the outbreak of World War I, a considerable number of interurban lines were built in the Netherlands, Belgium, Germany, Italy, and Canada; but the most extensive development of this mode occurred in the United States, where line construction reached explosive pro-

¹³The principal sources for this section are Cudahy (1982), Hilton (1960), and Klapper (1961).

portions during the period from 1901 to 1908 (Photo 1.21).

Flexibility of line layout (from street running to fully separated rights-of-way) and frequent service made possible by the use of single or paired vehicles, which gave the interurbans a competitive advantage over steam railroads on route lengths up to about 80 km. Typically, interurbans were developed in a radial pattern of lines linking a major city with surrounding country towns. In New England, the radial interurban networks were, in fact, extensions of urban streetcar systems. They were so extensive that at one time it was possible to travel from New York to Boston by transferring among streetcars and interurbans and never paying more than 5 cents for a fare. Extensive, heavily used interurban systems existed in Los Angeles (Photo 1.22) and Chicago as well as in the states of Ohio, Indiana, and Michigan. The interurban networks in the last three states represented over one-third of the national network length, which, at its peak in 1913, reached nearly 26,000 km (16,100 mi). The interurban terminal in Indianapolis was comparable in size to railroad stations in cities of similar size.

Very soon after their rapid initial development, the American interurbans began to decline. The profitability of many lines was very low even at the height of investment in the industry. In many cities, the interurbans were prevented legally or physically from penetrating downtown areas or from making efficient



Photo 1.21 An interurban train of the Pacific Electric at Fullerton, on the Santa Ana line, ca. 1920s



Photo 1.22 A typical high-speed interurban car of the Pacific Electric in Los Angeles (Courtesy of William D. Volkmer collection)

connections with other transit services. Some streetcar systems, for example, were deliberately built with non-standard-gauge tracks, to prevent joint interurban-streetcar operation. But by far the most important reason for the demise of interurbans was the automobile: the primary type of interurban service, 15 to 80 km, was also the most convenient one for auto travel. With increasing auto ownership and rapid construction of highways (which sometimes even took over the interurbans' separate rights-of-way), they lost ridership steadily. Reduced travel during the Great Depression speeded up closings. World War II caused a temporary return of riders, but by the mid-1950s this mode of transportation had practically disappeared in the United States. Only two lines have been retained permanently. One is the Norristown Line in Philadelphia, with fully separated rights-of-way, speed up to 110 km/h, and high-level platforms. The other is the South Shore Line in Chicago. Both have become electric regional transit lines in their respective metropolitan areas.

Several other countries have retained interurban lines. The best-known ones are in the Rhein-Ruhr region in Germany. The existing interurban lines (Düsseldorf-Duisburg, Essen-Müllheim, and others) have been upgraded and supplemented by additional lines into a regional light rail rapid transit system that is planned to serve all major cities in this densely pop-

ulated region. A rail line along the coast of Belgium is also an interurban, as are some lines in Switzerland, Italy, and France.

The private railways in Japan are by far the most extensive systems now providing interurban-type services. They have interurban functions, although they are closer to regional rail or even rapid transit in several respects. They have, for instance, rights-of-way with controlled crossings or full separation, stations with high-level platforms, and up to 10-car trains. These railways carry millions of passengers per day in the suburban areas of Tokyo, Osaka, Kobe, Kyoto, Nara, and other Japanese cities. Generally, they are closely integrated with other transit systems (some lines share tracks with rapid transit lines).

1.5.3 Rapid Transit/Metro¹⁴

Suffering from chronic street congestion, London was the first city in the world to build a fully separated, high-speed rail transit line. This was the Metropolitan Line, opened in 1863, which connected two railway terminals. Its 6-km (3.75-mi)-long tunnel was built by the cut-and-cover method, along existing street alignments wherever possible. The steam locomotives employed on the line incorporated special devices designed to minimize smoke emission, but these devices were never very effective and there were many complaints about the poor quality of the air in the carriages and in the stations. Nevertheless, the fast service provided on the line attracted large numbers of passengers.

The Metropolitan was the first in a long series of similar subway lines built in London over the ensuing 30 years, and it was in London that the next major innovations in subway technology were first introduced, on the City and South London Line, opened in 1890: this line ran in a 10-ft (3.05 m)-diameter steel-lined "deep tube" tunnel cut through the London clay and utilized electric traction (small electrically driven locomotives) with third-rail power pickup.

The Liverpool to Birkenhead line, connecting railway terminals in the two cities via a tunnel under the River Mersey, commenced operation in 1886. In the same year a similar line opened in Glasgow. Local as well as through services were provided on these lines. The extension of London's subway network was continuing, and in the 1890s subways designed for purely urban transit service were built in several other European cities. The first rapid transit (subway) line on the Continent was opened in Budapest in 1896, and the Glasgow District Subway, a tube-type 10.5-km (6.5-mi)-long circle line with 15 stations, was opened in 1897. The Glasgow line utilized cable traction until 1926, when it was electrified. The first line of the Paris Metro was opened in 1900; the Berlin U-Bahn followed in 1902, Hamburg's Hochbahn in 1912, and the Buenos Aires Subte in 1914.

Berlin's regional rail (S-Bahn) line, opened in 1882, had elevated sections on embankments and structures. So did Hamburg's rapid transit Ring Line, opened 30 years later, and lines in several other European cities. Yet, elevated lines were used much more widely in the United States than in Europe.

The first elevated line in New York City was built along Greenwich Street in the late 1860s. The railway tracks were carried approximately 15 ft above the level of the roadway on a structure supported by wrought-iron columns placed along the edges of the sidewalks. Cable traction was employed on the first section of the line, opened in 1868, but serious operating difficulties were encountered. In 1871, the line was successfully converted to steam traction and later extended north along Ninth Avenue. Three additional elevated lines were built in New York during the 1870s and 1880s, but in each case the service was unreliable and noise from the steam trains was a serious nuisance. Also, because the supporting structures kept light from the sidewalks, owners of adjacent buildings often objected to the construction of these lines.

In 1891, a publicly constituted Rapid Transit Commission decided that additional rapid transit facilities were needed in New York and that they should be built underground. It was known that construction expenses would be considerably greater for subways than for elevated rail lines, and there was some concern that

¹⁴Historical information about rapid transit was obtained from Barker (1963), Cudahy (1982), Howson (1964), Miller (1941), and Burr (1906).

tunneling along city streets might seriously weaken the foundations of adjacent tall office and apartment buildings; but elevated lines were considered inadequate to deal with the great and rapidly growing volume of traffic in the city, and developments in electric traction in the preceding decade gave the commission a salubrious alternative to steam traction. In 1900, following a long period of negotiation and planning, construction was begun on a total of 29 km (18 mi) of line, most of it as a subway, and including 8 km of four-track subway (express and local). This first part of New York's vast subway network opened for service as a great civic event in 1904.

Rapid transit subway lines were built in several other American cities around the turn of the century. Actually, the first transit tunnel in the Western Hemisphere was opened in 1897 in Boston for operation of streetcars converging on the city center from many lines. The first rapid transit tunnel in that city was opened in 1908. Philadelphia's Market Street Line, opened one year earlier, comprised a central section of subway with elevated sections at each end. Part of the subway contained two streetcar tracks paralleling the rapid transit tracks.

The first elevated line in Chicago opened in 1892 with steam traction. In 1897, the line was converted to electrical operation, with a multiple-unit (MU) control system designed by Frank Sprague. Previous electrically operated rapid transit lines (such as the City and South London line and the Chicago line, opened in 1895) had employed electric locomotives and trailer cars; MU control provided greater flexibility and efficiency in the deployment of rapid transit vehicles.

Construction of rapid transit lines in several large cities on three continents during the 1890–1910 period shows that there was already a distinct need for a high-speed, high-capacity, reliable transit service. The high costs of construction, however, represented a major constraint on the development of this mode. The outbreak of World War I, which put a stop to most municipal building activities, found 11 cities around the world with rapid transit systems.

Difficult and unstable economic conditions between the two world wars in most countries limited further construction. Only six cities opened new systems between 1919 and 1935, when the Moscow Metropolitan

opened as the last new prewar subway. There was, however, construction of additional lines in cities that had opened their first lines prior to World War I. For example, rapid transit networks in Hamburg, New York, Paris, and Philadelphia were expanded considerably during the period between the two world wars. Photos 1.23 and 1.24 show, respectively, a U.S. and a German rapid transit train from that period.

World War II caused a major interruption in rapid transit development: few cities had any construction between late 1930s and mid-1950s. Following the war, European and Japanese cities had little capital available, while U.S. cities concentrated on the construction



Photo 1.23 New York City rapid transit train of the Brooklyn-Manhattan Transit Corporation, built ca. 1936 (Courtesy of William D. Volkmer collection)



Photo 1.24 Berlin rapid transit train

of freeways and other facilities for private transportation. Eventually, however, public officials and civic leaders began to realize that the private automobile does not diminish but rather increases the need for rapid transit because the separate right-of-way is the major element making a transit system competitive with the automobile. This recognition of the importance of rapid transit and gradually increasing financial resources led to a continuous acceleration of rapid transit construction. The scale of this activity is evident from the fact that the number of cities in the world that have rapid transit quintupled (increased from 20 to over 100) during the period from 1955 to 2006 (see Section 6.7).

1.6 OVERVIEW AND CONCLUSIONS: TRANSIT DEVELOPMENT AND CITIES

The preceding review of the history of transit development and the chronology of major milestone events presented in Table 1.5 show the tremendous progress in urban transportation technology that has been achieved since the early 1800s but particularly during the last 125 years. The great impact that these developments have had on modern civilization is also evident: the intensive urbanization that has taken place in all countries would not have been possible without modern transportation systems.

At the beginning of this period of technological progress, the main problems in providing efficient urban transportation services were technological: motors for vehicles were impractical; vehicle, road, and track designs were rudimentary and offered limited speed, comfort, safety, and performance in general. The long series of inventions that subsequently took place created a number of different technological systems. As Chapter 2 will show, there exists today a “family of urban transportation modes” that offers a nearly continuous spectrum of modes and performance characteristics. These modes are capable of satisfying the needs of any urban area, from a small town to a large metropolis.

In light of this abundance of technologies, it appears paradoxical that today many cities suffer from serious transportation problems, albeit different ones

from those faced a century ago. The problems often include chronic street/highway congestion, unsatisfactory quality of transit services, lack of adequate transportation for some population groups, financial problems, and—often the most serious one—negative impacts of transportation conditions on cities and their environments

A particularly complex problem facing cities has been how to allocate proper roles to different transportation modes. The basic policy decision with respect to transportation is what roles the two basic modes—private automobile and public transit—should play in the city; that decision depends on the city size, its character and topography, living standard and habits, etc. This decision is in many cases neither well understood nor given adequate attention. Regulation of automobile traffic is in many cities so inadequate that the great potential mobility of this mode is defeated by congestion, while pedestrians have little pleasure, or even safety, while walking in many urban areas. The balance between auto and transit modes is usually determined more by the degree of street congestion than by rational regulatory and economic measures.

Neglect of public transit is a major problem in many cities and countries despite many policy recommendations at the national level. For example, the Federal Electric Railway Commission appointed by President Wilson to resolve the serious crisis in the “electric railway” (transit) industry stated that “urban transit is an essential public utility and should have the sympathetic understanding and cooperation of the public if it is to continue to perform a useful public service” (FERC 1920). The report also stressed the need for integration of services into coordinated systems and for regulatory control by public bodies. It further stated that “The employees [in the transit industry] . . . should have a living wage and humane hours of labor and working conditions.” and “All labor disputes should be settled voluntarily or by arbitration. . .” because “It is intolerable that the transportation service of a city should be subject to occasional paralysis, whether by strikes or by lockouts.”

Most of these statements apply to the requirements for transit services today as they did in 1920. Actually, a number of similar statements pointing out the im-

Table 1.5 Chronology of inventions in urban public transportation

Year	Location	Event
ca. 1600	London	"Hackney coaches"—taxicab services
1612	Paris	" <i>Fiacre</i> "—taxicab service
1662	Paris	First urban public coaches—common carriers, horse-drawn carriage
ca. 1765	England	Invention of steam engine (Watt)
1825	Stockton-Darlington, England	First railway opened (Stephenson)
1826	Nantes, France	First horse-drawn omnibuses
1832	New York	First horse-drawn streetcar line
1838	Boston	First commuter fares on a railway line
1838	London	First suburban railway service
1863	London	First underground rapid transit line
1868	New York	First elevated rapid transit
1873	San Francisco	Invention of cable car (Hallidie)
1876	Germany	Invention of internal combustion engine (Otto)
1879	Berlin	First application of electric motor for traction (Siemens)
1881	Berlin	First electric streetcar (Siemens)
1882	Hallensee, Germany	Demonstration of the first trolleybus (Siemens)
1883	Germany	First lightweight ICE (Daimler)
1886	Mannheim, Germany	First ICE-powered automobile built (Benz)
1886	Montgomery, Alabama	Invention of underrunning spring-loaded trolley pole for streetcars (Van Depoele)
1888	Richmond, Virginia	First successful major electric streetcar line (Sprague)
1890	London	First rapid transit with electric traction
1892	Germany	Invention of compression-ignition engine (Diesel)
1893	Ohio and Oregon	First interurban lines
1897	United States	Invention of multiple-unit train control (Sprague)
1897	Boston	First streetcar tunnel
1899	Great Britain	First motorbuses
1901	Wuppertal, Germany	First successful monorail
1901	Fontainebleau, France	First trolleybus line in operation (Lombard-Gerin)
1902	Bielatal, Germany	Practical overhead power pickup for trolleybus (Schiemann)
1904	New York	First four-track rapid transit subway line for local and express services
1914	United States	Introduction of jitneys
ca. 1920	United States	Use of pneumatic tires for buses
ca. 1927	Nottinghamshire, England	Introduction of diesel motors for bus propulsion
1936	Brooklyn, New York City	First PCC car in service
1955	Düsseldorf	First modern articulated streetcar, contributing to the development of LRT mode (DÜWAG)
1955	Cleveland	First extensive park-and-ride system (with rapid transit)
1956	Paris	First rubber-tired metro
1957	Hamburg	First rapid transit with one-person train crews
Late 1950s	West Germany	First modern articulated buses and trolleybuses
1962	New York	First fully automated rapid transit line (42nd Street shuttle)
1960s	Europe	Widespread use of self-service fare collection
1966	Hamburg	First Transit Federation (<i>Verkehrsverbund</i>) with integrated fares and services
1968	Victoria Line, London	First automated fare collection with graduated fare

Table 1.5 (*continued*)

<i>Year</i>	<i>Location</i>	<i>Event</i>
Late 1960s	Western Europe, U.S.	Introduction of transit (LRT, bus) malls
1969	Shirley Highway, Washington	First exclusive busway for commuter transit (later converted into HOV roadway)
Early 1970s	Western Europe, U.S., Japan	First major use of thyristor chopper control of electric motors
1972	BART, San Francisco	First computer-controlled rapid transit system
1970s	United States	Widespread development of innovative types of paratransit services
1974	Dallas-Fort Worth Airport	First fully automated guided transit network with driverless vehicles (AGT) in airport
1975	Morgantown, West Virginia	First AGT system in public service
Late 1970s	Western Europe, United States	Testing of AC electric motors on transit vehicles
1977	San Diego	First wheelchair-lift-equipped bus on transit line
ca. 1978	West Germany	Dual-mode trolleybus with remote trolley pole control
1979	Hamburg	Low-floor bus tested; wide use from late 1980s
From 1980s	Sao Paulo, Curitiba, Ottawa, Pittsburgh	Bus lines on separated lanes and high-frequency service; first BRT systems
1983–88	Lille, Vancouver, London, Miami	First fully automated regular transit lines
1985	Geneva	First 60% low-floor LRT vehicles
1990	Bremen	First 100% low-floor LRT vehicles
1993–2002	Lyon, Paris, Singapore	Fully automated full-size metro lines
Since 1990	Western Europe, U.S.A., Japan, Singapore	Extensive applications of Intelligent Transportation Systems (ITS) technology in transit systems

portance of transit for cities' economic viability and living conditions can be found in the three last federal transportation acts: ISTEA of 1991, NEXTEA of 1996, and SAFETEA-LU of 2005. Implementation of these policy goals, however, is often a major problem.

With respect to the integration and regulation of transit services, considerable progress has been achieved. In most large cities, formerly independent transit services have been integrated into regional transit authorities, districts, and other forms of public agencies. Since the 1990s, the trend toward intermodal coordination has resulted in the founding of agencies that coordinate transit with parking control, traffic regulation, and, particularly, incorporation of transit in pedestrian-oriented areas, resulting in the increased livability of cities. Today by far the best transit services are found in cities that have achieved full integration of all transit operators and improved coordination of transit, street traffic, and pedestrians in attractive, livable environments, such as Munich, Paris, Portland (Oregon), Stockholm and Toronto.

Although the nature of contemporary urban transportation problems varies among different cities and countries, their general causes have many common elements. For example, most large cities in developing countries suffer very seriously from poor mobility, pollution, noise, accidents, and economic waste caused by chronic traffic congestion. This condition is often a consequence of the failure to ensure an acceptable level of transit service through separation of this mode from other traffic and the introduction of high-capacity rail systems.

Consequently, technological and operational innovations of transportation systems dominated the first decades of the development of modern urban transportation systems. They have by no means been exhausted: technological progress is still very important, and it is continuing. But in recent decades the main problems in urban transportation have occurred due to deficiencies in the treatment of transportation—its planning, organization, and policies—rather than by a lack of technological solutions. Inadequate understand-

ing of urban transportation has often caused technological problems, such as incorrect selection of modes and the decline of technical expertise in the field of transit. Thus, to achieve efficient urban transportation

and healthy cities in general, it is necessary to improve understanding of both areas—planning, organization, and policies on the one hand and transit systems and technology on the other.

EXERCISES

- 1.1. Select two cities and analyze the probable reasons for their locations: which local factors and which external forces influenced the initial development of each of these cities? Can transportation be traced as one of the major forces?
- 1.2. Define urbanization and describe its major causes.
- 1.3. Find data, show them graphically, and discuss the urbanization process in two different countries for approximately the last 100 years.
- 1.4. a) Describe the basic principles of cable car technology. b) Explain why its invention led to intensive construction of cable car lines in various cities. c) Which invention of a new transit mode caused the end of cable car expansion and the replacement of this mode?
- 1.5. Explain why the invention of electric streetcars is considered to have been a major “revolution” in urban transportation. Compare the service characteristics that electric streetcars could offer with those available by previously available modes.
- 1.6. Describe the following developments:
 - a) The introduction of long-distance railways and their effects on the sizes and densities of cities.
 - b) The introduction of mechanized transit and its effect on residential densities, physical sizes, and forms of cities.
- 1.7. Select a city you know well and research the beginnings of its public transportation. Present a short review of major developments and discuss the impacts of these developments on the city’s growth and character, including its population, physical size (area), and form.
- 1.8. List and briefly describe the major technological/operational improvements in the development of streetcar/LRT vehicles from 1880 to the 1950s.
- 1.9. What were the major factors that led to the replacement of streetcars/tramways by buses in many countries? Under what conditions was that change of modes logical, and in which cases was it a mistake?
- 1.10. What were the main technological inventions that led to the development of operational trolleybuses?
- 1.11. Describe the technological advances in bus design between 1915 and 1935 that made buses efficient transit vehicles.
- 1.12. List and briefly describe the technical and operational innovations led to the creation of BRT.
- 1.13. Why did jitney services practically disappear from U.S. cities?
- 1.14. List and briefly describe the changes in streetcar/tramway systems that led to the creation of LRT.

- 1.15. What impact did suburban railways have on cities prior to the introduction of mechanized transit?
- 1.16. Describe recent trends in suburban/regional rail systems in U.S. cities: usage, extensions, and modifications of networks. Which developments contributed to the reversal, since the 1980s, of their decline, which occurred from 1930 to 1960?
- 1.17. Discuss the reasons for the relatively rapid disappearance of interurbans in the United States.
- 1.18. What were the main reasons for the construction of the first “underground” (rapid transit) in the world, and why did that happen in London so much earlier than in other cities?
- 1.19. Explain the major reasons for the accelerated construction of rapid transit systems since the mid-1950s.
- 1.20. Discuss the influence of two recent trends on the role and performance of transit in cities:
 - a) The provision of separate transit rights-of-way; and
 - b) The introduction of transit lines (particularly rail on surface or in tunnel) into the centers of pedestrian-oriented areas such as city centers or suburban major activity centers.

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2

URBAN PASSENGER TRANSPORT MODES

This chapter presents, first, a systematic classification and definitions of concepts and terms in urban passenger transportation, focusing mainly on transit systems. The definitions are concise, but references to later chapters where they are elaborated are given. The second section develops a conceptual model of an optimal evolution of transportation system features and modes as a human settlement grows from a village to a large metropolis. This hypothetical evolution of system components—such as different types of travel ways or rights-of-way, guided versus steered technologies and small versus large vehicles—builds a basis for technical definitions of transit modes and their places in the “family of modes.” Chapters 5 to 9 contain detailed descriptions of modes, while their comparisons are given in the final, 10th chapter. The last two sections of this chapter present brief definitions of modes and their actual present roles in cities.

2.1 TRANSPORT SYSTEMS DEFINITIONS AND CLASSIFICATION

Urban transportation modes and operational concepts can be classified according to several different bases. Some of the classifications are interdependent. For example, modes are often identified with system technology only, but their technology is actually strongly influenced by the characteristics of rights-of-way and operations. All major classifications are given here, from the basic classification of all urban travel to the definitions of physical systems and their components and performance concepts.

2.1.1 Classification by Type of Usage

There are three basic categories of transportation by type of operation and usage: *private*, *for-hire*, and *public* or *common carrier*. The main characteristics, typical modes, and optimal operating domains of these categories are shown in Table 2.1.

Private transportation consists of privately owned vehicles operated by owners for their own use, usually on publicly provided and operated streets. Private auto is the most common mode, but motorcycle, bicycle, and, of course, walking also belong in this category.

For-hire urban passenger transportation, commonly designated as *paratransit*, is transportation service provided by an operator and available to all parties who meet the conditions of a contract for carriage (i.e., pay prescribed fares or rates), but which is adjustable in various degrees to the individual user's desires. Most paratransit modes do not have fixed routes and schedules. Taxi, dial-a-ride, and jitney are major modes.

Public transport, *mass transportation*, or *transit* is the *common carrier* type of urban passenger transport. These are transport systems with fixed routes and schedules, available for use by all persons who pay the established fare. The most common representatives are bus, light rail transit, and rapid transit or metro, but there are a number of other modes.

Paratransit modes with routes and schedules that change with the requests of individual users are referred to as *demand-responsive*; when the difference is pointed out, transit is described as *fixed-route*, *fixed-schedule* service.

Table 2.1 Classification of urban passenger transportation by type of usage

Characteristic	Usage type		Public or Common Carrier
	Private	For-hire	
Common designation	Private transportation	Paratransit	Transit
Service availability	Owner	Individuals, groups	Public
Service supplier	User	Carrier	Carrier
Route determination	User (flexible)	User (carrier)	Carrier (fixed)
Time-schedule determination	User (flexible)	User (carrier)	Carrier (fixed)
Cost-price	User absorbs	Fixed rate	Fixed fare
Carrier type	Individual		Group
Modes	Walking Bicycle Motorcycle Automobile	(Rental car) Car sharing Taxi	Street transit (bus, trolleybus, streetcar) Semirapid transit (bus rapid transit, light rail transit) Rapid transit (rail and rubber-tired metros, regional rail) Specialized modes
Optimum (but not exclusive) domain of operation	Low-medium	Any	High-medium
Area density		Origin: low; Destination: high	
Routing	Dispersed	Dispersed	Concentrated (radial), ubiquitous
Time	Off-peak	All times	Peak, daily hours
Trip purposes	Recreation, shopping, business, other	Business Special services	Work, school, business, social, other emergency

Urban public transportation, strictly defined, includes both transit and paratransit categories, since both are available for public use. However, the term *public transport* is commonly identified with transit only, and inclusion of paratransit is specifically emphasized.

A secondary classification of travel categorizes transport as individual or group. *Individual transport* refers to systems in which each vehicle serves a separate party (person or organized group); *group transport* usually carries unrelated persons in the same vehicles. As Table 2.1 shows, the former is predominantly private transport and the latter is transit, while paratransit encompasses modes from both categories.

2.1.2 Transit Modes

A transit mode is defined by its three basic characteristics:

- Right-of-way (ROW) category
- System technology
- Type of service

Transit modes vary with each one of these characteristics. Contrary to the common belief that technology mostly determines modal characteristics, the ROW category has a major influence on both performance and costs of modes. For example, by its operating speed, reliability, and other performance elements, streetcar service is more similar to street bus than to rail rapid transit service. Actually, street transit consists predominantly of steered modes (buses), while with upgrading of ROW through separation, rail becomes the dominant or exclusive technology.

2.1.2.1 Rights-of-Way. A transit way or ROW is the travel way or strip of land on which the transit vehicles operate. There are three basic ROW categories distinguished by the degree of their separation from other traffic.

- **Category C** represents surface streets with *mixed traffic*. Transit may have preferential treatment, such as reserved lanes separated by lines or spe-

cial signals or travel mixed with other traffic, as in Photo 2.1.

- **Category B** includes ROW types that are *longitudinally physically separated* by curbs, barriers, grade separation, and the like from other traffic but with grade crossings for vehicles and pedestrians, including regular street intersections. This ROW category is most frequently used for light rail transit (LRT) systems (Photo 2.2). High-occupancy vehicle (HOV) lanes or roadways represent a low-quality ROW category B: they provide better traffic flow than general lanes but do not separate public from private vehicles, the most important element for giving transit the favored role on the basis of its public service and higher efficiency than private transportation.
- **Category A** is a *fully controlled ROW* without grade crossings or any legal access by other vehicles or persons. It is also referred to as “grade-separated,” “private,” or “exclusive” ROW, and it can be a tunnel, an aerial structure (Photo 2.3), or at-grade level. In exceptional cases, usually on regional rail systems in suburban areas, the ROW may have widely spaced grade crossings with full signal override and gate protection of the tracks and yet be considered as category A, since such crossings have practically no effect on line performance.

2.1.2.2 System Technologies. Technology of transit modes refers to the mechanical features of their vehicles and ways. The four most important features are defined here.

- **Support** is the vertical contact between vehicle and riding surface, which transfers the vehicle weight and traction force. The most common types are rubber tire on concrete, asphalt, or other surface and steel wheel on steel rail. Other types of support are vehicle body on water (boats and hydrofoils), air cushion (hovercraft), and magnetic levitation. Technologies with vehicles running on a ROW surface or guideway are *supported*; those with the vehicle body around the guideway are *straddled*; systems with support



Photo 2.1 ROW category C: transit in mixed traffic (Prague; courtesy of Gabriel Tompkins)



Photo 2.2 ROW category B: partial separation (Karlsruhe; courtesy of UITP)



Photo 2.3 ROW category A: fully controlled (Bangkok; courtesy of Hartfried Schmid)

above the vehicle body are *suspended*. The supported type is by far the most common.

- **Guidance** refers to the means of lateral vehicle guidance. Highway vehicles are *steered* (by the driver) and their lateral stability is provided by wheel/support adhesion. Rail vehicles are *guided* by flanges and the conical form of the wheel surfaces. A distinct feature of rail technology is that its wheel/rail assembly combines both support and guidance. Externally guided rubber-tired vehicles in all forms must have additional wheels and surfaces for guidance.
- **Propulsion** refers to the type of propulsion unit and method of traction, or transferring acceleration/deceleration forces (see Chapter 3). Its major components are:
 - *Type of propulsion unit*, the most common ones being diesel internal combustion engine (ICE), used on buses and some regional rail lines; and electric motors, used on trolleybuses and all rail and other guided modes except some regional rail lines. Gasoline ICE dominates small highway vehicles, while the gas turbine, steam engine, linear induction motor (LIM), and others are mostly specialized or experimental.
 - *Methods of transferring tractive force*, including friction/adhesion (dominant), magnetic forces, cable, rotor (helicopter) and propeller, among others.
- **Control** is the means of regulating the travel of one or all vehicles in a system. The most important control is for longitudinal spacing of

the vehicles, which may be manual-visual, manual-signal, fully automatic, or various combinations of these (see Section 6.6.1).

Traditionally, transit technologies were defined only by the techniques of support and guidance. Such definitions are not precise enough to distinguish bus from trolleybus or light rail from rapid transit. With support, guidance, propulsion, and control, all technologies can be defined to any desired degree of precision.

2.1.2.3 Types of Service. There are many different types of transit services. They can be classified into groups by three characteristics:

First, by the *types of routes and trips served*:

- *Short-haul transit* is defined as low- to medium-speed services within small areas of high travel density, such as central business districts (CBDs), campuses, airports, and exhibition grounds.
- *City transit*, the most common type, includes transit lines serving an entire city. They may operate on any ROW category (C, B, or A).
- *Regional transit* consists of long high-speed lines with few stops, serving long trips within the metropolitan region. Regional rail and some express bus lines exemplify this category.

Second, by *stopping schedule or type of operation*:

- *Local service* is with all transit units (TUs; see Section 2.1.3) stopping at all stops (or as required by passengers).
- *Accelerated service* is operation when successive TUs skip different sets of stations on a predetermined schedule (e.g., skip-stop and zonal service).
- *Express service* is provided when all TUs on a line stop only at widely spaced stops. These lines often parallel local service but serve fewer stops /stations, comprising express/local service.

Third, by *time of operation*:

- *Regular or all-day service* is transit operated during most daily hours. This is the basic transit ser-

vice, and it includes the great majority of transit lines.

- *Commuter transit or peak-hour service* refers to routes operated during peak hours only. They are usually radial from suburbs, focusing on the CBD, and designed for work trips only. *Commuter transit is a supplement to an all-day, regular transit but not a substitute for it.*
- *Special or irregular service* is transit operated only during special events (e.g., sporting events, conventions, exhibitions, or public celebrations) and emergency conditions (snowstorms, floods, etc.).

2.1.2.4 Generic Classes of Transit Modes. There is no rigorous definition of what differences in ROW, technology, or type of service make a separate mode, but it is common to consider systems as different modes if they differ substantially in one or more of the three characteristics. Thus buses and trolleybuses operating the same type of service on the same ROW are different modes because of their substantial technological and performance differences, but standard and articulated buses operating under the same conditions would not be considered different modes. An express bus line is a different mode than a shopper shuttle, even if the vehicles are identical, because of the drastically different services; but skip-stop rapid transit service during peak hours is not considered a different mode from the same line operating locally at other times because the two services are quite similar.

The most important classification of transit modes is into three generic classes, based mostly but not entirely on ROW type. These are defined here.

1. *Street transit* (also known as *surface transit*) designates modes operated on streets with mixed traffic (ROW category C). Its reliability depends on traffic conditions, primarily traffic congestion and various interferences, and its speed is lower than the speed of traffic flow due to the time lost at passenger stops; buses, trolleybuses, and streetcars/tramways are in this class.
2. *Semirapid transit* consists of modes utilizing mostly ROW category B, but C or A may also

Table 2.2 Classification of urban public transportation modes by ROW category and technology^a

ROW \ Technology	Highway Driver-Steered	Rubber-Tired Guided, Partially Guided	Rail	Specialized
C	<i>Paratransit</i> <i>Shuttle bus</i> <i>Regular bus (on street)</i>	<i>Trolleybus</i>	<i>Streetcar / tramway</i> <i>Cable car</i>	<i>Ferryboat</i> <i>Hydrofoil</i>
B	<i>Bus rapid transit (BRT)</i>	<i>Guided bus</i>	<i>Light rail transit (LRT)</i>	(Cog railway)
A	Bus on busway only ^b	<i>Rubber-tired metro</i> <i>Rubber-tired monorail</i> <i>Automated guided transit (AGT)</i> <i>PRT^b</i>	<i>Light rail rapid transit</i> <i>Rail rapid transit / metro</i> <i>Regional / commuter rail</i> <i>Monorail Schwebbahn</i>	<i>Cog railway</i> <i>Funicular</i> <i>Aerial tramway</i>

^a Modes extensively used are shown in italic type.^b Modes that are not in operation.

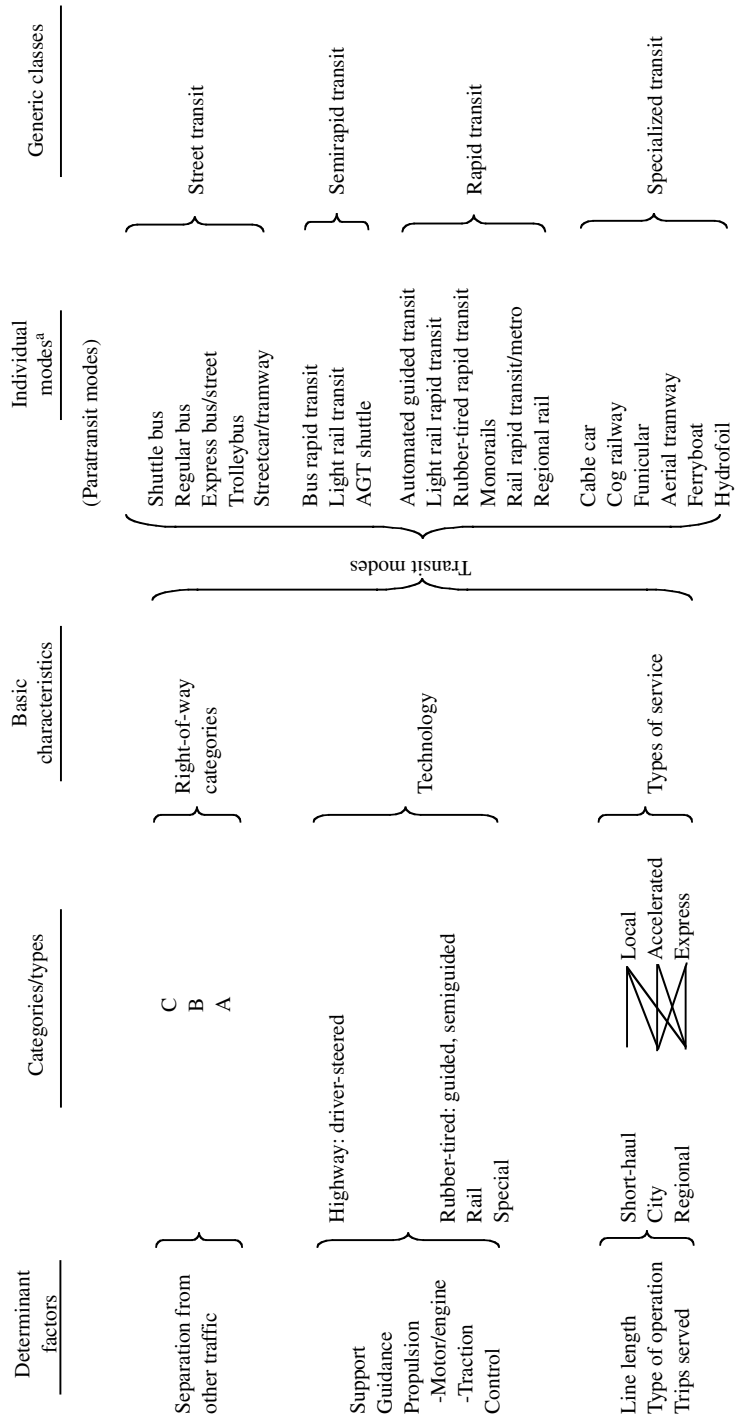
be used on some sections. This class includes a wide range of modes from those with B and C categories, such as buses and light rail transit (LRT) operating on separated ROW and streets on the low side, to largely grade-separated LRT with tunnels or aerial structures (B and A) on the high side. Performance of these modes depends greatly on the degree and locations of ROW separations: it is particularly important that transit be separated from other vehicular traffic in central, congested urban areas. Another factor is technology: rail modes can operate in short trains and have higher safety through automatic signalization than buses. Higher types of semirapid transit (with little or no category C ROW) can match or exceed the speed and reliability of auto travel.

3. *Rapid transit* modes operate exclusively on category A ROW and have high speed, capacity, reliability, and safety. All existing rapid transit systems utilize *guided technologies* (rail or rubber tire), which permit the operation of trains (high capacity and low operating costs) and automatic signal control (high safety). Because the term “rapid transit” is very popular, some cities use it for their transit systems, although they consist of buses or LRT only. Technically speaking, the bus rapid transit (BRT) mode is semirapid, rather than rapid transit.

Most transit modes belong to one of the three generic classes. The exceptions are such modes as moving sidewalks, ferryboats, aerial tramways, funiculars, and some automated guided transit (AGT) systems. The last three do have exclusive ROW, but they have no other features of rapid transit, particularly high speed and capacity. These modes are therefore classified as *specialized technologies*, or *special transit modes*.

A matrix of mode classification by ROW category and major technological features (mainly support and guidance) is given in Table 2.2. Other technological and some service variations are given in individual matrix boxes. In addition to all street transit modes, category C also contains water- and airborne modes. Semirapid transit modes are in category B, while all rapid transit modes belong by definition in category A. However, this category also includes all guided nonrail modes, since they cannot tolerate grade crossings. Inclines and aials are also included. Thus the generic classes correspond closely but not exactly to the ROW categories.

An overview of the preceding mode definitions, classifications, and characteristics is presented in Figure 2.1. An analysis of the basic technological and operational features and their impact on characteristics of modes are presented in Section 2.2. A brief review of characteristics, of all major modes is given in Section 2.3.



^a The list is not exhaustive.

Figure 2.1 An overview of transit mode definition, classification, and characteristics

2.1.3 Transit System Components

Physical components of the transit systems are generally classified into the following items:

- *Vehicles or cars* are referred to collectively as the *fleet* for any mode and *rolling stock* for rail vehicles. A *transit unit (TU)* is a set of vehicles traveling together; it may be a *single vehicle* unit or a *train* with several coupled vehicles.
- *Ways, travel ways, or rights-of-way* may be common streets and roads, reserved lanes (designated only), exclusive lanes (physically separated), transit streets, busways (grade-separated roadways for buses only), tracks in roadways, on partially or fully controlled ROW at grade, above grade (embankments and aerials), or below grade (cuts and tunnels).
- Locations and facilities at which vehicles stop to pick up and drop off passengers can be of several types. *Stops* are locations along streets with simple facilities (signs, shelters, etc.). *Stations* are usually facilities below, on, or above ground for passengers and system operation. *Terminals* are end stations of major transit lines. *Transfer stations* serve more than one line and provide for passenger interchange among them. *Multimodal transfer stations* are served by several modes, as Photo 2.4 illustrates. *Interface* is another term for *intermodal transfer station*.
- *Bus garages or depots* and *rail yards* are buildings or areas for vehicle storage. *Shops* are facilities for vehicle maintenance and repair.
- *Control systems* include electric, computer and other electronic equipment for vehicle detection, communication and signals, as well as *central control facilities*.
- *Intelligent Transportation System (ITS)* is a broad set of devices, facilities, and processes that utilizes computer and other electronic technology devices for control and efficient operation of transportation systems. In transit systems, ITS is used mostly in the monitoring and control of TU operations, in fare collection and control, collection of statistical data, and passenger information systems.

- *Power supply systems* on electrically powered modes consist of substations, distribution cables, catenary or third-rail structures, and related equipment.

Except for the vehicles, all the foregoing items constitute *fixed facilities* of transit systems, or their *infrastructure*.

- *Transit route or transit line* is a designated set of streets or separated rights-of-way that transit TUs regularly serve. The term “route” is commonly used for buses and “line” for rail modes and for sections on which several routes overlap; but the two terms are sometimes used interchangeably. The collection of all routes/lines in a city is its *transit network*.

2.1.4 Transit System Operations, Service, and Characteristics

Transit operations include such activities as scheduling, crew rostering, the running and supervision of TUs, fare collection, and system maintenance. They produce transportation that is offered to potential users.

Transit service is the system as seen by its actual and potential users. *Transit system characteristics* are classified in four categories.

1. *System performance* refers to the entire set of *performance elements*, the most important being:
 - Service frequency (f)*, number of TU departures per hour.
 - Operating speed (V_o)*, speed of travel on the line which passengers experience.
 - Reliability*, expressed as a percentage of TU arrivals with less than a fixed time deviation from schedule (e.g., 4 min).
 - Safety*, measured by the number of fatalities, injuries, and property damage per 100 million passenger-km, or a similar unit.
 - Line capacity (C)*, the maximum number of spaces (offered capacity) or persons (utilized capacity) TUs can carry past a point along the line during one hour.



Photo 2.4 Intermodal transfer: bus feeders to ferry in Istanbul (Courtesy of Dana L. Bland)

Productive capacity (P_c), the product of operating speed and capacity of the line, $V_o \cdot C$. As a composite indicator incorporating one basic element affecting passengers (speed) and one affecting the operator (capacity), productive capacity is a very convenient performance indicator for mode evaluation.

Productivity, the quantity of output per unit of resource (e.g., vehicle-km or space-km per unit of labor, operating cost, fuel, ROW width, and so on).

Utilization, also the ratio of output to input, but of the same or a similar unit; for example, person-km/space-km offered.

2. *Level of service (LOS)* is the overall measure of all service characteristics that affect users. LOS is a basic element in attracting potential users to the system. Major factors comprising LOS can be divided into three groups:

Performance elements that affect users, such as operating speed, reliability, and safety

Service quality (SQ), consisting of qualitative elements of service, such as convenience and simplicity of using the system, riding comfort, aesthetics, cleanliness, and behavior of passengers

Price, the amount a user must pay for service (i.e., its fare or rate).

3. *Impacts* are the effects transit service has on its surroundings and the entire area it serves. They may be *positive* or *negative*. *Short-run impacts* include reduced street congestion, changes in air pollution, noise, and aesthetics along a new line. *Long-run impacts* consist of changes in land values, economic activity, physical form, and the social environment of the city.
4. *Costs* are usually divided into two major categories: *investment* (or *capital*) *costs* are those required to construct or later make permanent changes in the physical plant of the transit system. *Operating costs* are costs incurred by regular operation of the system.

Evaluation and comparative analysis of transit systems must include all four categories: performance, LOS, impacts, and costs of each system. The preferred mode is usually not the one with the highest performance or lowest costs but the one with the most advantageous “package” or combination of the four.

2.2 THEORY OF URBAN PASSENGER TRANSPORT MODES

Urban transportation modes differ greatly in their technical, operational, and economic characteristics as well as their impacts. A thorough understanding of the features of modes and their places in the family of modes is needed for the formulation of a rational policy and sound urban transportation planning. This section presents a conceptual description of the evolution of modes, from pedestrians and bicycles to freeways and metros, which is based on and applicable to actual cities of different sizes and local characteristics.

2.2.1 Evolution of a Transportation System in a Model Urban Area

To understand the *inherent characteristics* of different modes, one must free oneself from real-world experiences influenced by factors that distort the optimal uses of modes. These include investment, pricing, and regulatory policies favoring one mode; different ages and

operating practices of existing systems; local conditions in different cities; and many others. A conceptual analysis based on a model of an urban area of increasing population and size is therefore used here.

The model, shown in Figure 2.2, represents a human agglomeration that grows from a sparse settlement (a) to a large metropolis (d). Requirements for transportation change through this evolution from low volume, dispersed travel to high volume, and heavily concentrated travel along a number of major arterials. Thus the entire range of requirements is observed and the optimal sequence of transportation modes through the entire spectrum of capacities and performance levels is defined in a systematic way. Each one of the significant steps in changing the modal features—such as the introduction of large vehicles, separated ways, external vehicle guidance, and automation—is sequentially defined. The advantages (+) and disadvantages (–) that major steps bring over the preceding systems are listed for a clear overview.

The analysis is divided into four growth periods, corresponding approximately to small settlements, towns, medium-sized cities, and large cities. Naturally, these four urban-area sizes are not precisely defined, nor are different modes employed strictly by area population. For general orientation, the population ranges may be considered to be as follows: small settlements, up to 100,000; towns, 100,000 to 500,000; medium-sized cities, 500,000 to 2 million; and large cities, over 2 million. European cities with similar transportation characteristics would have the three population boundaries at approximately 50,000, 300,000, and 1.3 million, respectively.

2.2.1.1 Small Settlements: Private Travel and Paratransit. Starting from the very beginning, the model represents a small settlement consisting of a few residences, stores, and other buildings connected by a network of paths or roads, as shown in Figure 2.2a. The short trips among different buildings in this settlement can best be performed by *walking*. This basic mode of travel is always available, requires no investment and can be used for travel between any two points at any time. Its limitations are low speed, limited

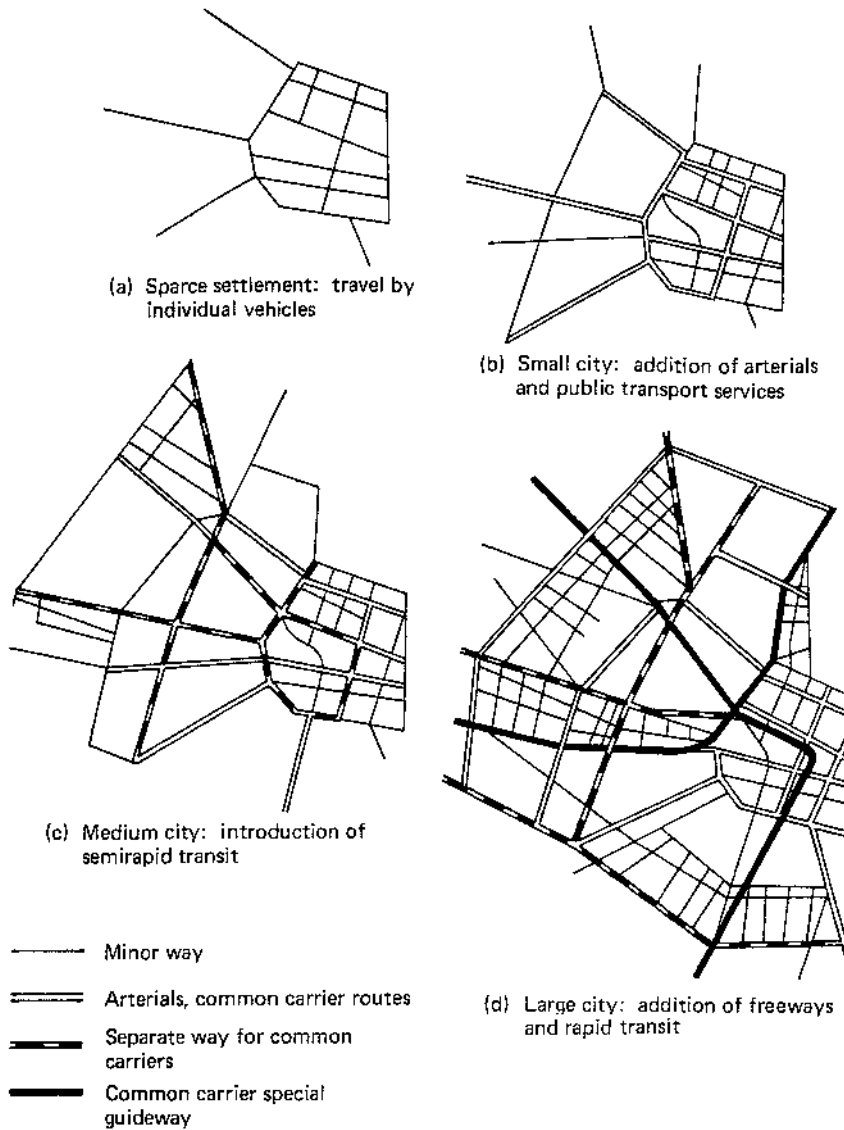


Figure 2.2 Transportation system evolution with urban area growth

ability to carry load, and discomfort in inclement weather.

Step 1: Walking—Pedestrians

As the settlement grows in size, walking takes too long and involves increasing effort. A new mode of transportation is needed for the longer trips. The few dispersed trips would be best served by *small motorized vehicles* that individual persons own and use for

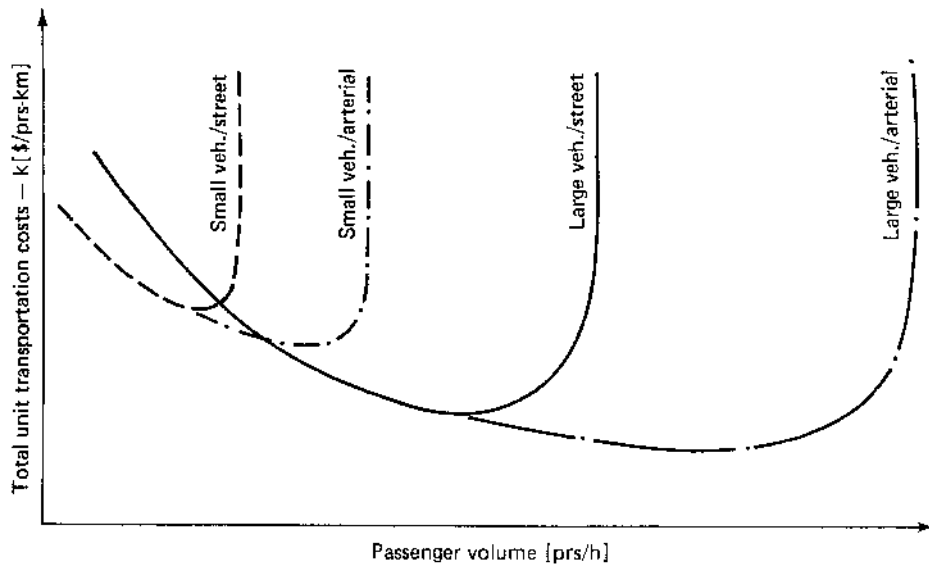


Figure 2.3 Impact of street capacity and vehicle size on unit costs

travel to any place at any time they choose. The vehicles satisfy the transportation needs of small settlements extremely well: they provide ubiquitous, comfortable, and economical transportation at all times. They also have limitations, however: they are available only to the persons who (1) own or rent, and (2) are able to drive a vehicle. Persons who do not meet either one of these two conditions can travel only if someone else drives them, or if they walk.

These small motorized vehicles exist in the real world: they are *private automobiles*; *bicycles* and *motorcycles* belong in the same category.

Step 2: Use of individual private vehicles (automobiles)

A further improvement in the transportation system would be to provide some kind of motorized travel for people who do not meet the foregoing two conditions. This is achieved most efficiently by the introduction of a *common carrier* service. In a small settlement, the best solution for this would be to introduce vehicles

operated by professional drivers who would drive anybody for a fixed price, determined by a public authority.

The mode in the real world that corresponds to this definition is the *taxi*.

Step 3: Introduction of vehicles as common carrier service (taxis)

Individual transportation—as by *bicycles*, *private automobiles*, and *taxis*—comprises an ideal transportation system for small, low-density settlements.

2.2.1.2 Towns: Bus Transit and Arterial Streets.

As the small settlement grows into a town, the travel of small vehicles intensifies and the narrow roads frequently become congested. The capacity of the transport system must be increased. Two measures are most logical: the introduction of larger vehicles and widening of roads/streets. The effects of these changes on the unit cost of transportation—including investment, operating, and user costs—are shown in Figure 2.3.



Photo 2.5 Medium-capacity common carrier vehicle (midibus in Philadelphia; courtesy of Karyn J. Cullen)

Total costs of each mode decrease with increasing passenger volume and reach an optimal range, after which, as the system capacity is reached, cost increases rapidly. When a low-capacity system, such as cars traveling on narrow roads, operates at capacity, its unit costs are very high. When a higher-capacity system such as buses and cars on the same roads, is introduced, it operates at lower unit costs. Moreover, the costs of the smaller-capacity system (automobiles) are reduced because its volume decreases from capacity level to its optimum range. In addition, the social costs of congestion and resulting negative environmental impacts and accidents are decreased.

Capacity increase through introduction of large vehicles can be achieved only with common carrier (transit) service, since it is impossible to induce or force private owners to accept strangers as passengers to in-

crease vehicle loads. Joint use of private cars (carpooling) can be organized only for the fraction of trips that are made at regular intervals between the same points.

For low passenger volumes, medium-capacity vehicles (Photo 2.5) that stop wherever passengers want may represent the best solution, since they offer service somewhat adjusted to passengers' desires, with reasonable frequency and at moderate costs. As the volume increases, it becomes necessary to introduce large-capacity vehicles, exemplified by the bus in Photo 2.6.

With the introduction of large-instead of small- or medium-capacity vehicles, public transport changes its operation. Instead of serving a small number of persons by the irregular routing typical for small- and medium-capacity vehicles, large transit vehicles travel along fixed routes, stop at predetermined locations, and



Photo 2.6 Regular bus (Los Angeles; courtesy of Michael Strauch)

serve large numbers of persons. Schedules are fixed and regular headways provide more reliable service and shorter average waiting times. Fares are considerably lower. Higher-cost door-to-door service remains available from the small common carrier vehicles—taxis.

Each one of these developments—the introduction of transit service and of large vehicles—has a number of consequences, which can be summarized as follows.

The common carriers with medium-capacity vehicles that adjust their services to passenger desires (in various degrees) correspond to *paratransit modes*. Large vehicles in the real world are *transit buses*. The basic observations from this succession of developments are also valid in practice: (1) *Optimal vehicle size increases with passenger volume* (as in all other comparisons, *ceteris paribus* is assumed); and (2) *As passenger volume increases, service with adjustable*

Introduction of transit service results in the following changes:

- + Lower-cost transportation becomes available to all persons in the served area.
- + Simple and conveniently scheduled service is provided throughout the transit network.
- + Increased street capacity: higher LOS for all vehicles.
- + Less congestion and its negative impacts.
- Since it is difficult to charge auto drivers the full (including social) cost of their travel, transit must often be subsidized to attract its potential passengers.

Replacement of medium by large transit vehicles or units (TUs) results in:

- + Higher transporting capacity.
- + Lower cost per unit capacity, mostly due to higher labor productivity.
- + Greater riding comfort.
- Lower service frequency for given demand.

routing and schedules should be replaced by fixed routes and schedules.

Step 4: Introduction of common carrier service, first by medium-sized vehicles with irregular operations (paratransit), then by bus transit with fixed routes and schedules.

The next capacity-increasing measure is construction of wider roads or arterial streets.

Step 5: Construction of wider roads/streets

2.2.1.3 Medium-Sized Cities: Transit Way Separation and Guided Technology. Further growth of the model town into a medium-sized city again leads to congestion and a lower LOS. The next logical step is to create separate rights-of-way for different types of vehicles so that a uniform flow—with no friction from other vehicles, pedestrians, and so on—is obtained. Longitudinal separation (ROW category B) is

the first important step for the reduction of interferences because conflicts at street intersections can be regulated through traffic control devices. As the large vehicles carry 5 to 50 times more persons than the small vehicles, it is logical that public rather than private modes be given separate rights-of-way first.

Placement of transit on reserved ROW is its most important single improvement: its partial independence from other traffic allows increases in travel speed and reliability, which can make transit service competitive with the auto. Ridership therefore increases appreciably.

Step 6: Partial separation of modes (transit ROW category B)

When a set of transit vehicles operate on ROW category B, the advantages of using guided vehicle technology generally outweigh its disadvantages, as the following list shows.

Guided technology is utilized in the real world in several forms, but the only one that can operate on ROW category B is rail, that is, the *LRT mode*.

Construction of higher-capacity roads brings:

- + Higher LOS.
- + Lower unit transportation costs.
- + Stimulus to economic growth (result of the preceding two).
- High investment requirements.
- Negative environmental impact of wide paths and large vehicle storage facilities.

Longitudinal separation of transit vehicles (ROW category B) results in:

- + Higher level of service and system performance.
- + Stronger system image and identity.
- + Higher passenger attraction (consequence of the above two).
- + Lower unit operating cost because of higher speed and reliability.
- + Stronger impact on land use and urban form due to permanence.
- ± Changed traffic conditions, depending on whether the transit ROW is outside or within existing streets (e.g., curbed median).
- Additional land area required.
- Substantial investment and construction required.

Guided modes, compared with *steered transit modes*, differ in the following:

- + Much larger, spacious, and more comfortable vehicles, particularly with rail technology.
- + Operation of trains possible, with much greater line capacity and labor productivity.
- + Lower operating cost per unit of offered capacity.
- + Electric traction introduced with better performance, no exhaust, and noise (see Section 3.4.8).
- + Greater reliability and safety (fail-safe operation).
- + Narrower ROW.
- + Operation in tunnels, on viaducts, and in park areas feasible without environmental damage.
- Requires higher investment.
- Less compatible with other traffic in street operation.
- Limited to the guideway network only, therefore uneconomical for extensive routing in low-density areas.
- Lower operational flexibility (rerouting, detours, etc.).

Step 7: Introduction of guided transit (LRT)

2.2.1.4 Large Cities: Construction of Fully Controlled Ways. Finally, the model urban area grows into a large city. With its heavy travel volumes in many corridors and large spatial size, the large city requires higher-performance transportation than the automobiles on arterials and transit vehicles on partially separated ways can provide. The only way to achieve the

speed, capacity, and reliability of travel required in cities with multimillion populations is through the provision of fully controlled rights-of-way for major routes of both private and public modes (automobiles and transit, respectively).

These facilities are well known in the real world: they are *freeways* (Photo 2.7).

Step 8: Construction of grade-separated divided roads (freeways)

Fully controlled ways (grade-separated roads, ROW A), compared with *partially controlled arterials* (B) and *uncontrolled streets* (C), have:

- + Much higher performance (capacity, speed, reliability, etc.).
- + Higher LOS.
- + Lower operating costs per vehicle-km.
- + Greater permanence of system performance (frontages protected from developments).
- + Permanence that affects land uses.
- Considerably larger area requirements (particularly for interchanges).
- Very high investment costs.
- Disruption of corridor during construction.
- A large vehicle volume is attracted into center city.
- Wide highways and large interchanges create physical barriers in the city.



Photo 2.7 Fully controlled way for general traffic (freeway in Los Angeles)

Common carriers also need fully controlled ROW (*category A*) to achieve the performance required for large cities.

This comparison and the comparison of guided with steered modes show that for operation on streets with other traffic, the disadvantages of guided technology usually outweigh their advantages. For semirapid transit, the advantages of guidance are more significant than its disadvantages under most although not all conditions. Finally, for transit on ROW category A, guided technology is always superior to steered because its

very significant operational and performance advantages are not mitigated by its inability to operate off the guideways: the vehicles operate exclusively on fixed ROW anyway.

The described concept of guided common carriers on fully controlled ROW represents the *metro* or *rapid transit mode* in the real world: in most cases it is rail and in a few cities rubber-tired guided technology (the two are compared in Section 6.4.2). Photo 2.8a shows a modern metro train in a station. Photo 2.8b illustrates the large passenger volumes many metro systems carry.

Category A, compared with *category B* ROW, gives transit modes:

- + Much higher performance (speed, reliability, capacity due to long trains, etc.).
- + Higher LOS.
- + Lower operating costs per unit capacity due to very high labor productivity.
- + Stronger image and identity.
- + Higher passenger attraction (result of the preceding three).
- + Stronger positive land-use impacts.
- + Possibility of automation.
- Need for grade separation of the entire ROW.
- High investment.
- Disruptions of the corridor during the construction.
- Less extensive network (result of the preceding three items).



Photo 2.8(a) High-capacity mode for large cities (Munich U-Bahn; courtesy of Mathias Frey)



Photo 2.8(b) Metro—the highest capacity mode of urban transit (Paris; courtesy of Chen Zheng)

Some AGT modes, described in Chapter 7, also belong in this general category, except that their capacity is considerably lower.

Step 9: Provision of fully controlled ROW for common carriers (rapid transit)

The preceding comparisons also show that rapid transit—combining the characteristics of guided technology, electric traction, and category A ROW—represents a mode with the highest performance and LOS but also with the highest investment requirements of all transit modes.

There is only one additional major improvement that can be made: full automation of train operation (trains without crews). That brings the technology of line-haul transit to the ultimate step of development that can be practically achieved.

Full automation requires three features: (1) ROW category A, (2) guided technology, and (3) electric traction. It does not depend on such features as vehicle size, off-line stations, or unconventional technology: rail systems are actually the best candidates for full automation because of their simplicity, reliability, and high capacity.

The first advantage of automation is by far the most important, since it allows economical deployment of high-quality transit for medium passenger volumes (i.e., in cities that presently cannot justify rapid transit).

For further discussion of automation, see Sections 6.6.1 and 7.2.4.

Several modes of fully automated transit exist. In addition to AGT systems, there is an increasing number of light rail rapid transit (LRRT) and conventional metro systems that operate without crews.

Step 10: Full automation of common carriers (AGT, LRRT, and automated metro)

A summary review of the 10 steps of urban transportation system evolution, their major effects on system performance, and their real-world forms are presented in Figure 2.4.

2.2.2 Review of Modal Features

The preceding conceptual analysis shows that there is a strong interdependence between the volume of travel and the characteristics of modes optimal for a given application. The evolutionary process of transportation mode change that has been described is not absolute because of many influencing factors. In some cases the sequence of steps may be reversed without any significant inefficiencies. For example, the introduction of guided modes (step 7) may come before the provision

Fully automated compared with manually operated systems have:

- + Increased frequency of service without additional cost.
- + Lower energy consumption and vehicle wear due to preprogrammed driving.
- + Easier recovery from service disturbances.
- + Lower operating cost (if labor savings outweigh the cost of increased system complexity).
- + Higher operating safety (human error eliminated).
- Considerably higher investment cost.
- Much greater technical complexity and therefore lower reliability.
- Requirement for automated track supervision and communication with passengers for handling emergencies and security.

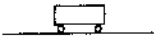
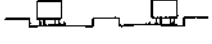
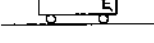
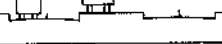
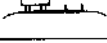
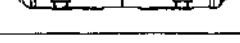
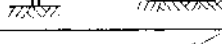
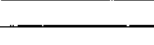
Step no.	Description	Sketch	Major improvements	Corresponding real world system
1	Paths, walking		---	Walking-pedestrians
2	Private motorized vehicles		Speed Comfort Convenience	Private automobiles
3	Common carrier (rental) vehicles		Service available to all people	Taxis
4	Widening of the paths		Capacity LOS	Arterials
5	Introduction of large vehicles		Capacity Cost Comfort	Bus transit
6	Separation of modes		Capacity Reliability Speed of transit	Transit ROW category B
7	Guided technology		Capacity Electric traction Comfort Operating cost	LRT
8	Grade-separated paths		Capacity Speed Safety Convenience	Freeways
9	Fully controlled common carrier ROW		Capacity Speed Reliability Area impact	ROW category A, rapid transit
10	Automated common carrier cabins		Frequency Operating cost Performance	Automated guided modes: AGT, RRT

Figure 2.4 Review of the evolutionary steps of an urban transport system in a growing settlement, from a town to a large city

of ROW category B (step 6) or after freeways have been built (step 8). Steps 8 and 9 can also be reversed. Yet, the general sequence of the development steps is valid for most urban areas; a significant deviation from them usually reflects planning errors and results in major deficiencies. For example, serious transportation

problems in many cities have been created when extensive freeway networks were built to accommodate and stimulate auto travel, while the transit system consisted only of buses in mixed traffic: step 8 preceded steps 6 and 7. Step 1, walking, remains essential for cities of all sizes (actually, it is often more important

in large cities than in small settlements); yet many cities neglected it while they worked on accommodating motorized traffic through steps 2, 5, and 8.

The evolutionary development process shows that with increasing density of travel, each new modal feature results in:

- Higher initial investment.
- Lower operating cost per unit capacity unless a drastically higher-quality mode with better performance replaces an obsolete system.
- Higher system performance, including capacity, speed, and service quality.
- Greater passenger attraction (consequence of the preceding result).

Thus low travel volumes are best served by low-investment/low-capacity modes; with increasing volumes, higher-investment/higher-capacity modes become superior in terms of both performance and operating costs.

Because of the differences among the operating conditions of various transit systems, it is not possible to precisely define the passenger attraction by individual modes. There is, however, ample evidence that higher-performance modes (ROW category B and, especially, A) attract a substantially higher ridership than do street transit modes. Moreover, rail technology has a higher attraction than highway modes because of its stronger identity, reliability, and higher LOS. Owing to these features, high-performance modes tend to attract not only higher regular ridership but also more diverse trip categories: travel in directions opposite to dominant commuter flows, tourist travel, school excursions, and so on, than street transit services on similar alignments.

Consequently, higher-performance modes are often built to replace lower-performance ones (e.g., metro to replace bus or LRT), not so much because of their higher physical capacity but because of their higher LOS, which attracts more passengers during all times, peak as well as non-peak hours.

This analysis of mode evolution as cities grow also shows that some transportation modes are sometimes fully replaced by their higher-capacity successors

(minibus by bus, LRT by metro), since the new modes provide a higher LOS. Several modes do, however, retain an important role in all city sizes either because they provide unique services (e.g., walking, private auto, and taxi) or because they remain optimal modes for services not requiring higher-performance modes (buses and LRT).

2.3 THE FAMILY OF TRANSIT MODES: CATEGORIES AND DESCRIPTIONS

Utilizing the preceding theory of urban transportation modes, actual paratransit and transit modes can be ordered into a “family,” ranging from taxis to regional rail systems. Brief definitions and characteristics of the commonly used modes are presented here, classified as paratransit and three major categories of transit by their performance/capacity characteristics. These categories correspond largely to the ROW categories they use, as described in Section 2.2. More detailed descriptions of individual modes are given in Chapters 5 through 9. Mutual comparisons of most important modes are presented in Chapter 10.

2.3.1 Paratransit

The paratransit category of transportation systems consists of a variety of mostly highway vehicles providing services between private cars and fixed-route fixed-schedule transit modes. Their types of operation—routing, scheduling and methods of obtaining service by users—makes different modes, rather than strictly defined types of vehicles by technology.

Car sharing organizations, renting passenger cars to their subscribers for individual trips or time periods, have been established in many cities in recent years. This type of passenger car use has become a mode providing services between private cars and taxis.

Taxis are automobiles operated by drivers and hired by users for individual trips. The service they offer is tailored entirely to the user’s desire. Travel by taxi may sometimes involve a longer time to start a trip than with a private car, but there is no parking problem. The user avoids the financial responsibility of owning a car,

but the out-of-pocket cost of taxi travel is the highest of all modes. Since most of the cost covers the driver's time, the high price is inherent in this mode.

Dial-a-ride (DAR) and *hybrid services* have different combinations of features of on-call paratransit and fixed-route transit services. For example, a DAR system consists of vans or minibuses directed from a central dispatching office. Passengers call the office and give their origin, destination, and desired time of travel. The office plans the van/bus routings so that as many passengers as possible are served by each bus trip.

Dial-a-ride usually operates within geographically delineated low- or medium-density areas. It serves trips that have dispersed ends ("many-to-many") or trips with one common end ("one-to-many"). Thus this mode provides a service between those of a taxi and a regular, fixed-route bus. With its personalized service, DAR is often the optimal mode for serving disabled persons.

Jitneys, known under different names in many developing countries, are privately owned passenger cars or vans (5- to 15-seat vehicles) that operate on fixed routes (in some cases with minor deviations) without fixed schedules. They pick up and drop off passengers along their routes by request, often contributing to traffic congestion. Because of their low capacity and much lower labor cost (they are often driven by their owners, who work long hours), jitneys operate with higher frequency, making them convenient for potential users. Their reliability and safety are lower than those of transit buses in cities where regular transit is well organized. Jitneys are used extensively in developing countries, particularly where labor costs are very low and regular buses do not offer sufficient capacity or quality of service.

2.3.2 Street Transit Modes

The most common type of transit in every city, operating on streets, includes three different modes—buses, trolleybuses, and streetcars/tramways.

Regular bus (RB) mode consists of buses operating along fixed lines on fixed schedules. Buses are by far

the most widely used transit mode. With vehicles varying in capacity from minibuses (20 to 35 spaces) to double-articulated buses (up to 150 spaces), and the ability to operate on nearly all streets, arterials, and freeways, buses provide services covering a wide range of LOS, performance, costs, and impacts.

At the lower end of their application range, regular buses serve low-volume suburban routes, overlapping somewhat with DAR and other hybrid-type services.

The most typical bus services are street transit lines, which may represent the entire transit network (small- and most medium-sized cities) or supplementary and feeder services to rail networks (in medium- and large-sized cities). At the upper end of their applications range, RB with articulated vehicles on reserved single lanes that serves heavily traveled corridors with frequent operations can serve lines with volumes of 3000 to 5000 persons/hour. With exclusive roadways, multiple lanes, and stops with overtaking, much higher volumes can be served. See "bus rapid transit" in Section 2.3.3.

Express bus service typically consists of buses operating on long lines with widely spaced stops. It is characterized by higher-speed, more comfortable travel, but service between fewer points and sometimes with higher fares than RB service. Its reliability of service depends on traffic conditions along the line.

Trolleybuses (TB) are the same vehicles as buses except that instead of a diesel engine, they are propelled by an electric motor and obtain power from two overhead wires along their lines. Trolleybuses are in most cases used for the same services as regular buses. They involve higher investment costs and somewhat more complex operations than diesel buses, but they offer higher riding quality (smooth vehicle motion) and excellent environmental features (extremely low noise, no exhaust). A detailed description and comparison of the two modes is given in Chapter 5.

Streetcars (SCR) or *tramways* (in many U.S. cities known as "trolleys") are electrically powered rail transit vehicles operating as one- to three-car TUs with a total TU capacity of 80 to 300 spaces, mostly on streets with ROW categories B and C. Their tracks and distinct vehicles give this mode a strong identity. The spacious vehicles, comfortable ride, and distinct



Photo 2.9 Different modes of street transit (Market Street in San Francisco; courtesy of Tim Lesle)

appearance of the vehicles and lines make them very popular with the passengers.

The operation of streetcars on streets with congested traffic may cause friction with other vehicles, impeding both the streetcars and the auto traffic. In such conditions, buses often have higher speed and greater reliability. For this and several other reasons streetcars, which used to be the basic transit mode until the 1950s, have been replaced in many cities by buses and trolleybuses. However, there are a number of street design and regulatory traffic engineering techniques that can alleviate these problems and, in some situations, provide even a better flow for streetcars than for buses.

Many cities in western and eastern European countries and elsewhere (Melbourne, Toronto) have retained tramways, in some cases greatly improved through

their preferential treatment in traffic (Amsterdam, Zürich). In recent years, however, parallel with intensive construction of LRT systems, there has been some revival of tramways. New streetcar lines have been built in San Francisco (Photo 2.9); Portland, Oregon; and a number of other cities in North America and Europe. They have been introduced mostly in high-density central cities, in tourist-oriented areas, and elsewhere.

2.3.3 Medium-Capacity Modes: Semirapid Transit

Transit modes utilizing mostly ROW category B are characterized by distinctly higher performance—capacity, reliability, speed, and passenger attraction—than the street transit modes. Transit systems in this

category include BRT and LRT as well as automated-medium capacity systems, such as automated guided transit (AGT), also known as automated people movers (APM), which use ROW category A but have much smaller capacity TUs than rail rapid transit. These modes cover a considerable range of characteristics depending on their ROW geometry, types of vehicles/trains, and operations. Thus, semirapid transit covers the range from moderate-performance BRT on the low to high performance LRT on the high end.

Bus rapid transit (BRT) includes bus systems with many physical and operational elements that give them higher capacity, better performance, and a stronger image than regular buses. The minimal features a bus line must have to be considered BRT are:

- Most of ROW is category B and limited line sections of ROW category C.
- Clearly designated stops/stations with passenger amenities spaced 300 to 500 m apart.
- Regular or articulated buses with distinct appearance, good riding comfort, low floor or high platform, and multiple doors for easy and fast boarding/alighting at stops/stations.
- Service offered with regular headways throughout the day—i.e., it is regular transit rather than commuter transit.
- Movement of buses along the line, dispatching at stops and passenger information are well organized and controlled by various ITS measures, guaranteeing reasonably high reliability.

Performance of BRT systems depends greatly on the design and quality of the elements mentioned above. Its quality of service, particularly reliability and image, depend mostly on the enforcement of bus priorities along ROW and operational organization. If other vehicle categories are allowed to use formerly exclusive bus lines or busways, BRT is degraded into a regular bus mode on HOV facilities.

There is a broad range of improved bus services. In some cases, bus lines may include only a few of the above-mentioned elements. For example, buses may use HOV lanes, travel only in the peak direction, and operate for several hours. Such systems are not BRT.

Typical BRT, such as a line with physically protected lanes, operating articulated buses at 2-min headways during peak hours, offers a capacity of 3000 to 5000 spaces/hour. Much greater capacities can be reached on lines with multiple stations, with four lanes at stations allowing overtaking of buses, or even four-lane roadways along most sections of a line (Bogota).

In a number of U.S. cities (Houston, Washington, D.C., Los Angeles) there are *buses on busways* or on HOV roadways operating during peak hours only. They represent *commuter transit* rather than *regular transit*. They are an efficient mode for peak-hour service but offer a lower type of service, if any, in the off-peak hours. The main reason for this deficiency is that, since they usually follow freeway alignments, their routes are often not optimally located with respect to transit demand. Moreover, they provide high-speed travel in outlying, low-density areas but often operate as regular bus lines on streets in the center city.

For further description of all BRT forms, see Section 5.4.

Light rail transit (LRT) is a mode utilizing predominantly ROW B, sometimes A and, exceptionally, C category. Its electrically propelled rail vehicles (Photo 2.10) operate singly or as two- to four-car trains. LRT provides a wide range of LOS and performance characteristics.

LRT was first developed by upgrading streetcars/tramways in many physical and operating elements. The two modes have overlapping characteristics, and



Photo 2.10 A large-capacity vehicle for semirapid transit (LRT in Sacramento; courtesy of Peter Ehrlich)

there are systems that are “between” them. However, a typical LRT system is very different from a typical streetcar system. The main elements that a rail system must have to be defined as LRT are the following:

- Most of the ROW is category B or A, as compared to streetcars with ROW C and B.
- Track crossings of streets are regulated by signals, usually with priority in signal control.
- Stops/stations are separated from the street roadway, and have passenger protection, amenities, and information.
- Average spacing between stops is 300 to 600 m.
- Vehicles are articulated, high-capacity units often operated as two- to four-car TUs.
- Vehicles have multiple doors and low floors or high platforms for easy and rapid access; they are spacious, with a comfortable, quiet ride.
- Maximum speeds are 70 km/h or higher, with protected grade crossing in the latter case.
- High-quality ROW, particularly in tunnels, are often designed with provision for possible later conversion to metro.

LRT takes advantage of a unique feature of rail technology: guided vehicle technology that can run on streets and mix with highway vehicles and pedestrians. This gives LRT the ability to utilize all types of ROW on the same route and yet have the advantages of guided technology: high capacity, high labor productivity (train operation), comfortable ride, distinct image, permanence, and so on. Street running is least desirable because of the disadvantages described above for streetcar operation; fully controlled ROW is the most desirable but the most capital-intensive type.

A typical LRT network has tracks in medians of wide avenues, crossing intersections at grade with preferential signal timing. In high-density central city areas, LRT may use tunnels or operate in traffic-free zones or pedestrian malls. Its lower noise, absence of exhaust fumes, and a better safety record make LRT more compatible with pedestrian environments than buses. Because of the limited speed, however, mall running can be used only on short sections. In outlying

areas, LRT alignment is usually along arterial streets or on fully separated sections (category A). At stations, pedestrian crossings are usually at grade, requiring low investment costs and great convenience for passengers. Running speed on urban LRT lines is usually up to 70 km/h, but there are LRT systems with speeds up to 120 km/h.

Automated guided transit (AGT), also known as *automated people movers (APM)*, are transit modes usually with medium-sized two-axle electric vehicles operated automatically, without crews, on ROW category A only. Exclusive ROW and full automation make the AGT mode very capital-intensive, but they also result in several high-performance features, such as high reliability and service frequency. The most distinct feature of AGT is that its operating cost is relatively low (low labor requirement), so that a frequent and reliable transit service can be offered on lines with medium passenger volumes. In some ways, AGT is a small-scale, lower-cost, medium-performance version of rapid transit. Applications of this mode can be grouped in two general categories.

1. *Shuttle-loop lines, usually referred to as APMs*, which are by far the most numerous type of application. Most of these are in the category of semipublic transit: they serve airports, university campuses, exhibition grounds, etc., so that they have a special group of users, such as airport passengers, and their service is free. In most of these applications, AGT systems consist of rubber-tired guided vehicles with 15 to 80 space capacity, mostly for standees, operated in one- to three-car TUs. Owing to the short lines, many stations, and often sharp curves and steep gradients, their maximum speeds usually do not exceed 40 to 50 km/h. Thus, this mode plays a special role of local passenger travel in major-activity areas (Photo 2.11).
2. *Regular transit line* is the second type of AGT application—a mode requiring considerably higher investment but offering more frequent and faster service than LRT. However, LRT offers higher capacity, superior riding comfort, and better integration in urban areas (AGT requires



Photo 2.11 Automated guided transit (Miami DPM; courtesy Tuija Aalto)

underground stations and cannot enter pedestrian areas on surface, etc.).

This category of AGT, such as Siemens' VAL in several French cities, is functionally very similar to automated LRRT, such as the systems operated in Vancouver and Copenhagen. However, the latter, with four-axle rail vehicles, offer greater capacity and better riding comfort. In its role as a CBD loop distributor (*Downtown people mover*, or *DPM*, in Miami and Detroit) the ability of both technologies—rubber-tired and rail AGT systems to negotiate sharp curves and steep gradients is utilized.

In overview, fully automated operation (TUs without crews) is technically feasible for all guided modes

on ROW category A. However, for AGT modes, such operation is a *sine qua non* for their economic feasibility, since the small size of their TUs would make labor costs prohibitively high; for rapid transit modes, full automation is desirable but not crucial because of their inherently high labor productivity.

2.3.4 High-Performance Modes: Rapid Transit

As explained in Section 2.1.2.4, exclusive use of ROW category A is the main element required for high-performance transit systems. With that ROW, it is logical that guided technologies, electric traction, train operation, and fail-safe signalization are used, giving

the system high capacity, reliability, safety, and other performance elements.

By far the most dominant high-performance transit modes are rail rapid transit and regional rail. On the lower-capacity side, light rail rapid transit and medium-capacity AGT are included, as are two rapid transit systems with different wheel technology: rubber-tired rapid transit and monorail. These six modes are defined here.

Light rail rapid transit (LRRT) or light rapid transit represents small-scale rapid transit: it consists of light rail vehicles operating on ROW category A only. This mode is used on lines that require high performance, but do not have the high passenger volumes to justify long trains and large stations. There are few of these systems in operation (the Norristown Line in Philadelphia and Manila Metro are good examples). However, the significance of this mode has increased greatly with introduction of full automation. Operation of trains without crews allows frequent service with short trains, making service attractive to passengers even with moderate volumes. The SkyTrain in Vancouver, London-Docklands line, and lines in Kuala Lumpur and Copenhagen are new automated systems with this technology, representing a “minimetro” transit mode.

Rubber-tired rapid transit (RTRT) consists of moderately large four-axle vehicles (gross floor areas between 36 and 53 m²) supported and guided by rubber tires, running on steel or concrete surfaces in trains of three to nine cars on fully controlled (A) ROW. The cars also have steel wheels for switching and for support in the case of a tire failure. A comparison of this mode with the much more common RRT is given in Section 6.4.

Monorails are rapid transit systems with a fundamentally different technology of vehicles and guideway. Among many designs, including vehicles supported and suspended from the guideway, the most common is with rubber-tired vehicles straddling a concrete guidebeam developed by the Alweg company in the 1950s. Monorail systems are operated as single regular transit lines in about a dozen cities, mostly in Japan, as well as in many amusement parks.

Rail rapid transit (RRT) or metro typically consists of large four-axle electrically powered rail vehicles (area up to 70 m²) that operate in trains of up to 10

cars on fully controlled (A) ROW with full signal control. This allows high speed, reliability, and capacity, rapid boarding/alighting at stations, and fail-safe operation (in the case of driver’s error or disability, the train is stopped automatically). Some RRT systems are further characterized by a high degree of automated operation or fully automated operation without a driver.

Rail rapid transit, shown in Photo 2.12, represents the ultimate mode for line-haul transport (i.e., for serving a number of points along a route). Trains of spacious vehicles with several doors on each side board passengers from high-level platforms without fare collection delays at rates of up to 40 persons/second (prs/s), many times higher than any other mode. With train capacities, where required, exceeding 2000 spaces and up to 40 trains/hour (TU/h) passing a point, the capacity of RRT greatly exceeds those of other modes; full ROW control allows the most reliable and safe travel of all modes at the maximum speeds that station spacings and passenger comfort permit. In all these features there is no physical way that a further major improvement in performance can be achieved for line-haul service. This highest performance is achieved, however, at an investment cost higher than that for any other mode: provision of its major component, a fully controlled ROW and stations in urban areas, requires considerably higher investment cost than any other transit mode infrastructure.



Photo 2.12 A high-performance mode: regional rapid transit (BART; courtesy of Eric Haas)

Regional (or commuter) rail (RGR), usually operated by railroads, has high standards of alignment geometry. It utilizes the largest vehicles of all rail transit systems (with gross floor areas up to 80 m² or more on bilevel cars, as in Photo 2.13), which operate in trains, on longer routes, with fewer stations, and at higher speeds than those typical for RRT. Thus RGR functionally represents a “large-scale RRT,” which serves regional and long urban trips most efficiently.

2.3.5 Specialized Transit Modes

A considerable number of different transportation systems is used as transit modes or components in passenger movements through transit systems. They are briefly defined and described here.

Pedestrians and pedestrian-assisting facilities. Walking, as an important component of travel in cities, particularly in transit travel, must be considered and provided for in designing access to stops/stations, entry, exit and transfer among transit vehicles. Pedestrian systems include paths, sidewalks, station areas and halls, stairways, and other fixed facilities. Pedestrian-assisting systems include moving walkways, escalators, elevators and, in some cases, shuttle vehicles.

Terrain-specialized transit modes are used for transit systems that have to negotiate difficult terrain barriers and water bodies. The major types are:

- *Cog railways* are rail systems with a continuous gear between rails. The vehicles have a gear on one of their wheel axles that engages the fixed linear gear for positive traction on transit lines with gradients from 12% to about 30% (Lyon, Stuttgart).
- *Cable cars* are rail vehicles powered by physically attaching the vehicle to a continuously moving cable in an underground slot. Cable cars are used on different lines operating on steep gradients. Once used in many cities, they are now operated as a unique, efficient, and tourist-attracting system in San Francisco.
- *Funiculars or inclined railways* are rail systems used on extremely steep gradients on which two vehicles tied on two ends of a cable are pulled as a balanced pair by a motor on the top of the line powering the cable (Hong Kong, Pittsburgh, Salzburg, and many other cities).
- *Aerial tramways* are systems of cable-suspended and cable-powered pairs of balanced cars traveling to high peaks, over a body of water or a gorge (Cape Town, New York, Rio de Janeiro).

Water-based transit modes, which represent very important transit components in cities located on or incorporating bodies of water, such as rivers, lakes, sea coasts or bays (Amsterdam, Hong Kong, Istanbul, New York, Seattle, Sydney, and dozens of other cities).

- *Ferryboats* are boats designed for short-distance travel with fast docking and departure and fast passenger exchange. They usually carry passengers only, sometimes also vehicles.
- *Hydrofoils* provide the same service as ferryboats, but they have floats on which they rise and then travel at a considerably higher speed than conventional boats (St. Petersburg).



Photo 2.13 Large-capacity vehicles for regional rail (Chicago; courtesy of Paul Duda)

2.3.6 Review of the Family of Regular Transit Modes

A systematic overview of the categories and types of characteristics for all major modes defined here is presented in Table 2.3. Characteristics of the factors de-

Table 2.3 Review of basic features of urban public transport modes

Determinant Factors						Modes										
ROW Category	Support	Guidance	Propulsion	Control	Transit Unit		Paratransit	RB	TB	SCR	Bus Rapid Transit	LRT	Rubber-tired RT	Rail Rapid Transit	Regional Rail	
Street (C)	●					Minimum performance	x	x	x	x			x			
Rubber tires	●						x	x	x		x					
Steered		●					x	x	x		x					
ICE			●				x	x			x					(x) ^a
Manual				●			x	x	x	x	x	x				
Small vehicle (< 30 sps)					●		x									
Medium-sized vehicle (30–100 sps)					●			x	x		x	x				
Part control (B)	●											x	x			
Large vehicles (>100 sps)					●			(x)	(x)	x	(x)	x		x	x	x
Electric			●							x	x		x	x	x	x
Guided		●							x	x	x	x	x	x	x	
Steel wheels		●								x	x	(x)	x	x	x	
Short trains (1–3 cars)					●				(x)			x				
Semiautomatic				●								x		x	x	
Full control (A)	●												x	x	x	
Long trains (> 3 trains)					●								x	x	x	
Fully automatic				●									(x)	(x)	(x)	
						Maximum performance										

^a (x) indicates less-common applications; sps = spaces

termining modes (see Section 2.1 and Figure 2.4) are ordered in the sequence of increasing performance; modes are also ordered ascending from the lowest performance up; the correlation between the two is shown in the table as the diagonal set of “x” marks. The frames designate the lowest- and highest-performance sets in the family of modes. It is emphasized, however, that “performance” refers to absolute values of system capacity, productivity, and efficiency and does not imply evaluation of modes; the lowest- and highest-performance modes are by no means “the worst” and “the best” in the family; they are only best suited to

the minimum and maximum demand conditions, respectively.

Several other comparisons of modes and their generic classes are given in the following three tables and three figures. The ranges given encompass all existing systems with the exception of some extreme values found in very special cases. Since individual systems seldom have several extreme values (e.g., maximum transit unit capacity *and* maximum frequency), the maximum values of derived performance measures (capacity and productive capacity) are less than the products of the maximum values of their components.

Thus the boundaries of modal characteristics depicted in the diagrams are neither absolute nor precise limits; they represent the ranges of values found on existing systems.

Table 2.4 gives ranges for the basic technical, operational, and system characteristics of the most important modes, classified into the three generic classes: street transit, semirapid transit, and rapid transit. Private auto is included for comparison. Several modes that are similar in the given characteristics to the selected ones are not included (e.g., taxi is similar to auto, trolleybus to bus, RTRT to RRT).

Table 2.5 summarizes the values from Table 2.4 by generic classes and presents several numerical examples of systems typical for each class. This table is the basis for Figures 2.5, 2.6, and 2.7, which graphically show such basic characteristics as maximum frequency, vehicle, TU and line capacity, speed, cost, and productive capacity. Both representative systems and ranges of values for each class are plotted. Other important aspects, including LOS and impacts, cannot be shown graphically. They are discussed in later chapters.

Figure 2.5 shows the relationships among TU capacities, maximum line frequencies, and line capacities (as areas) of different modes. The diagram shows that, starting from the auto (taxi) toward higher-performance modes, maximum frequencies decrease while TU capacities increase. The most common values form a hyperbolic set of points (dashed lines) with rapidly increasing line capacities.

Since a comparison of capacities is incomplete without consideration of speeds, Figure 2.6 shows mode capacities, speeds, and productive capacities (as areas). The diagram clearly shows the large differences in all these performance elements among the classes; street transit has far lower capacities and operating speeds than do semirapid and rapid transit. The last one has by far the highest performance and the broadest range of performance values.

The most important factor for mode evaluation, relationship of performance and investment costs, is presented in Figure 2.7. Productive capacity is plotted as the best representative of mode performance: it is the

product of speed, affecting primarily passengers, and capacity, important for the operator.

Similar to Figure 2.6, the differences among classes are major. There is a jump in investment cost between street transit and semirapid transit, then a continuous investment range through rapid transit, with a rapid increase in productive capacity. Maximum productive capacity increases from street transit to semirapid transit; then there is a continuous investment range through rapid transit, with a rapid increase in productive capacity. Maximum productive capacity increases from street transit to semirapid transit by a factor of 4 to rapid transit by about 13. The low performance of the auto/highway mode is conspicuous.

The diagram shows that although RRT can be designed for 40,000 prs/h, 50 km/h, and cost $\$25 \times 10^6/\text{km}$, it can also have much lower values of all these items. Its particularly broad range stretches from high-performance systems, such as San Francisco BART (by its design specifications it would have 2.16×10^6 space-km/h², i.e., at the upper boundary) to low-performance systems, such as some RRT lines in Chicago. The latter, in turn, overlap with high-performance LRTs (e.g., Boston's Green Line).

Another important modal characteristic is passenger attraction, which is a function of LOS. Since LOS is generally strongly correlated with system performance, passenger attraction of transit modes increases significantly from street transit to rapid transit, as the conceptual dashed lines in Figure 2.7 indicate. Street transit, usually inferior in LOS to that of auto, mostly serves captive riders. Rapid transit, usually superior to auto in the same corridor, attracts most of the trips and generates additional travel.

It is clear from Figure 2.7 that comparisons of modes based on costs only can be highly deceptive: they compare ordinates of modes, disregarding their abscissa values. For modes with similar performance, the error caused by disregarding abscissa values may not be great; but for modes as diverse as street transit and rapid transit, the error is always very large.

Mode comparison must include many different factors; the relationship between two of them, unit costs and passenger volume, is illustrated in Figure 2.7 by hypothetical particular transit systems I, II, and III.

Table 2.4 Technical, operational, and system characteristics of urban transport modes^a

Generic Class		Private		Street Transit		Semirapid Transit		Rapid Transit		
Characteristics	Unit	Mode	Auto on Street	Auto on Freeway	RB	SCR	BRT	LRT	RRT	RGR
Vehicle capacity, C _v	sps/veh		4–6, total	1.2–2.0 usable	40–120	100–250	40–150	110–250	140–280	140–210
Vehicles/TU	veh/TU		1	1	1	1–3	1	1–4	1–10	1–10
TU capacity	sps/TU		4–6, total	1.2–2.0 usable	40–120	100–500	40–150	100–750	140–2400	140–2000
Max. technical speed, V	km/h		40–80	80–120	40–80	60–70	70–90	60–100	80–100	80–130
Max. frequency, ^b f _{max}	TU/h		600–800	1500–2000	60–180	60–120	60–300 ^d	40–60	20–40	10–30
Line capacity, ^c C	sps/h		720–1050 ^d	1800–2600 ^d	2400–8000	4000–15,000	4000–8000–20,000 ^d	6000–20,000	10,000–70,000	8000–60,000
Normal operating speed, V _o	km/h		20–50	60–90	15–25	12–20	20–40	20–45	25–60	40–80
Operating speed at capacity, V _c	km/h		10–30	20–60	8–15	8–13	15–40	15–40	24–55	38–75
Productive capacity, ^e P _c	10 ³ sp-km/h		10–25 ^e	50–120 ^e	25–90	35–150	75–200–600	120–600	700–1800	800–4000
Lane width (one-way)	m		3.00–3.65	3.65–3.75	3.00–3.65	3.00–3.35	3.65–3.75	3.40–3.60	3.70–4.30	4.00–4.75
Vehicle control ^f	—		Man./vis.	Man./vis.	Man./vis.	Man./vis.	Man./vis.	Man./vis.-sig.	Man.-auto./sig.	Man.-auto./sig.
Reliability	—		Low-med.	Low-high	Low-med	Low-med	High	High	Very high	Very high
Safety	—		Low	Low-med	Med	Med	High	High	Very high	Very high
Station spacing	m		—	—	200–500	300–500	500–800	500–1000	500–2000	1200–4500
Investment cost per pairs of lanes	10 ⁶ \$/km		1.0–8.0	20.0–100.0	0.5–6.0	5.0–10.0	5.0–40.0	10.0–50.0	40.0–100.0	50.0–120.0

^a Abbreviations: sps = spaces; veh = vehicles; TU = transit unit; RB = regular bus; SCR = streetcar; BRT = bus rapid transit; LRT = light rail transit; RRT = rail rapid transit; RGR = regional rail.

^b For auto, lane capacity, for transit, line (station) capacity in TU/h.

^c Values for C and P_c are not necessarily products for the extreme values of their components because these seldom coincide.

^d With multiple parallel lanes and overtaking at stations.

^e For private auto, capacity is product of average occupancy (1.2–1.3) and f_{max}, since all spaces cannot be utilized.

^f Abbreviations are for manual, visual, signal, and automatic.

Generic Class		Private Auto on		Street Transit		Semirapid Transit		Rapid Transit	
Characteristics	Unit	Street	Freeway						
Transit unit capacity	sp/s/TU	1.2-2.0 ^b		40-500		40-750		140-2000	
Max. frequency, f _{max}	TU/h	600-800	1500-2000	60-120		40-90		10-40	
Line capacity, C	sp/s/h	720-1050	1800-2600	2400-15,000		4000-20,000		10,000-70,000	
Operating speed, V _o	km/h	20-50	60-90	15-25		20-45		25-80	
Productive capacity, P _c	10 ³ sp-km/h	10-25	50-120	20-150		75-600		700-4000	
Investment cost per pair of lanes	10 ⁶ \$/km	1.0-8.0	20.0-100.0	0.5-10.0		5.0-50.0		40.0-120.0	
Typical systems ^c									
Transit unit capacity	sp/s/TU	1.3	1.3	65	75	140	180	800	1100
Max. frequency, f _{max}	TU/h	700	1800	120	90	90	90	30	35
Line capacity, C	sp/s/h	910	2340	1800	6750	10,000	16,200	24,000	38,500
Normal operating speed, V _o	km/h	35	80	20	18	26	30	38	36
Operating speed at capacity, V _c	km/h	20	40	10	12	18	23	38	34
Productive capacity, P _c	10 ³ sp-km/h	18.2	93.6	78	81	180	372.6	912	1309
Investment cost per pair of lanes	10 ⁶ \$/km	3.0	40.0	1.0	1.5	35.0	40.0	60.0	100.0

^bMaximum number of spaces that can be utilized.

^dArticulated buses.

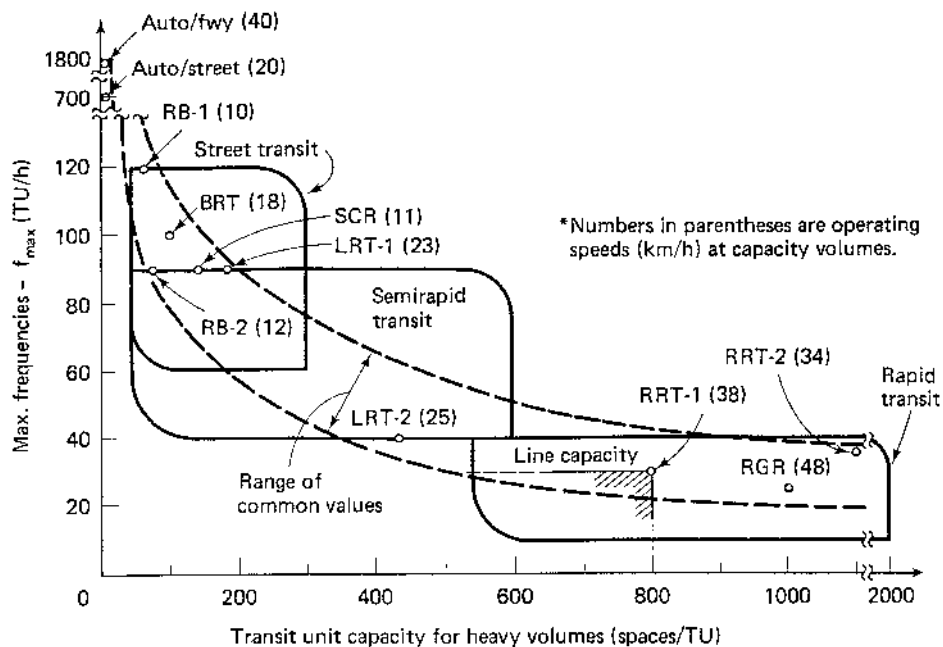


Figure 2.5 Vehicle capacities, maximum frequencies, and line capacities of different modes

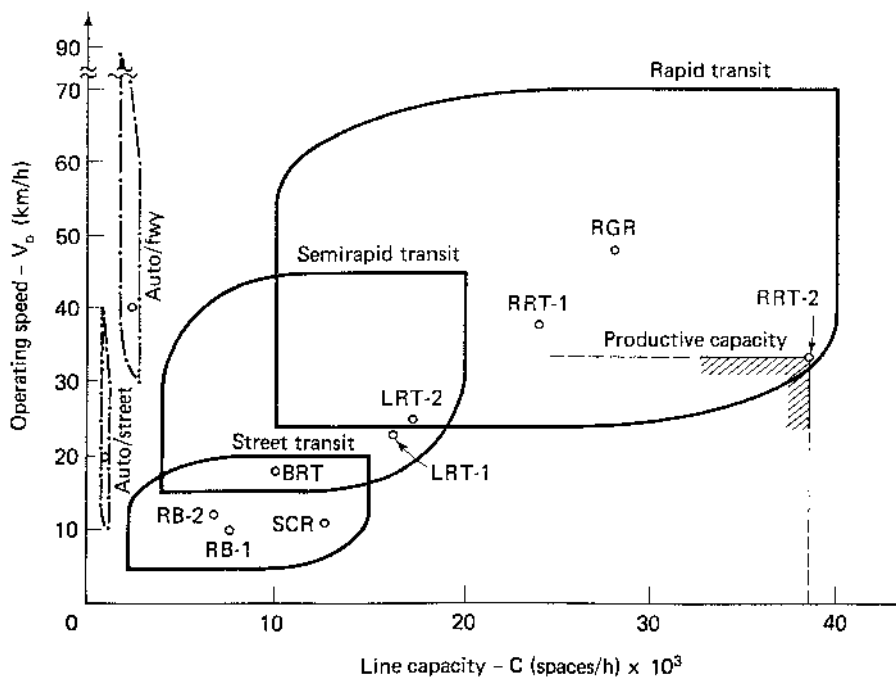


Figure 2.6 Line capacities, operating speeds, and productive capacities of different modes

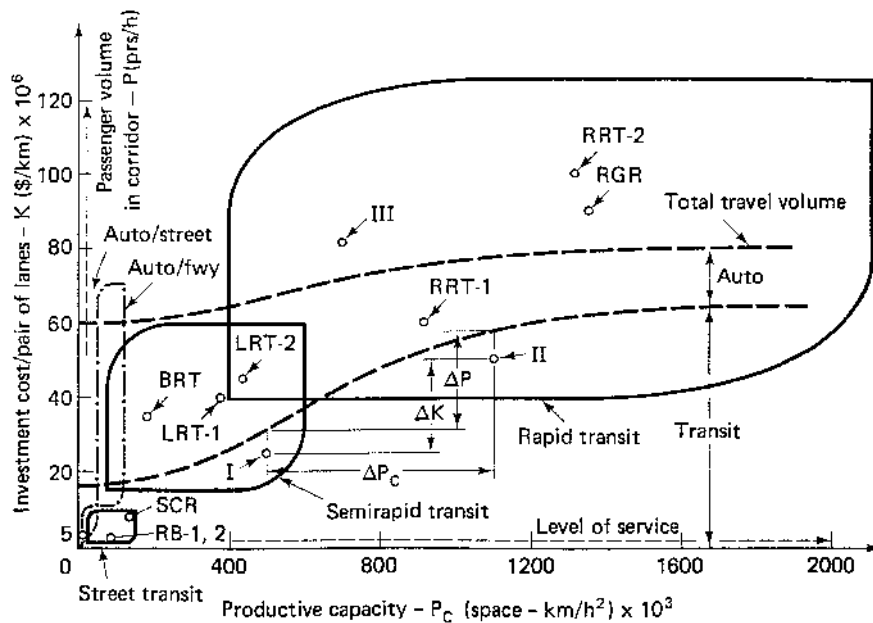


Figure 2.7 Relationships between productive capacities, investment cost, and passenger attraction of different generic classes of transit modes

System III can be easily eliminated as inferior to system II: it has a higher cost, much lower productivity, and attracts fewer passengers. A comparison of systems I and II must evaluate the trade-off between the higher productive capacity (ΔP_c) and passenger attraction (ΔP) of system II, against the lower cost (ΔK) of system I.

Observing modal characteristics in the three diagrams (Figures 2.5 to 2.7), it is interesting to note that the relative positions of the plotted 11 systems vary considerably: LRT-1 and LRT-2 are remote in the first, but close in the second and third diagrams. However, they all fall in the ranges of their generic classes. The overlaps between classes also vary among the diagrams, but in all three they clearly show the same sequence from low to high performance. Most modes fall in the central zone of the class areas (e.g., dashed lines in Figure 2.5), forming a nearly continuous *family of transit modes*. The extreme corners have been rounded off on the diagrams, since they represent either extremes impractical to operate (e.g., smallest TUs and lowest maximum frequency), or a nonoptimal combi-

nation (e.g., highest investment and lowest performance).

Another way of illustrating differences in modal capacities is by a sketch of facilities required for transporting 15,000 persons/hour by different modes, shown in Figure 2.8. This volume is found in many cities, since even facilities carrying only 5000 to 7000 prs/h obtain *rates of flow* of 15,000 to 20,000 prs/h during a 15- to 20-min peak period, determining the design volume. Line-capacity reserves are also given, since they influence LOS (comfort). Terminal areas are quoted as a significant component of space efficiency of modes. The table clearly shows the superiority of high-capacity modes in serving high-density areas, particularly when their much lower terminal area requirements are also taken into account.

In conclusion, this review of the family of modes shows that all major transit modes have optimal domains of application; "adjacent" modes overlap their domains to some extent (DAR and RB, or LRT and RRT), but *modes as remote from each other as taxi and RB, or RB and RRT, should never be competitive*

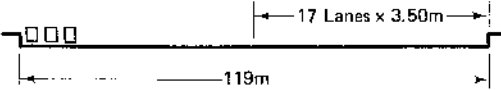
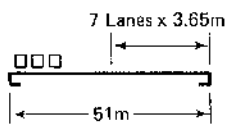
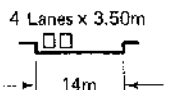
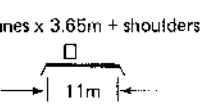
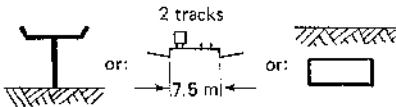
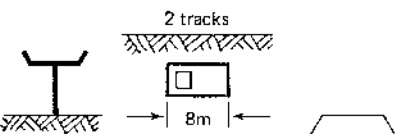
Mode	Schematic of ROW	Line Capacity Reserve	Terminal Area Requirements
Private autos on street (Persons/vehicle: 1,3 Maximum freq.: 700)		None	Parking: 23 m ² /person For 15,000 people 34.5 ha (85 acres)
Private autos on freeway (1,3: 1800)		None	Same as above, plus interchanges
Regular buses (ROW C) (75; 100)		None (station and way capacities reached)	Each station 20 x 80 m on the surface
Bus-rapid transit (artic., ROW B) (100; 90)		None (station capacity reached, way capacity not)	Each station 25 x 100 m on the surface
Light rail transit (2 artic. car trains) (400; 50)		33%	Each station from 12 x 50m on the surface to 20 x 90 grade separated
Rail rapid transit (1000; 25 RGR, 1000; 40 ART)		67-167%	Each station from 20 x 100 to 25 x 210m grade separated. No surface occupancy

Figure 2.8 Areas required for transporting 15,000 persons per hour by different modes

but complementary. For example, there is no way in which it can be more efficient and economical to transport 40 persons from point A to point B at one time in 20 taxis than in one bus, or 750 people in 15 buses than in one train, unless the lower-capacity mode is operated by underpaid drivers, has low comfort and safety standards, and is indirectly subsidized, while the higher-capacity mode is excessively luxurious, inefficiently operated, and driven by overpaid drivers. Similarly, it can never be more efficient to transport a single passenger from one suburb to another by a bus than by a taxi. As a matter of fact, when such remote modes are competitive, it is a clear sign that the con-

ditions (policies, financing, planning, regulation, design, etc.) are greatly distorted against the mode which should be optimal in that application. That is the case in many cities where auto travel into the CBD during peak hours is not only competitive but superior to bus services, or even to RRT.

This analysis also shows that there can never be a single "optimal" mode for all urban transportation. Conditions and requirements for urban travel vary so much that in most cities except very small ones the optimal (often referred to as "balanced") transportation system should consist of several complementary modes coordinated in a single multimodal system.

2.3.7 Commuter Transit

In addition to the regular public transport services operated by the modes previously defined, some cities have separate commuter services that use standard transit technologies as well as other modes. In small cities, commuter transit represents a significant share of public transport; some bus routes operate during the peaks only. As city size increases, the relative role of these services decreases. In large cities, commuter transit should be only a minor supplement of regular transit if the latter adequately serves as the main carrier of public transport throughout the city at all times of the day. The great attention given to commuter transit in U.S. cities is a consequence of unsatisfactory condition of regular transit.

The modes used for commuter transit are as follows.

Carpooling is travel of different parties (two to six persons) together in a private car on a regular basis. Since carpooling is private transport, it cannot be organized, scheduled, or regulated by an agency, but its use can be encouraged by such measures as assistance in establishing contacts among potential users, reduced or eliminated toll and parking charges, and the provision of special lanes.

Carpools are socially more desirable than individual travel by car because they take less space and cause fewer negative side effects. However, their use is limited to commuting because they require that travel of the participants in each pool coincide in origin, destination, time of departure, and time of return. Moreover, carpooling is usually a greater deprivation of privacy than transit travel; it involves precise travel coordination, cost sharing, and joint ride in private cars of persons who may have nothing else in common but travel habit.

Vanpools are privately or publicly provided vans (7- to 15-seat vehicles) transporting groups of persons to and from work on a regular basis. Because of their lower unit transportation cost and space occupancy, vanpools are even more socially desirable than carpools. However, they require a more formal organization for vehicle purchase, maintenance, driving, and so on.

Subscription bus is bus service provided for persons who subscribe for a time period (month, week) to travel every working day at the same time on the same route (commuting).

Express commuter bus, express bus service, operated during peak hours only, is the most common mode of commuter transit. Usually, express commuter bus routes operate on local streets in suburbs and then use arterials and freeways for fast travel into the CBD, as Photo 2.14 shows.

Commuter rail is regional rail operating during peak hours only.

Commuter buses utilizing bus lanes and commuter rails have fixed facilities used for transit during peak hours only. This represents a poor utilization of facilities, which can often be greatly improved by introduction of properly marketed and efficiently operated regular transit services.

Figure 2.9 shows corridor service by regular transit and by commuter transit and lists their characteristics. The figure shows that regular transit offers service between any two stops on feeder routes or stations on the trunk line, while commuter transit serves only the trips between the suburban collection area and the CBD. Moreover, each one of the m collector routes offers service to only one of the n CBD distributors. Transfers to the other distributors can be organized if all routes use the same freeway exit, but this is seldom the case. Direct connections among all feeders and all distributors would require $m \times n$ routes (33 in the example), resulting in very low frequencies on each one of them. A schematic of the network in Figure 2.10 shows that commuter transit serves a smaller fraction of all urban trips than corridor trips. The more decentralized the city is, the more important is the role of regular transit relative to commuter transit. Equally important is the fact that regular transit operates at all hours and commuter transit only during the peak periods.

2.4 TRENDS IN TRANSIT RIDERSHIP AND IN USE OF DIFFERENT MODES

Transit modes can be generally found in their optimal roles in cities that have pursued a rational, long-range



Photo 2.14 *Commuter transit: contraflow bus lane on a freeway (Marin County, San Francisco)*

transportation policy toward all modes. In cities without such a policy, the influence of short-range, piecemeal actions, inadequate financing, the favoring of one mode over others, deficiencies of supply industries, and various political and interest group pressures often lead to the disallocation of the roles of the different modes. A brief overview of ridership trends and utilization of the different modes is presented here.

2.4.1 Urban Travel and Transit Ridership

Mobility of urban populations, expressed in person-km or person-trips per capita per year, has been generally increasing in recent decades. Intensifying economic and social activities, decentralization of the cities, and a low marginal cost of travel usually outweigh the changes that tend to decrease the need for travel, such as increasing use of the telephone, TV, and weekly, auto-based food shopping. *Total urban travel* (total person-km or person-trips in an urban area per year) shows an even faster increase because it compounds increasing mobility and population growth.

Transit riding habit, defined as the number of annual transit trips per capita, was increasing until the private auto became widely used. The auto attracts so many trips that in most countries a significant decrease

in transit ridership takes place during the period of major increases in *auto ownership or motorization* (number of cars per 1000 persons). In Figure 2.11 a conceptual schematic of this change in *modal split* (distribution of travel between modes, primarily auto and transit) is shown. As the saturation level of auto ownership is reached, the modal split levels off. The rate at which diversion from transit to the auto occurs and the level at which a balance between private and public transport is reached depend on the following major groups of factors:

- The character of the city and urbanized area: its physical form, density, types of activities, population characteristics.
- The level and quality of existing transit service: where it is similar to that which the auto offers, diversion of travel from transit to auto is moderate; where transit is only basic, oriented to “transit captive riders” or persons who do not own cars or do not drive, the switch of travel to autos can be large. Thus in the cities with semirapid and rapid transit, losses of transit passengers are much lower than in cities with street transit only.
- The extent to which auto travel is accommodated in cities: it may vary from limited adjustments to

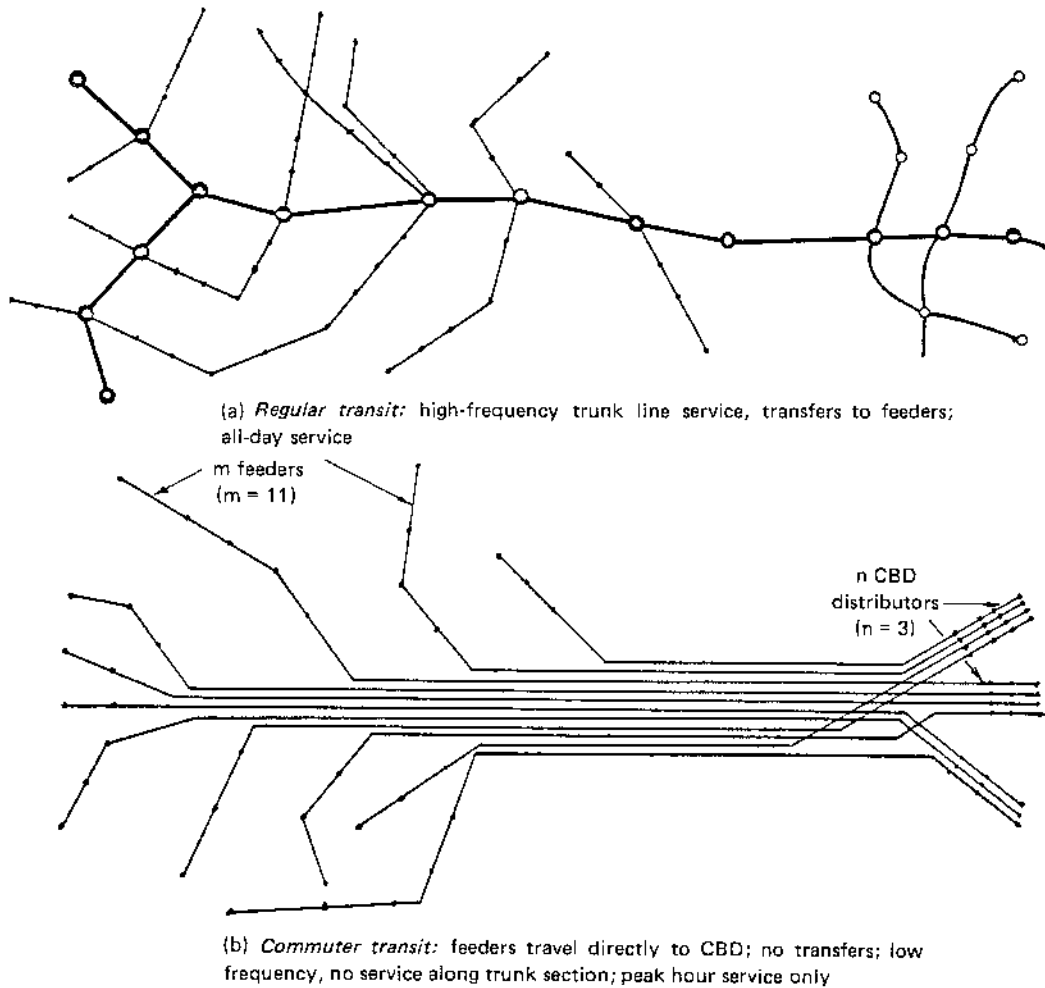


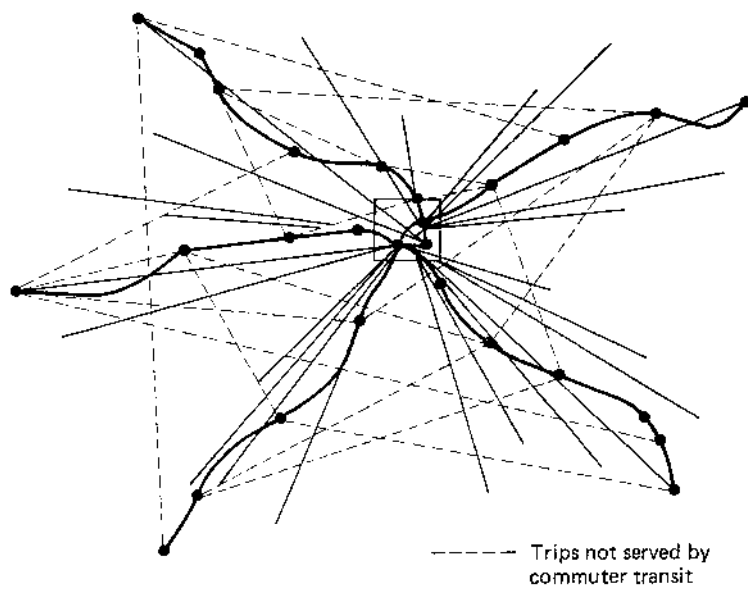
Figure 2.9 Corridor service by regular transit and by commuter transit

the street network and provision of some parking to extensive freeway construction and heavily subsidized, large parking facilities.

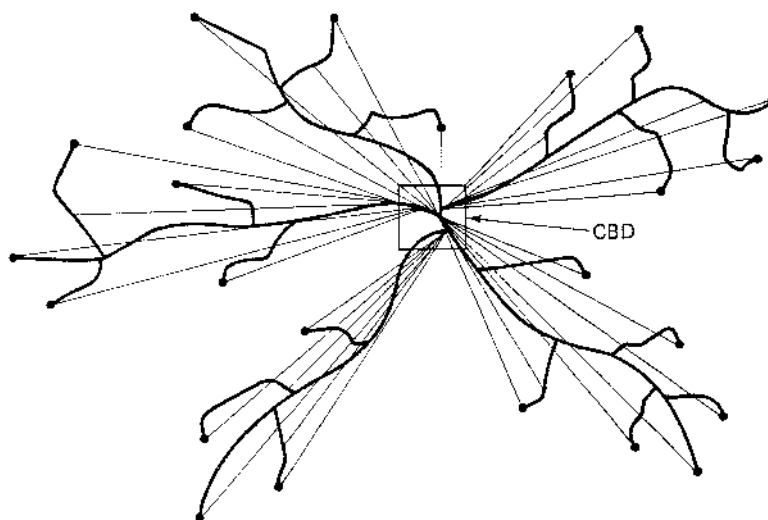
- Changes in urban development patterns caused by different policies and factors but made possible by the auto. This “secondary effect” of the auto can be very strong if planning and land-use controls are weak. Uncontrolled development designed for service by the auto only creates urban areas poorly suited to transit service {sprawl}.

- Planning for improvements of a transit system and its services, from priority treatments for street transit to building higher performance systems, such as rail transit.

Consequently, the role of transit system in an urbanized area generally depends on the size, physical conditions, and character of the city as well as on its transportation policies and planning. Policies oriented to the maximum accommodation of auto travel have resulted in auto-dependent cities in which walking is



(a) Regular transit network and trips it can serve



(b) Commuter transit network and trips it can serve

Figure 2.10 Urban trips served by regular transit and by commuter transit

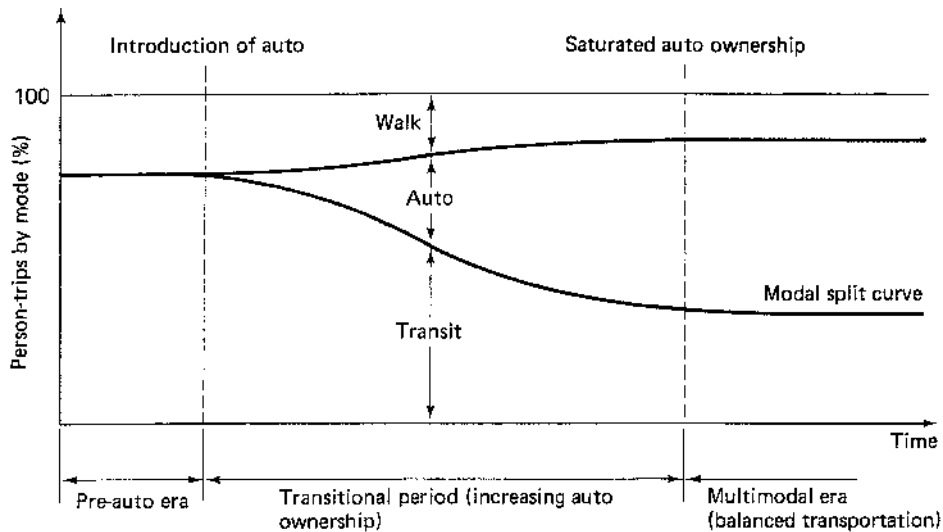


Figure 2.11 Conceptual diagram of modal split change due to the introduction of the private auto

difficult and transit serves mostly captive riders. The difference between living styles and opportunities of auto owners and drivers and those who do not drive can be rather drastic. Policies resulting in parallel improvements of auto travel and significant improvements of transit systems create a balanced intermodal highway/transit system that is, in the long run, more efficient, offering better mobility to its population and better quality of life than those in auto-dominated cities. No city, particularly a medium-sized or large one, can be truly livable without an efficient transit system (Newman 1989, Newman and Kenworthy 1998, Vuchic 1999, Mees 2000).

The importance of transportation policies and planning has been demonstrated in many cities and countries. Heavily highway-oriented policies and neglect of transit have led to creation of many auto-dependent cities in countries with very high auto ownership, such as the United States and Australia. However, some cities in these countries, such as San Francisco, Washington D.C., and Melbourne—as well as Singapore and most cities in Germany, Austria, Sweden and other western European countries—have made great efforts to build modern rail systems and improved bus services and to stimulate the use of bicycles, walking, and the development of pedestrian-oriented areas. The result

has been a stable modal split and, in several European countries, an increase in the share of transit trips over automobile travel.

Comparisons of these trends lead to the following conclusions:

- Increasing auto ownership causes significant changes in modal split, but it need not lead to a drastic decrease in transit ridership coordinated intermodal policies and coordinated land use and transportation planning are applied.
- The most important single factor in determining the roles of public and private transport is the policy toward land use and transportation and its implementation.
- Lack of a rational urban transportation policy, long-range planning, and land-use controls lead to urban sprawl and neglect of transit. Eventually, transit riding is either reduced to captive users only or its service is discontinued, as happened in many small U.S. cities.
- Policies of coordinated parallel improvements of both public and private transportation can create a multimodal system, with the modal split between these two major modes closely correspond-

ing to their optimal roles. In such a system, transit permanently serves major portions of many categories of urban travel.

2.4.2 Increasing Diversity of Transit Modes

The majority of transit services are performed today by several conventional modes: bus, trolleybus, streetcar/light rail, rapid transit, and regional rail. Numerous variations in their characteristics—such as ROW types, vehicle sizes, and operational methods—allow these modes to meet requirements for mobility in most urban areas.

It can be observed that cities with good transit planning and operations generally make use of a greater variety of modes than do cities in which transit is neglected. This is illustrated by the recent history of transit in several countries. In the United States, lack of public funds for transit and the serious financial straits experienced by the transit industry during the 1950s and 1960s led to a serious neglect of nearly all modes except buses. Not considering regional rail systems, which are often difficult to assign to individual cities or to separate from long-distance railroads, as well as specialized systems dictated by topography, such as funiculars, there were only 13 cities in the United States that had modes other than buses. Rapid transit existed in New York, Chicago, Philadelphia, Boston, and Cleveland. Streetcars existed in only 7, trolleybuses in 5, and ferries in 3 cities. Even such large cities as Los Angeles, Detroit, Baltimore, and St. Louis had degraded to buses on streets as the only transit mode.

In Canada a total of seven cities operated modes other than buses on streets. In Great Britain at that time, only London had its large Underground network, Glasgow had one underground line, and Blackpool its famous tourist-oriented tramways. Other tramway and trolleybus systems had disappeared from the entire country. In France, in addition to the huge Paris rail system consisting of Metro, regional, and commuter lines, cities of Marseille and Lyon had metros and a few cities had tramway and trolleybus systems.

This situation led to short-term finances as the only factor and disregard of all other considerations—such

as long-term efficiencies, operational characteristics, and passenger attraction—in which the neglected high-performance modes were superior in many applications. Only the modes utilizing diesel buses were maintained, and even these vehicles were available in a very limited choice of sizes and models. The result was that there was no modern semirapid transit in the country. A huge gap was created between bus and rail rapid transit (see Figures 2.5 to 2.7). A large number of cities that badly needed better service than street transit could offer but could not afford the high investment for rapid transit had no available choice. The inefficiencies in many cities caused by the use of a single mode for such a variety of tasks are very serious in terms of poor operating characteristics, but even more so in the inability of such services to attract a significant number of choice passengers—those who could use their private cars.

The condition of transit and diversity of modes was quite different in the countries that pursued policies of modernizing transit to make it competitive with private auto and achieve a balanced intermodal transportation system. Their cities made steady investments in building high-performance transit systems and they utilized modes rather closely to their optimal roles, as defined in Sections 2.2 and 2.3. Good examples of this type of modal composition were found in (then) West and East Germany, The Netherlands, Belgium, Switzerland, Sweden, and Austria. Large cities in these countries were introducing and expanding rapid transit; dozens of medium-sized cities had tramways, mostly upgraded into LRT as their basic mode, while trolleybuses operated in environmentally sensitive areas, on hilly routes, and so on. Buses, diversified as shuttle, regular and express, supplemented the rail modes or served in small cities as their only mode (Vuchic 1999).

In the United States, federal assistance in financing, research, and development became significant in early 1970s, and made it possible for cities to diversify their mode selection. The problem of the choice basically limited to buses on streets and five conventional rapid transit systems was gradually reversed. A similar trend also occurred in Canada.

Opening of the San Francisco Bay Area Rapid Transit (BART) System in 1972 introduced an ex-

tremely advanced and highly automated regional rapid transit system to North America. That was followed by openings of the metro systems in Washington (1976), Atlanta (1979), Baltimore (1983), Miami (1984), Los Angeles (1993), and San Juan, Puerto Rico (2005). Network extensions were built in subsequent years on these systems as well as on some of the existing older rail systems, such as the PATCO line in Philadelphia–New Jersey, Chicago, Boston, and others.

The most extensive activities in building new transit systems focused on developing medium-capacity modes, i.e., the semirapid transit category which “fills the gap” between buses on streets and metro systems. This has been primarily LRT, followed by BRT, regional rail, and several automated systems, using both rubber-tired and rail technology.

The wave of building new, advanced LRT systems with articulated vehicles and many new concepts in infrastructure design and operations was started by Edmonton in 1978, followed by San Diego in 1981 and then by nearly 20 cities in North America in the following 25 years. Following the first single lines, multiline LRT networks have been built in Calgary, Portland, Dallas, Denver, and other cities. San Francisco and Boston upgraded their streetcars into LRT systems. San Francisco and New Orleans have subsequently build substantial extensions to their networks, including LRT and very popular lines with modern streetcars. These new systems have become major new elements not only in improving transit in the entire cities they serve but also in increasing economic and social vitality as well as quality of life or livability in them.

Similar trend of building new LRT and other modern medium-capacity modes has taken place in many other countries. In France, 10 cities opened new tramway systems between 1985 and 2005. Most of these systems are in medium-sized cities such as Nantes, Grenoble, Strasbourg, and Montpellier. However, large cities, such as Lyon and Paris, have also built new tramway lines, mostly complementing their metro systems in suburban areas. While in the spread-out cities of North America new LRT lines often have lengths of 20 to 30 km and operate at technical speeds of 80 to 100 km/h (St. Louis, Sacramento, Dallas), in

France’s more compact cities the new rail systems are built extensively in central areas as components of motor vehicle traffic calming measures and enhanced pedestrianization. Thus, the new tramway systems usually represent the central component of measures to increase livability of cities.

This trend of mode diversification in French cities has also resulted in the modernization of trolleybus systems and introduction of new AGT mode VAL. In the city of Lille, VAL represents a very successful mini-rapid transit system that serves large passenger volumes. The same technology has been introduced in Toulouse and Rennes. Bus upgrading, which started during the 1970s, has recently resulted in construction of several variations of BRT lines. A newly designed “tramway on tires” has been tested in the city of Caen.

Following a long period of planning but no construction of new rail systems in the United Kingdom, the needed government financial assistance began to make the building of several new systems possible. This progress started in 1980 by the opening of the extremely successful LRT system in Newcastle-upon-Tyne. Utilizing mostly railway ROW, LRT was brought into the center city via newly built bridge and tunnel section. Having nearly entirely ROW category A, this system actually represents a light rail rapid transit mode.

Manchester followed by adapting several of its regional rail lines to operation of LRT rolling stock, which allowed extension of these lines into center city on ROW category B. Thus, similar to the tram-train concept in several European cities, Manchester provides direct service of regional rail lines through city streets, greatly improving their collection-distribution. In addition, four cities opened typical LRT lines between 1994 and 2004: Sheffield, Birmingham, Croydon/London, and Nottingham. Several other cities are actively planning new LRT systems.

Particularly interesting and successful has been the Docklands network of rail lines in London. Initially planned as an LRT line for connecting the newly developed Docklands area to the Underground network, it was decided to utilize its entirely separated ROW to adopt fully automated operation with single articulated LRT cars. With passenger volumes greatly exceeding

projections, the stations had to be extended for the operation of two-car trains, and the network of lines was extended several times.

Several cities in the United Kingdom have improved their bus services through the introduction of bus lanes, express, and other diversification of bus services.

Planning and construction of new LRT systems for upgrading transit has taken place in other countries also. For example, since 1989, five cities in Turkey and four in Spain have opened new LRT lines. In addition, Madrid has initiated the planning of several LRT lines, joining the very large cities that had abandoned tramways several decades ago but which are now reintroducing them as a very effective medium-capacity mode complementing their metros, usually in suburban areas. As mentioned, this has occurred in London, Paris, New York (northern New Jersey suburbs), Washington DC and several other cities.

Since the late 1970s, when the intensive diversification of modes started in North America, five cities opened new metro systems, over 20 cities opened or are constructing new LRT systems, a number of them have opened local streetcar systems in city centers, and four cities introduced rubber-tired and rail AGT systems on transit lines. The latest survey by the Light Rail Transit Association (www.lрта.org) shows that worldwide new LRT lines and networks since 1970 have been opened in about 100 cities. More than 30 AGT/APM systems have been opened in airports, university campuses, medical complexes, but also as regular transit lines (Schumann and Loetterle 2003, Nickel 2005, UITP). Distinct BRT systems in cities like Ottawa, Pittsburgh, Dublin, Mexico, Los Angeles, and especially cities in South America are being joined by new BRT systems under development in many other cities.

Regional rail mode has also been introduced in a number of cities of industrialized and developing countries in different capacities. In the former, recently opened and presently planned regional rail systems offer an attractive alternative for auto drivers, thus increasing mobility and reducing highway congestion. In the latter, large segments of population are offered an efficient mode of transportation from distant suburban areas that previously was not available.

Introduction of additional transit modes has been very significant for increased mobility, stronger role of public transit, and quality of life in cities. Medium-capacity modes have enabled many medium-sized cities too small for metro systems to have high quality transit. This effort has in most cases proven to be an extremely successful investment. For example, in cities like Portland, Dallas, and Dublin, the new LRT and BRT lines have attracted so many new transit passengers that the remaining bus services were carrying more passengers after the new mode was introduced even though that new mode replaced one or several major sets of former bus lines. Typically, one or two new metro or LRT line, carry 25 to 35% of total transit ridership, and the remaining 65 to 75% of passengers who are carried by bus lines is a greater number than the total transit ridership prior to the opening of the new rail line.

These observations lead to the conclusion that major modernization and improvements of transit in medium-sized and large cities around the world can be achieved only through utilization of a greater variety of modes, although mostly conventional ones, than has been the case in the 1960–1980 period. For the selection of optimal modes, a thorough knowledge of mode characteristics and performance under different conditions, as presented in this chapter, is of particular importance.

EXERCISES

- 2.1. Which functional characteristics of transportation service distinguishes private from public transportation? List several characteristics in which these two types of services differ and explain how.

- 2.2.** Utilizing conceptual definitions of urban transport modes, define the similarities and dissimilarities between:
- Private auto and bicycle
 - Private auto and taxi
 - Taxi and bus
- Include physical, operational, and service characteristics of these modes.
- 2.3.** Which basic characteristics define a transit mode? Apply that definition to show what makes the following pairs of transit systems different modes:
- Bus and trolleybus
 - Express bus and shuttle bus
 - Light rail and rapid transit
- 2.4.** Bus lines never operate on ROW category A on their entire length. Why is it more logical to use guided modes than buses on fully separated lines?
- 2.5.** A transit line (bus, trolleybus, or streetcar) operates on urban streets (ROW category C). You are supposed to evaluate the feasibility of upgrading its ROW to category B without changing the basic technology (only size or type of vehicle may be changed if the new operating conditions justify that). List the elements that you would analyze, including costs (construction, area required, etc.) and benefits (improved LOS and its consequences). Define which groups accrue benefits and which costs of this project.
- 2.6.** You are asked to select ROW category B or A for a rail transit line with probable later extensions. Describe the methodology you would use and the items you would include.
- 2.7.** Find several examples of cities that developed transportation systems in a drastically different way from that proposed in the theory of urban transportation modes: for example, large cities that relied extensively on steps 2, 4 and 8 but neglected 1 and never came to steps 6, 7, and 9 of the transportation system development sequence. Analyze present transportation conditions in one of these cities and define the missing components, deficiencies, and problems which they now have because of this deviation of development sequence from the theoretically optimal one.
- 2.8.** Define bus rapid transit (BRT) and define its differences from regular bus mode.
- 2.9.** What conditions lead to introduction of guided transit modes? Which operational and service features does guided transit bring and what are its effects on transit usage and land use development?
- 2.10.** Find several transit lines, preferably on different ROW categories, that operate close to capacity. Compute their TU capacities, frequencies, line capacities, operating speeds, and productive capacities. Plot the diagrams corresponding to diagrams in Figures 2.5 and 2.6 for these lines. Discuss and compare their performances.
- 2.11.** Compare general characteristics of automated LRRT with regular LRT. Include investment and operating costs, service frequency, and reliability and differences in ROW alignment.
- 2.12.** Define, give characteristics, and describe the role of commuter transit systems or services, primarily referring to large cities.
- 2.13.** How does the ROW category influence the choice of vehicle technology? Which technology is mostly used for transit lines on ROW C and which one dominates lines with ROW categories B and A, and why?

- 2.14. Which technology is required to operate trains of vehicles?
- 2.15. What are the advantages of operating trains as compared with single vehicles only? Include type of propulsion, line capacity, vehicle riding quality, operating safety, and labor efficiency.
- 2.16. Describe the two types of uses of the AGT mode.
- 2.17. During the 1940–1960 period many cities reduced the number of transit modes (e.g., converted trolleybuses to buses) to achieve simpler and cheaper operation. It was claimed that cities should not have more than two transit modes. Which factors against this simplification were often neglected in such decisions? What are the disadvantages of operating only two modes in some large cities that should also be considered and compared with the advantages in the search for the best combination of modes? Classify the main advantages and disadvantages by the two directly affected parties: operator and users.

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3

VEHICLE MOTION AND PERFORMANCE¹

Dynamic characteristics of transit vehicles, such as propulsion and braking, must be known in order to determine their maximum speed, acceleration, deceleration, and energy consumption. The transit engineer must be familiar with these characteristics to analyze such operational aspects as:

- Different combinations of vehicle and line characteristics (alignment, station spacings, etc.) in the planning of new lines
- Travel time and operating costs of existing services
- Possible changes in schedules or types of operations, such as express or skip-stop

Many other evaluations of alternative plans, vehicle designs, or operational practices involve vehicle characteristics and motion.

In most of these analyses, the number of influencing factors and the number of objectives are so great that there is no single algorithm for deriving an optimum solution. Rather, several selected alternatives must be tested through judicious use of the equations presented in this chapter for computations and for the development of analytical or computer-based models.

This chapter presents the most important elements of transit vehicle performance. Basic equations of vehicle motion are followed by a description of the forces acting on the vehicle: resistance and propulsion. A definition of adhesion then leads to expressions for ve-

hicle traction, directly determining acceleration and stopping.

Computations of station-to-station travel times of transit vehicles are presented in a separate section, followed by a review of energy consumption and efficiency in the final section.

3.1 VEHICLE MOTION

The basic equation of motion is derived from Newton's second law, which relates force, mass, and acceleration of a body:

$$F = m \cdot a = m \frac{dv}{dt} \quad \left| \frac{F}{\text{N}} \right| \left| \frac{m}{\text{kg}} \right| \left| \frac{a}{\text{m/s}^2} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{t}{\text{s}} \right| \quad (3.1)$$

The force acting on a vehicle in motion is the difference between its *tractive effort* TE and *resistance to motion* R . Thus,

$$TE - R = m \frac{dv}{dt} \quad \left| \frac{TE, R}{\text{N}} \right| \left| \frac{m}{\text{kg}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{t}{\text{s}} \right| \quad (3.2)$$

The tractive effort acts on the periphery of the tractive wheels, while resistance consists of two components: basic resistance consists of forces acting on the vehicle wheels, and air resistance represents forces acting externally on the body.

Whenever a vehicle moves at constant speed, its acceleration is $a = 0$, and Eq. (3.2) shows that its $TE = R$. When this condition does not exist, there is a positive or a negative acceleration: the difference be-

¹ A list of symbols used in Chapter 3 is given in Table 3.0.

Table 3.0 List of Symbols

Symbol	Unit	Definition
a	m/s ²	Acceleration rate
a _i	m/s ²	Initial acceleration rate
a _{max}	m/s ²	Maximum acceleration rate
$\bar{a}$	m/s ²	Average acceleration rate
A	m ²	Vehicle cross-sectional area
b	m/s ²	Braking rate
$\bar{b}$	m/s ²	Average braking rate
c	m/s ²	Coasting rate
c _a , c' _a	(various)	Coefficients of air resistance
c ₁ –c ₃	(various)	Coefficients of vehicle resistance
D	m	Diameter of tractive wheels
e	m	Track gauge
F	N	Force
g	m/s ²	Acceleration of gravity
G	kN	Vehicle weight
G _a	kN	Adhesion weight of vehicle
_h	(superscript)	Highway vehicles
i	%	Way gradient
_i	(superscript)	Improved performance
I	A	Current
k	—	Number of spacings along transit line
K	m	Radius of curvature
l _a	m	Distance between axles in a light rail vehicle truck
L	m	Length of line
m	kg	Mass
n	min ⁻¹	Rotations per minute
p	kN	Axle loading (weight/axle)
P	HP	Motor power
q	g/(HP · h)	Fuel consumption rate
r	%	Coefficient of vehicle resistance
r _c	%	Coefficient of curvature resistance
r _o	%	Coefficient of basic vehicle resistance
_r	(superscript)	Rail vehicles
R	N	Resistance to motion
R _a , R _c , R _g	N	Air, curvature, and gradient resistances
R _i	N	Force of inertia
R _o	N	Basic resistance
R ^e	W	Electrical resistance
s	m	Distance between axles in a light rail vehicle truck
s _a , s _b	m	Acceleration and deceleration distances
s _c	m	Coasting distance
s _d	m	Vehicle stopping distance

Table 3.0 (continued)

Symbol	Unit	Definition
s _m	m	Length of vehicle skid marks
s _r	m	Reaction time travel distance
s _v	m	Distance of travel at V _{max}
S	m or km	Station spacing
S _c	m	Critical station spacing
S _e	m	Equi-travel-time distance
t	s	Time
t _a , t _b	s	Acceleration and deceleration time intervals
t _c	s	Coasting time interval
t _r	s	Reaction time travel distance
t _s	s	Vehicle standing (dwell) time at stations
t _v	s	Constant-speed time interval
T _c	s	Travel time on S _c
T _i	s	Incremental time loss per station
T _o	s	Operating time for a line
T _q	N · m	Motor torque
T _s	s	Interstation travel time
TE	N	Tractive effort
TE _a	N	Tractive effort for acceleration
u _j	—	Transmission ratio for j th gear
v	m/s	Speed
V	km/h	Speed
V _c	km/h	Speed at end of coasting
V _i	km/h	Initial speed
V _{max}	km/h	Maximum vehicle speed
V _o	km/h	Operating speed on line
V _r	km/h	Relative speed between two surfaces
V _t	V	Voltage
w	—	Differential reduction ratio
z	m/s ³	Jerk (change of acceleration)
(')	(prime)	Parameters of travel time on S < S _c spacings
α	°	Angle of way gradient
γ	N/m ³	Air density
η	—	Coefficient of efficiency
μ	—	Coefficient of adhesion (friction)
ρ	—	Coefficient of rotating masses on vehicle

tween the two forces changes the vehicle's speed until equilibrium is reestablished.

Consequently, to compute vehicle motion, one must analyze the two sets of forces that cause it, resistance to motion and propulsion/traction. The body of prin-

ciples and analyses of these phenomena is called the *theory of traction*.

3.2 RESISTANCE TO MOTION

Resistance of vehicles to movement (also known as “drag”) is a very complex set of forces caused by many factors. Therefore its analysis is performed by decomposing total resistance into its individual elements. Some of these can be expressed by exact physical equations; others must be measured empirically and introduced into resistance equations as coefficients.

The resistance of land vehicles (rail and highway) can be classified as follows:

1. Vehicle resistance (straight, level, dry way, mild weather)
 - 1.1 Basic resistance
 - 1.2 Air resistance
2. Alignment resistance
 - 2.1 Gradient
 - 2.2 Curvature

Resistance R , being a force, is expressed in newtons (N). In old measurement systems, kilograms (kg) and pounds (lb) were used as units. The coefficient of resistance r , representing resistance per unit of vehicle weight G , is expressed here in general units of 1 per 1000 or “per mill,” designated by ‰. Thus, this coefficient may represent newtons per kilonewton (N/kN) or kilograms per ton (kg/t), while the same coefficient expressed in pounds per (short) ton (lb/tn) is twice greater.

3.2.1 Vehicle Resistance

3.2.1.1 Basic Resistance. Resistance created at the contacts between the vehicle and the way consists of two categories, both of which are included in the same empirical equation.

Rolling resistance is created at the contact of the wheels with the riding surface. Three factors contribute to the rolling resistance: (1) deformation of the wheel and surface of the way; (2) a sucking effect caused by

the underpressure at the separation of the wheel from the surface; and (3) slippage of the wheel. The magnitude of this resistance is mostly a function of the *smoothness* and *hardness* of the wheel and support surfaces and the load on the wheels. Thus the hardest wheel/surface combination, steel wheel on steel rail, has the lowest rolling resistance; its resistance coefficient is approximately 10 times lower than the coefficient for rubber-tired vehicles on a concrete roadway. Because of that, rail vehicles have a much lower energy consumption per unit weight than highway vehicles with the same performance (acceleration and maximum speed). Rubber-tired guided vehicles have the highest resistance of the three technologies because they have many more wheels and running surfaces than do highway vehicles.

Way resistance depends primarily on the characteristics, composition, and condition of the way. Individual resistances usually cannot be measured precisely, but numerous experimental studies [the best-known ones are those by the Society of Automotive Engineers (SAE) for highway vehicles and by Davis (1926) for railroad vehicles] indicate that a few of these resistances (flange, concussion, sway, oscillation) depend on the vehicle speed, while most of them are constant at all speeds.

All elements of basic resistance depend on vehicle weight. They can therefore be expressed through a basic resistance coefficient, r_o (‰), or as absolute resistance, R_o , which may be in N , kg , or with different values, in lb .

The respective general expressions for the coefficient and absolute basic resistance for highway vehicles have the form

$$r_o^h = c_1^h + c_2^h \cdot V \quad (3.3)$$

and

$$R_o^h = r_o^h \cdot G = (c_1^h + c_2^h \cdot V)G, \quad (3.4)$$

$$\left| \frac{r}{\text{‰}} \right| \left| \frac{c_1}{\text{‰}} \right| \left| \frac{c_2}{\text{‰} \cdot \text{h/km}} \right| \left| \frac{V}{\text{km/h}} \right| \left| \frac{R}{\text{N}} \right| \left| \frac{G}{\text{kN}} \right|$$

where V is the speed of the vehicle, G its weight, while c_1^h and c_2^h are coefficients.

For rail vehicles, Davis empirically developed the expression for resistance coefficient

$$r_o^r = c_1^r + \frac{c_3^r}{p} + c_2^r V, \quad \left| \frac{r}{\%o} \right| \left| \frac{c_1}{\%o} \right| \left| \frac{c_3}{N} \right| \left| \frac{p}{kN} \right| \left| \frac{c_2}{\%o \cdot h/km} \right| \left| \frac{V}{km/h} \right| \quad (3.5)$$

c_1^r , c_2^r , and c_3^r being coefficients, and p the axle loading (weight per axle). Absolute rail vehicle resistance is then:

$$R_o^r = \left(c_1^r + \frac{c_3^r}{p} + c_2^r V \right) G, \quad \left| \frac{R}{N} \right| \left| \frac{c_1}{\%o} \right| \left| \frac{c_3}{N} \right| \left| \frac{p}{kN} \right| \left| \frac{c_2}{\%o \cdot h/km} \right| \left| \frac{V}{km/h} \right| \left| \frac{G}{kN} \right| \quad (3.6)$$

3.2.1.2 Air Resistance. Since air resistance depends mostly on the vehicle body, it is calculated from the same basic formula for rail and highway vehicles; only the coefficients differ. This resistance depends on:

- The *frontal area*, or projected composite cross section of the vehicle or train, A
- The *length* and *shape* of the vehicle body and the *smoothness* of its surface (these factors are included in a “body coefficient,” c_a')
- The *density of air* γ (at sea level, $\gamma = 12.03 \text{ N/m}^3$) which enters the resistance equation as mass per unit volume (i.e., divided by the acceleration of gravity $g = 9.81 \text{ m/s}^2$)
- The *velocity* of the vehicle relative to the air movement in the same direction, V_r .

The expression for air resistance is thus:

$$R_a = \frac{\gamma}{2g} \cdot c_a' \cdot A \left(\frac{V_r}{3.6} \right)^2 = 0.0473 c_a' \cdot A \cdot V_r^2, \quad \left| \frac{R}{N} \right| \left| \frac{\gamma}{N/m^3} \right| \left| \frac{g}{m/s^2} \right| \left| \frac{c_a'}{m^2} \right| \left| \frac{A}{m^2} \right| \left| \frac{V}{km/h} \right| \quad (3.7)$$

where the factor 3.6 converts km/h into m/s, and $c_a = 0.0473 c_a'$. This equation is applicable to highway and rail vehicles.

3.2.1.3 Total Vehicle Resistance. The expression for vehicle resistance R on a straight, level way is obtained by adding the basic and air resistances. Thus the equations for the highway and rail vehicles are, respectively:

$$R^h = (c_1^h + c_2^h \cdot V) G + c_a^h \cdot A \cdot V_r^2 \quad (3.8)$$

and

$$R^r = \left(c_1^r + \frac{c_3^r}{p} + c_2^r \cdot V \right) G + c_a^r \cdot A \cdot V_r^2, \quad \left| \frac{R, c_3}{N} \right| \left| \frac{c_1}{\%o} \right| \left| \frac{p, G}{kN} \right| \left| \frac{c_2}{\%o \cdot h/km} \right| \left| \frac{V}{km/h} \right| \left| \frac{c_a}{N \cdot h^2/m^2 \cdot km^2} \right| \left| \frac{A}{m^2} \right| \quad (3.9)$$

The values of coefficients c_1 , c_2 , and c_3 contain several dimension conversion factors, and they vary with different characteristics of vehicles. Generally, c_1 is about 10^2 times greater than c_2 , so that in some general analysis the basic resistance can be assumed to be constant, independent of speed. For highway vehicles, the values recommended by the Society of Automotive Engineers are $c_1^h = 7.6$ and $c_2^h = 0.056$. The body resistance coefficient c_a is for passenger automobiles in the range from 0.020 to 0.025, while for buses it is 0.011 to 0.025. Thus for a transit bus, a typical equation is:

$$R^h = (7.6 + 0.056V) G + 0.018A \cdot V_r^2, \quad \left| \frac{R}{N} \right| \left| \frac{V}{km/h} \right| \left| \frac{G}{kN} \right| \left| \frac{A}{m^2} \right| \quad (3.10)$$

However, for detailed analyses of different vehicle types in a fleet, it is always desirable to check the values of coefficients experimentally, because vehicle suspension, length, streamlining, and other elements may have considerable influence on them.

For rail vehicles, the typical values are $c_1' = 0.65$ to 0.70, $c_3' = 120$ to 130, and $c_2' = 0.009$, while the coefficient c_a' varies greatly with the vehicle type. Some values of c_a' are: streamlined diesel and electric locomotive, 0.016 to 0.024; regional rail car, 0.012; rapid transit lead car 0.013. The equation recommended by the Association of American Railroads for railroad passenger cars is:

$$R' = \left(0.65 + \frac{129}{p} + 0.009 V \right) G + 0.0716 V_r^2 \cdot \left| \frac{R}{N} \right| \left| \frac{p, G}{\text{kN}} \right| \left| \frac{V}{\text{km/h}} \right| \quad (3.11)$$

Numerical coefficients again contain dimensional conversions. The last member does not contain A because the car is behind the locomotive. The coefficient c_a' therefore expresses resistance of car walls rather than its frontal area.

Values for cross-sectional profile A can be computed from the basic vehicle dimensions given with technical specifications. Typical values (in m^2) are:

Highway Vehicles		Rail Vehicles	
Passenger automobile	1.6–2.4	LRT car	7.0–8.0
Van	2.7–4.0	RRT/RTRT car	7.5–10.0
Bus/trolleybus:		RGR car:	
Single-decker	6.5–7.0	Single-level	10.0–12.4
Double-decker	9.0–10.0	Bilevel	12.6–13.8

It is emphasized that the values of resistance coefficients and even the basic forms of equations presented here should not be considered as absolute. Variations among vehicle wheel and axle design, way alignment and track quality, tunnel profile (influencing the c_a coefficient) and so on are great, and it is therefore necessary to determine these equations very carefully. It is actually desirable to establish a special formula for each individual fleet through experimental field measurements. Major transit companies have such internally developed formulas. For example, at different times, transit agencies in Hamburg, London, Mos-

cow, and St. Petersburg developed such formulas for some of their rail rolling stock models.

The general form of the derived expressions for a vehicle's resistance as a function of its speed, Eqs. (3.8) and (3.9), are plotted on a diagram in Figure 3.1. This $R = f(V)$ curve represents a basic diagram for the analyses of vehicle performance. The components of the curve show that an increase in speed results in a very slow increase in basic resistance but in a rapid increase in air resistance. Consequently, streamlining of the vehicle body, which reduces the coefficient c_a , has little effect on resistance at low speeds (e.g., local buses), but it is very significant for high-speed transit vehicles, particularly metro lines in tunnels and regional rail systems.

3.2.2 Alignment Resistance

Gradient resistance, which has a major influence on vehicle performance, can be computed by physical equations exactly, while curvature resistance is obtained through empirical measurements.

3.2.2.1 Gradient Resistance. This resistance to the motion of a vehicle with weight G traveling on a surface with a slope α is the component vector of the gravity force along the surface, as shown in Figure 3.2:

$$R_g = 1000 G \cdot \sin \alpha, \quad \left| \frac{R}{N} \right| \left| \frac{G}{\text{kN}} \right| \left| \frac{\alpha}{^\circ} \right| \quad (3.12)$$

where the factor 1000 reconciles the different units of R and G . Street or track gradient i is measured as meters of elevation per 100 m of distance [i.e., in percents, or $i (\%) = 100 \tan \alpha$]. Since most gradients on which transit vehicles operate are small, α is small, and for such values $\sin \alpha = \tan \alpha$. Substituting these relationships in Eq. (3.12) gives

$$R_g = 1000 G \cdot \tan \alpha = 10 G \cdot i. \quad \left| \frac{R}{N} \right| \left| \frac{G}{\text{kN}} \right| \left| \frac{\alpha}{^\circ} \right| \left| \frac{i}{\%} \right| \quad (3.13)$$

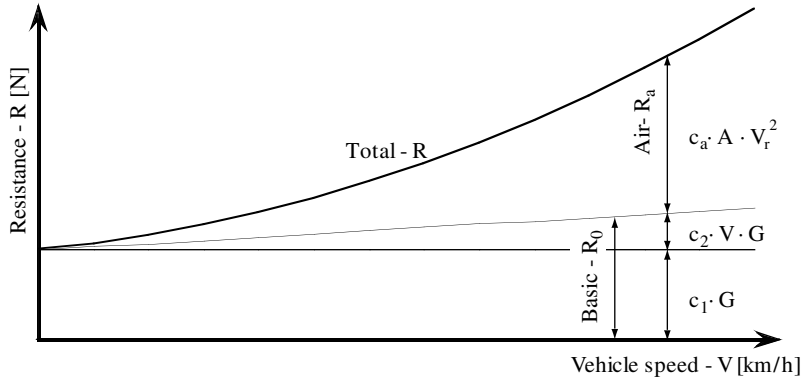


Figure 3.1 Vehicle resistance as a function of speed

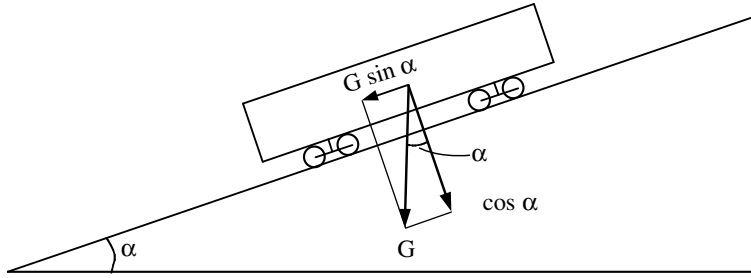


Figure 3.2 Gravity force acting on a vehicle on an incline

Thus for a gradient of, for example, 4%, the value $i = 4$ should be used. The formula for total vehicle resistance with gradient is

$$R = R_o + R_a + R_g. \quad (3.14)$$

For highway and rail vehicles, this equation is, respectively,

$$R^h = (c_1^h + 10i + c_2^h \cdot V)G + c_a^h \cdot A \cdot V_r^2 \quad (3.15)$$

and

$$R^r = \left(c_1^r + \frac{c_3^r}{p} + 10i + c_2^r \cdot V \right) G + c_a^r \cdot A \cdot V_r^2$$

$$\left| \frac{R, c_3}{\text{N}} \right| \left| \frac{c_1}{\text{‰}} \right| \left| \frac{p, G}{\text{kN}} \right| \left| \frac{i}{\text{‰}} \right| \left| \frac{c_2}{\text{‰} \cdot \text{h/km}} \right| \left| \frac{V}{\text{km/h}} \right|$$

$$\left| \frac{c_a}{\text{N} \cdot \text{h}^2/\text{m}^2 \cdot \text{km}^2} \right| \left| \frac{A}{\text{m}^2} \right| \quad (3.16)$$

If this expression for highway or rail vehicle resistance, including the effect of slope, is plotted for several different gradients, one obtains a family of resistance curves, as shown in Figure 3.3. Point E on the diagram represents the speed to which the vehicle would accelerate and then maintain constant speed motion on a 6% downhill gradient. It is obvious that the gravity force (R_g) on that slope (in this case as a “negative resistance,” or accelerating force) would be counterbalanced mostly by the air resistance, since the basic resistance does not change significantly with speed.

3.2.2.2 Curvature Resistance. For highway vehicles, this resistance is difficult to measure, since it varies with surface, type of vehicle, its actual path, and so on. For rail vehicles, rather exact measurements can be made for any given type of vehicle. Several transit agencies derived empirically equations of curve resistance as a function of radius of curvature, the friction

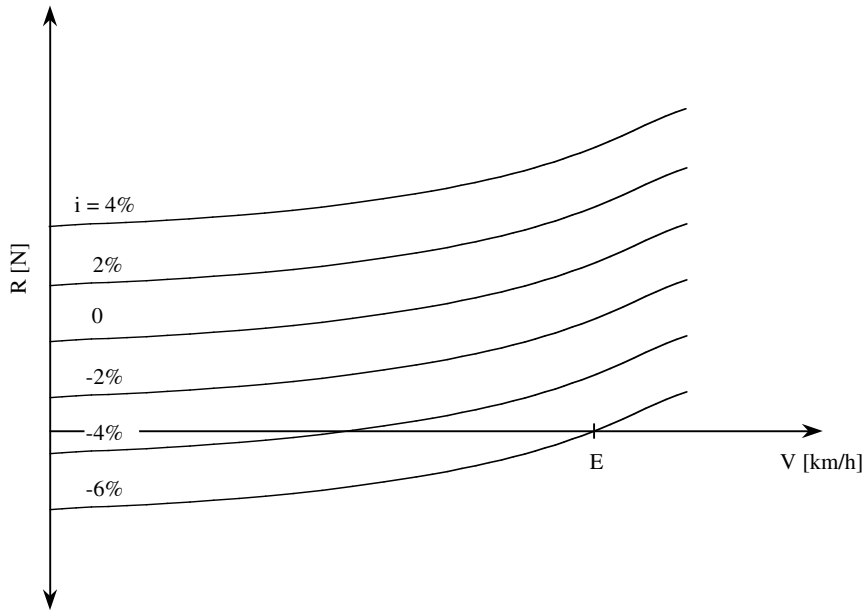


Figure 3.3 Vehicle resistance curves for different gradients

coefficient between wheels and rails μ , the track gauge, and the distance between fixed axles in trucks (bogies).

3.3 INTERNAL COMBUSTION ENGINE PROPULSION

Propulsion of a vehicle must provide the force necessary to overcome resistance to motion and accelerate the vehicle (i.e., to overcome its inertia). The highest acceleration rate (and largest force) is required in moving the vehicle from a standing position.

Power of an internal combustion engine (ICE), diesel or gasoline, is expressed in horsepower (*HP*) or in kilowatts (*kW*). It can be defined in three different ways:

- *Indicated power*—the power measured in the cylinders
- *Brake power*—the power measured at the motor shaft (usually applying a dynamometer, i.e., by friction or “braking,” not related to vehicle braking)

- *Effective power*—the power at the perimeter of the wheels

Indicated power, being the total power the engine produces, is the greatest. Subtracting from it the internal losses in the motor, such as shaft and valve bearings, one obtains the brake power, which represents the net usable power produced by the motor. That power is further reduced by the resistances between the motor and the tractive wheels. For automobiles and buses, these include resistances in the clutch, gear box (which is different for each gear), differential, and shaft and axle bearings. Electrically propelled vehicles have only one pair of gears and axle bearings, so that their power losses are smaller. The power remaining after these resistances is the effective power at the wheels (i.e., the net power available for traction).

3.3.1 Characteristic Diagram for ICEs

Shown in Figure 3.4, this diagram consists of curves of motor power P (HP), torque T_q (N · m), and fuel consumption q [grams per horsepower-hour, g/(HP ·

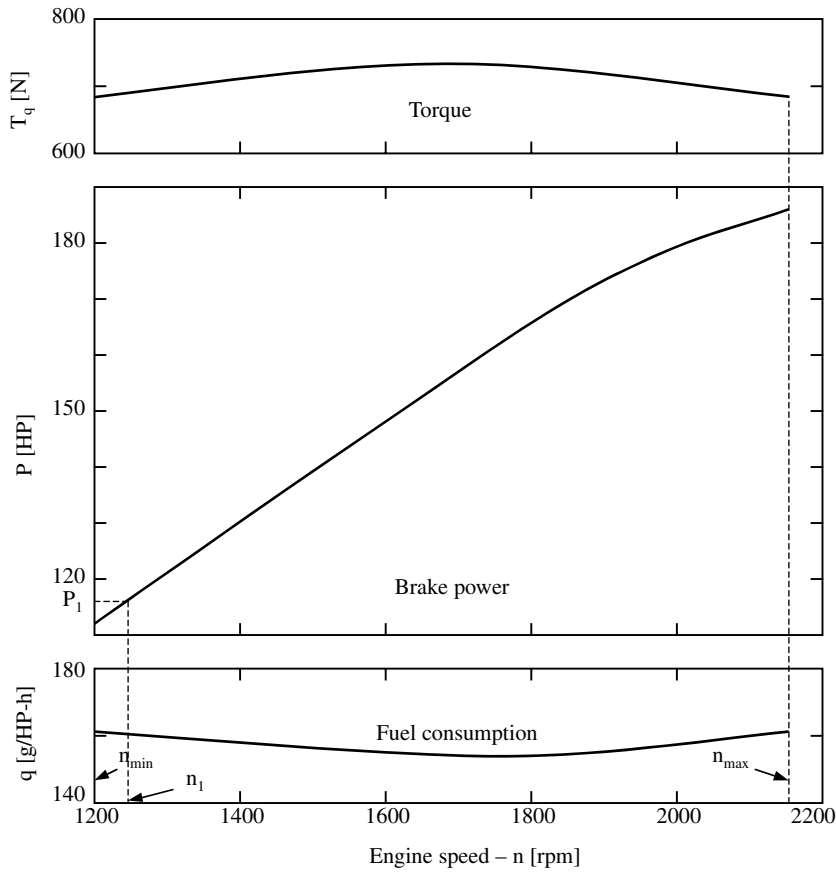


Figure 3.4 Characteristic performance diagram for an internal combustion engine

h)], plotted as functions of motor speed n (revolutions per minute, rpm). These diagrams for actual bus models are given in Chapter 5.

3.3.2 Speed-Tractive Effort Diagram:

$TE = f(V)$

The diagram of tractive effort TE as a function of vehicle speed V is needed for the analysis of traction and vehicle movement. It can be obtained from the basic diagram of motor brake power P as a function of motor speed n by relating vehicle speed to motor rotations and then tractive effort to power.

The relationship between V and n is given by Eq (3.17):

$$V = \frac{60 \cdot n \cdot D \cdot \pi}{1000 u_j \cdot w} = 0.06 \frac{n \cdot D \cdot \pi}{u_j \cdot w}, \quad (3.17)$$

$$\left| \frac{V}{\text{km/h}} \right| \left| \frac{n}{\text{min}^{-1}} \right| \left| \frac{D}{\text{m}} \right| \left| \frac{u}{-} \right| \left| \frac{w}{-} \right|$$

where D = diameter of tractive wheels

u_j = transmission ratio, different for each gear j

w = differential reduction ratio, constant for each vehicle.

The factor 0.06 converts m/min into km/h.

The other relationship, between P and TE , is given on the basis of the physical relationship that power is the product of force and velocity. The formula is

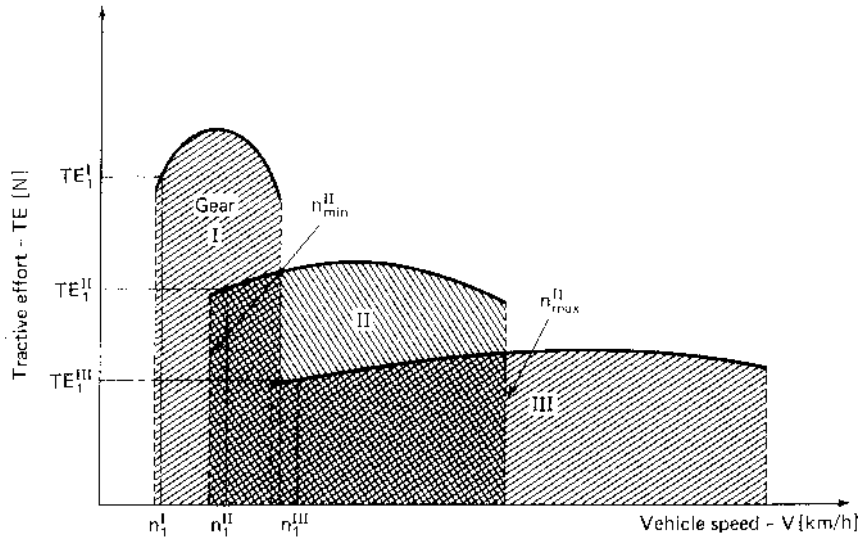


Figure 3.5 Tractive effort curves for a bus with three gears

$$TE = 2650 \frac{P}{V} \eta \cdot \left| \frac{TE}{N} \right| \left| \frac{P}{HP} \right| \left| \frac{\eta}{-} \right| \left| \frac{V}{km/h} \right| \quad (3.18)$$

The factor 2650 is for conversion of units, and η is the coefficient of losses between the motor and the wheels, which has different values for different gears. They typically range from 0.78 to 0.84 for the first (I) through third (III) gears, respectively.

The $P = f(n)$ diagram can now be converted into a $TE = f(V)$ diagram. Since the motor runs through the whole range of its operating speed (n_{min} to n_{max}) within each gear, there are separate tractive effort curves for each gear (i.e., for each value of u_j). The steps for converting $P = f(n)$ into a $TE = f(V)$ diagram are as follows:

1. Take a low value for n and read on the $P = f(n)$ diagram the corresponding value of P (e.g., n_1 and P_1 in Figure 3.4).
2. Compute V for the selected n for each gear (i.e., for each value of u_j), using Eq. (3.17).
3. Introduce the obtained value of P and each one of the values of the computed V 's into Eq. (3.18), obtain values of TE for each gear (TE^I , TE^{II} , and TE^{III}), and plot them on a V - TE diagram.

4. Repeat the procedure for as many values of n as desired to obtain the complete $TE = f(V)$ diagram by connecting the obtained points for each gear. The resulting curves are shown in Figure 3.5.

The computed curves represent the maximum motor power output. For lower output (less than fully depressed gas pedal), lower curves of similar shape are obtained. Thus tractive effort is actually not represented by the curves alone but by the entire shaded area below them in Figure 3.5.

The diagram shows that the transmission enables the motor to provide tractive effort of the desired magnitude over a wide range of vehicle speeds. If there were only one transmission ratio, the motor could produce either high acceleration or high maximum speed but not both. The transmission allows the motor, running within its operating speed range, to produce various combinations of acceleration and speed, changing from high TE and small speed range in the first gear to lower TE and wider speed range in higher gears. The motor can thus provide traction for a wide range of vehicle speeds with its relatively limited range of rpms.

The curves in Figure 3.5 also show that, during acceleration, the motor goes from minimum to maximum

motor speed ($n_{\min}$ to $n_{\max}$) in each gear, and each such cycle produces a concave curve. The highest TE for each gear is not at the $n_{\max}$ of revolutions but usually somewhat lower.

The overlap of adjacent TE curves in some speed sections shows that the vehicle can travel at those speeds in either of the two gears as long as both are higher than the resistance force R . Driving in the lower of the two gears requires faster motor running and usually higher fuel consumption, but it also has higher potential acceleration ability. Shifting of gears must take place within these overlapping sections of the TE curves, since the vehicle loses some speed during shifting; the overlap ensures that the vehicle has traction in the higher gear to continue acceleration.

3.3.3 Vehicle Motion Force as a Function of Speed

Figure 3.6 presents both TE and R curves on the same diagram as functions of speed. The vertical distance between the TE and R curves, TE_a , represents the force available for acceleration of the vehicle when it travels at any given speed. It is obvious that the highest acceleration rate can be achieved in the first gear. The intersection of the TE and R curves represents the max-

imum speed, $V_{\max}$, the vehicle is capable of achieving on a level way under standard operating conditions. This is referred to as the *balancing speed*.

If the R curve falls between two TE curves without intersecting either one, the maximum speed at which the vehicle can travel for a sustained period is the maximum speed in the lower of the two gears. This condition is shown in Figure 3.6, with the dashed R' curve passing between the TE curves for second and third gears. The maximum attainable speed in this case is V' .

3.4 ELECTRIC PROPULSION²

The power of electric motors, usually expressed in kilowatts (kW), has two definitions:

- *Hourly rating*—the maximum power the motor can deliver during one hour of continuous operation without overheating
- *Continuous rating*—the maximum power the motor can produce in unlimited operation

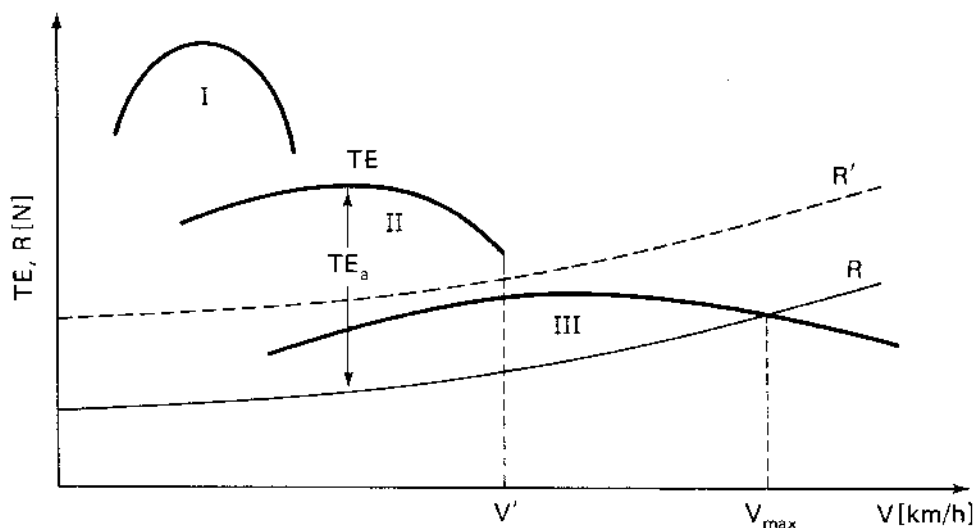


Figure 3.6 Tractive effort, resistance, and acceleration force for an ICE-powered vehicle

²Mr. Norman Vutz, consulting engineer with LTK Engineering Services in Philadelphia, provided guidance and wrote substantial parts of this section on electric propulsion.

The hourly rating is some 15% to 25% greater than the continuous rating, but it does not represent the maximum power the motor can deliver. An electric motor can take an overload and for limited periods of time produce, without any damage, 30% to 50% more power than its hourly rating. Such overloading for a longer period of time would, however, damage the motor, since it would cause overheating or burning. This capability to accept very high overloading for limited periods of time is an important characteristic of electric motors, since it provides traction characteristics superior to those of vehicles powered by other kinds of motors. The capability to produce very high tractive effort is particularly useful during acceleration intervals; thus electric traction is especially well suited for urban transit vehicles because of their frequent stopping and acceleration.

The design and operating characteristics of electrically powered transit vehicles is a large technical field with a rich history. The travel regime of a transit vehicle is very demanding, with frequent intervals of acceleration and braking, brief runs at constant speed, and short standing intervals. This requires precise, dynamic, and reliable control of motor operation. To meet these performance requirements, the propulsion equipment must be capable of producing high acceleration and braking forces at any speed and do so in repetitive cycles. The basic characteristics of the commonly used types of electric propulsion are presented. Electric propulsion in transit draws its power by continuous contact with a wayside source. For rail systems, this is the third rail or overhead wire; for trolleybus systems, two trolley poles obtain power from two overhead wires.

3.4.1 Wayside Electric Power Supply and Its Distribution to Lines

Electric power transmission over long distances is most efficient with high-voltage three-phase AC. For a given power level, higher voltage allows lower current (and therefore lower resistance losses) because the maximum delivered power is the voltage times the current. Thus, for the same conductor cross-section, the voltage drop is lower. Rail transit vehicle on-board equipment typically utilizes 600 to 1500 V DC picked up from

an overhead wire or from a third rail. Propulsion motors may be direct current (DC) or alternating current (AC). For efficient distribution of power, high-voltage utility power is brought to substations. Transit substations with step-down transformers and rectifiers are located at relatively short spacings along the line, as shown in Figure 3.7.

The substations, which reduce voltage and transform AC into DC, allow reduction of the distance that lower voltage DC power travels. To further reduce losses, some recently built metro systems (e.g., Hong Kong) have introduced line operating voltage of 1500 V instead of the customary 600 to 750 V. The typical voltage drop design criterion allows 30% worst case between the substation and the vehicle. Using 1500 V instead of 750 V halves the current and the voltage drop, while the 30% criterion allows twice the actual voltage difference. The result is that substations can be spaced four times farther apart based purely on distribution voltage considerations. At 750 V, the typical substation spacing on an LRT line is 1.5 km, compared to 6 km possible at 1500 volts. A system with a travel speed of 30 km/h operating with a 15-min headway has trains spaced 7.5 km apart in each direction of travel. With 6-km substation spacing, each substation gets almost steady duty. Conversely, with 1.5-km spacing, each substation would work for about 3 minutes and be idle for 12 minutes during the passage of each train in a given direction.

A pantograph and electrical equipment on the roof of an articulated LRT vehicle is shown in Photo 3.1.

In some cases, usually on regional rail systems connected with long-distance railroad lines, single-phase higher-voltage AC (11, 15, or 25 kV are typical) is brought to the vehicles, reduced by an on-board transformer, and rectified. Disadvantages of this approach are the added vehicle weight of the transformer and the single-phase unbalanced load placed on the utility supply grid.

3.4.2 Propulsion Motors and Their Control

For all types of electric motors, voltage and speed are directly related; similarly, torque (force) and current are directly related. The electric traction control equip-

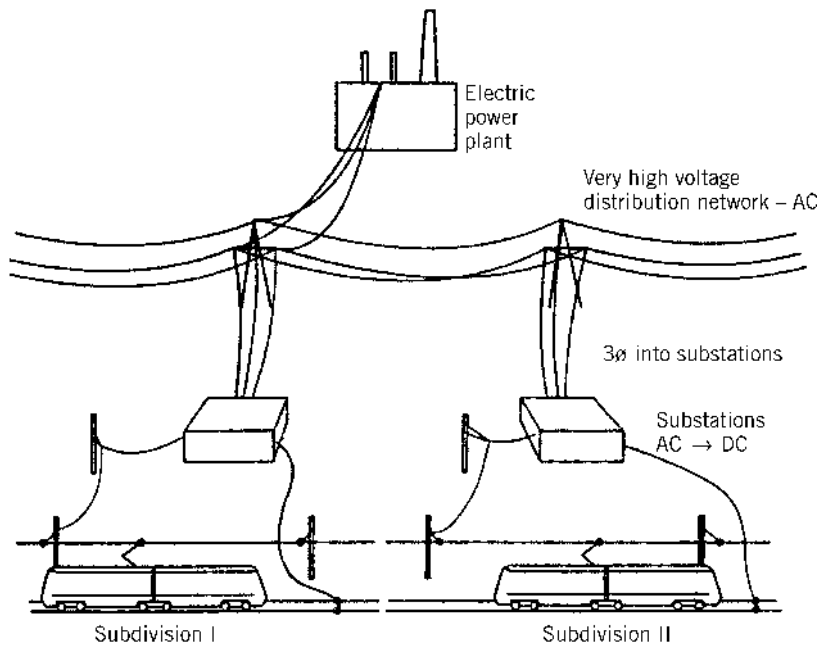


Figure 3.7 Power distribution system of a typical transit line

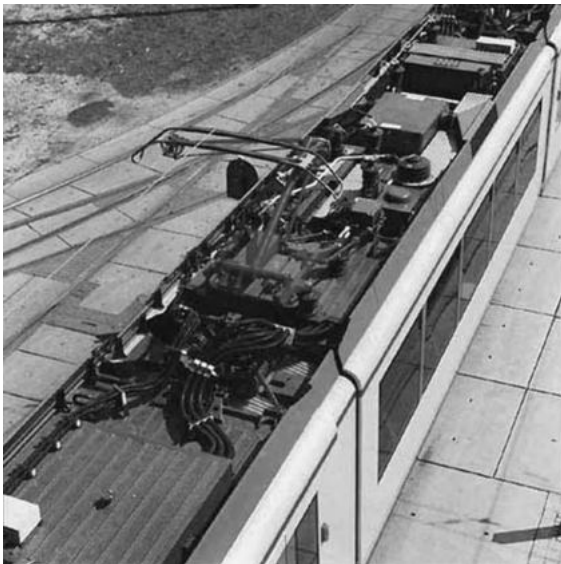


Photo 3.1 Roof of light rail vehicle showing pantograph and electrical equipment (Karlsruhe; courtesy of VDV)

ment must increase the motor voltage as the vehicle increases speed while maintaining the motor current to produce the desired acceleration.

Electric motors acting as generators are also used very effectively as the basic devices for vehicle braking (see Section 3.4.2.2). The characteristics of commonly used motors for electric propulsion and their control for traction and braking are presented here.

3.4.2.1 DC Propulsion Motors and Their Speed

Control. Until the 1980s, the DC series wound motor was used for vehicle traction. Its major advantages over other motor types are high starting tractive effort (torque) and easy speed regulation, both with relatively simple motor control equipment (accelerators and cams with rheostats, later electronic choppers) as well as inherent tolerance of large supply voltage variations. The variable resistance or electronic chopper controls served to vary the applied motor voltage in relation to speed and to cause current flows that developed the requested torque.

The typical shape of electric traction motor characteristic diagram for a series-wound DC motor operating at constant voltage is shown in Figure 3.8. It includes speed V , tractive effort TE , and the coefficient of efficiency η as functions of current intensity I on the armature. Two cases are shown: the first (dashed) with all the armature current going through the field and the second (solid) with a portion of the armature current being shunted past the field. At any given current, the motor power is the same for full or shunted field. These curves show that with increasing current, tractive effort increases while speed decreases. Conversely, with decreasing speed, the current and the tractive effort rise beyond practical limits. Therefore this motor type cannot be operated directly from a wayside supply. As the vehicle starts from standing, current intensity is controlled in two ways: first, motors are connected in series and then parallel; thereafter, with each

one of these connections, rheostats are used to provide a gradual increase of current intensity. For the highest speed, field shunting is used. These connections and rheostatic controls (now superseded by choppers) are shown in Figure 3.9.

To obtain the diagram of vehicle traction characteristics needed for travel analysis, these motor characteristic curves are converted into the $TE = f(V)$ diagram (Figure 3.10). It shows two sets of curves for a series of steps produced by rheostatic control for the two types of motor connections, explained above. A through B represent TE curves for rheostat positions from maximum resistance to no resistance when two motors are connected in series. In series with no resistance, each motor receives half of the supply voltage. C through D curves show TE from maximum resistance to no resistance when motors are connected in parallel, and FS represents motor operation with field

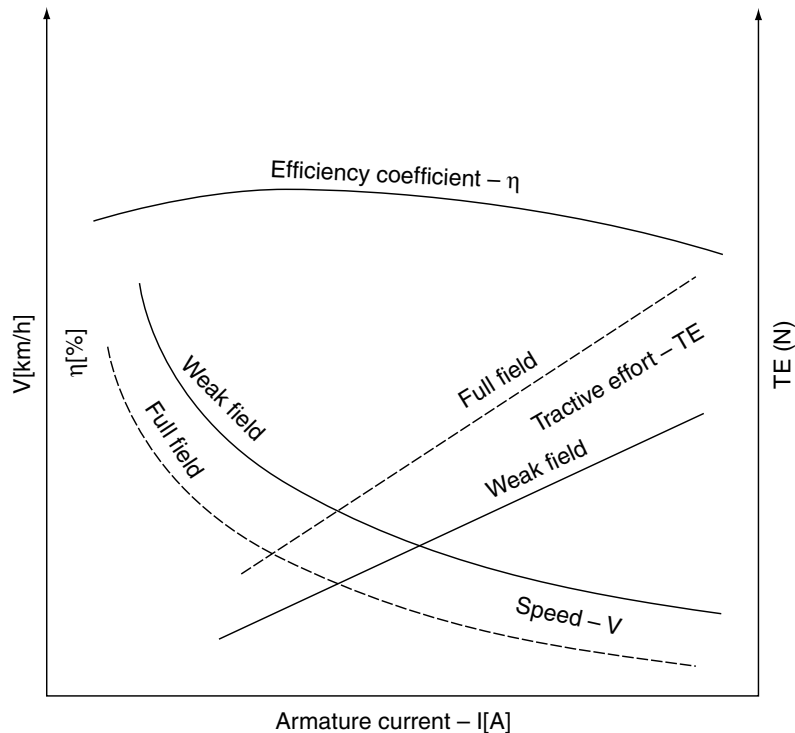
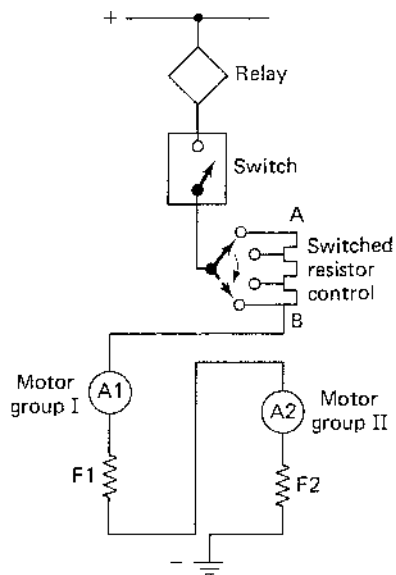
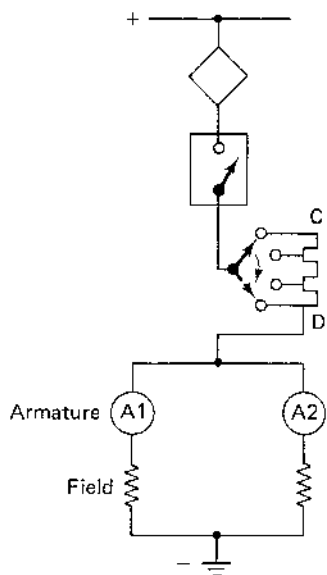


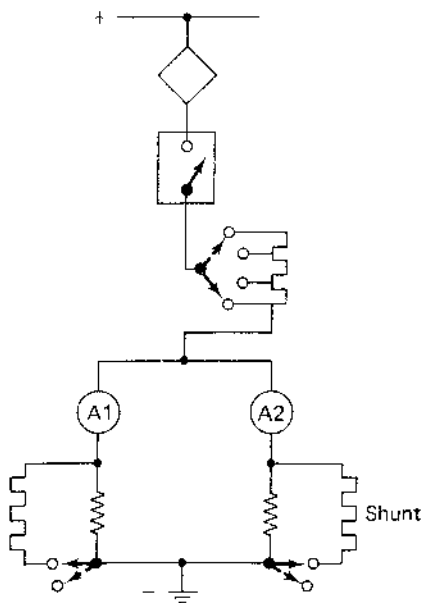
Figure 3.8 Diagram of constant voltage characteristics for an electric traction motor



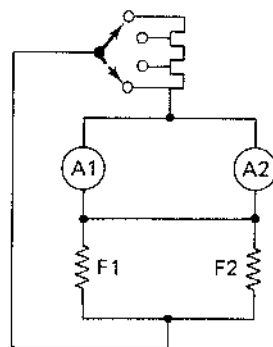
(a) Acceleration-series



(b) Acceleration-parallel



(c) Shunting



(d) Braking (parallel connection)

Figure 3.9 Motor and resistor connections for vehicle acceleration and braking

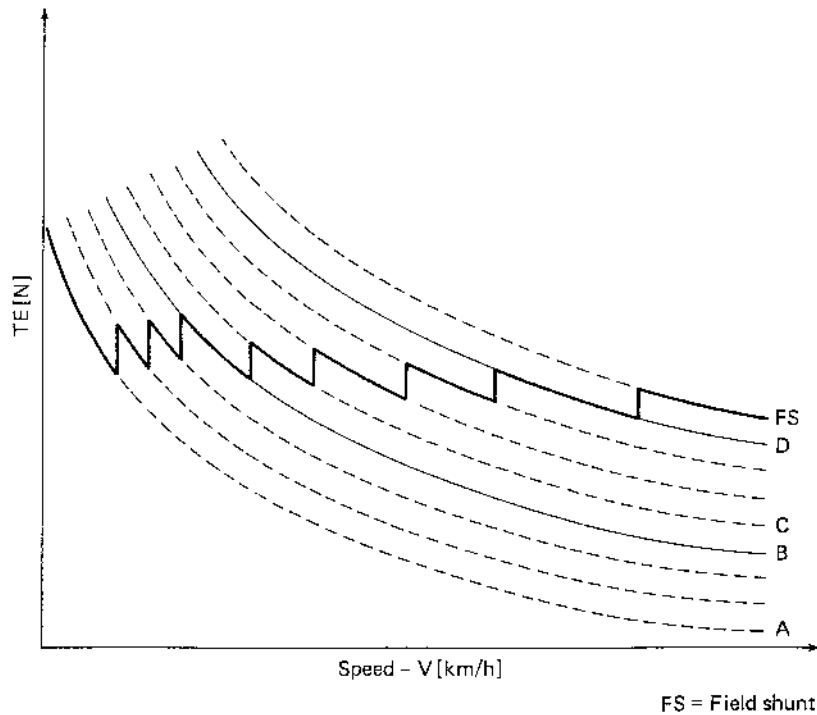


Figure 3.10 Tractive effort for acceleration with resistor control

shunt. Chopper control performs that transitional regime in a nearly continuous fashion (see explanation below and Figure 3.11).

Similar to the corresponding curves for internal combustion engines (ICEs), the tractive effort of electric motors decreases with speed if field flux and impressed armature voltage are constant. However, there are two important differences between electric and internal combustion motors. First, at very low speeds, especially at the moment of starting, the tractive effort of electric motors can be very high, while ICEs stall below a certain value of rpms. Second, TE curves for electric motors show continuity over the whole range of vehicle speed, while ICEs operate only over a limited speed range and must utilize several different gear transmissions to increase this range to all desired speeds.

The continuity of electric motor operation makes it possible to regulate speed through electrical changes

(in voltage and current) rather than through mechanical means. Consequently, electric vehicles do not have transmission via changeable gears, as do vehicles powered by ICEs; rather, their motors are connected with axles via a fixed pair of gears, and the required motor tractive effort is controlled through changes in voltage and current during acceleration from standing to maximum speed or in braking of the vehicle from high to very low speeds.

Electric vehicles have most or all of their wheels powered. There is usually one motor for each axle (or, in with low-floor LRT vehicles, one motor per wheel), so that a four-axle vehicle has four motors (see Section 6.2.2.1).

Rheostatic controls waste energy by dissipating power as heat when the required voltage is less than the supply voltage. Full-load current flows through the rheostat and the power wasted is the load current times the voltage drop. Solid-state power electronics

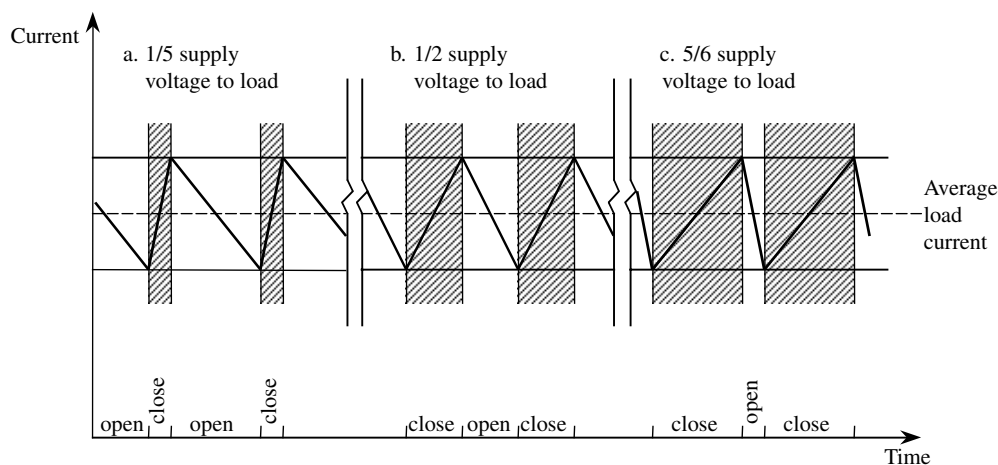


Figure 3.11 Solid-state chopper current control (Courtesy of Norman Vutz)

achieves the same control of motors by the rapid switching of high currents. This rapid switching combined with electric energy storage devices (capacitors and inductors) makes possible voltage control with minimal losses. Consider the circuit operation in Figure 3.11. When the switch is closed, energy from the line and energy stored in the capacitor flows toward the inductor and the load. When the switch is open, energy from the line replenishes the capacitor while energy in the inductor feeds the load. The load and line currents for three intensities are shown in Figures 3.11 a, b, and c. These three cases are (a) load voltage at one-sixth of line voltage (100 V on a 600-V line), (b) load voltage at half of line voltage (300 V on a 600-V line), and (c) load voltage at five-sixths of line voltage (500 V on a 600-V line). The difference among these cases is the relative length of time the switch is closed. Inductors absorb energy when the current through them increases and dispense energy when the current declines. Rapid switching is called “chopping,” and a circuit such as that depicted in Figure 3.11 is called a chopper.

With electronic controllers, a chopper replaces and performs the same function as the rheostat, thus avoiding resistor energy losses. After full voltage is brought to the motors (curve D in Figure 3.10), the shunting mechanism, described below, can be used with either stepped resistance or chopper control.

With rheostatic control of motors, energy lost in resistors was dissipated as heat; this could be used for seasonal vehicle heating, but otherwise it was wasted. Thus rheostatic control involved considerable energy losses during acceleration. Vehicles with only one type of motor group connection, such as PCC cars, which had a permanent parallel connection of two groups of series-connected motors, had greater losses, since they utilized resistors for all driving except at maximum speed. Measurements of *actual* consumption observed under typical operating conditions in cities have shown that, due to frequent accelerations, the PCC-type controls resulted in 25% to 30% higher energy consumption than similar vehicles with series and parallel connections (Lehner 1957, p. 252).

The first successful power electronics switch development was the silicon-controlled rectifier (SCREC), a semiconductor device that is capable of switching the current on for variable periods of time. This device blocks current flow in both directions until it is gated “on” and transitions to conducting freely in one direction, called the forward direction. Attempts to make current flow in the reverse direction cause the device to revert to the nonconducting state. Two such devices can be combined with a capacitor and inductor (both electric storage elements) to form a chopper circuit capable of rapidly (200 to 400 times or cycles per second) turning “on” and “off.” By starting with the

“on” time very short compared to the “off” time, the chopper produces a low motor voltage. Advancing the control to have increasing length of “on” time relative to the “off” time produces the high motor voltage needed for high motor speed. Ultimately, the “chopping” ceases and the motor operates with full current and maximum speed. The initial fleet of San Francisco BART cars was an early example of chopper motor control.

Early SCREC chopper circuits were large and complex, finding traction use primarily in locomotives, some metro cars, and some light rail vehicles with DC motors. Development of the gate turn off thyristor (GTO) soon followed and made traction inverters controlling induction motors a practical choice for transit vehicle propulsion. The GTO blocks current flow in both directions until it is gated “on,” like the SCREC. It can also be gated “off.” Gating a GTO “off” requires a high gate current, typically 10% to 20% of the maximum current to be turned off. The GTO gate drive circuits become a significant part of the control equipment. A single GTO replaces two SCRECs (main and turn-off) for each of the six switches needed to make an inverter.

In addition to the energy waste, there are operational shortcomings of rheostatic control of DC motors involving numerous high-current mechanical contact switches that establish the circuit for motor direction, operating mode (acceleration or dynamic braking), and to modify the resistance value in a stepwise fashion by progressively shunting portions of the resistor. Coordination and sequencing of these contacts was done by actuating some of them from a multicam camshaft controller and others electrically through low-voltage interlocks on the related control devices.

In control circuits of some vehicles, the useful torque range of the DC motor is extended beyond the point when all resistors are turned off through the use of field-shunt resistors, as shown in Figure 3.9c. The introduction of the resistor in parallel (shunt) with the field allows current that would normally pass through the field to be diverted into the resistors, weakening the field and enabling the motor to reach a higher speed with constant average current and thus constant power, but with decreasing torque, as shown on the diagram in Figure 3.10.

3.4.2.2 Motor Braking. ICE and electric motors can be used for braking. Motor braking on electric vehicles is particularly advantageous because it utilizes magnetic forces, so that it involves no physical friction within the vehicle; consequently, there is no wear and tear, dust, smell, or sound, typical by-products of friction braking or ICE engine braking. Even more significantly, with electronic motor controls, electric motor braking results in useful recovery of the vehicle’s kinetic energy during braking, thus significantly reducing power consumption on the line. Moreover, electric traction allows very precise selection of braking intensity, which is not the case with ICE-braked vehicles.

Using motors for braking on electric vehicles is usually called *dynamic* and sometimes *electric braking*. Most electric transit vehicles, particularly recently built ones, use dynamic braking as the principal brake in operation. Dynamic braking can also allow return of generated electric energy to the power supply system. That type of braking is called *regenerative braking*.

Dynamic braking is based on the fact that motors are inherently two way electric-mechanical energy conversion devices. Normally, electric power is used by the motor to propel the vehicle. However, it is possible to convert motor into an electric generator, so that when the vehicle is in motion, the kinetic energy of the vehicle is used to generate electricity. The work involved in generating the electricity decelerates the vehicle.

Dynamic braking is particularly effective for vehicle deceleration from high speeds because it does not cause full skidding. As soon as the wheels stop, the motors cease to be generators, so that dynamic braking cannot lock the wheels (and create “flat spots” on wheels), as friction brakes can. There is the disadvantage that dynamic braking cannot bring the vehicle to a full stop or hold it when it is stopped.

With rheostatic motor control, the generated current is sent through the same resistors used to regulate acceleration. Electricity is converted into heat and dissipated (or used for heating of the vehicle). However, chopper and GTO control allows easier control of motors and their use as generators than is possible with rheostatic motor control. GTO controllers can control

the sending of generated power into power supply lines only when the power network is receptive, so that line overvoltage is not a problem. Consequently, the substitution of chopper circuits and GTO controls for the rheostatic controls has made the recovery of regenerative braking energy practical, and it is now widely used, resulting in increased energy efficiency of transit modes with electric traction. The control allows nearly constant braking effort from any running speed to a low speed (10 to 15 km/h), where it fades out; then friction braking is blended in to complete the stopping and hold the stopped vehicle.

3.4.2.3 Wheel Slip Control. Most electric rail vehicles have a wheel slip control mechanisms to prevent spinning in acceleration and sliding in braking. The speed of rotation of different axles is continuously measured and compared. If an excessive difference in speed among the axles or an excessive rate for any axle is detected, the slip control promptly decreases the motor power until the slip disappears. At that time it resumes acceleration, initially at a slightly lower rate and then at the commanded rate, until the desired vehicle speed is reached. Similarly, detection of slip in braking causes reduction of braking intensity until the speed signals indicate that the slippage has ceased, and then, similarly, it reapplies the braking. One problem arises with the slow onset of synchronous slip of all axles in braking. In that case no speed difference exists to be sensed, and all axles cease to turn while the car continues to slide with wheels locked. The solution is to use slightly different response characteristics between trucks of a car to minimize the probability of a synchronous slip arising.

3.4.3 Electronic Motor Control

It has been demonstrated that in some cases choppers can achieve an energy utilization of 97%. Rheostatic control combined with motor group (series, parallel) transition usually achieves a utilization during acceleration of 67%, while with rheostats only (PCC cars), the utilization is even lower. Thus, on lines with frequent acceleration, slow driving, and steep gradients,

energy savings from the choppers can be quite significant; on lines with long station spacings and no interference (e.g., regional rail) the savings are smaller. A diagrammatic presentation of energy consumption for the three types of motor control is shown in Figure 3.12.

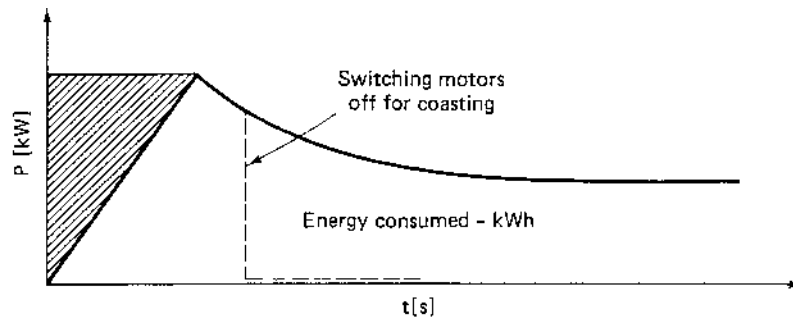
In the late 1960s, more complex chopper circuits were developed to produce three-phase AC (*Drehstrom*, in German, translates to “rotating current”), suitable for operating AC induction motors. These circuits involved six switch functions, each with two SCRECs, and were called inverter circuits. As covered further in Section 3.4.4, they invert DC into controlled frequency and voltage three-phase AC. The rotating current translation correctly suggests motor operation. AC motor design was already highly refined due to extensive prior constant speed use in industrial machinery powered by fixed-frequency utility three-phase power.

Dual-mode (diesel-electric) articulated buses in Seattle and rail cars for the Norristown Line in Philadelphia were the first North American users of GTO inverter drives. The TTC (Toronto) H6 fleet, LACMTA (Los Angeles) Red Line fleet, and the SEPTA (Philadelphia) M-4 metro fleet followed as examples of new cars with GTO inverter propulsion. Several other fleets have been converted from rheostatic control and from SCR chopper control as part of the midlife car overhaul.

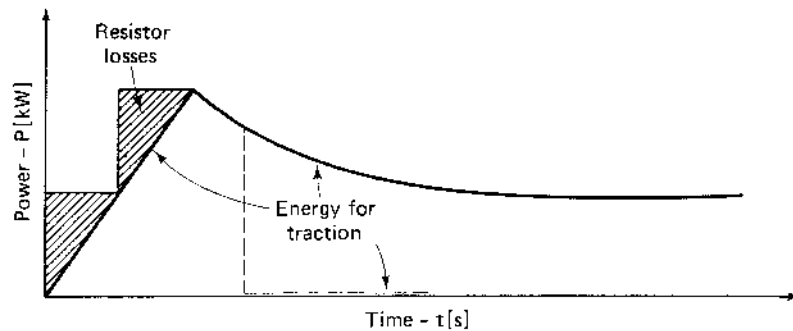
3.4.4 AC Propulsion Motors and Their Electronic Control

Considerable progress in motor control designs in recent decades has made AC induction motors more advantageous than DC motors for many variable-speed applications, including vehicle propulsion. Compared to DC, the AC motor has these advantages:

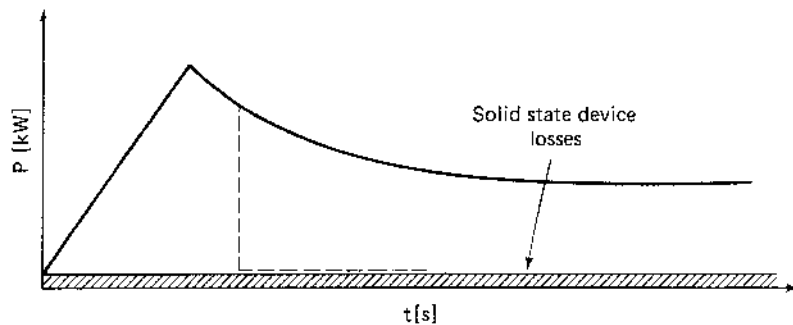
- Lighter weight for the same power rating
- Simpler construction (no insulated rotating windings, brushes, or commutator)
- Three instead of four power cable connections
- Resistance to water and other environmental influences



(a) Single motor connection (e.g., PCC car, trolleybus)



(b) Series and parallel motor connection



(c) Chopper control

Figure 3.12 Power consumption and utilization during vehicle acceleration for different types of motor control

The AC motor requires both voltage and frequency control of the electricity applied to it. That is achieved by control equipment called an *inverter*. The inverter controls both the voltage applied to individual motor

coil groups and the sequence for energizing those coil groups. The result is contactorless control of speed, torque, direction, and mode (acceleration/braking). Several induction motors can be operated in parallel

from a single inverter. The paralleled motors are closely coupled electrically and act as if mechanically linked. That aspect has significant benefit for wheel slip control in application to rail vehicles, which have truck (bogie) configuration with individual axle motors.

The speed characteristic of an induction motor fed constant frequency and constant voltage AC is shown in Figure 3.13. Where the curve crosses the zero torque line is the synchronous speed where the rotating internal magnetic field exactly matches the rotor speed. At this point the motor does not convert energy, either electrical to mechanical or mechanical to electrical. To the left, when the rotor speed is less than synchronous, conversion is electrical to mechanical, termed *motoring*. To the right, when the rotor speed is above synchronous, conversion is mechanical to electrical, termed *overhauling* or *braking*. For large differences between the rotor speed and the synchronous speed (beyond the humps of the curve or under pull-out conditions) the motor is not an efficient energy conversion device. The inverter controls must develop a frequency so that the synchronous speed is just above the rotor speed for acceleration or just below the rotor speed for braking.

In the latest generation of transit vehicles the GTO has been eclipsed by the insulated gate bipolar transistor (IGBT), as a power semiconductor in vehicle drives. The IGBT has lower internal losses, can switch at higher frequencies (1000 to 2000 Hz), and does not require high gate current to turn off. IGBT inverter drives have been increasingly used since their invention during the 1990s. Asian development has resulted in compact IGBT traction inverters suitable for direct supply from 1500 V DC, offering significant economies for new transit systems.

Implicit in all the above is the electric energy coming in the form of DC at a nominally constant voltage, while the current varies with the required power as dictated by instantaneous vehicle speed and acceleration/braking.

3.4.5 Comparison of Motor Control Types

Instead of varying the terminal voltage through rheostats as described earlier, the chopper control provides average voltage lower than the line voltage by switching the thyristors and hence the current on and off. Of course, the basic DC motor performance curves, shown

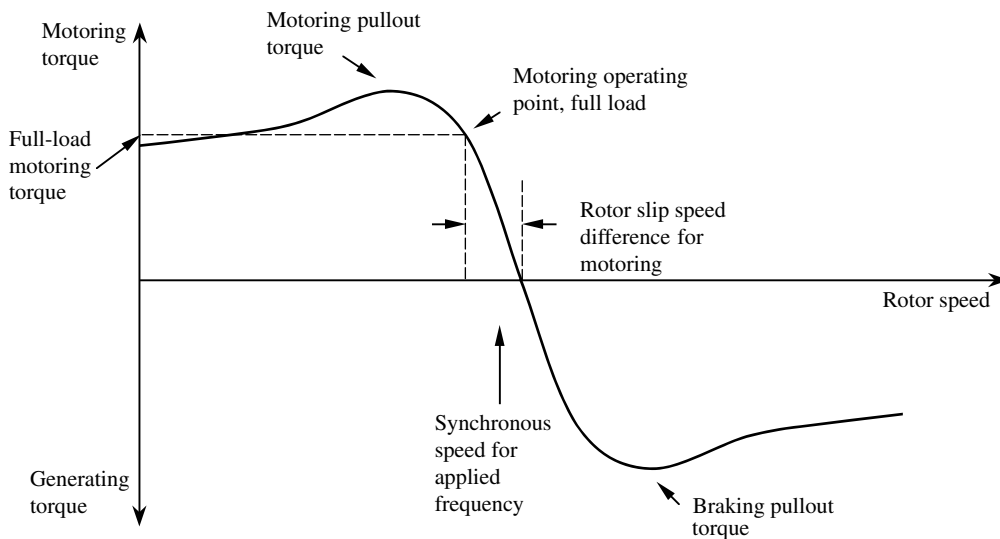


Figure 3.13 Induction (AC) motor characteristics (Courtesy of Norman Vutz)

in Figure 3.10, remain the same regardless of whether rheostatic or chopper controls are used.

Compared to rheostatic DC motor control, SCREC choppers, now succeeded by GTO and IGBT electronic inverter controls of AC induction motors, have the following differences:

- *Reduced energy consumption* is the primary advantage of electronic control. Since energy consumption varies considerably for each control system with specific operating functions, the energy savings due to choppers or inverters vary greatly. The major factors are as follows:
- *Regenerative braking* is possible with chopper control because of two properties of choppers not available with rheostats: (1) stable generation is possible with choppers for both series motors as well as separately excited motors; and (2) generation, and thus dynamic braking, exists until the vehicle nearly stops. The effectiveness of regeneration with respect to energy recovery depends on the receptiveness of the supply system. Generally, the reduction in energy consumption achieved by regeneration can be as high as 20% to 30% on urban lines with relatively short station spacings, although in most cases it is somewhat lower.
- An additional cost-reducing feature of this energy saving is that the peaking demand on the power supply system, which usually affects the unit cost of energy, is also reduced.
- *Vehicle performance* provided by choppers or inverters is superior to that obtained with rheostatic control. With their extremely fine acceleration control, choppers or inverters reduce the possibility for wheel slip to occur and correct it faster than rheostatic control if it ever occurs. In addition, choppers and inverters provide a fully satisfactory spin/slip prevention performance, which can be as gradual and sophisticated as is required under any operating conditions.
- Somewhat *easier adjustment of travel regime to schedule changes* can be achieved by choppers or inverters on trains with automatic train operation

(ATO). In some cases, particularly in networks with high-frequency operation, this maybe a valuable feature.

- *Lower maintenance costs* of chopper and inverter controls result from the use of solid-state components instead of numerous moving parts, which have greater wear and therefore require more maintenance and have lower reliability in operation. Chopper or inverter control requires very low maintenance. Moreover, inverter control lowers motor maintenance due to the simplicity of the AC induction motor. There is also lower heat generation (choppers or inverters produce up to 33% less heat than rheostatic control). This is particularly useful on rubber-tired metro systems, which have problems with high temperatures in tunnels.
- *Electrical interference* with track circuits, signals, and communications, as well as potential for interference with other electrical devices in the vicinity of a line, is greater for choppers and inverters than for rheostatic control.

In conclusion, the development of electronic motor control has allowed the replacement of resistors and switches, which required higher maintenance and energy losses during vehicle acceleration, by more sophisticated electronic controllers, which do not involve power losses in resistors. The first introductions of choppers during the 1960s, as on the BART system, required numerous adjustments in operations. When these were resolved and subsequent inventions led to introduction of AC motors with GTO and IGBT inverters, electronic motor control became so superior that it replaced rheostatic control on virtually all new vehicles. Moreover, it is being retrofitted in vehicles when they are rebuilt.

The benefits of the replacement of rheostatic by electronic controls have been multiple. First, operational benefits, listed in preceding paragraphs, have been significant, and they easily outweigh some disadvantages of the new systems, such as electric interferences and sometimes higher investment cost. Second, electronic controls have enabled the introduction of regenerative braking, resulting in significant reduction of power consumption. Finally, the new control

systems made AC motors feasible are superior for transit vehicle propulsion, leading to further increased efficiencies and operational benefits.

3.4.6 Other Propulsion Systems

Among the numerous inventions and innovations of vehicle propulsion systems, two have had significant applications in transit systems, and they are briefly described here.

3.4.6.1 Linear Induction Motor. For linear traction, which is needed on rail vehicles, the induction electric motor can be redesigned or unwrapped as a continuous “rotor” laid along the track, with the coil-carrying “stator” mounted under the car. As shown in Figure 3.14 and known as linear induction motor (LIM), this type of propulsion can be visualized like a conventional rotary electric motor that is “cut and stretched out,” so that the equivalent of the rotor is laid between track rails and stator windings are attached to the vehicle trucks at a small distance above the unrolled rotor. The motor then acts directly on vehicle

trucks and pulls (or decelerates) them, resulting in vehicle movement.

Since the 1980s, following several decades of development, the LIM propulsion became operational and efficient for transit use. This propulsion is used on the highly successful Skytrain, a fully automated “minimetro” rail line in Vancouver, and on the JFK Airport line with the same technology. LIM propulsion is also used on a manually driven LRRT line in Toronto (Scarborough) and on several metro lines in Tokyo and Osaka.

Compared to conventional rotary motors propelling vehicle wheels, LIM has several important differences in line design (profile), performance, and operational characteristics. The main ones are as follows:

- The propulsion and most of the braking is performed by LIM, so that wheels perform only the support for the vehicle but do not transfer any adhesion forces for acceleration or braking. The spinning, skidding, and wear of wheels and rails are therefore far smaller problems than with conventional rail vehicles.

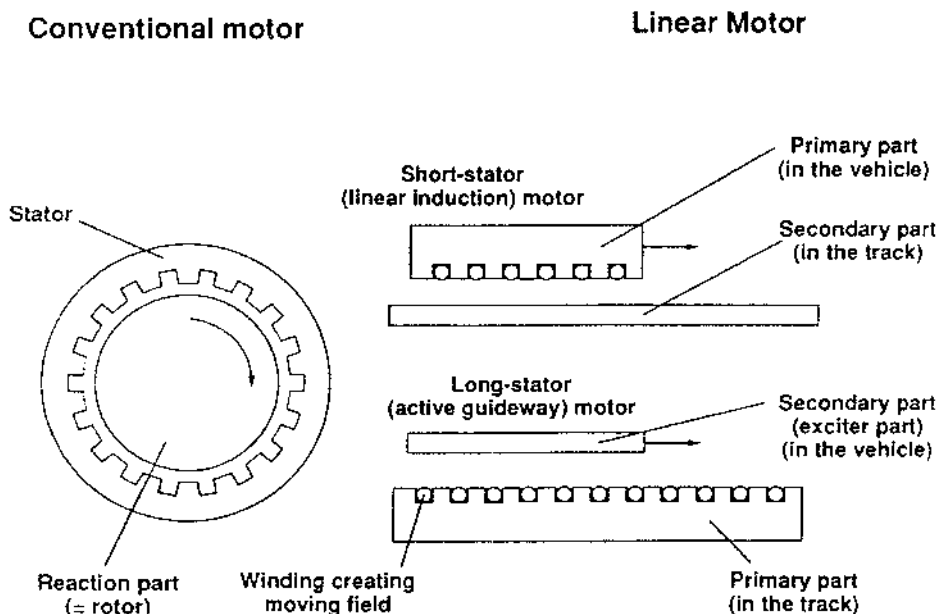


Figure 3.14 Schematic of conventional rotary and linear induction motors

- Energy consumption of LIM was initially estimated to be about 20% to 30% greater than with conventional motors, but increased energy efficiency of LIM has later been claimed.
- LIM has considerably smaller vertical dimension than rotary motors. The metro lines with LIMs therefore have smaller-profile vehicles, resulting in lower tunnel construction costs. The LIM line in Osaka is claimed to have required a 40% smaller profile, resulting in 20% lower construction costs. However, this comparison is not so simple because the vehicle bodies are also smaller and have a lower passenger capacity.

3.4.6.2 Energy Storage Systems. *Energy storage devices.* In addition to regeneration feeding power back to the wayside, energy consumption by electric vehicles may be reduced by the application of on-board energy storage. Two different approaches have been used for this purpose: mechanical (flywheels) and electrical (storage batteries and/or ultracapacitors). Batteries store energy by chemical changes and are limited in the rate at which they can accept or return the stored energy. Batteries also provide essentially constant voltage as the energy is accepted or returned; small voltage differences arise from internal resistance. Ultracapacitors (supercapacitors) store energy electrostatically and do not have limits on the rate of acceptance or return of stored energy. Like all capacitors, they are variable-voltage devices with voltage increasing as energy is stored and voltage decreasing as energy is returned. The variable voltage aspect for storage then needs an electronic converter to obtain the constant voltage for practical use.

An example of a mechanical system as developed by the Garrett Corporation and tested in New York is shown in Figure 3.15. It consisted of a flywheel housed in a low-pressure chamber (to minimize friction), an auxiliary electric motor that can also operate as a generator, and a control system. As shown in the lower part of the figure, the control system was also connected with the traction motor and, through it, with the wheels.

During braking of the vehicle, the electricity generated by the traction motors goes to the auxiliary mo-

tor, which accelerates the spinning of the flywheel. During acceleration, the kinetic energy of the flywheel is used for turning the auxiliary motor, acting as a generator to supplement the power drawn from the third rail for the traction motors to accelerate the vehicle. The basic principle is shown in the upper parts of the Figure 3.15 and technical design in its lower section.

Data on the amount of energy saving through this system indicated that it may only be significant for lines with short station spacings. This energy storage system increases investment cost per vehicle and results in greater mechanical complexity. A particularly serious disadvantage is the additional weight, which, in the case of Garrett's system, exceeded four tons per vehicle.

On-board energy storage for rail transit vehicles has continued to draw attention of vehicle manufacturers. A test LRV vehicle in Mannheim has an ultracapacitor system from Bombardier. LRV on-board storage is being considered to permit short-range operation without overhead wires for new systems going into historically sensitive areas.

3.4.7 Vehicle Acceleration Force

As with ICE propulsion, tractive effort curves for electric vehicles [$TE = f(V)$] may be plotted on the same diagram with vehicle resistance curve, so that a $TE_a = TE - R$ diagram is obtained. This diagram then shows the force available for acceleration as well as the balancing (maximum on level track) vehicle speed ($V_{\max}$) for a given resistance curve (see Figure 3.16). This type of diagram was previously introduced (Figure 3.10 in Section 3.4.2.1). The sawtooth shape at low speed represents the individual resistor steps of a stepped resistor control, with the series and parallel lines representing motor group changing. Two balancing speeds are shown, the lower for the motors in series group connection, each group seeing half voltage, and the higher for the motors in parallel connection, each group seeing full voltage. For a chopper control with DC motors, the low-speed TE can be a smooth horizontal line going to the curve representing tractive force at maximum powering.

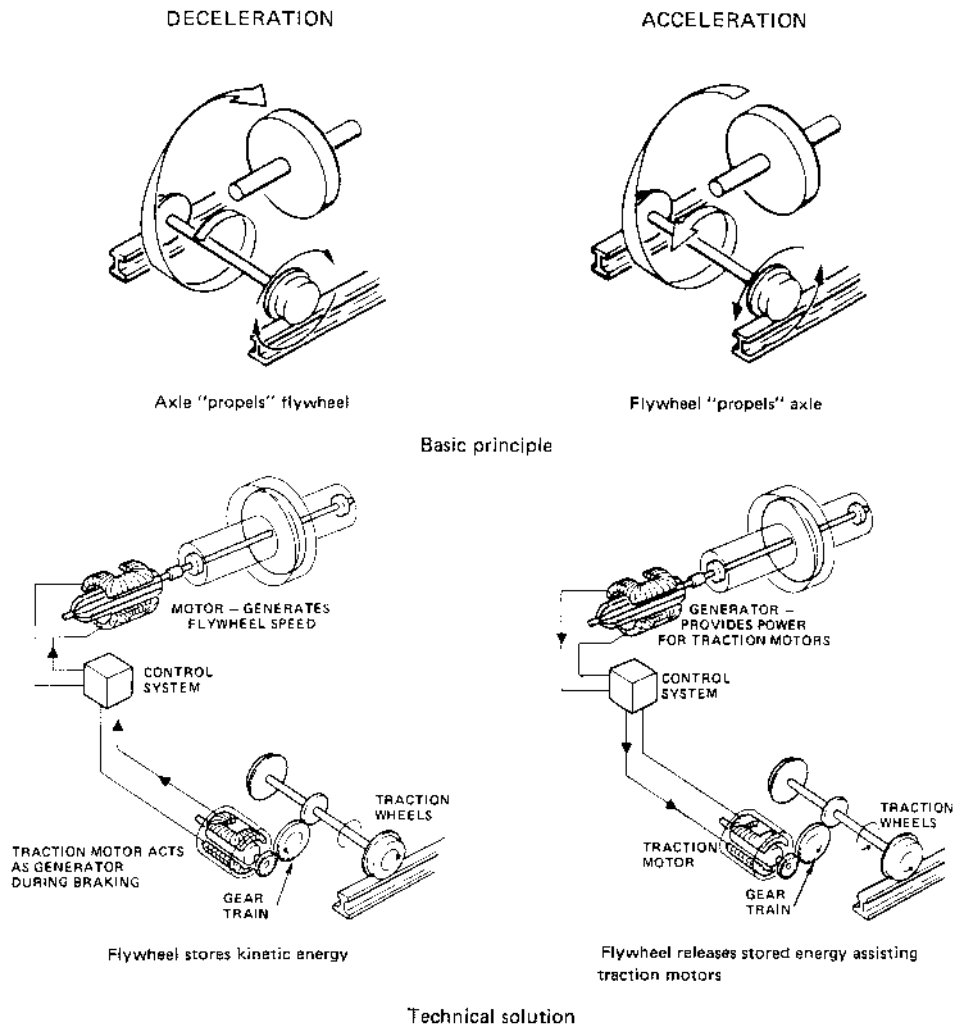


Figure 3.15 Operation of flywheel energy storage system for electric rail vehicles (Courtesy of The Garrett Corporation, Los Angeles)

3.4.8 Comparison of Electric and Diesel Propulsions

The choice between electric and diesel traction is very important, since it affects both the performance and cost of transit services. For correct comparison, the same basic technology must be observed: trolleybus versus bus or electric versus diesel traction on regional rail. The major differences between the two are summarized in the box on page 116.

Consequently, electric traction is clearly superior in its performance, passenger comfort, and external impacts, but it involves a higher investment. It therefore represents a higher "performance/cost package" than does ICE traction. Wherever the investment can be justified on the basis of better performance and, in many cases, lower operating costs, electric traction is superior to ICE. This is the case on heavily traveled transit lines, such as all rail transit lines except long, lightly

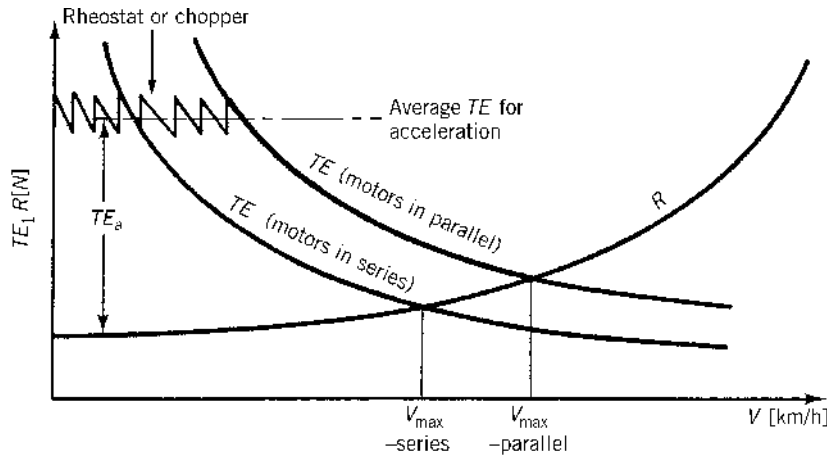


Figure 3.16 Tractive effort–resistance diagram for electric vehicles

traveled regional lines. Diesel and other ICEs, requiring little preparation and investment, are the more efficient mode for lines with light or moderate traffic; it therefore serves a much more extensive and less intensively used bus network in all cities.

3.5 VEHICLE ACCELERATION, BRAKING, AND STOPPING DISTANCES

Forces creating vehicle motion—propulsion for acceleration and braking for deceleration—are transferred on highway and rail vehicles by friction between wheels and running surfaces. The transmission of these forces is therefore described here, leading to the computations of vehicle dynamics and its acceleration and braking distances.

3.5.1 Adhesion for Wheel Traction

Adhesion (attraction of two surfaces) and friction (resistance to relative motion of adjacent surfaces) are rather complex physical phenomena. This section describes these phenomena, omitting some scientific rigor but including the detail needed for the study of traction.

3.5.1.1 Definition and Characteristics. In order to achieve acceleration or deceleration of a vehicle, the tractive effort or braking force must be transferred between the wheels and the running surface. This transfer is made through a friction force F between the two surfaces, which can be shown on a simple sketch of a physical experiment (Figure 3.17). In the context of vehicle traction, this force is referred to as *adhesion*. For practical purposes, the approximation can be used that its magnitude depends on two factors only: the normal force G_a between the two surfaces and a dimensionless coefficient of friction μ :

$$F = \mu \cdot G_a \quad \left| \frac{F, G}{N} \right| \left| \frac{\mu}{-} \right| \quad (3.19)$$

The value of the coefficient μ depends on the characteristics of the two surfaces, primarily their smoothness and hardness, and on the relative speed between them V_r ; for most surfaces, as V_r increases, μ decreases. When the two surfaces do not move ($V_r = 0$), μ assumes a considerably higher value, referred to as the *static adhesion coefficient*.

Adhesion should not be confused with rolling resistance; the two may but need not be related. For example, a softer wheel has both higher adhesion and

Electric traction, compared with *diesel and other ICE traction*, has the following advantages (+), disadvantages (−), and comparable features (∼):

- + Higher acceleration rate for the same motor (engine) rating, because of the ability of the electric motor to produce more power than its nominal rating for a limited time.
- + Smoother acceleration and braking through electronic control and no gear shifting.
- + Much lower noise level: electric traction produces virtually no noise, while ICE always has some noise and vibration.
- + Electric vehicles cause no air pollution, while ICE vehicles do. (Both primary energy production processes, electric power plants and diesel oil refineries, can be located outside of populated areas and their pollution can be controlled.)
- + Electric motors are cleaner to operate and maintain (virtually no physical friction) than ICEs, which involve oil, fuel, and explosions.
- + Electric motors are more durable than ICEs.
- + Electricity can be produced from any primary energy source (oil, coal, atomic, hydro, wind, etc.), while ICE depends on oil and gases burned in vehicles.
- + Considerable energy can be recovered through regenerative braking.
- + Tunnel operation is possible; with ICEs, it is unacceptable except for very short sections or dual-power vehicles.
- ∼ Overhead wires or other power supply lines may be aesthetically objectionable, but they give the line a distinct identity, which passengers like.
- ∼ Operating cost may be lower or higher, depending on the prices of electricity and diesel oil or gas.
- − Electric traction involves a much higher investment cost: power supply system, catenary wiring or third rail, and other fixed equipment must be installed.
- − Implementation time is practically nil for ICE traction but considerable for electric traction.
- − Electric power supply system requires maintenance; ICE involves only fuel storage.
- − Power interruption blocks entire sections or lines; ICE vehicles are independent.
- − Electric vehicles can move only over an electrified network, while buses can move on virtually all streets and highways and diesel trains on all tracks.

higher rolling resistance than does a hard wheel. Highway vehicles on smooth, dry pavement have about twice higher adhesion but 10 times higher rolling re-

sistance than rail vehicles. However, rubber tires on loose snow have a very low adhesion but very high rolling resistance.

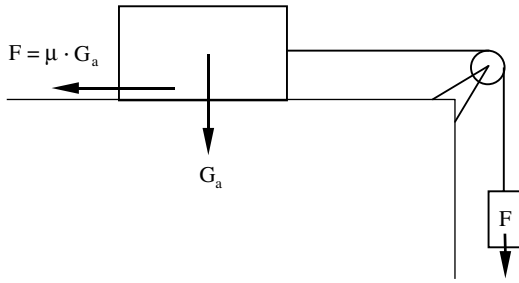


Figure 3.17 Physical representation of friction (adhesion) force F

Applying Eq. (3.19) to traction, it is clear that the maximum tractive or braking effort that can be utilized is limited by adhesion:

$$TE_{\max} = \mu \cdot G_a, \quad \left| \frac{TE, G}{N} \right| \left| \frac{\mu}{-} \right| \quad (3.20)$$

G_a being the weight on the wheels which transfer friction force. For propulsion, G_a is weight on the powered axle(s), while for braking, G_a represents total vehicle weight G , since brakes act on all wheels.

The change of μ with speed is very important in traction. First, it makes braking at high speeds more difficult than at low speeds because V_r between friction surfaces within brakes is very high. Second, any spinning or skidding of wheels results in a rapid increase in V_r between the wheels and supporting surfaces and therefore a sudden reduction of μ (the static coefficient is changed into a dynamic one), so that traction is weakened. To restore the static coefficient, spinning or skidding must be terminated by reducing tractive or braking effort. For this purpose modern electric vehicles have antispinning devices that switch off the motors as soon as spinning is detected and then reapply gradual acceleration. Similarly, antiskidding devices that decrease braking effort when skidding occurs are applied on some highway and rail vehicles. Third, the change of μ inside brakes requires a decrease of braking effort at lower speeds to achieve a constant deceleration rate and lower jerk rate for passenger comfort.

The total force that can be transferred between two surfaces can act in any direction; therefore, it is possible that its utilization in one direction “exhausts” this force and leaves the two surfaces without adhesion in any other direction. Shown schematically, a rubber wheel on pavement projected in a plan view can produce an adhesion force μG_a , which can be decomposed into $(\mu G_a)_l$ in the direction of movement (longitudinal), and $(\mu G_a)_t$ perpendicular to it (transversal), as shown in Figure 3.18.

Longitudinal adhesion is needed for traction during constant speed, acceleration, and deceleration, while transversal adhesion provides guidance—the lateral stability of highway vehicles. If a very high tractive force is applied (rapid acceleration or intensive braking), $(\mu G_a)_l$ approaches μG_a and $(\mu G_a)_t$ goes to zero:

$$(\mu G_a)_t = \sqrt{(\mu G_a)^2 - (\mu G_a)_l^2} \rightarrow 0. \quad \left| \frac{\mu}{-} \right| \left| \frac{G}{N} \right| \quad (3.21)$$

At low speed, TE is large and can exceed the $TE_{\max}$ defined by Eq. (3.20). In that case wheel spinning may occur. Similarly, if, during intensive (e.g., emergency) braking, the applied force exceeds the value of μG_a , skidding that does not allow any lateral resistance may

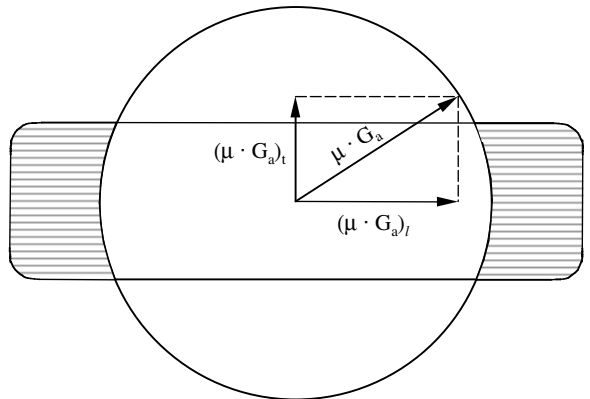
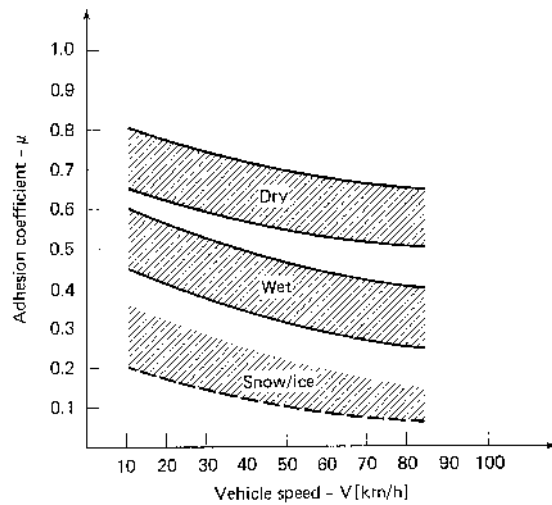
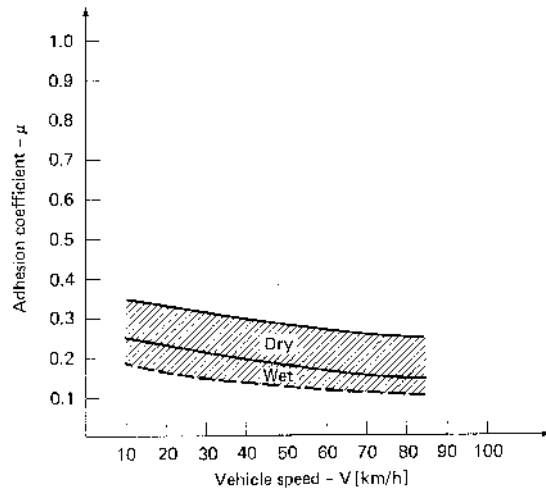


Figure 3.18 Plan view of a rubber tire with adhesion force vector



(a) Rubber-tired vehicles (highway)

Note: Type of surface, such as concrete, asphalt, etc., also has a major influence on μ and may give values outside the plotted ranges.



(b) Rail vehicles

Figure 3.19 Value ranges of adhesion coefficient μ as a function of speed for different surface conditions

occur, so that rubber-tired vehicles lose their lateral stability. This is the reason why highway vehicles “go out of control” during rapid starting or emergency braking, particularly on snow or icy surfaces.

3.5.1.2 Typical Values of μ . The value of μ for highway vehicles depends on the type and condition of the surface. A range of values encompassing most

types of normal conditions reported by many researchers is shown in Figure 3.19a as a function of speed for dry and for wet surfaces (weather). Diagram (b) of the figure shows corresponding values for rail vehicles. For general analyses, it can be assumed that μ for highway vehicles is about 0.6 to 0.7; for rail vehicles, it is 0.20 to 0.35, or two to three times lower than for highway vehicles. However, weather conditions have a stronger

effect on highway than on rail vehicles, particularly when a layer of water, snow, or ice is created [approximate values are shown in diagram (a)]. Water on a highway may cause hydroplaning of the vehicle, in which water acts as a “lubricant.” The extreme case is wet ice, where μ may be as low as 0.05. For rail vehicles, ice and snow conditions may decrease μ , but only to about 0.10. Leaves from trees may affect rail traction more than ice; therefore frequent cleaning of rails and the application of sand are required for such conditions.

Rubber tires on rails have very low μ , particularly when surfaces are wet. This makes use of highway transit vehicles on rails, such as the railbuses that were tested in several U.S. cities during the 1930s and the late 1960s, infeasible.

Since rail vehicles have lower μ but higher acceleration rates than highway vehicles, most rail transit vehicles have all axles powered (i.e., adhesion weight G_a is the same as total vehicle weight G). With highway vehicles it suffices to power only one of the axles, usually the rear, utilizing approximately two-thirds of the total vehicle weight for the tractive adhesion: $G_a = 0.67G$. Articulated buses have even lower percentage of adhesion weight.

3.5.2 Acceleration and Braking Forces and Distances

All the elements needed for the computation of distances for vehicle acceleration, stopping, and safe spacing are now known. These computations are used in the analysis of the operations and capacity of different modes and, specifically, for the design of signal control systems of rail modes.

Acceleration rate, a (m/s^2), can be computed from the net force available for vehicle acceleration (or deceleration), TE_a , on the basis of Eq. (3.1). If, at a given speed, a motor provides *force* TE_a in excess of resistance R , that force is available for acceleration of the vehicle and of rotating masses within the vehicle. These masses, including wheels, shafts, axles, and so on, are accelerated in their rotational movements in addition to the linear acceleration of the vehicle, and that usually adds an equivalent of 4% to 10% to the

required force TE . This is included in the equations as a nondimensional factor $\rho = 1.04$ to 1.10. Expressing vehicle mass m as its weight divided by the acceleration of gravity ($m = G/g$), the *acceleration rate* the vehicle can achieve at any given speed is obtained as:

$$a_{\max} = \frac{TE - R}{\rho \cdot m} = \frac{g \cdot TE_a}{\rho \cdot G} \quad \left| \frac{a, g}{\text{m/s}^2} \right| \left| \frac{TE, R, G}{\text{N}} \right| \left| \frac{\rho}{-} \right| \left| \frac{m}{\text{kg}} \right| \quad (3.22)$$

Acceleration or deceleration distance s_a/s_b (m) for vehicle travel from standing to speed V (or braking from an initial speed V_i to a stop) can be derived from the values of a (b) and v (m/s) or V (km/h) by the following respective equations:

$$s_a = \frac{v^2}{2a} = \frac{V^2}{25.92a} \quad \text{and} \quad s_b = \frac{v^2}{2b} = \frac{V^2}{25.92b} \quad \left| \frac{s}{\text{m}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{V}{\text{km/h}} \right| \left| \frac{a, b}{\text{m/s}^2} \right| \quad (3.23)$$

Maximum braking rate, $b_{\max}$ (m/s^2), which influences braking distances, is determined by the adhesion between the braked wheels and the running surface. It is computed from the equation of braking force consisting of the braking adhesion force and the gravity force when traveling on a sloped path with gradient i (%):

$$m \cdot b_{\max} = \mu \cdot G + 0.01i \cdot G \quad \left| \frac{m}{\text{kg}} \right| \left| \frac{b}{\text{m/s}^2} \right| \left| \frac{\mu}{-} \right| \left| \frac{G}{\text{N}} \right| \left| \frac{i}{\%} \right| \quad (3.24)$$

Replacing m by G/g and multiplying this equation by g/G , gives the maximum achievable braking rate as:

$$b_{\max} = g(\mu + 0.01i), \quad \left| \frac{b, g}{\text{m/s}^2} \right| \left| \frac{\mu}{-} \right| \left| \frac{i}{\%} \right| \quad (3.25)$$

g being 9.81 m/s^2 .

Several instructions for computations of maximum acceleration rate and for different operating conditions follow here.

- The $\mu \cdot G$ expression in Eq. (3.24) applies to total vehicle weight because all wheels are braked. However, on many vehicles, bus and rail, not all axles are powered, so that during acceleration only the vehicle weight on the powered axles provides traction. Therefore, in accelerating, the expression for traction in Eq. (3.24) is $\mu \cdot G_a$, G_a being weight on powered axles only.
- In the equation for acceleration, the sign before the last item is negative: while uphill gradient adds to the braking (increases the deceleration rate), it works against acceleration and is therefore subtracted.
- In all cases, downhill travel is expressed by a negative value of the gradient i .

The following examples illustrate the application of Eq. (3.24) to different sets of conditions. First, suppose that an LRT articulated vehicle that has 80% of its weight on powered axles, accelerates on an $i = -4\%$ downhill gradient. Adhesion coefficient is $\mu = 0.30$. Assuming that its acceleration rate is not limited by motor power but by wheel traction, its maximum acceleration can be computed as:

$$\begin{aligned} m \cdot a_{\max} &= \mu \cdot G_a - (-0.04) G \\ a_{\max} &= g/G (\mu \cdot 0.80G + 0.04G) \\ &= 9.81 (0.30 \cdot 0.80 + 0.04) = 2.75 \text{ m/s}^2. \end{aligned}$$

The same vehicle traveling on an uphill $i = 4\%$ gradient could accelerate only at $a = 1.96 \text{ m/s}^2$. Second, what braking rates can a bus achieve on a 3% uphill and -3% downhill gradients if $\mu = 0.48$? Introducing $i = +3\%$ and $i = -3\%$ into Eq. (3.25) gives, respectively:

$$b_{\max} = 9.81(0.48 + 0.03) = 5.00 \text{ m/s}^2 \quad \text{and}$$

$$b_{\max} = 9.81(0.48 - 0.03) = 4.41 \text{ m/s}^2.$$

Minimum braking distance, $s_{b \min}$, (m), is achieved when the maximum braking rate is used. This distance is computed by introducing the expression for $b_{\max}$ from Eq. (3.25) for b into Eq. (3.23):

$$s_{b \min} = \frac{V_i^2}{254(\mu + 0.01i)} \cdot \left| \frac{s}{\text{m}} \left| \frac{V}{\text{km/h}} \right| \frac{\mu}{-} \frac{i}{\%} \right| \quad (3.26)$$

Stopping distance S_d of vehicles is of greater importance than braking distance for the design of signals, analyses of vehicle spacings, and so on. It consists of a distance s_r passed by the vehicle during the driver's reaction time, and of the braking distance S_b , given as Eq. (3.26). The expressions for the stopping distance applying any braking rate b is:

$$\begin{aligned} s_d &= s_r + s_b = 0.278 t_r \cdot V_i + \frac{V_i^2}{25.92 b} \cdot \\ &\quad \left| \frac{s}{\text{m}} \left| \frac{t_r}{\text{s}} \right| \frac{V}{\text{km/h}} \left| \frac{b}{\text{m/s}^2} \right| \frac{\mu}{-} \frac{i}{\%} \right| \quad (3.27) \end{aligned}$$

Minimum stopping distance $S_{d \min}$, when braking from an initial speed V_i by applying the braking that used the entire adhesion force, is obtained by introducing $b_{\max}$ from Eq. (3.25) into Eq. (3.27):

$$\begin{aligned} s_{d \min} &= 0.278 t_r V_i + \frac{V_i^2}{254(\mu + 0.01i)} \cdot \\ &\quad \left| \frac{s}{\text{m}} \left| \frac{t_r}{\text{s}} \right| \frac{V}{\text{km/h}} \left| \frac{\mu}{-} \frac{i}{\%} \right| \right| \quad (3.28) \end{aligned}$$

3.6 STATION-TO-STATION TRAVEL ANALYSIS

The great majority of transit systems operate in such a manner that they serve a series of stations along a line. Their travel therefore represents a discrete stop-and-go movement with station-to-station travel as a basic element. The vehicle (or TU) movement on fully controlled systems (rapid transit) is rather deterministic (minor variations among drivers are being reduced

through increasing automation), while for street transit (buses and streetcars) it varies considerably due to external interferences such as traffic, signals, and pedestrians. Analysis of the travel times in the latter group is less precise, since it must be done with average values for any specific set of conditions. The analysis in this section refers primarily to fully controlled systems. For street transit the same basic equations are valid, but different average values of acceleration, speed, etc., may be obtained from field measurements, or computer simulation models may be used.

For the analysis of station-to-station travel, first, the basic variables of vehicle motion are defined here. Their typical and limiting values for transit vehicles are presented. Then different regimes of motion for vehicle travel along a line are described. Finally, the equations and diagrams for station-to-station travel are presented. Figure 3.20 shows all the basic variables and regimes of motion for a typical station-to-station vehicle movement.

3.6.1 Basic Variables of Vehicle Motion

Most analyses of vehicle characteristics, travel time, headways, scheduling, passenger comfort, and so on are performed through the basic variables of vehicle motion. These variables are distance and its three subsequent derivatives with respect to time:

$$\text{Distance: } s = f(t); \quad (3.29a)$$

$$\text{Speed: } v = \frac{ds}{dt}; \quad (3.29b)$$

$$\text{Acceleration: } a = \frac{d^2s}{t^2}; \text{ and } \quad (3.29c)$$

$$\text{Jerk: } z = \frac{d^3s}{dt^3} \quad (3.29d)$$

Distance s [m] is most frequently analyzed through time-distance diagrams (often incorrectly referred to as “space-time diagrams”). This diagram is used, for example, for the scheduling of transit lines, the determination of block signals for rapid transit, the analysis

of vehicle movement on a street with signalized intersections, and the analysis of station-to-station travel time, presented in the following section.

Speed v [m/s] is represented on the time-distance diagram by the slope of the vehicle travel line at any given point (see Figure 3.20). However, analysis of vehicle characteristics and their impact on travel time can be better performed by a time-speed diagram (also in Figure 3.20), which shows speed as the ordinate and distance passed as the area under the curve:

$$s = \int v \, dt.$$

Some typical vehicle motion analyses for which the time-speed diagram is utilized are (1) the effects of acceleration rate, maximum speed, and coasting on travel time; (2) the impact of interstation distance on average travel speed; and (3) the influence of travel regime on power consumption. In the cases when vehicle speed at different points along the way is analyzed, the distance-speed diagram can be utilized.

Maximum attainable speeds of transit vehicles on a line depend on the ROW type (category C, B, or A), the geometry of its alignment, and the interstation distance. Vehicles designed for short-haul transportation in urban centers (e.g., minibuses) sometimes have a maximum *technical speed* of only about 40 km/h; surface transit vehicles usually travel at maximum speeds of 40 to 65 km/h, although they are technically capable of running at speeds from 65 to 80 km/h; metro trains typically have maximum speeds between 65 and 100 km/h; buses operating on freeways can travel at up to 90 km/h (55 mph); for regional rail lines and recently built rapid transit systems with long interstation distances (PATCO in Philadelphia, BART, Washington Metro), maximum speeds as high as 120 to 130 km/h are used.

Acceleration a [m/s²], the derivative of speed with respect to time, is sometimes plotted on a diagram as a function of time. On the more common time-speed diagram, acceleration is presented by the slope of the speed curve (Figure 3.20).

Acceleration influences travel time and energy consumption, particularly in services with frequent stop-

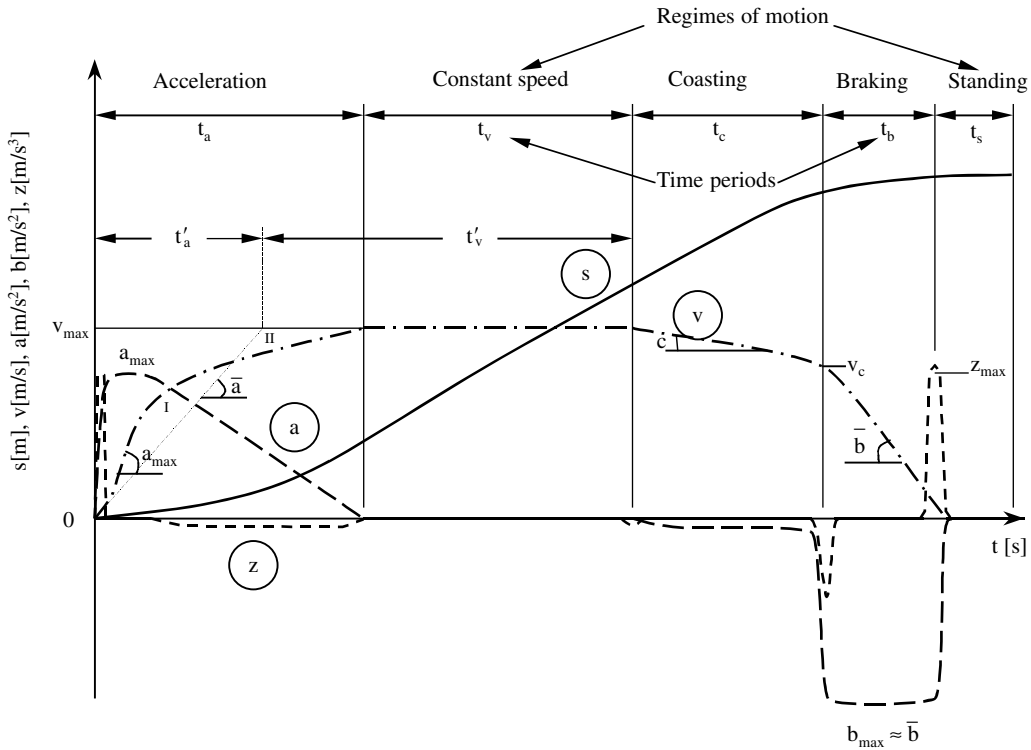


Figure 3.20 Variables and regimes for station-to-station travel for electrically powered vehicles

ping. Its maximum values are usually limited by the comfort and safety of standing passengers, although sometimes the motor power (on steep gradients) or adhesion (under slippery conditions) may represent limiting factors.

The maximum acceleration rate, limited by passenger comfort and safety, is 1.0 to 1.8 m/s^2 . The same factor limits the deceleration (braking) rate to these same values, although emergency braking, as a safety factor, is usually allowed at somewhat higher rates: 2.0 to 3.0 m/s^2 .

Jerk z [m/s^3], the change of acceleration per unit of time, is actually the most important factor for passenger riding comfort. Persons in a vehicle do not feel any forces at constant speed, regardless of its magnitude; they do feel acceleration, but if it is constant, they can brace themselves against it; however, jerk is the force that tends to throw passengers off balance, and

it is therefore necessary to design vehicles so that their acceleration rate changes not faster than 0.5 to 0.6 m/s^3 . The diagram in Figure 3.20 shows changes of jerk during a station-to-station vehicle movement.

3.6.2 Regimes of Motion

For most transit operations, station-to-station movement represents a cycle of four or five different regimes of motion: acceleration, constant speed, coasting, braking, and standing. Their descriptions and mathematical expressions for travel time and travel distance are presented next.

3.6.2.1 Acceleration Regime. During the first regime of the station-to-station movement, as Figure 3.20 shows, the vehicle accelerates initially at the maximum

rate that can be applied, $a_{\max}$. That rate of acceleration is sustained for some time and then it decreases with speed, asymptotically approaching zero at the maximum speed of the vehicle.

To increase average travel speed, it is desirable to achieve and retain the maximum acceleration rate as long as possible. Since electric motors have the ability to produce, for limited periods of time, considerably higher tractive effort than during constant operation, electric vehicles usually have much better acceleration characteristics than do vehicles with internal combustion engines with respect to both maximum acceleration rate and its duration.

For rail vehicles, specifications usually contain precise data on maximum and average acceleration rates as well as on the maximum jerk. Bus specifications do not include these data, so that, for their derivation, field testing is necessary. In general, bus acceleration is not precisely programmed except that the motor is often governed to allow only a limited jerk.

Owing to the changeable rate of acceleration during the first travel regime, this motion is represented on the time-speed diagram by a straight line, which then changes into a concave curve. Precise computation of travel time and distance passed during this interval is therefore not simple. The t - v curve can be computed approximately by the equation

$$v = v_{\max}(1 - e^{-t/\tau}), \quad (3.30)$$

where $\tau = v_{\max}/a_{\max}$. In some cases all the variables can be computed by analog computer. For general analyses of travel time, however, great precision is not essential, so that the approximation can be made that the acceleration rate is constant. This approximation, which greatly simplifies analyses of interstation distances, can be made in several ways. If interstation distances are long enough so that the vehicle can reach its maximum speed $V_{\max}$, the average acceleration rate $\bar{a}$ for acceleration from standing to maximum speed should be used. This average rate is selected so that the areas between that line and the curve of actual acceleration on the time-speed diagram, designated as I and II in Figure 3.20, are equal. As the diagram

shows, when $\bar{a}$ is used for computations, a shorter acceleration period t'_a and a longer constant speed period t'_c must be used. For distances on which $V_{\max}$ cannot be reached, the average rate increases and its exact value must be determined from the acceleration curve. Its highest possible value is $a_{\max}$, the initial acceleration rate. Transit engineers must always carefully examine for which analyses the use of $\bar{a}$ is adequate and for which greater precision is needed.

With the assumption of constant acceleration rate $\bar{a}$, expressions are simplified. When the duration of the acceleration interval t_a is known, distance passed s_a and speed reached at the end of the acceleration interval V' are, respectively:

$$s_a = \frac{\bar{a} \cdot t_a^2}{2} \quad \left| \frac{s}{\text{m}} \left| \frac{a}{\text{m/s}^2} \right| \frac{t}{\text{s}} \right| \quad (3.31)$$

and

$$V' = 3.6\bar{a}t_a \quad \left| \frac{V}{\text{km/h}} \left| \frac{a}{\text{m/s}^2} \right| \frac{t}{\text{s}} \right| \quad (3.32)$$

The factor 3.6 converts v (m/s) into V (km/h).

3.6.2.2 Constant-Speed Regime. The duration of interval during which transit vehicle travels at constant speed depends on the interstation distance. If the distance is short, the vehicle may not reach constant speed before it must begin to brake; if it is long, most of the travel may be performed at that speed. The former is typical for intraurban sections and the latter for suburban sections of rapid transit lines and regional systems.

The relationships of variables during the constant speed $V_{\max}$ interval is simple. If the interval of that running is t_v , the distance s_v passed during that interval is:

$$s_v = \frac{V_{\max} \cdot t_v}{3.6} \quad \left| \frac{s}{\text{m}} \left| \frac{V}{\text{km/h}} \right| \frac{t}{\text{s}} \right| \quad (3.33)$$

3.6.2.3 Coasting Regime. Because of their extremely low rolling resistance, rail vehicles are often

operated with coasting; when the maximum speed $V_{\max}$ is reached, the motors are switched off and the vehicle coasts until the brakes must be applied for a stop at the next station. Since the deceleration rate is very low, coasting often results in a slightly increased travel time but also a considerable energy saving.

Coasting represents a motion at a constant deceleration rate c . Computation of speed at the end of the coasting interval V_c and of the total travel time when coasting is applied is given in Section 3.6.3.

3.6.2.4 Braking Regime. The fourth regime of station-to-station travel is braking. In most cases regular braking is performed at a rate that can be assumed as constant during the entire interval without significant error.

The equations relating braking distance s_b , braking time t_b , average deceleration rate $\bar{b}$, and initial speed V_i , assuming that the vehicle comes to a stop, are similar to those for the acceleration interval, Eqs. (3.31) and (3.32):

$$s_b = \frac{\bar{b} t_b^2}{2} \quad \left| \frac{s}{\text{m}} \right| \left| \frac{b}{\text{m/s}^2} \right| \left| \frac{t}{\text{s}} \right| \quad (3.34)$$

and

$$V_i = 3.6 \bar{b} t_b \quad \left| \frac{V}{\text{km/h}} \right| \left| \frac{b}{\text{m/s}^2} \right| \left| \frac{t}{\text{s}} \right| \quad (3.35)$$

V_i may be any speed, but in regular travel it is usually either V_c or $V_{\max}$.

3.6.2.5 Station Standing Time. Since the average operating speed and the capacity of the transit line are strongly influenced by the duration of standing at stops or stations t_s , it is important to keep this interval as short as possible (standing for traffic and signal delays are not included here). Station standing time varies greatly among modes, door sizes and steps, passenger volumes, and types of departure control.

3.6.3 Travel Time Equations and Diagrams

The relationship between interstation distance S and travel time on it T_s depends on whether a transit vehicle can reach its maximum speed or not. Let S_c , designated as critical distance, be the distance required for a train to accelerate to $V_{\max}$ and then immediately apply braking and come to a full stop. Then for all station spacings $S < S_c$ travel consists of acceleration, deceleration, and standing regimes only, and the relationship between S and T_s is nonlinear. For spacings with $S > S_c$, the relationship is linear, but equations vary depending on what travel regimes are applied. Three combinations are possible, so that including distances $S > S_c$, there are four basic cases for station-to-station travel. The cases, shown in Figure 3.21, are:

- $S = S' < S_c$
- $S \geq S_c$, no coasting
- $S \geq S_c$, no constant speed
- $S \geq S_c$, with constant speed and coasting

Descriptions of these four cases and their expressions for distance and travel time are presented next.

3.6.3.1 Case a: $S = S' < S_c$. To distinguish from later cases, the spacing S , which is shorter than the critical distance S_c and its station-to-station travel time T_s , will be designated by a prime ($'$). The maximum speed reached will be designated as V' . By definition of this case, $V' < V_{\max}$.

The station spacing S' is passed in two travel regimes only: acceleration and braking. Based on Eq. (3.31), the expression for S' is

$$S = \frac{1}{2} (\bar{a} \cdot t_a^2 + \bar{b} \cdot t_b^2) \quad \left| \frac{S}{\text{m}} \right| \left| \frac{a}{\text{m/s}^2} \right| \left| \frac{t}{\text{s}} \right| \left| \frac{b}{\text{m/s}^2} \right| \quad (3.36)$$

The duration of acceleration and deceleration regimes, t_a and t_b , respectively, are not known, but their relationship is fixed through the fact that the speed at the end of the acceleration interval is the same as the speed at the beginning of the deceleration interval:

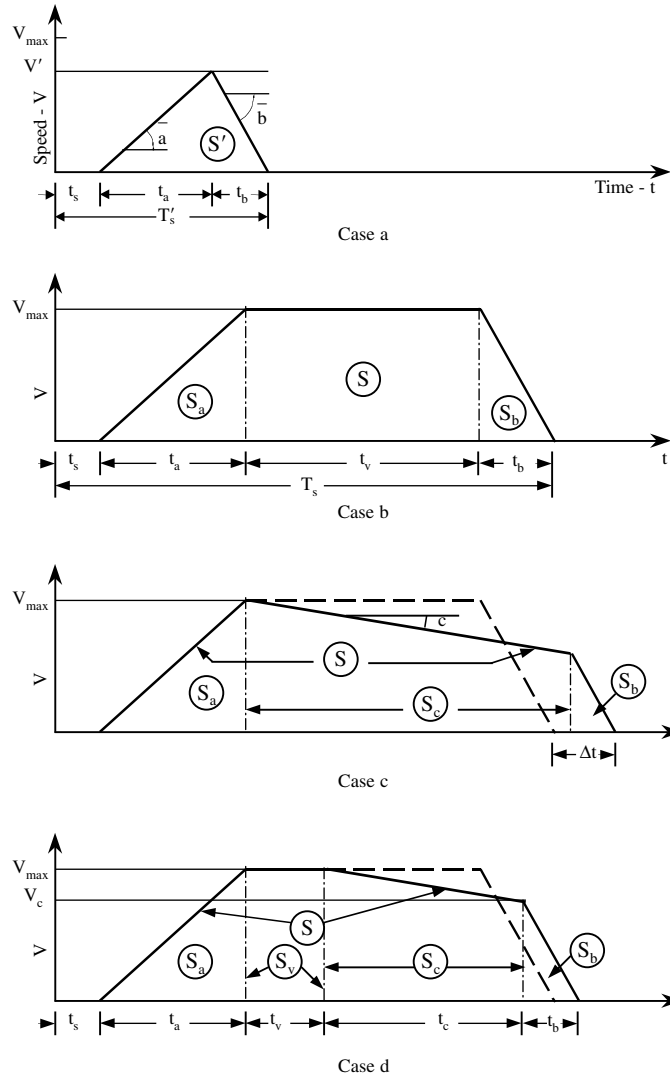


Figure 3.21 Four cases of interstation travel regimes

$$v' = \bar{a} \cdot t_a = \bar{b} \cdot t_b \quad \left| \frac{v}{\text{m/s}} \left| \frac{a}{\text{m/s}^2} \right| \frac{t}{\text{s}} \right| \frac{b}{\text{m/s}^2} \quad (3.37) \quad t_a = \frac{v'}{a} \quad \text{and} \quad t_b = \frac{v'}{b}, \quad \left| \frac{t}{\text{s}} \left| \frac{v}{\text{m/s}} \right| \frac{\bar{a}}{\text{m/s}^2} \right| \frac{\bar{b}}{\text{m/s}^2} \quad (3.38)$$

[for clarity of relationships v (m/s) is used; V (km/h) is introduced for final expressions only].

This gives

which, when substituted in Eq. (3.36) and solved for v' , gives the maximum speed reached as a function of

station spacing S' , with average acceleration and deceleration rates as parameters:

$$v' = \sqrt{\frac{2\bar{a} \cdot \bar{b} \cdot S'}{\bar{a} + \bar{b}}}. \quad \left| \frac{v}{\text{m/s}} \right| \left| \frac{\bar{a}}{\text{m/s}^2} \right| \left| \frac{\bar{b}}{\text{m/s}^2} \right| \left| \frac{S}{\text{m}} \right| \quad (3.39)$$

Station-to-station travel time T'_s consists in this case of the acceleration, braking, and standing intervals. T'_s is derived from the preceding equations and expressed as a function of the spacing S' :

$$T'_s = t_a + t_b + t_s = \sqrt{\frac{2(\bar{a} + \bar{b})S'}{\bar{a}\bar{b}}} + t_s. \quad \left| \frac{T}{\text{s}} \right| \left| \frac{t}{\text{s}} \right| \left| \frac{\bar{a}}{\text{m/s}^2} \right| \left| \frac{\bar{b}}{\text{m/s}^2} \right| \left| \frac{S}{\text{m}} \right| \quad (3.40)$$

The critical distance S_c is computed from Eq. (3.39), substituting v for v' and solving for S :

$$S_c = \frac{v_{\max}^2}{2} \left(\frac{1}{\bar{a}} + \frac{1}{\bar{b}} \right) = \frac{V_{\max}^2}{25.92} \left(\frac{1}{\bar{a}} + \frac{1}{\bar{b}} \right). \quad \left| \frac{S}{\text{m}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{V}{\text{km/h}} \right| \left| \frac{\bar{a}}{\text{m/s}^2} \right| \left| \frac{\bar{b}}{\text{m/s}^2} \right| \quad (3.41)$$

The travel time for that boundary case is derived from Eqs. (3.40) and (3.41):

$$T_c = v_{\max} \left(\frac{1}{\bar{a}} + \frac{1}{\bar{b}} \right) + t_s = \frac{V_{\max}}{3.6} \left(\frac{1}{\bar{a}} + \frac{1}{\bar{b}} \right) + t_s. \quad \left| \frac{T}{\text{s}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{V}{\text{km/h}} \right| \left| \frac{\bar{a}}{\text{m/s}^2} \right| \left| \frac{\bar{b}}{\text{m/s}^2} \right| \left| \frac{t}{\text{s}} \right| \quad (3.42)$$

In all computations for this case it must be remembered that a is not a constant value: the shorter the acceleration period is (lower v'), the greater is the value of a . Therefore, if accurate values are needed for short spacings S' , iterative computations may be required to derive mutually compatible values of v' and a .

3.6.3.2 Case b: $S \geq S_c$, No Coasting. In this case the vehicle reaches $v_{\max}$ and maintains it until braking must be applied for stop at the next station. Since

$$S_a + S_b = S_c, \quad \left| \frac{S}{\text{m}} \right| \quad (3.43)$$

the distance S_v traveled at constant (maximum) speed $v_{\max}$ can be expressed as

$$S_v = S - S_a - S_b = S - S_c. \quad \left| \frac{S}{\text{m}} \right| \quad (3.44)$$

The travel time T_s consists of four intervals. Since t_a , t_b , and t_s constitute T_c , and $t_v \cdot V_{\max} = S_v$, it can be expressed as

$$T_s = t_a + t_v + t_b + t_s = T_c + \frac{S - S_c}{v_{\max}}, \quad \left| \frac{T}{\text{s}} \right| \left| \frac{t}{\text{s}} \right| \left| \frac{S}{\text{m}} \right| \left| \frac{v}{\text{m/s}} \right| \quad (3.45)$$

t_v being the constant speed interval. Substituting the expressions from Eqs. (3.42) and (3.41) for T_c and S_c , respectively, one obtains:

$$\begin{aligned} T_s &= v_{\max} \left(\frac{1}{\bar{a}} + \frac{1}{\bar{b}} \right) + \frac{S}{v_{\max}} - \frac{v_{\max}}{2} \left(\frac{1}{\bar{a}} + \frac{1}{\bar{b}} \right) + t_s \\ &= \frac{S}{v_{\max}} + \frac{v_{\max}}{2} \left(\frac{1}{\bar{a}} + \frac{1}{\bar{b}} \right) + t_s. \end{aligned} \quad \left| \frac{T}{\text{s}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{\bar{a}}{\text{m/s}^2} \right| \left| \frac{\bar{b}}{\text{m/s}^2} \right| \left| \frac{S}{\text{m}} \right| \left| \frac{t}{\text{s}} \right| \quad (3.46)$$

This equation can be further simplified if the incremental time loss per stopping at one station T_l is defined:

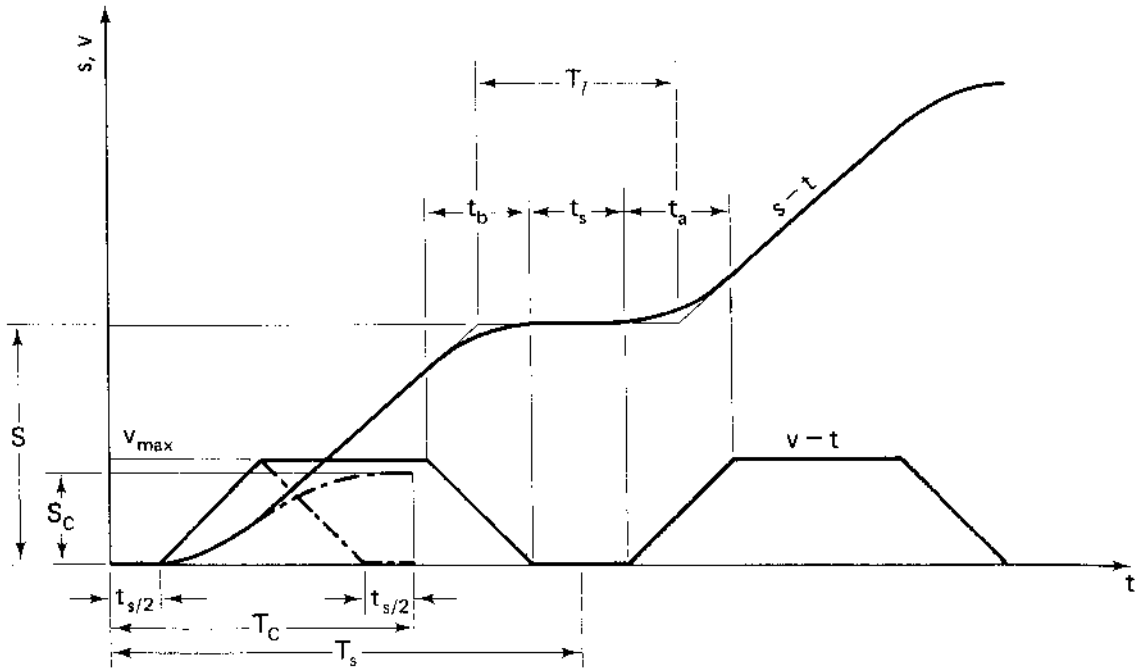


Figure 3.22 Distance and speed-versus-time diagram of train movement

$$T_l = \frac{v_{\max}}{2} \left(\frac{1}{a} + \frac{1}{b} \right) + t_s = \frac{V_{\max}}{7.2} \left(\frac{1}{a} + \frac{1}{b} \right) + t_s$$

$$\left| \frac{T}{s} \right| \left| \frac{v}{m/s} \right| \left| \frac{V}{km/h} \right| \left| \frac{\bar{a}}{m/s^2} \right| \left| \frac{\bar{b}}{m/s^2} \right| \left| \frac{t}{s} \right| \quad (3.47)$$

so that Eq. (3.46) becomes

$$T_s = \frac{S}{v_{\max}} + T_l = \frac{3.6S}{V_{\max}} + T_l$$

$$\left| \frac{T}{s} \right| \left| \frac{S}{m} \right| \left| \frac{v}{m/s} \right| \left| \frac{V}{km/h} \right| \quad (3.48)$$

T_l represents the difference between actual travel time and what the travel time would be if the vehicle (TU) traveled the whole interstation distance at speed $V_{\max}$ (with instantaneous acceleration to $V_{\max}$, deceleration to a stop, and no standing time). This time can be easily measured for any line and type of rolling stock by the following method. A TU is driven twice

on a line section with three stations, where $V_{\max}$ is reached on each interstation spacing, and its travel times are recorded. On one run the TU makes a regular stop at the middle station; on the other run it travels from the first to the third station without that stopping. The difference between the two travel times, with and without stopping at the intermediate station, represents the incremental time loss per station stopping T_l , as illustrated in Figure 3.22.

3.6.3.3 Case c: $S \geq S_c$, No Constant Speed. For station spacings that are not extremely long, the most economical driving with respect to energy consumption consists of acceleration to $v_{\max}$, then coasting at the deceleration rate c until braking must be applied. For this case the station-to-station travel time T_s consists of four intervals: acceleration (t_a), coasting (t_c), braking (t_b), and standing (t_s). While t_a and t_b can be expressed in the form given by Eq. (3.38), t_c is defined as

$$t_c = \frac{v_{\max} - v_c}{c}, \quad \left| \frac{t}{s} \left| \frac{v}{\text{m/s}} \right| \frac{c}{\text{m/s}^2} \right| \quad (3.49)$$

where v_c is the speed at the end of the coasting interval. The total travel time is then

$$\begin{aligned} T_s &= \frac{v_{\max}}{\bar{a}} + \frac{v_{\max} - v_c}{c} + \frac{v_c}{\bar{b}} + t_s \\ &= v_{\max} \left(\frac{1}{\bar{a}} + \frac{1}{c} \right) + v_c \left(\frac{1}{\bar{b}} - \frac{1}{c} \right) + t_s. \\ &\quad \left| \frac{T}{s} \left| \frac{v}{\text{m/s}} \right| \frac{c}{\text{m/s}^2} \right| \frac{\bar{b}}{\text{m/s}^2} \left| \frac{t}{s} \right| \end{aligned} \quad (3.50)$$

To derive v_c , the station spacing S is set equal to the sum of the distances passed during the intervals t_a , t_c and t_b ; utilizing Eqs. (3.31), (3.33), and (3.34), one obtains

$$\begin{aligned} S &= \frac{1}{2} [\bar{a}t_a^2 + (v_{\max} + v_c)t_c + \bar{b}t_b^2]. \\ &\quad \left| \frac{S}{\text{m}} \left| \frac{\bar{a}}{\text{m/s}^2} \right| \frac{t}{s} \left| \frac{v}{\text{m/s}} \right| \frac{\bar{b}}{\text{m/s}^2} \right| \end{aligned} \quad (3.51)$$

Expressing the time intervals by speeds and acceleration rates [Eqs. (3.38) and (3.49)], Eq. (3.51) becomes

$$\begin{aligned} S &= \frac{1}{2} \left(\frac{v_{\max}^2}{\bar{a}} + \frac{v_{\max}^2 - v_c^2}{c} + \frac{v_c^2}{\bar{b}} \right). \\ &\quad \left| \frac{S}{\text{m}} \left| \frac{v}{\text{m/s}} \right| \frac{\bar{a}}{\text{m/s}^2} \right| \frac{c}{\text{m/s}^2} \left| \frac{\bar{b}}{\text{m/s}^2} \right| \end{aligned} \quad (3.52)$$

Solving this equation for v_c and converting to V 's gives

$$\begin{aligned} V_c &= \sqrt{\frac{25.92\bar{a}\bar{b}cS - \bar{b}(\bar{a} + c)V_{\max}^2}{\bar{a}(c - \bar{b})}}. \\ &\quad \left| \frac{V}{\text{km/h}} \left| \frac{\bar{a}}{\text{m/s}^2} \right| \frac{\bar{b}}{\text{m/s}^2} \right| \frac{c}{\text{m/s}^2} \left| \frac{S}{\text{m}} \right| \end{aligned} \quad (3.53)$$

In practice, when this travel regime is considered, it is necessary to first compute V_c by Eq. (3.53). If V_c is very low, the regime may be considered undesirable

and a constant speed interval must be introduced. If V_c is satisfactory, its value is introduced into Eq. (3.50) and T_s is computed for any value of S .

3.6.3.4 Case d: $S \geq S_c$, With Constant Speed and Coasting.

For long station spacings, the most common regime of travel consists of an acceleration interval to reach the cruising speed (usually $v_{\max}$), travel at that speed, coasting to some speed V_c , and then braking to a stop. Total travel time for this case is obviously longer than for case b , but shorter than for case c on the same spacing. Utilizing the expressions for time intervals as in Eq. (3.50), one obtains:

$$\begin{aligned} T_s &= t_a + t_v - t_c - t_b + t_s \\ &= v_{\max} \left(\frac{1}{\bar{a}} + \frac{1}{c} \right) + v_c \left(\frac{1}{\bar{b}} - \frac{1}{c} \right) + t_v - t_s. \\ &\quad \left| \frac{T}{s} \left| \frac{t}{s} \right| \frac{v}{\text{m/s}} \right| \frac{\bar{a}}{\text{m/s}^2} \left| \frac{c}{\text{m/s}^2} \right| \frac{\bar{b}}{\text{m/s}^2} \end{aligned} \quad (3.54)$$

This equation has two unknowns, t_v and v_c , which are related in the following way:

$$\begin{aligned} t_v &= \frac{S}{v_{\max}} - \frac{v_{\max}}{2} \left(\frac{1}{\bar{a}} + \frac{1}{c} \right) - \frac{v_c^2}{2v_{\max}} \left(\frac{1}{\bar{b}} - \frac{1}{c} \right). \\ &\quad \left| \frac{t}{s} \left| \frac{S}{\text{m}} \right| \frac{v}{\text{m/s}} \right| \frac{\bar{a}}{\text{m/s}^2} \left| \frac{c}{\text{m/s}^2} \right| \frac{\bar{b}}{\text{m/s}^2} \end{aligned} \quad (3.55)$$

Naturally, for $t_v = 0$ (case c), this equation becomes the same as Eq. (3.52).

In planning the travel regime for a specific transit line, a value for v_c is selected and introduced into Eq. (3.55) to compute t_v , then into Eq. (3.54). The obtained value of T_s is then evaluated: if it would result in an unacceptably low average speed, a higher value of v_c is tested. This is repeated until the desired average speed, traded off against energy consumption influenced by the length of t_v , is found.

3.6.3.5 Interstation Travel Time versus Station Spacing Diagram. The most important relationship to be derived from the preceding analyses is that of

the interstation travel time T_s and station spacing S . This relationship for all four cases is plotted on a diagram in Figure 3.23. The $T_s - S$ curves shown are not actual time-distance plots of vehicle travel (the dashed curve in the diagram is such a plot). They represent envelopes of interstation travel times T_s for all station spacings S under different regimes of travel.

The curved section between the origin and S_c represents case *a*, Eq. (3.40). The curve for case *b* represents Eq. (3.48), a linear relationship between S and T_s . Case *c*, Eq. (3.50) with Eq. (3.53), is represented by a curve that is asymptotic to that value of S (not shown) for which the vehicle would come to a halt by coasting only. The value of T_s for that point can be obtained from Eq. (3.50) for $V_c = 0$ [it becomes the same as Eq. (3.42) except that the deceleration rate is c instead of $\bar{b}$]. When $V_c = 0$ is introduced into Eq. (3.53), one obtains the expression for the corresponding value of S :

$$S = \frac{(\bar{a} + c)v_{\max}^2}{2\bar{a}c} = \frac{(\bar{a} + c)V_{\max}^2}{25.92\bar{a}c}.$$

$$\left| \frac{S}{\text{m}} \right| \left| \frac{\bar{a}}{\text{m/s}^2} \right| \left| \frac{c}{\text{m/s}^2} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{V}{\text{km/h}} \right| \quad (3.56)$$

Case *d*, Eq. (3.54) with Eq. (3.55), is represented by a curve between those for cases *b* and *c*, determined by the given value of the constant speed interval t_v , as shown on the diagram.

This diagram can be used for easy estimation of travel times on individual spacings along a line for a given fleet (i.e., fixed a , b , c , and $V_{\max}$). It is also very useful for the selection of the travel regime on individual sections, since it gives a clear comparison of travel times among the regimes *b*, *c*, and *d*.

When combined with a diagram of cumulative energy consumption, a $T_s - S$ plot can easily show in a graphical manner the trade-off between energy consumption and travel time. Finally, these equations and diagrams allow easy computation of the distance S on which two vehicles with different dynamic characteristics have equal travel times T_s . An example of such an analysis follows.

Suppose that a vehicle type I has high values of a_1 and b_1 but not very high $V_{\max 1}$ and t_{s1} , while type II, designed for longer spacings S , has lower a_2 and b_2 but higher $V_{\max 2}$ and t_{s2} . The spacing S_e for which both vehicle types will have equal travel times with, for example, regime *b* operation, can be computed by equat-

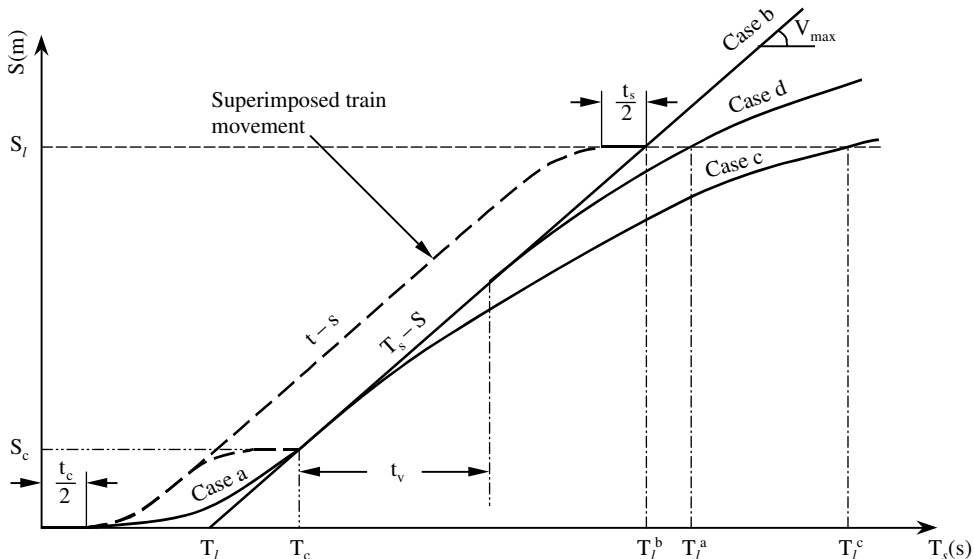


Figure 3.23 $T_s - S$ diagram for different travel regimes on a distance S_l

ing Eq. (3.48) for vehicle type I with the same expression for type II and solving the equation for S_e :

$$S_e = (T_{I2} - T_{II}) \frac{V_{\max 1} \cdot V_{\max 2}}{3.6 (V_{\max 2} - V_{\max 1})} \cdot \left| \frac{S}{\text{m}} \left| \frac{T}{\text{s}} \right| \frac{V}{\text{km/h}} \right| \quad (3.57)$$

For this example, vehicle type I will be faster on all distances shorter than the computed S_e , while on distances longer than S_e , equipment II will be faster.

3.6.3.6 Travel Time for the Line. Travel or operating time for the whole line, T_o , is simply the sum of travel times on individual interstation spacings. If each spacing has $S \geq S_c$ and travel regime b is applied, the equation for the total travel, based on Eq. (3.48), becomes very simple:

$$T_o = \sum_{j=1}^k T_{sj} = \frac{3.6}{V_{\max}} \sum_{j=1}^k S_j + k \cdot T_l$$

$$= \frac{3.6 \cdot L}{V_{\max}} + k \cdot T_l \quad \left| \frac{T}{\text{s}} \right| \left| \frac{V}{\text{km/h}} \right| \left| \frac{S}{\text{m}} \right| \left| \frac{k}{-} \right| \left| \frac{L}{\text{m}} \right| \quad (3.58)$$

where L is the one-way length of the line and k the number of spacings or the number of acceleration-deceleration pairs. If travel regimes differ among spacings, the value for each T_j must be computed individually and then summed. For short spacings S' , higher values of a may be used for greater accuracy (see Section 3.6.2.1).

3.6.4 Sensitivity of Travel Time and Speed to Individual Parameters

In the planning of new lines or in the determination of fleet characteristics for an existing line, it is necessary to analyze the sensitivity of travel time or travel speed to the changes of individual parameters, primarily to acceleration-deceleration rates, station standing time, and maximum speed. The relationships needed for these analyses can be shown clearly by several types of diagrams based on the preceding equations. To demonstrate these analyses, the most commonly used diagrams of vehicle travel characteristics are shown in the following three subsections.

3.6.4.1 Travel Time as a Function of Station Spacing. Numerical values from Table 3.1 and Eqs. (3.40) and (3.48) are used to develop sensitivity analysis diagrams for rapid transit and street transit. The first diagram, Figure 3.24, is developed in the following manner. First, a “basic curve” of the T_s -versus- S relationship is drawn for a set of operating values shown in the first column of Table 3.1. These values are typical for an older, relatively slow rapid transit system. Then, to analyze the effects of improvements in each individual parameter, one curve is plotted, assuming that only one of the parameters is improved to its value in the second column in Table 3.1. The improved values are realistic, typical for modern equipment and operation. For example, the initial values of $a = b = 0.9 \text{ m/s}^2$ and $t_s = 22 \text{ s}$ with the improved value of $V_{\max}$ (120 km/h) give curve V^i in the diagram. Similarly, curves a^i and t_s^i represent improved values of a and b , and of t_s , respectively. Finally, a curve based on all improved values in the second column of the table is also plotted. This curve incorporates im-

Table 3.1 Parameter values for travel time sensitivity analysis

Parameter	Dimension	Rapid Transit		Street Transit	
		Basic	Improved	Basic	Improved
$V_{\max}$	km/h	80.0	120.0	25.0	35.0
$a = b$	m/s ²	0.9	1.2	0.7	0.9
t_s	s	22.0	12.0	25.0	15.0

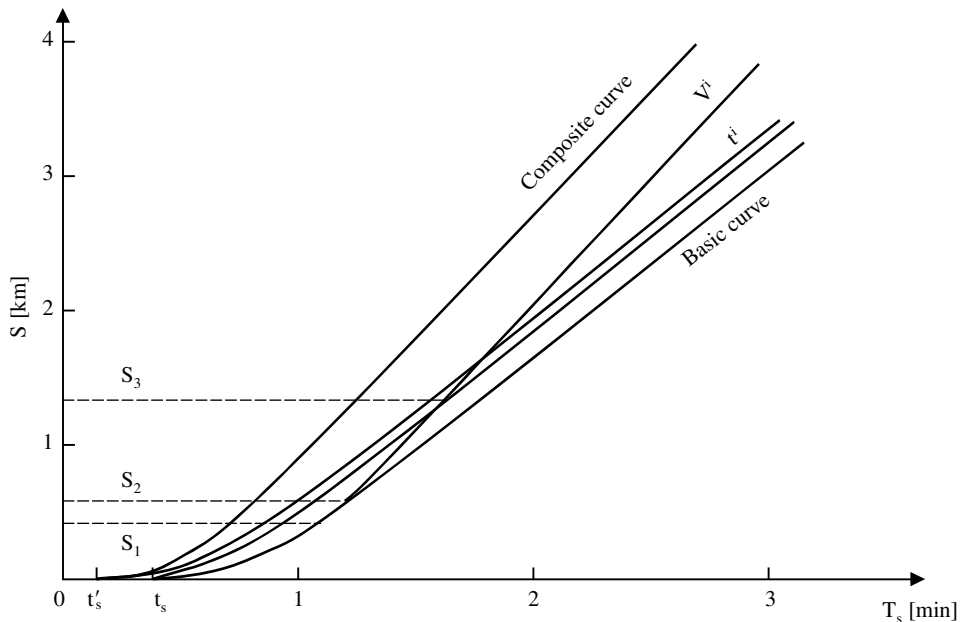


Figure 3.24 Sensitivity of travel time to individual parameters—rapid transit

provements of all parameters and it is designated as “composite curve.” Thus the first and the last curves, the basic and the composite ones, show the two extreme values of the slowest and fastest travel, respectively, while the curves between them indicate effectiveness of improvements of individual parameters.

Figure 3.24 permits analysis of possible travel time reduction through each individual parameter for any given interstation distance S . For example, by drawing a horizontal line for a short interstation distance such as S_1 , one can see that an increase of maximum vehicle speed $V_{\max}$ does not have any influence on travel time. For the example given, this is true for any $S < S_2$, which is S_c for the initial parameters. Its impact on travel time beyond that distance increases rather rapidly; for very long distances, high maximum speed is the most important characteristic. Acceleration-braking rates, on the other hand, strongly influence travel time for shorter distances. Their relative importance then decreases with interstation distance. For this reason typical urban rapid transit lines with short station spac-

ings require rolling stock with high acceleration-braking rates and relatively low maximum speed. For long interstation distances, both high speed and high acceleration-braking rates are desirable. If, for economic reasons (lower vehicle cost, energy savings), only one can be maximized, then an increase of maximum speed should be favored over higher acceleration-braking rates for distances greater than the one shown as S_3 on the diagram.

Reduction of standing time has a constant effect regardless of interstation distance. Although this saving appears very small on the diagram, in many cases its relative significance may be rather high. Since shortening of that time does not require higher vehicle cost and energy consumption, as changes in vehicle dynamic characteristics do, it is always reasonable to start reduction of travel time by examining possibilities of reducing t_s through speeding up of station operations.

Since typical operating characteristics of street transit systems differ substantially from those typical for rapid transit, a separate diagram is plotted in the same manner for street systems, utilizing values in the last

two columns of Table 3.1. The diagram, shown in Figure 3.25, indicates that the relationships of parameters for street transit are the same as those for rapid transit, although their absolute values are usually quite different.

Although the preceding two diagrams are based on single sets of typical values, they can easily be developed for any other set. For analysis of a given service, the engineer should take the existing characteristics of rolling stock for the basic curve and then plot additional curves for individual improved values being considered. Computer programs for these computations and diagram plotting can easily be developed. Elaborate simulation programs for transit line operations—which include various line alignment elements (curves, gradients, speed reductions at some locations), signal operations and others—are based on these fundamental travel time equations.

Another type of travel diagram, showing speed as a function of distance, is more convenient for certain types of analyses than time-speed. Since this diagram

shows vehicle speed at any point along the way between stations, it allows programming of driving regimes along the line, analysis of braking distance, determination of signal locations, and so on. Figure 3.26 shows a typical distance-speed diagram for rapid transit combined with a plot of cumulative energy consumption below the abscissa. This combination diagram is used in examining the impact of various travel regimes on energy consumption. The figure shows three alternatives: (a) acceleration to a speed lower than $V_{\max}$ with coasting, (b) acceleration to $V_{\max}$ with coasting, and (c) acceleration to $V_{\max}$ without coasting. Dashed lines on the energy diagram show the cases for vehicles with regenerative braking.

3.6.4.2 Operating Speed as a Function of Station Spacing. It is sometimes more convenient to analyze travel speed on a line rather than travel time, since speed represents one of the basic system performance characteristics whereas travel time is always related to specific distances only.

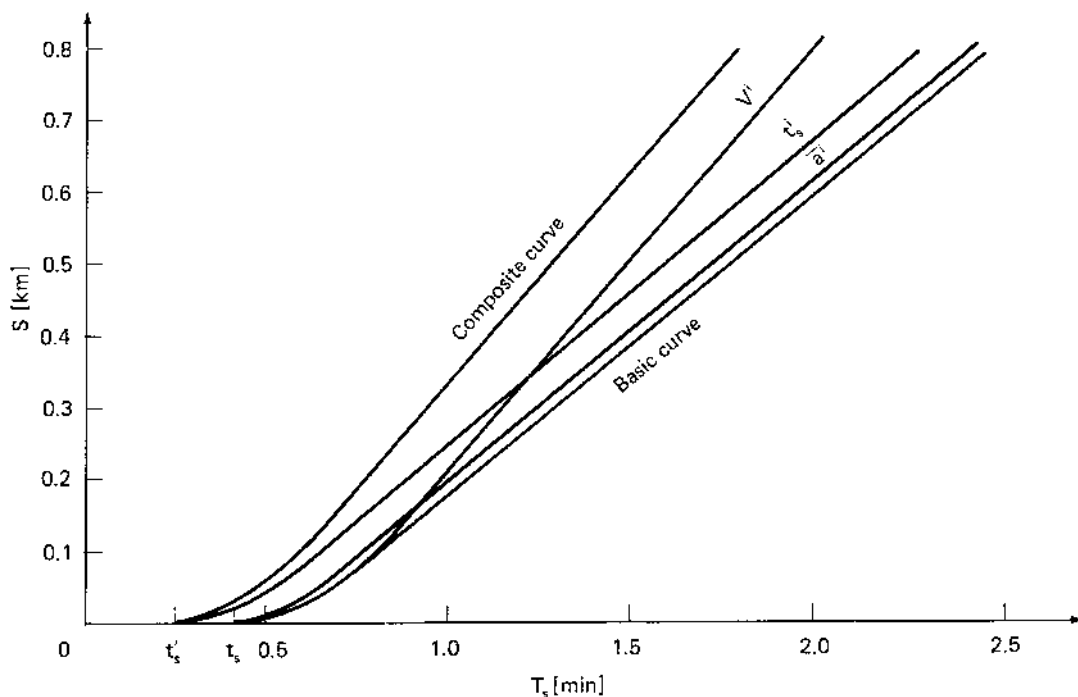


Figure 3.25 Sensitivity of travel time to individual parameters—street transit

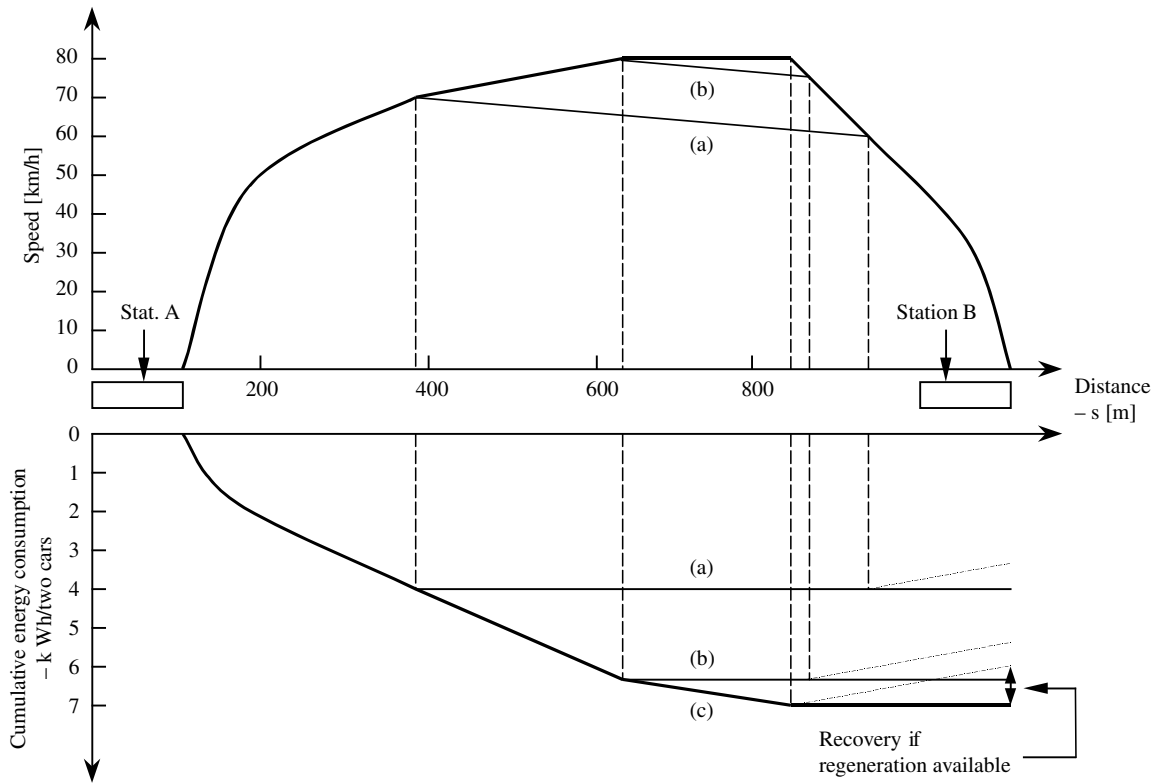


Figure 3.26 Distance-speed and distance-consumed energy diagrams for rapid transit (Hamburg rolling stock; Source: Mies, 1974)

Sets of curves similar to those in the preceding section are plotted in Figure 3.27. The parameters are the same as in the preceding diagram for rapid transit (i.e., as listed in Table 3.1), but the operating speed v_o is the dependent variable, defined as

$$v_o = \frac{s}{T_s}, \quad \left| \frac{v}{\text{m/s}} \right| \left| \frac{s}{\text{m}} \right| \left| \frac{T}{\text{s}} \right| \quad (3.59)$$

or, with dimensions more common in practice:

$$V_o = 3600 \frac{S}{T_s}, \quad \left| \frac{V}{\text{km/h}} \right| \left| \frac{S}{\text{km}} \right| \left| \frac{T}{\text{s}} \right| \quad (3.60)$$

interstation travel T_s being defined by Eq. (3.57) for $S < S_c$, and by Eq. (3.48) for $S > S_c$; S_c is defined by Eq. (3.41).

Figure 3.27 is particularly useful for the analysis of average parameters for overall performance of the whole line. For example, it is often an explicit goal to provide transit service with an operating speed of at least X (km/h). In that case this diagram would indicate various combinations of parameters that would provide such an operating speed. For any given interstation distance, a horizontal line for the desired value of V_o indicates which values of parameters would be required. However, for a combination of several partial improvements of the parameters, additional computation is necessary.

3.6.4.3 Special Diagrams for Individual Relationships. Although the preceding diagrams show a set of basic relationships of variables and parameters, there are cases in which a separate analysis of an in-

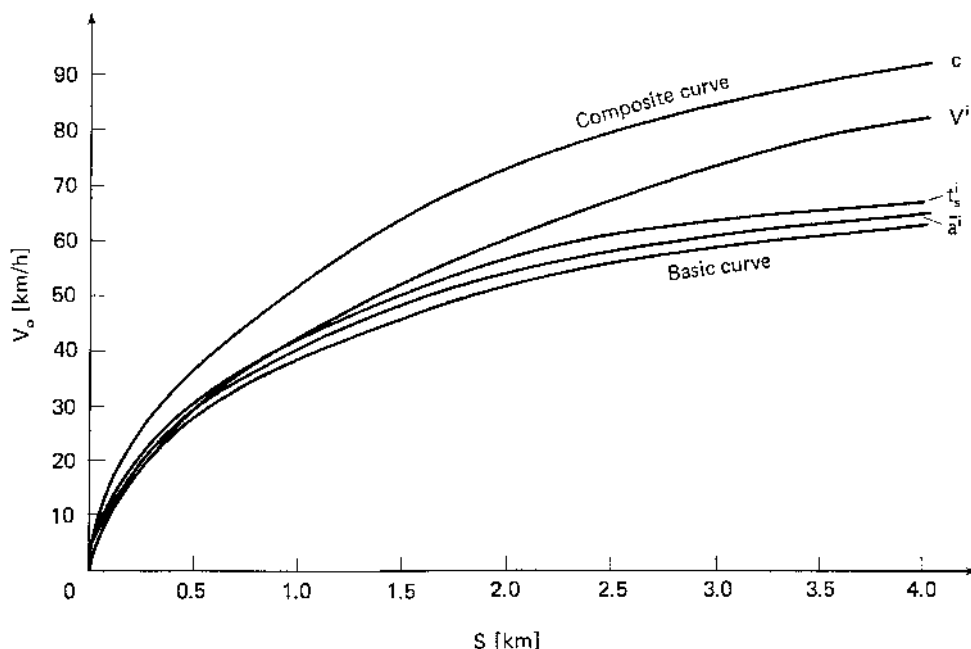


Figure 3.27 Sensitivity of operating speed to individual parameters—rapid transit

dividual system parameter performance characteristic must be made. There are numerous combinations of relationships that may be of interest in different situations. A diagram for one such relationship is given in Figure 3.28 as an example.

If it is necessary to assess the effectiveness of an increase of maximum technical speed of TUs for system performance, a diagram can be plotted for operating speed V_o as a function of maximum speed $V_{\max}$ for several values of interstation distance S , assuming constant values of a , b , and t_s . Such a diagram, based on the values in the second column of Table 3.1 and distances of 400, 800, 1200, and 1600 m, is shown in Figure 3.28. Equation (3.60) is used again, but the independent variable is $V_{\max}$ instead of S . T_s for this equation is computed again by Eqs. (3.40) and (3.48).

3.7 ENERGY CONSUMPTION AND EFFICIENCY

The most important factor determining unit energy consumption for transporting passengers (kilowatt-

hours or joules³ per person-km) for a given route is usually the vehicle occupancy (person-km/vehicle-km). Because of their high average occupancies, transit modes generally have a considerably lower consumption of energy per unit than do other modes, particularly the private automobile. Yet despite this inherent relative advantage over other modes, transit systems are large consumers of energy in absolute quantities. Therefore transit agencies must always be concerned with achieving the maximum possible energy efficiency in their operations. In addition to compliance with the national policy of energy conservation, every increase in energy efficiency can result in a substantial reduction of operating costs for the transit operator.

In many countries and particularly the United States, the energy efficiency of transit systems was seriously neglected during the 1950s and 1960s. How-

³The SI unit for energy is the joule, but the metric system unit, kilowatt-hour, is still predominantly used and better understood. For conversion from Btu to either kWh or J, see the conversion table in Appendix I.

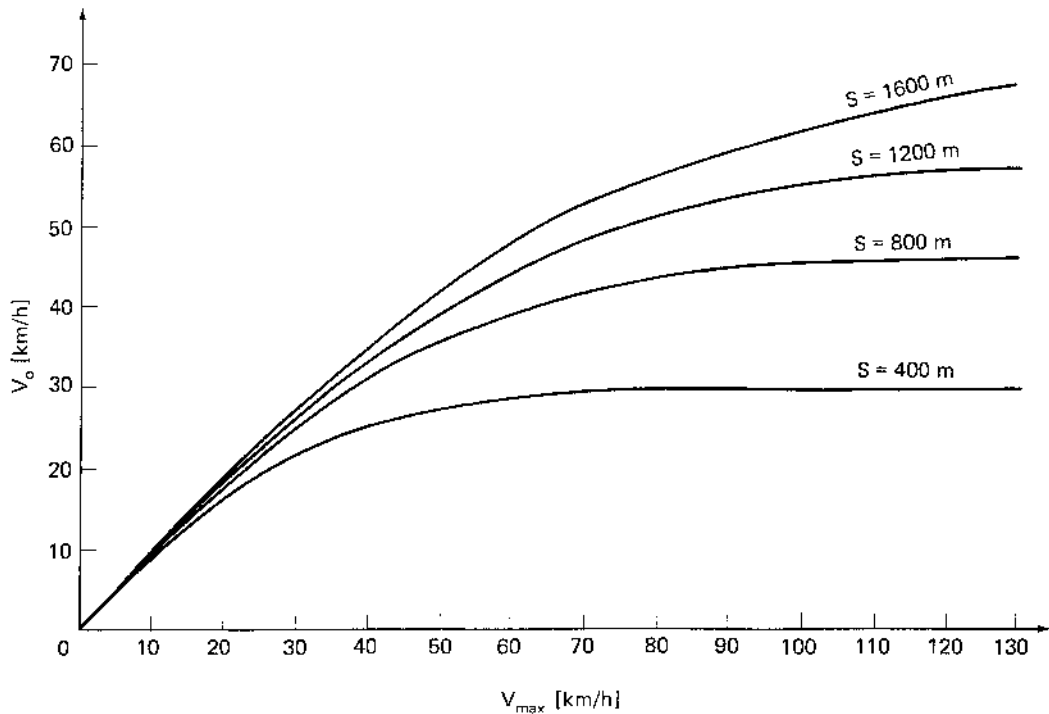


Figure 3.28 Influence of maximum speed and station spacing on operating speed

ever, recent systems have been built with more attention to energy consumption. Regardless, there are numerous ways in which the energy efficiency of existing systems can be substantially improved. Some improvements can be achieved in the short run (e.g., through changes in operations), while others require a longer time period (changes in rolling stock and infrastructure design).

Several very significant increases in energy efficiency of transit vehicles introduced in recent years are described elsewhere in this and other chapters. In Section 3.4 replacement of rheostatic by electronic control of electric motors starting from thyristor choppers, then introduction of GTO and IGBT is described. These changes have resulted in elimination of energy waste in resistors, reduced internal losses and, most significantly, introduction of regenerative braking on contemporary electrically powered transit vehicles.

Section 5 describes numerous innovations in bus vehicle designs through introduction of hybrid ICE/

electric vehicle propulsion. Similar hybrid propulsion systems are used on some regional rail systems, allowing vehicles to operate with electric as well as with ICE propulsion on different sections of their lines.

3.7.1 Structure of Energy Consumption Analysis

The great number of factors that influence the energy consumption of a transit system or mode can be classified into three general categories: vehicle characteristics, ROW characteristics, and operational aspects of the service.

Vehicle characteristics:

- Technology, particularly type of propulsion, control, and guidance (steered versus externally guided)

- Design features, such as specific weight of vehicle (kg/m^2), its seating/standing ratio, and various amenities (air conditioning being a major item)
- Vehicle capacity and its utilization, including acceleration rate, maximum speed, and method of braking
- Dynamic performance of vehicles, including acceleration rate, maximum speed, and method of braking
- Type of motor control (resistor, chopper, GTO, IGBT), transmission (gears) hybrid types of propulsion

Right-of-way characteristics:

- Technology features (type of guidance and support and related vehicle characteristics)
- Alignment, particularly route profile (grades)

Operational aspects:

- Scheduling (turnbacks, deadheading, etc.)
- Traffic conditions (for modes with ROW categories C and B)
- Station spacings and stopping policy (demand or all-stop, etc.)
- Local, accelerated, or express service
- Operating regime (applications of coasting, different braking rates, etc.) for modes with partially or fully separated rights-of-way

Vehicle and ROW characteristics usually cannot be significantly changed in the short run with one major exception. Vehicle capacity utilization can always be influenced, and it can have more effect on unit energy consumption than any other single factor. As Figure 3.29a shows conceptually, total vehicle energy consumption increases with the number of persons (although the relationship is not always linear). The unit energy consumption, obtained when the total consumption is divided by the values of the abscissa, is shown in part (b): it drops off nearly hyperbolically as passenger load increases.

In addition to increasing utilization of transit services, considerable reduction in both absolute and unit energy consumption can often be achieved through

various changes in operation. Such changes are often overlooked and their results underestimated.

3.7.2 Influence of Operating Regimes

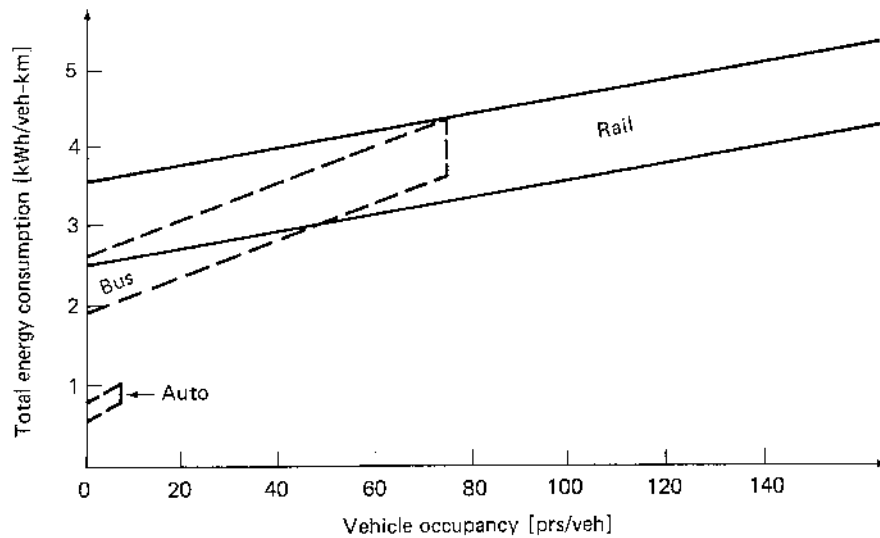
All operational improvement measures that increase the average operating speed of transit vehicles—such as the provision of separate lanes, preferential treatments, and less frequent stops—also result in reductions of their energy consumption. However, except for general sound driving practices, little can be done to significantly improve the energy consumption of vehicles with an ICE, such as a diesel bus, for given route and operational conditions. The typical fuel efficiency of transit buses on urban streets is between 1.3 and 2.1 km/L (3 and 5 mi/gal).

With electrically powered guided modes, primarily RRT, there is a much greater control over the driving regime (acceleration, coasting, etc.). The control is achieved either by careful driver training and close monitoring of their performance on the line, or by ATO (see Section 6.6.1). Each of the basic station-to-station travel regimes has technical and operational variations that influence energy consumption. These variations are shown in Figure 3.30.

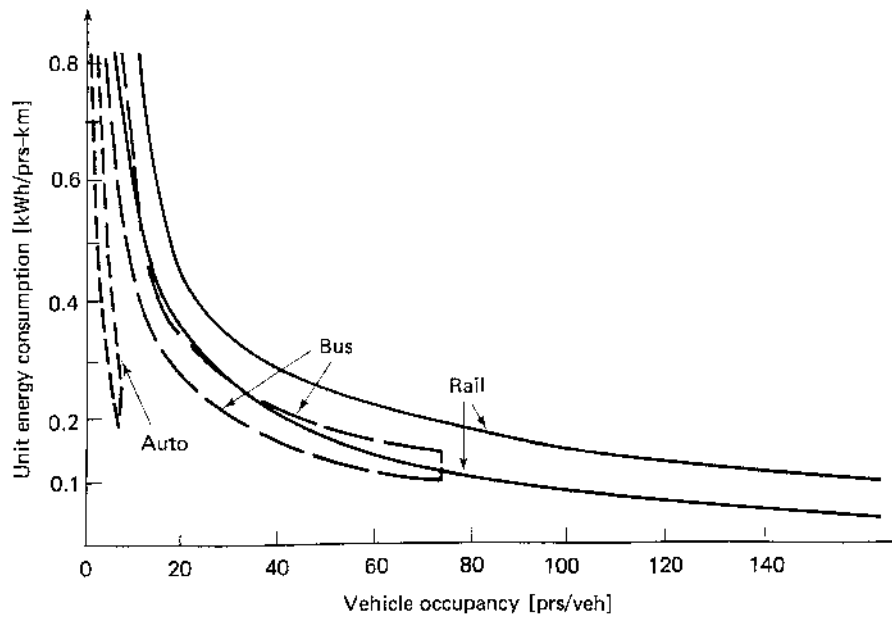
The *acceleration phase* can produce different energy consumption curves, depending on the types of motors and their control. Two typical cases are shown as curves 1 and 2 in part (b). For any given vehicle design, this curve is fixed and often automatically controlled during the acceleration regime.

Constant speed and coasting regimes are shown in both parts (a) and (b) by lines 3 and 4, respectively. They represent a direct trade-off between a higher top speed under full power (3) and energy saving with coasting (4). Most U.S. rail systems use alternative 3, introduced during the years of very cheap energy. Most European systems utilize alternative 4 as a standard driving method, based on the decision that a few seconds of longer travel on moderately long station spacings are worth sacrificing for the very significant amount of saved energy.

Braking methods, conventional or regenerative, are shown by lines 5 and 6 in part (b). Conventional brak-

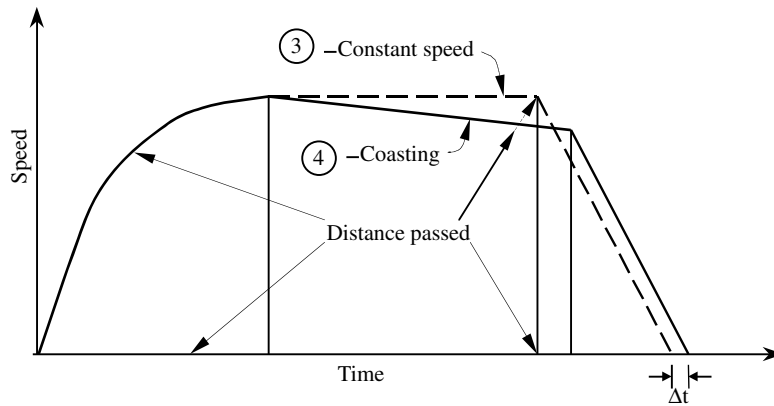


(a) Total energy consumption per vehicle-km

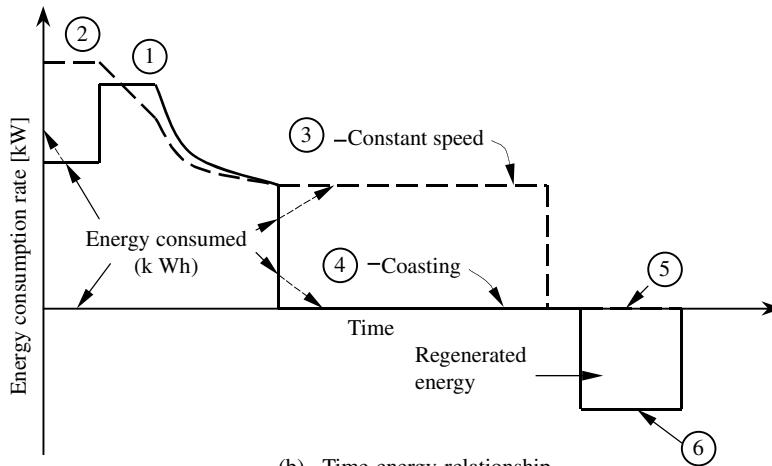


(b) Energy consumed per person-km

Figure 3.29 Energy consumption as a function of vehicle occupancy



(a) Time-speed relationship



(b) Time-energy relationship

Figure 3.30 Different station-to-station travel regimes affecting energy consumption of electric rail transit vehicles

ing (line 5)—dynamic or pneumatic—has no influence on energy consumption except that the power produced by dynamic braking is often used for vehicle heating or reducing the rolling stock's auxiliary power consumption. Regenerative braking (6), used by most recently built vehicles with electronic control, results in a “negative consumption” (i.e., “returning” of some power into the power lines).

The three sets of alternatives are not, of course, related to each other: either one of the two acceleration energy curves may be applicable to vehicles that use any one of the alternatives in the two latter regimes.

3.7.3 Potential Energy Savings through Preprogrammed Driving

The importance of different driving regimes for energy consumption is clearly demonstrated by the interesting empirical and computer simulation studies of Hamburger Hochbahn AG in Hamburg, reported by Mies (1974, 1969). Conditions of the study were as follows: rolling stock with conventional braking; variations in energy consumption due to different durations of the acceleration interval; coasting as long as schedule time permits; constant speed under power not used, since it was considered uneconomical under all conditions.

The time-speed-energy consumption diagram in Figure 3.31a shows that accelerating to $V_{\max}$, then coasting and braking to the next station (regime I), results in the highest energy consumption and the shortest travel time. Regimes II and III have lower energy consumption and longer travel times. The resulting trade-off between energy and travel time is plotted in Figure 3.31b. The scheduled travel time cannot be the shortest one because some reserve is needed for maintaining a reliable schedule. The diagram shows that, compared with the selected scheduled time of 69 s, the shortest time (63 s) would require 40% more energy, while an additional 23% of energy could be saved if travel time were extended by another 8 s.

The two diagrams in Figure 3.32 show other influences of travel regime on energy consumption. Part (a) shows that with preprogrammed travel, variations in station standing time, t_s , can be corrected through the selection of an appropriate travel regime, always ensuring the minimum energy consumption for that particular travel time. Part (b) shows that for a given travel time, higher deceleration rates in braking can be used to shorten the acceleration interval and thus reduce energy consumption.

The substantial percentage differences in energy consumption in all these cases show that the choice of the optimal travel regime can result in very significant energy savings. Since the “net” energy, that utilized for vehicle traction, is considerably smaller than the “gross” energy that must be produced for it (the difference is caused by various transmission losses, drive train losses, etc.), each saving in traction energy means even greater total energy savings at the generating source.

3.7.4 Influence of Stop/Station Spacing

The analyses in the previous section were all based on a fixed station spacing. Because acceleration consumes most of the energy used in travel, energy consumption can be reduced by increasing stop or station spacing, resulting in fewer accelerations. This is significant for the design of new lines for all modes. It is also significant for the periodic reexamination of stop location for street transit lines where stops have little fixed in-

frastructure that prevent them from being moved. It can be seen from Figure 3.33 that reducing the number of stops on a bus line can have significant impacts on energy consumption. Stop reduction or consolidation on lines with stops at every intersection, an obsolete practice in many North American cities, also has other beneficial operational impacts. For discussion of this topic and for selection of optimal stop spacings as a function of passenger volume see Vuchic (2005), Chapter 2.

3.7.5 Measures of Energy Consumption

The amount of energy used per unit of output represents a measure or indicator of *energy consumption*. Its inverse, quantity of output per unit of consumed energy, is referred to as *energy efficiency* of a transportation system. Energy consumption can be based on different units of output, but the most characteristic ones are the following four.

Kilowatt-hours/vehicle-kilometer can be most directly measured in transit system operation. It is useful for comparison of vehicles with similar capacities and performance characteristics or of the same vehicle types under different operating conditions (alignments, station spacings, traffic conditions).

Kilowatt-hours/ton-kilometer can be used for the same purposes as the preceding indicator, but it eliminates influences of different vehicle weights.

Kilowatt-hours/space-kilometer is the basic indicator of energy consumption per unit of offered service. This is the most important indicator of energy consumption of a mode under full-capacity utilization. For transit systems, this unit shows the extreme values to which energy consumption can be reduced (or efficiency of energy utilization increased) when maximum utilization is achieved; thus it represents the maximum potential energy efficiency of modes.

Kilowatt-hours/person-kilometer represents the energy consumption actually achieved with a given level of system (or vehicle) utilization.

The measured quantity of consumed energy can also refer to several different items. Energy consumption for vehicle travel represents the amount used directly for transport. In addition, system consumption

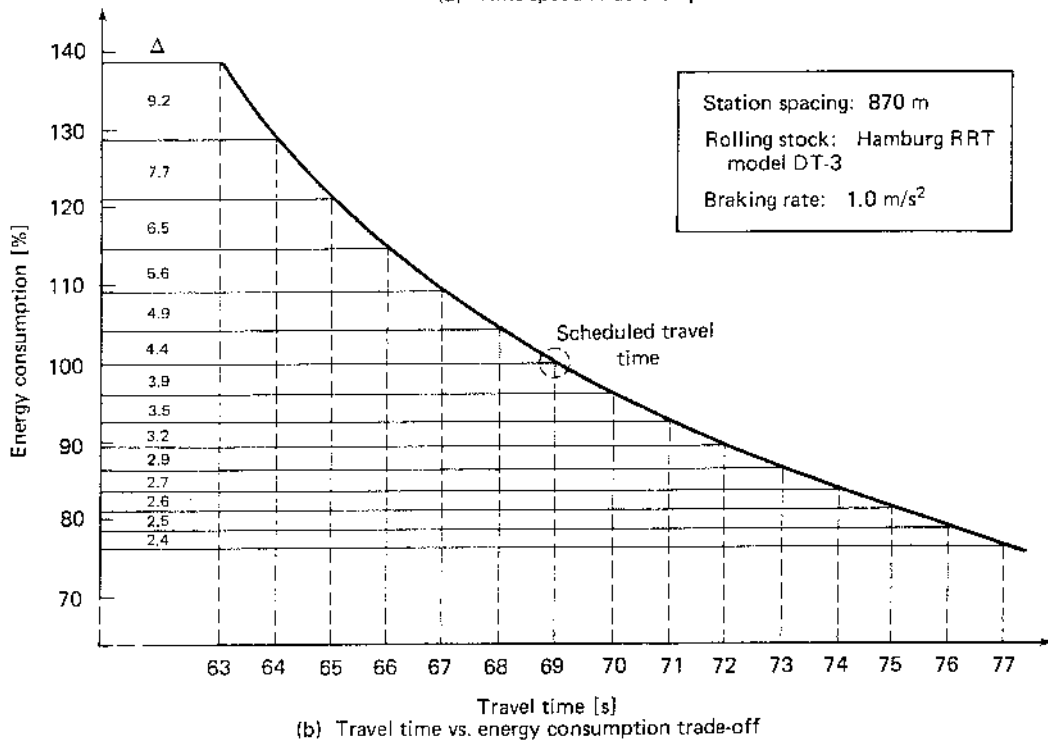
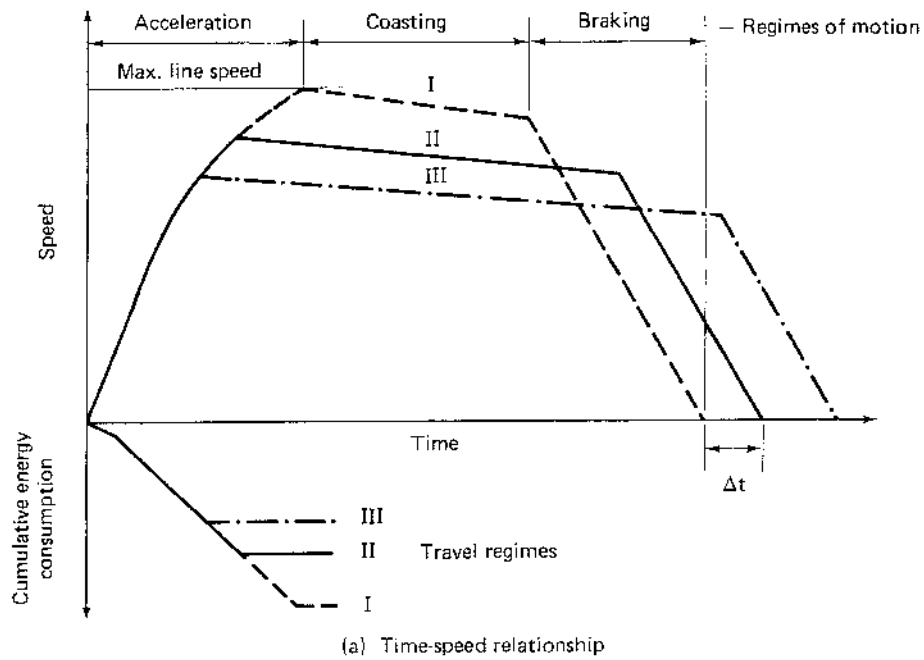


Figure 3.31 Trade-off between energy consumption and travel time as a result of variations in acceleration-coasting intervals (Source: Mies, 1969)

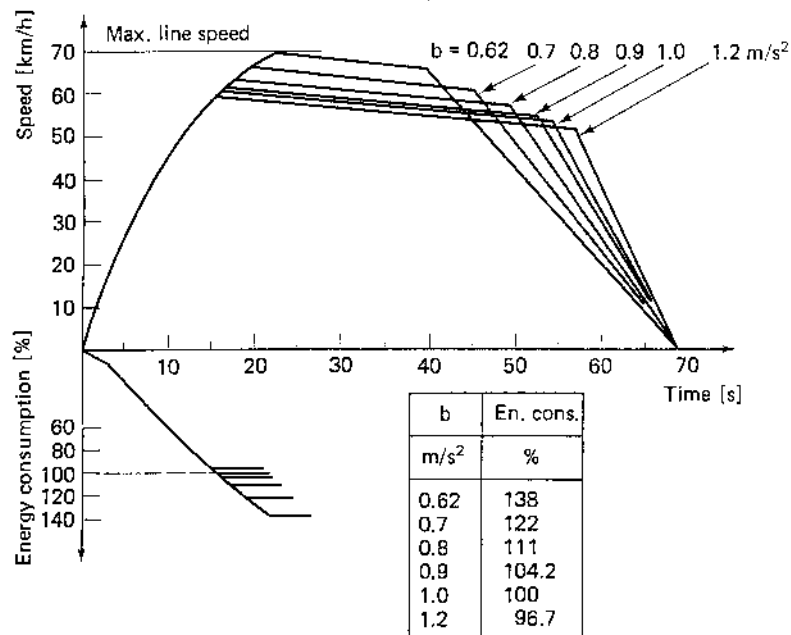
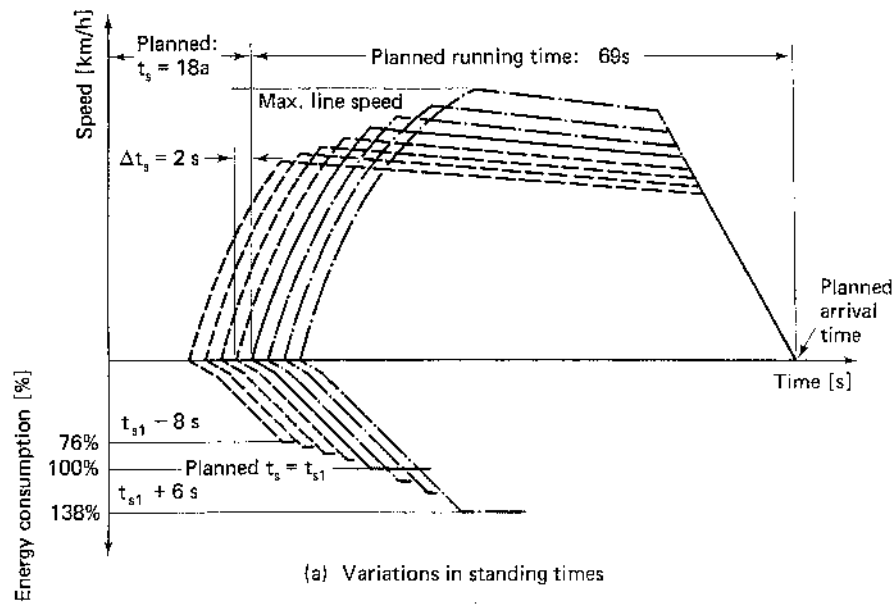


Figure 3.32 Variations in travel programs and energy consumption for a constant total station-to-station time
(Source: Mies, 1969)

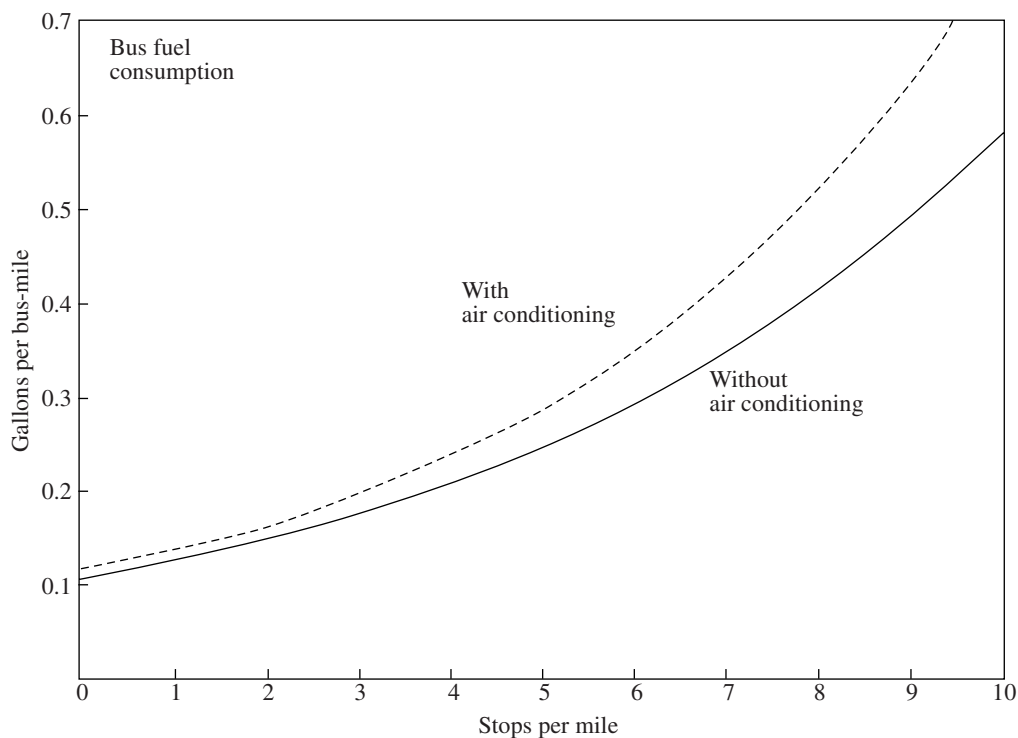


Figure 3.33 Bus fuel consumption as a function of stop spacings (Source: Raus, 1981)

includes the energy used by fixed facilities (for transit, stations, yards, signals, etc.; for auto, highways, streets, parking facilities, and others), and by supporting functions (vehicle maintenance, cleaning, inspection, etc.). Both of these categories represent “net” consumption (i.e., the actually utilized energy).

The total, “gross” energy consumption represents the energy used to produce the “net” utilized energy. For electric traction, the difference between the two includes the losses in electricity generation, in transmission, pickup by vehicles along the line, and others. For ICE-powered vehicles, the losses occur in fuel refinery processes, transportation of fuel from oil wells via refineries to the pumps, and others. To convert net into gross consumption, the net amounts must be divided by efficiency factors of each one of the processes mentioned between the original sources and the points of consumption, such as energy conversion, refining,

transportation, and distribution. Such analysis is often referred to as well-to-wheels analysis.

Since the unit energy consumption of different modes is also a function of vehicle performance, it is important to compare consumptions of vehicles with similar performance characteristics, primarily acceleration rates and maximum speeds, or consumptions of different modes with similar station spacings and average operating speeds. Otherwise, each system or mode must be evaluated by its energy consumption/performance relationship. Thus the transit mode with minimum energy consumption per some unit of output is not necessarily the best. Its performance, which affects user benefits and passenger attraction, must also be compared with the corresponding characteristics of other modes. Additionally, as technology progresses, energy consumption typically decreases from one vehicle generation to another. Thus equal levels of tech-

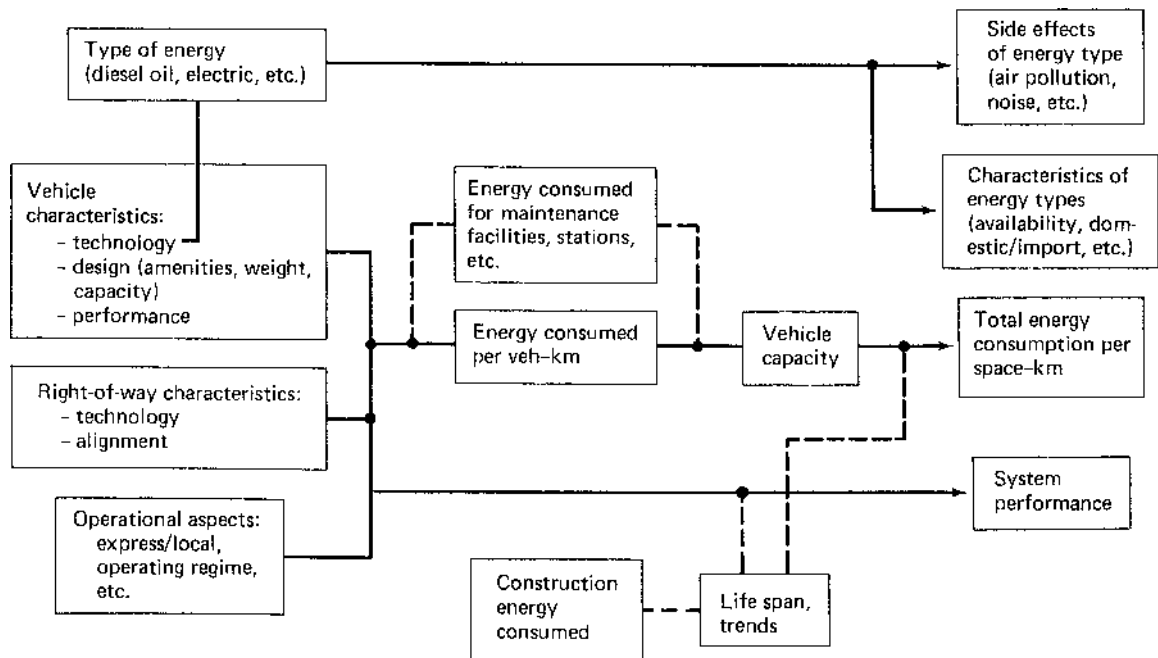


Figure 3.34 Conceptualization of a procedure to evaluate transit system energy characteristics

nology should be used in making comparisons. For example, a new BRT line should not be compared for energy consumption to a rail line with 30-year-old rolling stock.

Two additional factors must also be considered in energy consumption analyses: (1) side effects of consumption of each type of energy, such as production of air pollution, dirt, and noise (electricity is typically superior to other energy forms in all these respects), and (2) characteristics of each energy type in terms of its primary source availability, desirability of use, domestic versus imported supplies, and so on.

The passenger attraction capabilities of different modes are also relevant. The ability of a transit mode to attract passengers from high-energy modes, such as single occupancy vehicle (SOV) automobile, might offset higher energy consumption as compared with a mode or operating regime with a lower ability to attract passengers. While out of the scope of most analyses, land-use impacts are also relevant.

A systematic overview of relationships among the discussed major factors in transit system energy consumption is given in Figure 3.34. The long-range impacts of different modes on energy consumption, another major element giving advantage to transit over auto, is not included in this analysis. That aspect is discussed elsewhere (see, e.g., Section 6.7.5).

A set of precise, simple numbers of energy consumption by different modes cannot be presented because of great variety of influencing factors. But for general orientation, typical value ranges of energy efficiencies of several major modes are presented in Table 3.2. The values encompass most cases, but special conditions may create atypical values.

The figures in the table show that even at off peak times, *transit modes generally have several times greater energy efficiencies than automobiles*. The difference is amplified during peak periods. It is pointed out that these are only single values for illustration: they vary considerably and should therefore not be

Table 3.2 Energy efficiencies of different urban transport modes

Mode	Vehicle Capacity (sps/veh)	Vehicle Occupancy (prs/veh)	Common Units of Effic./Consump. (veh-km/ℓ)	Energy Efficiency ^a	
				(veh-km/kWh)	(prs-km/kWh)
Standard auto	5	1.2–2.8	3.8–6.0	1.04–1.64	1.2–4.6
Compact auto	4	1.2–2.8	7.2–8.1	1.96–2.20	2.4–6.2
Carpool	6	2.0–6.0	3.8–6.0	1.04–1.64	2.1–9.8
RB	45–70	10–70	1.3–2.2	0.35–0.60	3.5–42
			(kWh/veh-km)		
TB	45–70	10–70	2.2–4.1	0.24–0.46	4.6–32
SCR/LRT	80–200	15–200	1.6–5.1	0.20–0.62	2.9–125
RRT: old systems	130–180	20–180	2.2–3.7	0.27–0.46	5.4–82
RRT: new systems	150–200	25–200	3.5–5.1	0.20–0.29	4.9–57

^aBased on the following conversion factors: 1 ℓ of diesel fuel = 3.67 kWh (= 38,500 Btu = 0.2642 gal).

Table 3.3 Fuel life-cycle energy consumption for different urban transport modes, peak and off-peak operations

Mode	Energy Consumption (MJ/seat-km)	Peak Travel		Off-Peak Travel	
		Assumed Occupancy (%)	Energy Consumption (MJ/p-km)	Assumed Occupancy (%)	Energy Consumption (MJ/p-km)
Urban electric train	0.39	60	0.65	25	1.56
Urban diesel train	0.50	60	0.83	25	2.00
Light rail	0.18	70	0.25	40	0.45
Metro	0.22	70	0.31	40	0.55
Single-deck bus	0.29	50	0.58	20	1.45
Double-deck bus	0.22	50	0.44	20	1.10
Minibus	0.36	70	0.51	20	1.80
Medium-sized car	0.70	23	3.04	40	1.75

Source: Potter, 2003.

used for any specific situation or as exact overall mode comparisons. Moreover, performance differences among these modes should also be evaluated in any given situation. Finally, these are average values; for passengers *added* to an existing transit service, marginal energy consumption is usually much lower, often negligible. Increasing transit ridership is therefore extremely effective for reducing energy consumption: it takes place in the high ranges of mode energy efficiencies, in which transit's advantage over auto is the greatest.

Measurements and comparisons of energy consumption by different modes of urban transportation vary greatly with respect to definitions of modes,

assumptions about their operations and methods of obtaining data. Thus, Table 3.2 presented energy efficiencies and consumption of different modes in typical urban situations. In Table 3.3, only consumption is given with single values. Although there are sets of values for peak and off-peak travel, single values make this information greatly dependent on specific assumptions made in estimations.

It should be borne in mind that all these energy consumption estimates refer to direct consumption by transportation modes. However, in the longer run, energy consumption is also heavily influenced by the urban form and intensity of land use activities, which are, in turn, strongly dependent on the composition of

modes used. For this reason, advantage of transit over automobile in energy efficiency is even greater in the long run. The relationship of urban density on total

energy consumption has been analyzed in considerable depth by Newman and Kenworthy (1998).

EXERCISES

- 3.1.** Draw a typical curve for bus resistance under normal conditions as a function of speed and designate it as R_o . Explain which factors in the resistance equation would be affected by each of the following changes:
- Vehicle's body streamlining is improved
 - Headwind appears (wind opposite to vehicle movement)
 - Downhill gradient
- Draw general shapes of the resistance curve for each one of these changes and designate them as R_a , R_b , and R_c , respectively.
- 3.2.** List the factors in the resistance equation for rail vehicles (Eq. 3.12) that are affected by the following differences on a rapid transit line and describe how they are changed.
- Old, poorly maintained track is improved and jointed rails are replaced by welded ones.
 - Train runs in a tunnel versus on an aerial structure.
 - Small versus large cross-sectional vehicle profile (e.g., "Tube" versus "Underground" rolling stock in London).
- 3.3.** A bus with weight $G = 100$ kN and $p = 1.06$ runs on an expressway at 80 km/h, then arrives at a 2% uphill grade. Its resistance on 2% grade and tractive effort curves in the highest gear have the following values for the high-speed range:

Speed (km/h)	55	60	65	70	75	80
Resistance (N)	2400	2500	2625	2800	3000	3300
Tractive effort (N)	2700	2800	2825	2800	2750	2700

What will be the acceleration or deceleration rates of the bus under the following conditions:

- At the beginning of the uphill section, when the bus still runs at 80 km/h and the driver applies maximum tractive effort (maximum pressure on accelerator) in the highest gear.
 - The bus travels at 70 km/h and the driver applies 90% of the maximum tractive effort.
 - The bus had reduced its speed to 60 km/h and the driver applies maximum effort to accelerate it to the balancing speed.
- 3.4.** As a planning engineer of a transit company, you must examine adequacy of a bus model for service on different lines of the system. You have the following data. Motor performance curve is plotted by connecting the following points:

N	800	1200	1600	2000	2400
P	80	130	160	180	200

The motor is governed so that $n_{\max} = 2400$ rpm. Gear and differential transmission ratios are:

$$u_1 = 4.43:1$$

$$u_2 = 2.48:1$$

$$u_3 = 1.49:1$$

$$u_4 = 1:1$$

$$w = 4.768:1$$

Coefficient of losses: $\eta = 0.88$.

The vehicle:

$$G = 110 \text{ kN} \quad c_1 = 8.0\% \quad \rho = 1.10$$

$$D = 0.90 \text{ m} \quad c_2 = 0.06\% \cdot \text{h/km}$$

$$A = 7.6 \text{ m}^2 \quad c_a = 0.025 \text{ N} \cdot \text{h}^2/(\text{m}^2 \cdot \text{km}^2)$$

The bus has 45 seats and room for 35 standees; the average passenger weight is assumed to be 760 N.

- a) Find, from the $TE, R = f(V)$ diagram, the maximum speeds of the bus on the following gradients: $i = 0, 2.5$ and 5% , assuming that all seats on the bus are occupied but there are no standees.
 - b) Compute the balancing speed of the full bus (seated and standing passengers) on a 2.5% downhill grade without the influence of motor or brakes.
 - c) Compute the maximum acceleration rate that the bus will be able to achieve when it travels at 14 km/h on a 2.5% uphill gradient, all seats occupied.
- 3.5. Suppose that a diesel bus and a trolleybus have the same bodies. The diesel engine is rated at 175 HP and the electric motor at 125 kW (both are effective, i.e., at the wheels). If the loadings and terrain are the same, which of the two vehicles would have a higher maximum acceleration rate? (Note: $1 \text{ kW} = 1.36 \text{ HP}$).
 - 3.6. Describe electric (dynamic) braking on electric vehicles: explain the basic physical principles (how is the braking obtained) and its operational characteristics, such as effectiveness at different speeds, wear and tear of the equipment as compared to friction braking, impact on skidding incidences.
 - 3.7. Define regenerative braking and its characteristics in comparison with friction braking. How has the invention of chopper and inverter control influenced the use of regenerative braking? How does regenerative braking influence power consumption?
 - 3.8. Compare electronic motor control (chopper/inverter, GTO and other versions) with rheostatic braking.
 - 3.9. Compare electric with diesel propulsion. Based on that comparison, specify physical or operating factors that favor electric propulsion over diesel.
 - 3.10. a) Compute braking and stopping distances for a bus assuming the following data: $t_r = 1 \text{ s}$; $b = 1.4 \text{ m/s}^2$; $V_i = 32 \text{ km/h}$.

- b) What would be the shortest possible braking and stopping distances on a 2% downhill grade if $\mu = 0.3$? What would be the average braking rate b ?
- c) A trolleybus with two-thirds of its weight on the rear axle, operating on a 3% uphill gradient in rainy weather, can achieve an acceleration rate of $a = 3 \text{ m/s}^2$ before its wheels begin to spin. What is then the value of μ ?
- 3.11. a)** What is the maximum acceleration rate a rapid transit train with all axles powered can achieve on a gradient $i = 2.8\%$ if $\mu = 0.22$ provided that its tractive effort is not a limiting factor?
- b) A six-axle articulated LRT vehicle with a total weight of 24 t traveling on a level track with $\mu = 0.18$ applies brakes on all its axles to the maximum prior to skidding. What deceleration rate can it achieve, and what is its braking distance from $V_i = 40 \text{ km/h}$? Would an additional passenger load increase or decrease its braking distance?
- c) In an emergency, the vehicle in part (b) applies not only braking via wheels but also its magnetic track brakes (two per truck), each one exerting 2 t of magnetic force. How much shorter will the braking distance from $V_i = 40 \text{ km/h}$ be in comparison with part (b)?
- 3.12.** (Closed book) Plot a typical composite diagram of speed v , acceleration a , and jerk z as functions of time t for an electrically powered vehicle traveling from one station to another.
- 3.13.** Assume an interstation spacing S greater than the critical distance S_c and draw a $V = f(t)$ diagram for an electric transit vehicle under the regime that minimizes travel time. Then draw the same diagram for a travel regime that minimizes energy consumption. Draw the diagrams of energy consumption for the two regimes below, assuming the vehicle has regenerative braking. Show on the diagram the trade-off between travel time and energy consumption for the two travel regimes and explain.
- 3.14.** A rapid transit vehicle manufacturer produces two types of vehicles that have different dynamic characteristics and door/capacity ratios, so that their specifications are:

	Model I	Model II
$V \text{ (km/h)}$	80	110
$a = b \text{ (m/s}^2\text{)}$	1.0	0.8
$t_s \text{ (s)}$	15	22

Assuming that trains accelerate to V and maintain that speed until braking must be applied, compute the interstation distance, which is the boundary between the optimal applications of the two models on the basis of the shorter travel time. Plot the $T_s - S$ diagram for the two models and show the optimal region for each one.

- 3.15.** Six-car RGR trains running between two stations with a distance of 2000 m accelerate to $V_{\max} = 100 \text{ km/h}$ on a distance $s_a = 600 \text{ m}$. From the moment $V_{\max}$ is reached, two alternative regimes are possible:
- a) Maintain $V_{\max}$ until braking must be applied.
- b) Coasting is immediately used ($c = 0.1 \text{ m/s}^2$) and maintained until braking must be applied.

Assuming that in both cases braking rate is $\bar{b} = 1.0 \text{ m/s}^2$ and that energy consumption during $V_{\max}$ travel is $e = 3 \text{ kWh/veh-km}$, compute the trade-off between the two regimes: energy saved per train, ΔE (kWh), versus additional travel time, Δt (s), which case (b) involves in comparison with case (a).

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4

TRANSIT SYSTEM PERFORMANCE: CAPACITY, PRODUCTIVITY, EFFICIENCY, AND UTILIZATION¹

Transit system performance consists of a number of quantitative and qualitative elements referred to as “attributes,” “measures,” or “indicators.” This chapter presents definitions and analyses of selected quantitative measures, introducing some new concepts and indicators of transit performance. The definitions given here are consistent with the definitions of basic concepts in physics, engineering, and economics, but they are tailored specifically for transit system operations and service. They are an extension of brief definitions in Section 2.1.4.

The first part of this chapter, Section 4.1, presents definitions of the basic elements and performance measures of a transportation process, such as objects, distance, work, and productivity. These definitions apply not only to urban transit but also to any other transportation system, such as passenger and freight, short- and long-distance, highway, rail, or air modes. That is followed by a major part of this chapter (Sections 4.2 to 4.5) devoted to capacities (both line capacity and productive capacity) of transit modes. The last part of the chapter, Section 4.6, focuses on other performance indicators—such as volume of transportation, work, productivity, efficiency, consumption rates, and utilization—often used in measuring transit system performance.

4.1 DEFINITIONS OF QUANTITATIVE PERFORMANCE ATTRIBUTES

4.1.1 Basic Attributes

At an elemental level, transportation is defined as the movement of a number of *objects* (u) over a *distance* (s) during an elapsed interval of *time* (t). “Objects” may be persons, goods, units of vehicle capacity (spaces, tons), vehicles, or trains consisting of several vehicles (transit units, or TUs). When a number of objects are transported over a single path or line, ratios of those three elements (u , s , and t) define basic performance attributes of that transportation system process or the service it provides. Those attributes are:

$$\text{Speed: } v = \frac{s}{t}; \quad \text{Slowness: } v^{-1} = \frac{t}{s}; \quad (4.1)$$

$$\text{Density: } k = \frac{u}{s}; \quad \text{Spacing: } s_s = \frac{s}{u}; \quad (4.2)$$

$$\text{Frequency: } f = \frac{u}{t}; \quad \text{Headway: } h = \frac{t}{u}. \quad (4.3)$$

Most of these attributes are used extensively in describing transit systems and their service. Several different speeds (running, operating, commercial, and others) are used in scheduling operations (see Vuchic 2005, Chapter 1), vehicle design, and so on. Slowness, which represents travel time required to pass a unit distance, is not commonly used. Density of vehicles is

¹Symbols used in Chapter 4 are defined on the following page (see Table 4.0).

Table 4.0 List of Symbols

Symbol	Unit ^a	Definition
a	m/s ²	Vehicle acceleration rate
A_g, A_n	m ² /veh	Gross and net vehicle floor areas, respectively
A_l	m ² /veh	Vehicle floor area not used ("lost") for passengers
B	m/s ²	Vehicle braking rate
b_e, b_n, b_r	m/s ²	Emergency, normal, and reduced braking rates, respectively
c	veh/h	Vehicle line capacity
c_s, c_w	veh/h	Vehicle station and way capacities, respectively
C	sps/h	Line capacity
C_s, C_w	sps/h	Station and way capacities, respectively
C_o	sps/h	Operating capacity
C_p	prs/h	Utilized line capacity
c_v	sps/m ²	Vehicle capacity coefficient
C_v	sps/veh	Vehicle capacity
D	m	Signal block length
F	TU/h	Frequency
H	s/TU	Headway
h_s, h_w	s/TU	Station and way headways, respectively
h_p	s/ptn	Average headway between TU platoons
k	veh/km	Traffic flow density
K	—	Safety factor, b_n/b_r
l, l'	m/veh	Vehicle length: body and over couplers or bumpers, respectively
m, m'	sps/veh	Number of seats and standing spaces in a vehicle, respectively
n	veh/TU	Number of vehicles per TU
N	veh	Number of vehicles on line
p_a, p_b	prs/TU	Number of alighting and boarding persons per TU, respectively
P	prs/h	Actual passenger volume
P_c	sp-km/h ²	Productive capacity
P_L, P_v	sp-km/veh-h	Line and vehicle productivity, respectively
q	TU/ptn	Number of TUs per platoon
s	m	Distance
s_g	m	Distance between successive TUs (gap)
s_b, s_d	m	Braking and stopping distances, respectively

Table 4.0 (continued)

Symbol	Unit ^a	Definition
s_o	m	Distance between stopped TUs
s_r	m	Distance passed during t_r
s_s	m/TU	Distance between corresponding points of successive TUs (TU spacing)
S	m	Station spacing
S_c	m	S on which $V_{\max}$ is just reached
t	s	Time
t'_a	s	Acceleration time to clear platform
t_r	s	Reaction time
t_s	s	Station standing time
TU	—	Transit unit, vehicle or train
u	—	Number of transported objects
v	m/s	Speed
v^{-1}	s/m	Slowness
v^*	m/s	Optimal speed for maximum capacity
V	km/h	Speed
V_c	km/h	Commercial speed
V_o	km/h	Operating speed
w	prs × km, sps × km	Transportation work
W	veh × km, TU × km	Transportation work
α	prs/sp	Load factor or coefficient of capacity utilization
$\bar{\alpha}$	prs-km/sp-km	Work utilization coefficient
γ	—	Terminal time/operating time
δ	—	Line capacity utilization coefficient
η	—	Operating personnel utilization coefficient
λ	prs/s	Boarding rate
μ	prs/s	Alighting rate
ξ	—	Vehicle area utilization factor
π	sps/m	Linear vehicle capacity
ρ	m ² /sp	Area per seat
σ	m ² /sp	Assumed area per standee

^aLess common abbreviations: prs = persons; ptn = platoon; sps = spaces.

used in analysis of highway traffic flow, while “static density” of passengers can be applied to vehicle capacity analysis (see Section 4.2.2). Spacing is an important concept in analyzing the flow of vehicles and safety from vehicle collision (braking and stopping distances, for example). Frequency and its inverse, headway, are the basic elements for scheduling. They are also determinants of capacity, one of the most important modal characteristics and the major subject of this chapter.

Generally speaking, capacity represents the maximum frequency with which some objects can be transported on a line. The objects or units in the case of transit can be persons (passengers), passenger spaces (seats and standing spaces), vehicles, trains, or several others. Each unit creates a different type of capacity, as will be shown in Section 4.2; when only the term “capacity” is used, it will refer to the “offered capacity,” the maximum number of spaces transported on a line past a fixed point during one hour.

4.1.2 Transportation Work and Productivity

Transportation work (w) is the quantity of performed movement. It is computed as the number of transported objects multiplied by the distance over which they are carried:

$$w = u \cdot s. \quad (4.4)$$

Work is one of the basic measures of a transportation system output. It is usually measured on an annual basis, but sometimes its amounts on daily or hourly basis are also used. Like capacity, transit work can be expressed in several different units, such as person-, space-, vehicle-, or train-km.

Work performed per unit time represents productivity in its basic definition. Several other concepts of productivity are used to describe transit system performance and efficiency. These measures are particularly useful for comparative analysis of different transit systems or modes.

Vehicle productivity P_v is the work a vehicle performs per unit time during revenue service. Using a

common unit for transported “objects”—spaces (persons can also be used)—it is computed as:

$$P_v = C_v \cdot V_c, \quad \left| \frac{P_v}{\text{sps-km/veh-h}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{V}{\text{km/h}} \right| \quad (4.5)$$

V_c being commercial speed, or average vehicle travel speed, including standing at stations and terminals.

Line productivity P_L is the product of vehicle productivity and number of vehicles operating in revenue service on a line, N :

$$P_L = N \cdot P_v = N \cdot C_v \cdot V_c \quad \left| \frac{P_L}{\text{sps-km/h}} \right| \left| \frac{N}{\text{veh}} \right| \left| \frac{P_v}{\text{sps-km/veh-h}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{V_c}{\text{km/h}} \right| \quad (4.6)$$

Productive capacity P_c of a transit line is the product of its capacity and operating speed (i.e., average travel speed from one terminal to the other):

$$P_c = C \cdot V_o, \quad \left| \frac{P_c}{\text{sps-km/h}^2} \right| \left| \frac{C}{\text{sps/h}} \right| \left| \frac{V_o}{\text{km/h}} \right| \quad (4.7)$$

Since line capacity alone, without consideration of speed, can often be misleading as a system performance measure, the concept of productive capacity is very useful: it incorporates line capacity (a quantity of output and a concern of the transit operator) and speed (a quality of service and primarily a concern of passengers). An application of this concept was demonstrated in the comparisons of modes in Chapter 2.

The transit performance measures and concepts defined up to now are presented graphically in Figure 4.1. The six basic performance attributes are in elliptical frames; work and productivity are in rectangular boxes. Vehicle and line productivities are not shown separately because they have the same basic dimensions.

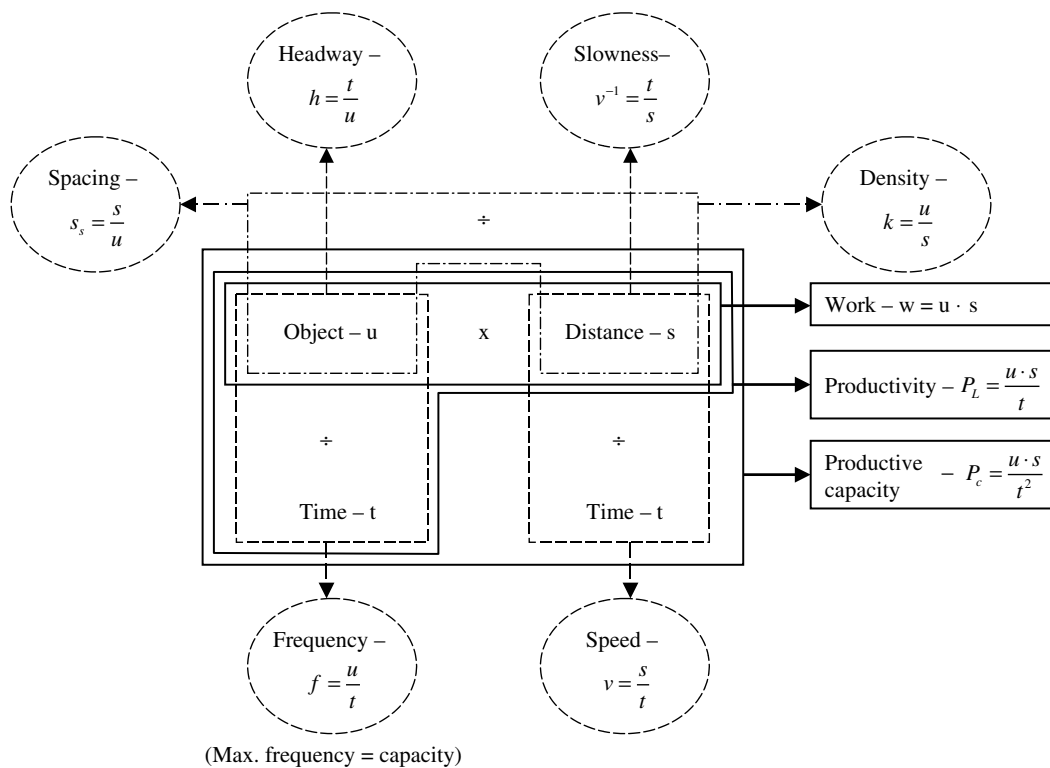


Figure 4.1 Basic transit system performance measures

4.1.3 Transit System Efficiency and Productivity

The efficiency of a transportation process can be described by various ratios of transportation output to the input consumed in the production process:

$$\text{Efficiency ratio} = \frac{\text{output quantity produced}}{\text{resource quantity expended}}$$

Since transit system output may be measured in various units (e.g., vehicle-km, person-km) and its input in different resources (monetary expenditures, labor, energy, and others), a number of efficiency indicators can be defined. Actually if, in a broader sense, time is considered as a basic resource, all service measures with time in the denominator represent *rates of pro-*

duction, or *efficiencies*. For example, speed can be defined as time efficiency of movement and capacity as time efficiency of “processing” (i.e., transporting spaces past a fixed point). More complex concepts of productivity can also be defined as time efficiencies of work output.

The most common efficiency indicators are, however, those related to such resources as cost, manpower, energy, ROW width, or area occupied by transit system infrastructure. It is through these resources that the term *productivity* is often used in a broader sense (i.e., interchangeably with *efficiency*). The most common overlap of the two terms is with respect to manpower resource. Units of output—such as daily passengers, passenger-km, or vehicle-km—when related to the number of employees or person-hours of work form what are usually referred to as “labor pro-

ductivity” measures; in a broader sense, these measures can be viewed as indicators of labor efficiency. Indicators related to other resources, such as energy or occupied urban area or space, are usually referred to as efficiencies rather than productivities. Because of this overlapping meaning of terms, it is important to define each indicator whenever it is used.

4.1.4 Consumption and Utilization

Consumption rate is the ratio of quantity of a certain resource utilized in a process to the quantity of a specific output of the process; thus a consumption rate is the inverse of efficiency:

$$\begin{aligned}\text{Consumption rate} &= \frac{\text{resource quantity expended}}{\text{output quantity produced}} \\ &= \frac{1}{\text{efficiency ratio}}.\end{aligned}$$

For example, slowness (the consumption rate of time in movement) is the inverse of speed (the time efficiency of movement). Consumption rates in transit are usually computed for the resources used for efficiency indicators, particularly different kinds of costs, labor, and energy.

Utilization is, similar to efficiency, a ratio of output to input (demand to supply) in transportation process. However, utilization is the ratio of the same or very similar input and output measures; it is therefore expressed either as a dimensionless number (percent, or a coefficient ≤ 1), or with dimensions similar to each other. For example, “spaces utilized/total spaces offered” can be expressed as a percent or as a coefficient (say, utilization is 75%, or the “load factor” is 0.75); or, in more practical terms, the same ratio is expressed as “passengers carried/spaces offered,” with the unit prs/sp. Vehicles in service/vehicles owned is another example of utilization factor.

The basic elements of resources and output—as well as several efficiency, consumption-rate, and utilization indicators common for transit operations—are

presented in Table 4.1. The indicators are discussed further in Section 4.6.

4.2 TRANSIT LINE CAPACITY

4.2.1 Definitions

Line capacity C , generally speaking, is the maximum number of units that can be transported on a line past a fixed point during one hour under a given set of conditions. For transit systems, several capacities are defined according to different units and operational factors. For their definitions, it is useful to review first several terms used in Chapters 2 and 6.

Transit unit (TU) refers to a set of n cars that travel coupled together. A TU may be a *single vehicle* ($n = 1$) or a *train* with several vehicles ($n > 1$). The number of TUs that pass a point on a line during an hour is the *service frequency* f , which is the inverse of *service headway* h , the time interval between two successive TUs:

$$f = \frac{3600}{h} \cdot \left| \frac{f}{\text{TU/h}} \right| \left| \frac{h}{\text{s/TU}} \right| \quad (4.8)$$

Based on the types of transported units, several different capacities can be defined. Following are the definitions of capacities based on TUs, vehicles, spaces, and passengers, respectively.

Line capacity in terms of TUs does not have a special designation, since it represents the *maximum frequency* $f_{\max}$. This frequency is determined by the shortest headway that can be achieved at all points and stations along a transit line.

On most lines two different headways can be defined: *way headway* h_w , which is operated on line sections without stations, and *station headway* h_s , representing the time interval between successive TUs at stations. The maximum frequency that can be achieved on a line is determined by the longest minimum headway:

Table 4.1 The most common transit system output, resource, and performance measures^a

Output Measures	Resource Measures	Efficiency (Productivity) Indicators	Consumption Rates	Utilization Indicators
"Objects" or "units":	Costs:	Sp-km/h	kWh/veh-km	Veh-h/veh/day
Persons	\$ _i , investment	Veh-km/veh/yr	Oper. empl/veh-km	Operated veh/total veh.
Seats	\$ _o , operating	Prs/veh-km	\$ _o /prs	Prs/space
Spaces	Manpower	Prs/veh/year	\$ _o /prs-km	Prs-km/sp-km
Vehicles } TUs	(employees):	Sp-km/route km/yr	\$ _o /sp-km	Hours worked/hours paid
Trains }	Operating personnel	yr	\$ _o /veh-km	Operating empl/total empl
Work:	Administrative	Prs-km/veh/yr	Veh/km of network	
Person-km	personnel	Veh-km/empl/yr	Sp-km/prs-km	
Space-km	Maintenance	Veh-km/kWh	ROW width/sp/h	
Vehicle-km	personnel	Sp-km/kWh		
Capacity:	Time:	Prs-km/kWh		
Persons/hour	Hour	Sp-km/day/\$		
Spaces/hour	Day	Prs-km/\$		
Vehicles/hour	Year	Prs/vehicle area		
Productivity:	Space:	Sps/h/ROW width		
Person-km/year	Vehicle length	\$ _r /prs		
Space-km/year	Vehicle area	\$ _r /veh-km		
Vehicle-km/year	ROW width			
Productive capacity:	Area occupied by			
Space-km/hour ²	vehicle			
Space-km/hour ²	Facilities:			
	Fleet capacity			
	Fleet size			
	Number of lines			
	Network length			
	Energy:			
	kWh for propulsion			
	kWh for entire			
	system			

^a\$_i = investment cost; \$_o = operating cost; \$_r = revenue; prs = persons (passengers); empl = employees.

$$f_{\max} = \frac{3600}{h_{\min}} = \frac{3600}{\text{Max } (h_{w \min}, h_{s \min})} \cdot \left| \frac{f}{\text{TU/h}} \right| \left| \frac{h}{\text{s/TU}} \right| \quad (4.9)$$

Vehicle line capacity c is the maximum number of vehicles that can pass a fixed point:

$$c = f_{\max} \cdot n. \quad \left| \frac{c}{\text{veh/h}} \right| \left| \frac{f}{\text{TU/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \quad (4.10)$$

In most cases $h_{s \min} \gg h_{w \min}$, so that station headways govern line capacity. However, in special cases, such as lines with multichannel or off-line stations, way headways may become critical. It is therefore important to analyze both way and station headways and capacities.

For operation of single vehicles only (e.g., buses), this capacity is equal to the maximum frequency: $c = f_{\max}$.

Maximum offered line capacity C , expressed in passenger spaces per hour, represents the maximum capability of a transit line to transport passengers. It is

therefore often referred to simply as “line capacity.” It is computed as the product of vehicle line capacity c and vehicle capacity C_v :

$$C = c \cdot C_v = f_{\max} \cdot n \cdot C_v.$$

$$\left| \frac{C}{\text{sps/h}} \right| \left| \frac{c}{\text{veh/h}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{f}{\text{TU/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \quad (4.11)$$

Introducing Eq. (4.9), C can be expressed as a function of the minimum headway:

$$C = \frac{3600n \cdot C_v}{h_{\min}}.$$

$$\left| \frac{C}{\text{sps/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{h}{\text{s/TU}} \right| \quad (4.12)$$

Consequently, two different capacities can be defined for transit lines: *way capacity* C_w , which is a function of $h_{w \min}$, and *station capacity* C_s , a function of $h_{s \min}$. The smaller of the two represents line capacity:

$$C = \min(C_w, C_s). \quad (4.13)$$

The two minimum headways, $h_{w \min}$ and $h_{s \min}$, depend on several factors that are not always constant: $h_{w \min}$ is influenced by vehicle performance and travel regime, but most of all by the degree of ROW control. $h_{s \min}$ depends additionally on the passenger boarding/alighting procedure and its control. As the analyses of capacities in Sections 4.3 and 4.4 refer mostly to guided, electrically powered modes with fully or partially controlled rights-of-way (categories A and B), on which headway variations are very small, the minimum headways are treated as constant values. For capacity computations of street transit modes, which generally have much less stable headways, variations in $h_{\min}$ values must be taken into account, since they can have a significant negative effect on line capacities.

Maximum utilized line capacity C_p is the maximum number of passengers that can be transported past a

point on a transit line under prevailing conditions. The passenger load of individual vehicles can be equal to their capacities, but such utilization usually cannot be maintained in all vehicles during a longer period of time (e.g., 30 or 60 min). Therefore C_p computed for one hour can only theoretically be equal to C . In the real world, $C_p < C$ to various degrees, depending on transit mode and local conditions.

Scheduled line capacity C_o is the number of passenger spaces that are transported past a fixed point under a given operating schedule. Obviously, $C_o \leq C$.

The *scheduled line capacity utilization coefficient* δ is the ratio of scheduled to offered line capacity:

$$\delta = \frac{C_o}{C}. \quad \left| \frac{\delta}{-} \right| \left| \frac{C}{\text{sps/h}} \right| \quad (4.14)$$

This coefficient is useful for analyses of utilization and available reserves of different transit lines.

The *capacity utilization coefficient* α is the ratio of actual passenger volume to provided capacity:

$$\alpha = \frac{P}{C_o}, \quad \left| \frac{\alpha}{\text{prs/sp}} \right| \left| \frac{P}{\text{prs/h}} \right| \left| \frac{C}{\text{sps/h}} \right| \quad (4.15)$$

where P is the number of passengers transported past a point during one hour. The coefficient α is used in scheduling transit service and is commonly known as the *load factor*. In a narrower sense, α can be computed for individual vehicles as the ratio of the number of passengers to vehicle capacity.

Consequently, the relationship of passenger volume transported on a line past a point during one hour and the line's capacity is:

$$P = \alpha \cdot C_o = \alpha \cdot \delta \cdot C.$$

$$\left| \frac{P}{\text{prs/h}} \right| \left| \frac{\alpha}{\text{prs/sp}} \right| \left| \frac{C_o}{\text{sps/h}} \right| \left| \frac{\delta}{-} \right| \quad (4.16)$$

For example, it is assumed that a metro line can be operated with at most six-car trains, each car with a capacity of 150 spaces, running at a minimum headway of 120 s (2 min). If, at a given time, the line is

operated with four-car trains at 300-s headways and carries a total of 4800 prs/h on its maximum load section, its capacities and coefficients are:

$$C = \frac{3600n \cdot C_v}{h_{\min}} = \frac{3600 \cdot 6 \cdot 150}{120} = 27,000 \text{ sps/h,}$$

$$C_o = \frac{3600 \cdot 4 \cdot 150}{300} = 7200 \text{ sps/h;}$$

$$\delta = \frac{C_o}{C} = \frac{7200}{27,000} = 0.267;$$

$$\alpha = \frac{P}{C_o} = \frac{4800}{7200} = 0.667 \text{ prs/sp.}$$

Finally, the product of the two factors, δ and α , gives the ratio of the passenger volume to line capacity:

$$\delta \cdot \alpha = \frac{P}{C} = \frac{4800}{27,000} = 0.178 \text{ prs/sp.}$$

4.2.2 Vehicle Capacity

The preceding definitions show that vehicle capacity C_v directly influences both way and station capacity of a line [see Eqs. (4.12) and (4.13)]. It is therefore important to understand all factors influencing this basic element. The vehicle capacity can be defined in two different ways:

- *Total capacity* C_v , consisting of the number of seats m and the number of standing spaces m' . This definition is used for all transit systems designed to carry standing passengers, such as heavily traveled bus lines and most LRT and RRT lines. The maximum possible utilization coefficient for such vehicles is $\alpha = 1.0$.
- *Seating capacity* m , not including standing spaces. This definition is common for vehicles on longer lines, which at most times provide seats for all passengers, such as lightly traveled bus lines, some LRT and RRT lines, and most RGR systems. Since these vehicles can accommodate standees when demand requires, their maximum

utilization coefficient is well in excess of unity, often around 1.5 to 2.0.

4.2.2.1 Determinant Factors. The optimal vehicle capacity depends mostly on the trade-off between frequency of service (higher with smaller vehicles) and cost of system operation (lower with larger vehicles), but it is also subject to several design factors. Four different physical elements influence vehicle capacity: (1) vehicle dimensions, (2) usable area, (3) comfort standards, and (4) seat/standee ratio.

Vehicle dimensions—including length, width, and number of floors—determine the *gross vehicle floor area* A_g . In designing new systems or lines, vehicle dimensions can be determined on the basis of the required vehicle capacity. However, it is often desirable to construct a vehicle as large as its external dimensions allow. The constraints on these dimensions may be:

- Legal dimension limits for vehicles utilizing public highways
- Clearance requirements of the way, as in curves, underpasses, and tunnels
- Maximum allowable axle loading (weight per axle), vehicle support and suspension limitations
- Compatibility with past design features to facilitate operation and maintenance
- Use of existing (“off-the-shelf”) components or entire vehicles

Net vehicle floor area available for passenger use A_n is smaller than A_g because of tapering of vehicle width at the ends for narrowing body clearances in curves (LRT vehicles only), thickness of vehicle walls, and the internal areas that cannot be utilized for passengers, A_l .

$$A_n = \xi \cdot A_g - A_l, \quad \left| \frac{A}{\text{m}^2/\text{veh}} \right| \left| \frac{\xi}{-} \right| \quad (4.17)$$

where the coefficient ξ accounts for body tapers and wall thickness, while A_l includes such “lost” areas as driver’s seat or cabin, door steps, and fare-collection area.

Comfort standards, determined by the vehicle floor area per unit capacity, can vary considerably. This comfort factor can be directly determined for seats, since the area allocated to each seat, ρ , is usually exactly defined. It varies between 0.30 and 0.55 m²/seat. For standees, this standard cannot be designed, since it depends on the degree of crowding; the same vehicle can be computed to have different standing capacities, depending on the assumed space per standee σ . The value of σ is assumed to be between 0.10 and 0.25 m²/space; the former value is unrealistically low and is used only for computation of vehicle structural strength. A desirable minimum value is $\sigma = 0.20$ m²/space, although 0.15 is achieved in some situations under “crush conditions” (see also Section 6.2.4.1).

The *seat/standee ratio* also strongly affects total vehicle capacity. Since the area taken by a seated passenger is about 1.5 to 3.0 times greater than the area occupied by a standee, the greater this ratio, the lower the vehicle capacity.

The net vehicle floor area A_n consists of the areas taken by seats and by standees:

$$A_n = m \cdot \rho + m' \cdot \sigma. \quad (4.18)$$

$$\left| \frac{A_n}{\text{m}^2/\text{veh}} \right| \left| \frac{m}{\text{sps}/\text{veh}} \right| \left| \frac{\rho, \sigma}{\text{m}^2/\text{sp}} \right|$$

Substituting m' in this equation by $(C_v - m)$ and solving it for C_v gives an expression for vehicle capacity as a function of its number of seats, comfort standards, and either A_n or A_g , ξ , and A_i :

$$C_v = m + \frac{A_n - m \cdot \rho}{\sigma}$$

$$= m + \frac{\xi \cdot A_g - A_i - m \cdot \rho}{\sigma}$$

$$\left| \frac{C_v, m}{\text{sps}/\text{veh}} \right| \left| \frac{A_n}{\text{m}^2/\text{veh}} \right| \left| \frac{\rho, \sigma}{\text{m}^2/\text{sp}} \right| \left| \frac{\xi}{-} \right| \quad (4.19)$$

At this point it is useful to introduce a new concept, the *vehicle capacity coefficient* c_v , which represents average capacity per unit area:

$$c_v = \frac{C_v}{A_n} \cdot \left| \frac{c_v}{\text{sps}/\text{m}^2} \right| \left| \frac{C_v}{\text{sps}/\text{veh}} \right| \left| \frac{A_n}{\text{m}^2/\text{veh}} \right| \quad (4.20)$$

If C_v from the first part of Eq. (4.19) is introduced in this equation, one obtains

$$c_v = \frac{m}{A_n} \left(1 - \frac{\rho}{\sigma} \right) + \frac{1}{\sigma}$$

$$\left| \frac{c_v}{\text{sps}/\text{m}^2} \right| \left| \frac{m}{\text{sps}/\text{veh}} \right| \left| \frac{A_n}{\text{m}^2/\text{veh}} \right| \left| \frac{\rho, \sigma}{\text{m}^2/\text{sp}} \right| \quad (4.21)$$

4.2.2.2 Vehicle Capacity Diagram. In comparing designs of different vehicles or designing a new vehicle, it is useful to have a diagram that shows both comfort standards (ρ and σ) and vehicle capacities (seating and total). Such a diagram, developed on the basis of Eq. (4.21), is shown in Figure 4.2.

The two capacities per unit area, total ($c_v = C_v/A_n$) and seating (m/A_n), are the variables plotted on the ordinate and the abscissa, respectively. The ordinate represents the unit capacity of vehicles that would have standing only, while the unit capacity of vehicles with seating only is plotted along the diagonal ($c_v = m/A_n$) line. For these two boundary cases, the two unit capacities are equal to the inverse values of the parameters in Eq. (4.21), ρ and σ . Therefore the typical values of ρ and σ are plotted on the diagonal line and on the ordinate, respectively. A family of lines connecting different values of ρ and σ represents the plot of Eq. (4.21) for the shown values of the two parameters. Those lines show the relationship between m and c_v . To find C_v for a specific vehicle with known m and A_n , the ratio m/A_n should be computed. From that value on the abscissa, a vertical line should be drawn to the line connecting the values of ρ and σ adopted for that vehicle, then horizontally to the ordinate. Total vehicle capacity is then computed from the obtained value of c_v by

$$C_v = c_v \cdot A_n \cdot \left| \frac{C_v}{\text{sps}/\text{veh}} \right| \left| \frac{c_v}{\text{sps}/\text{m}^2} \right| \left| \frac{A_n}{\text{m}^2/\text{veh}} \right| \quad (4.22)$$

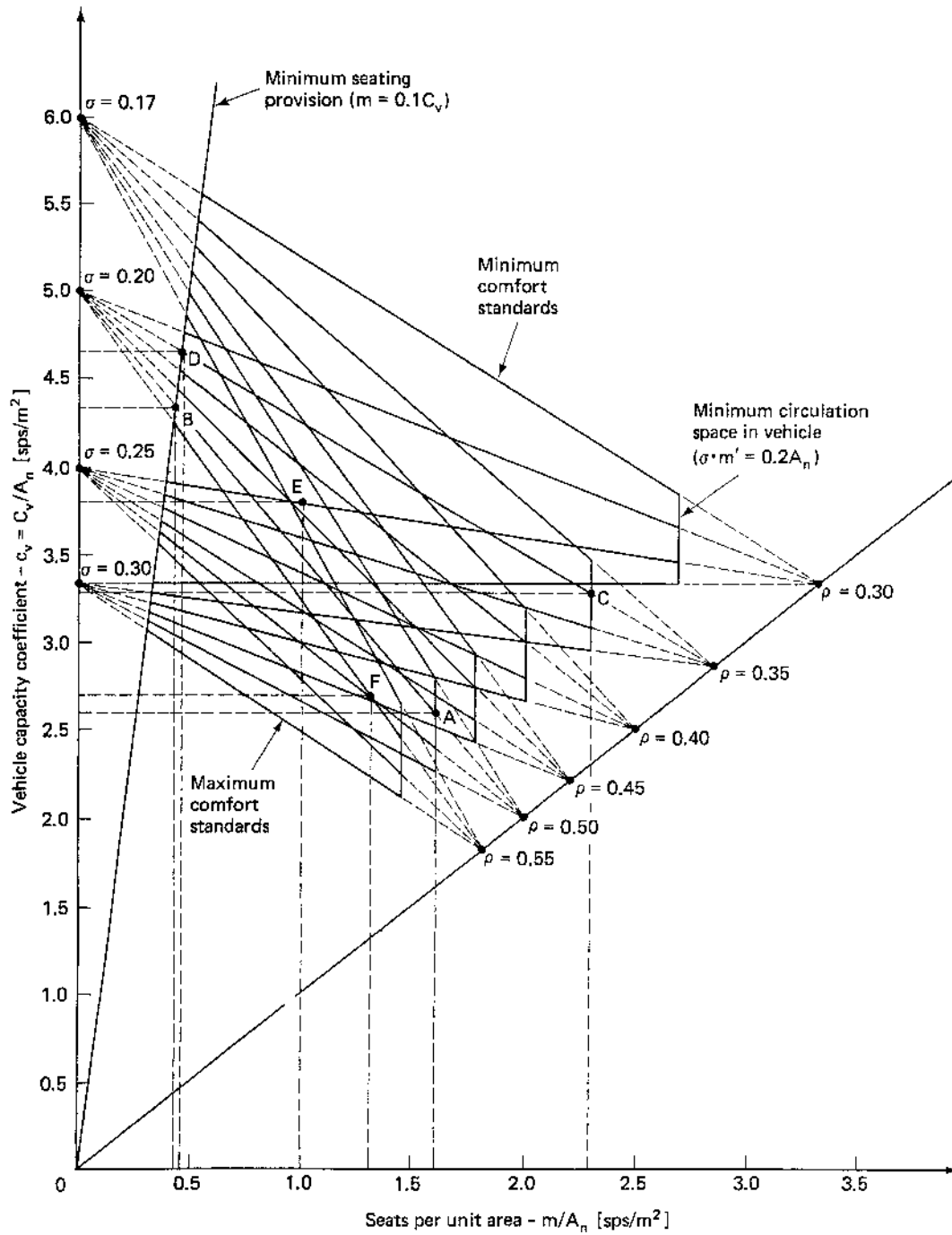


Figure 4.2 Vehicle capacities for different comfort standards

Thus the theoretical range of C_v values is given by the values of c_v on the line connecting the assumed ρ and σ values between the ordinate and the diagonal line. However, in practice, neither of the two extremes can be achieved, since no regular transit vehicles are designed either for all standees or for all seated passengers. A minimum number of seats, resulting in the maximum practical vehicle capacity, is usually achieved by longitudinal seating along both vehicle walls, which typically provide at least 10% of the vehicle capacity. Maximum practical seating can provide about 80% of the capacity, since the area required for internal circulation is always available for standing. Thus, as the diagram shows, ρ and σ combinations close to the ordinate and close to the diagonal line are not applicable in practice.

Two numerical examples will show possible applications of the diagram.

Suppose that an analysis of external constraints and type of operation has shown that a vehicle should have $A_n = 20 \text{ m}^2$. Design standards stipulate that $\sigma = 0.20 \text{ m}^2/\text{sp}$ should be used. What are the trade-offs among ρ , m , and C_v ?

The diagram shows that for a comfortable seating standard, such as $\rho = 0.50 \text{ m}^2/\text{sp}$, the values of m and c_v vary between points A and B, while for a lower standard $\rho = 0.35 \text{ m}^2/\text{sp}$, points C and D indicate the range of c_v . Consequently, multiplying the values of m and c_v by A_n , the following ranges are obtained:

	ρ	σ	$m_{\max}/C_{v \min}$	$m_{\min}/C_{v \max}$
High comfort	0.50	0.20	32/52 (A)	8/87 (B)
Low comfort	0.35	0.20	46/66 (C)	9/93 (D)

Thus the vehicle designer can provide a total capacity for the given vehicle in the range 52 to 87 spaces with $\rho = 0.50$, or 66 to 93 spaces if $\rho = 0.35$ is used.

Another application of the diagram is for a comparison of two different vehicles or vehicle designs. Suppose that vehicle I has $A_n = 30 \text{ m}^2$, $m = 30$, and the area occupied by seats is 9 m^2 . These data yield ρ

$= 9/30 = 0.30 \text{ m}^2/\text{seat}$. Adopting $\sigma = 0.25 \text{ m}^2/\text{standee}$ and computing $m/A_n = 1.0 \text{ seats}/\text{m}^2$, the diagram shows (point E) that $c_v = 3.8 \text{ sps}/\text{m}^2$, so that, by Eq. (4.22), $C_v = 114 \text{ sps}/\text{veh}$. Vehicle II has $A_n = 35 \text{ m}^2$, $m = 45$, and the area occupied by seats $= 22.5 \text{ m}^2$. Thus $\rho = 0.50$. For a correct comparison, one must adopt the same $\sigma = 0.25$. Further, $m/A_n = 1.29$ and the diagram gives (point F) $c_v = 2.7$, so that $C_v = 94 \text{ sps}/\text{veh}$.

From these data the trade-offs among total capacity, seating capacity, and comfort (ρ) are evident: the transit operator must decide whether the 15 extra seats and the higher level of comfort of vehicle II are worth its 20-space lower total capacity and a higher capital and operating costs for the line than with vehicle I.

In actual applications, computed vehicle capacities, particularly the number of seats, cannot be precisely obtained because of various physical constraints in vehicle design. For example, the number of seats in a bus depends on the number of seat rows, so that the seating capacity can be obtained only in increments of three or four: a bus model may have 45 or 49 seats, but 46, 47, or 48 would be impractical. The computed capacities are therefore used for general orientation rather than for precise design specifications.

4.2.2.3 Linear Vehicle Capacity. The concept of linear vehicle capacity, π , defined as the number of passenger spaces per meter of vehicle length (sps/m), is useful for comparison of vehicles of different modes or designs and for analysis of way capacity. It is computed as

$$\pi = \frac{C_v}{l'}, \quad \left| \frac{\pi}{\text{sps/m}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{l'}{\text{m/veh}} \right| \quad (4.23)$$

where l' is length of a single vehicle over couplers or bumpers.

The value of π depends on vehicle width as well as on the other factors influencing capacity: usable floor area, comfort standards, and seat/standee ratio. It varies considerably among modes, as Table 4.2 shows.

Major factors causing these differences among modes should be pointed out. Passenger autos have

Table 4.2 Linear vehicle capacity π of different modes^a

<i>Mode</i>	<i>Total Capacity C_v (sps/veh)</i>	<i>Length over Bumpers/Couplers l' (m)</i>	<i>π^b (sps/m)</i>
Passenger auto			
Maximum usable (average occupancy)	1.2–2.2	4–6	0.2–0.6
Theoretical maximum capacity	4–6	4–6	1.0–1.2
Van	8–12	4–6	1.5–2.0
Transit bus			
Minibus	20–30	6–7	3.5–5.0
Standard	60–80	10–12	5.0–7.0
Articulated	100–120	16–18	5.5–7.0
LRT			
Single-body	100–120	14–16	7.0–8.0
Articulated	160–250	18–30	7.0–8.5 ^c
Rapid transit	140–280	15–23	8.0–10.0
Regional rail			
Standard	140–210	18–26	6.0–9.0
Bilevel	200–280	22–26	9.0–11.0

^aExceptional extreme values are not included in the given ranges of values.

^bValues of π are rounded, incorporating typical designs.

^cArticulated LRT cars often have wider bodies than do single-body cars.

very low values of π for two reasons. First, with most models, only 30% to 70% of their length is used for the passenger compartment (with bus and rail transit vehicles, 90% to 98% of length is utilized). Second, because of the low, comfortable seats, the ρ values are high. However, the major reason for the low transporting capacity of automobiles is their very low occupancy: with an average of 1.2 to 2.2 prs/car, utilization of auto capacity is well below 50%.

The important difference between private and public vehicles (auto and transit) is that the occupancy of private vehicles changes only slightly with demand: even with strong encouragement of carpooling, average car occupancies in major commuting corridors have been increased by up to 20% to 30% over normal occupancies. “Casual carpooling,” which represents hitchhiking organized at certain locations during peak hours, works in a few cities under special conditions, with similar results. Except for stimulating carpooling and high parking charges, there is no practical method to fill up empty spaces in automobiles by persons who want to travel in the same direction. With public ve-

hicles, empty spaces can always be utilized as demand for travel increases, up to the maximum operationally feasible capacity utilization. Therefore the figures in Table 4.2 for transit vehicles, from bus to regional rail, include standees. The high values for π with LRT and rapid transit are due to their lower seat/standee ratios compared to buses, little unutilized space, and, with rapid transit, wider car bodies. Regional rail, despite its even greater car body width, has lower π values than rapid transit due to its higher seat/standee ratio. Bilevel regional rail cars have π values similar to those of rapid transit.

4.3 WAY CAPACITY

A thorough understanding of all factors influencing way capacity is necessary for the design of control systems, analysis of operational safety, and, in cases where stations have multiple tracks or parallel bus loading areas, the computation of line capacity. An analytical description of way capacity is presented here in general terms so that it can be applied to any mode.

4.3.1 Basic Elements

From Eqs. (4.9) through (4.12), the following expressions for way capacities in vehicles and spaces per hour, respectively, are obtained:

$$C_w = \frac{3600n}{h_{w \min}} \left| \frac{c}{\text{veh/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{h}{\text{s/TU}} \right| \quad (4.24)$$

and

$$C_w = \frac{3600n \cdot C_v}{h_{w \min}} \left| \frac{C_w}{\text{sps/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{h}{\text{s/TU}} \right| \quad (4.25)$$

While n and C_v are fixed parameters, $h_{w \min}$ varies with several operational factors, primarily speed, vehicle braking characteristics, and the degree of safety provided.

The $h_{w \min}$ can be expressed as the minimum TU spacing, $s_{s \min}$, divided by speed:

$$h_{w \min} = \frac{s_{s \min}}{v} \left| \frac{h}{\text{s/TU}} \right| \left| \frac{s}{\text{m/TU}} \right| \left| \frac{v}{\text{m/s}} \right| \quad (4.26)$$

This $s_{s \min}$ (i.e., minimum distance between corresponding points of two successive TUs) consists of the length of a TU plus the minimum distance that must be maintained between TUs for safety, $s_{g \min}$:

$$s_{s \min} = n \cdot l' + s_{g \min} \left| \frac{s}{\text{m/TU}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \quad (4.27)$$

Substituting this expression into Eq. (4.26) and then $h_{w \min}$ into Eq. (4.25) gives:

$$C_w = \frac{3600n + C_v + v}{n \cdot l' + s_{g \min}} \left| \frac{C_w}{\text{sps/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right| \quad (4.28)$$

After introduction of the linear vehicle capacity and rearrangement of the expression, one can derive the form:

$$C_w = \frac{3600\pi \cdot v}{1 + s_{g \min}/(n \cdot l')} \left| \frac{C_w}{\text{sps/h}} \right| \left| \frac{\pi}{\text{sps/m}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{s}{\text{m/TU}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \quad (4.29)$$

This expression shows the influence of three parameters, π , n , and l' , on way capacity. For any given v and $s_{g \min}$, way capacity is a linear function of π . But way capacity is inversely related to the ratio $s_{g \min}/(nl')$. This is intuitively clear: the expression actually represents a ratio of the distance between TUs and their length (i.e., the ratio of unoccupied to occupied lengths of the way). The greater the occupied length is, the greater the way capacity is, *ceteris paribus*. Thus, for operation of a given system at a constant speed and safety regime (fixed $s_{g \min}$), *capacity always increases with the length of vehicles or TUs*. This impact of vehicle length on way capacity for different modes is shown in the diagram in Figure 4.3. The impact of coupling vehicles into trains (TU size) is analyzed in greater detail in Section 4.3.4.1.

4.3.1.1 Distance Between TUs. The most complex factor influencing way capacity is the distance between TUs, which depends on speed, braking rate, and the operating safety regime. For operation of driver-controlled vehicles without way (signal) control, there is no possibility to predetermine this distance because it is selected by each driver. The degree of safety in this case is therefore variable: it depends only on the

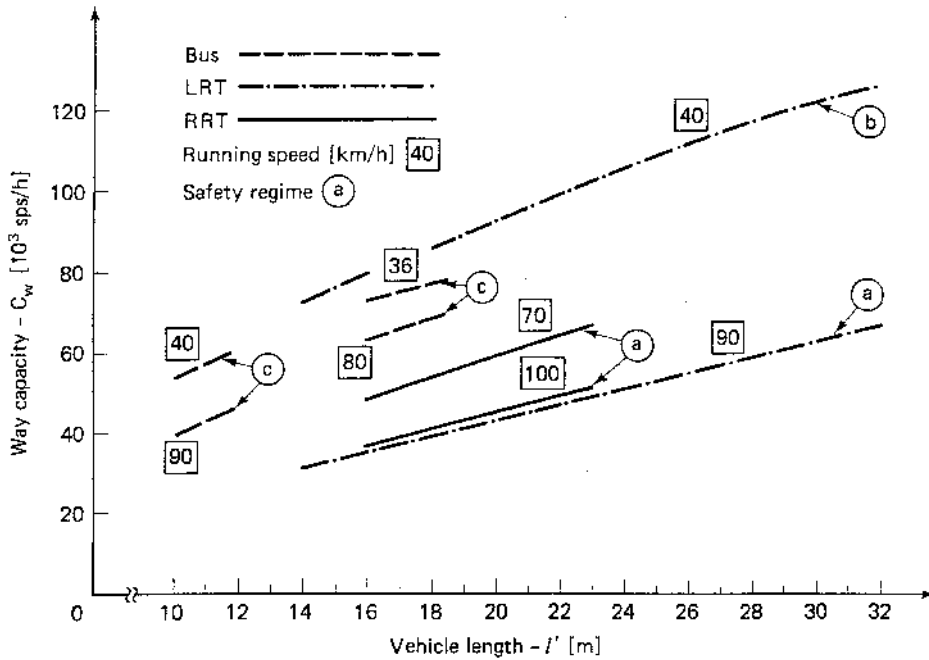


Figure 4.3 Effect of single-vehicle length on way capacity for selected modes

driver's skill and discipline. If positive, external, automatic control is provided (such as a guideway for vehicles and signals for their movement), a higher degree of safety is obtained, since the longer distances between TUs are always maintained.

Two major errors are often made in evaluating safety and capacity. First, capacities of different modes are sometimes compared without considering differences in their safety; second, unrealistically low safety regimes are assumed for untested modes or types of operation. Since an understanding of all these factors influencing capacity is sine qua non for correct comparisons of existing and proposed technologies and types of operation, the distance s_g between rear and front ends of two successive TUs is analyzed here.

The minimum distance ("gap") that must be maintained between successive TUs, $s_{g \min}$, is determined by the requirement that if a leading transit unit (LTU) stops, the following transit unit (FTU) must be able to stop without collision. Different combinations of braking rates for the LTU and the FTU determine various

safety regimes of flow. The vehicle stopping distance s_d , defined and derived in Section 3.5 [Eq. (3.27)], is based on these combinations. With the addition of a certain distance s_o to allow for variations in braking conditions and to provide a minimum spacing between stopped TUs, this distance is:

$$s_d = s_r + s_b + s_o = t_r \cdot v + \frac{v^2}{2b} + s_o, \quad (4.30)$$

$$\left| \frac{s}{\text{m/TU}} \right| \left| \frac{t}{\text{s/TU}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{b}{\text{m/s}^2} \right|$$

where s_r is the distance vehicle passes during reaction time t_r , s_b the braking distance, and b the braking rate.

The minimum distance between TUs is governed by the requirement that when the LTU begins deceleration, the separation distance should be sufficient to allow the FTU to stop at a distance s_o behind it. Thus, the distance $s_{g \min}$ must be equal to the difference between the stopping distance (s_d) of the FTU and the

braking distance (s_b) of the LTU. If the LTU and FTU are designated by indices 1 and 2, respectively, the expression for $s_{g \min}$ is:

$$\begin{aligned} s_{g \min} &= s_{d2} - s_{b1} \\ &= t_r \cdot v_2 + \frac{v_2^2}{2b_2} + s_o - \frac{v_1^2}{2b_1} \\ &\quad \left| \frac{s}{\text{m/TU}} \right| \left| \frac{t}{\text{s/TU}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{b}{\text{m/s}^2} \right| \end{aligned} \quad (4.31)$$

Since at capacity flow conditions $v_1 = v_2 = v$, this equation simplifies to:

$$\begin{aligned} s_{g \min} &= s_o + t_r \cdot v + \frac{v^2}{2} \frac{b_1 - b_2}{b_1 \cdot b_2} \\ &\quad \left| \frac{s}{\text{m/TU}} \right| \left| \frac{t}{\text{s/TU}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{b}{\text{m/s}^2} \right| \end{aligned} \quad (4.32)$$

This equation shows that the required minimum distance between TUs increases with the square of their common speed and that it also depends on the difference between the assumed deceleration rates b_1 and b_2 . All components of TU spacing, stopping distance, and TU paths during deceleration are shown on the time-distance diagram in Figure 4.4.

4.3.1.2 Way Capacity Expression. With these expressions it is now possible to return to the capacity equation and develop it in a form that contains all the basic factors. Eq. (4.32) is introduced into Eq. (4.27), and that equation into Eq. (4.26):

$$\begin{aligned} h_{w \min} &= \frac{n \cdot l' + s_o}{v} + t_r + \frac{v}{2} \frac{b_1 - b_2}{b_1 \cdot b_2} \\ &\quad \left| \frac{h}{\text{s/TU}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{t}{\text{s/TU}} \right| \left| \frac{b}{\text{m/s}^2} \right| \end{aligned} \quad (4.33)$$

Finally, this expression for $h_{w \min}$ is introduced into Eq. (4.25), giving an expression for way capacity in spaces

per hour, which includes braking rates for both units, LTU and FTU:

$$\begin{aligned} C_w &= \frac{3600n \cdot C_v}{(n \cdot l' + s_o)/v + t_r + v(b_1 - b_2)/(2b_1 \cdot b_2)} \\ &\quad \left| \frac{C_w}{\text{sps/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right| \\ &\quad \left| \frac{v}{\text{m/s}} \right| \left| \frac{t}{\text{s/TU}} \right| \left| \frac{b}{\text{m/s}^2} \right| \end{aligned} \quad (4.34)$$

The expression for the vehicle line capacity, c_w , is the same as Eq. (4.34) except that it does not have C_v .

4.3.2 Vehicle Control Categories in Transit Operation

With respect to vehicle travel control, transit systems can be classified into four basic categories (see also Section 6.6.1):

1. *Manual/visual driver control.* Systems with this type of operation have no signal control, so that spacing between vehicles depends on the driver's judgment only. All surface transit systems, BRT, and most LRT systems have this type of operation.
2. *Manual with signals.* Actuated by vehicle presence on a track section, wayside or cab signals inform the driver whether to proceed or stop. However, this system has no positive control over the driver's actions: the vehicle may be driven through a red signal with impunity. Many LRT and a few RRT and RGR systems utilize this type of control.
3. *Positive control of minimum spacing.* Positive vehicle control has, in addition to signals based on track occupancy information, a mechanism to trigger forced stopping of a vehicle that overrides a red signal. Such control is a significant feature, since it renders the operation fail-safe (i.e., independent of possible driver error). Most RRT and RGR systems (e.g., Berlin, London, Philadelphia) have this type of control.

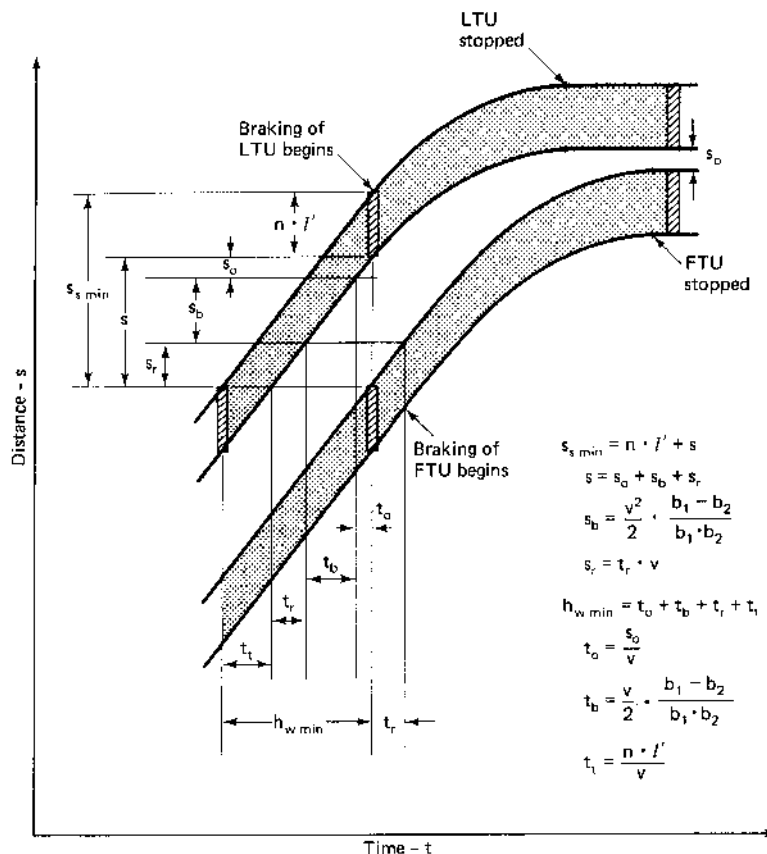


Figure 4.4 Components of TU headway, spacing, and stopping distance

4. *Automatic train operation (ATO).* Many recently built RRT and RGR systems (e.g., San Francisco BART, Washington Metro, Paris Metro Line 14) and all AGT systems have fully automated control that not only secures the minimum spacings but also controls the speed of vehicles. In most cases this operation utilizes “moving block” control, which provides for maximum way capacity.

Manual/visual control (category 1) has the lowest degree of safety, since proper driver training and discipline are the only means of control over it. Because some drivers accept less than an absolutely safe regime of driving, these systems may sometimes have a higher capacity than the signalized ones, but with either lower speed, safety, or both. It is not advisable, therefore, to

operate any mode that carries a high passenger volume with this regime. Consequently, the line capacity of systems with visual driver control should never be compared with capacities of controlled systems without acknowledging their different safety standards.

Systems with category 2 control have higher safety than category 1, but they are still unprotected from driver error. The last two categories, 3 and 4, provide the highest degree of safety: the fail-safe principle guards against any human errors. Category 4 has the same safety but higher capacity than category 3, owing to its optimally preprogrammed driving regime.

To provide the necessary degree of safety and ensure a certain minimum speed and reliability of service, all high-capacity, high-speed transit systems should have positive control of minimum spacings (category 3 or 4).

Table 4.3 Safety regimes of transit operation: combinations of deceleration types for successive transit units

Regime Designation		b_1	b_2	Comment
Way	Station	(LTU)	(FTU)	
a	a	∞	b_n	Absolute safety and comfort; possible overdesign
b	b	b_e	b_n	Safety high, but not absolute for all values of b_e and b_n
c	c	∞	b_e	Safety acceptable for most, but not for automated systems; For $b_e < 2b_n$, safer than regime <i>b</i> , discomfort for FTU passengers
d	$\left\{ \begin{array}{l} - \\ d_1 \\ d_2 \end{array} \right\}$	$\left\{ \begin{array}{l} \infty \\ b_e \\ b_n \end{array} \right\}$	$\left\{ \begin{array}{l} \infty \\ b_e \\ b_n \end{array} \right\}$	In emergencies safety inadequate
e	—	(No braking)		Hypothetical: continuous train

4.3.3 Operating Safety Regimes

Safety regimes of transit vehicle movement, which represent different degrees of operating safety (with possible corollary impacts on passenger comfort), are determined by combinations of the types of deceleration for consecutive TUs traveling initially with equal speeds. The three basic types of vehicle deceleration are defined as follows:

- *Normal braking* ($b = b_n$), which is applied in regular operation. The maximum value of b_n is limited by the safety and comfort of standing passengers.
- *Emergency braking* ($b = b_e$), for which the maximum braking capability of the TU is applied (often utilizing a special brake, such as a magnetic track brake). Passengers experience discomfort and some safety hazard.
- Instant (“stonewall”) stop ($b = \infty$), represents a catastrophic collision. It is only analyzed theoretically for providing safe stopping for the FTU when the LTU has such an accident.

Several authors, mostly in Germany and the United States, analyzed these types of stopping and safety regimes during the 1920s and 1930s. Utilizing these studies, Lehner (1949–1950) published a systematic analysis of safety regimes and way capacities. He developed capacity curves for different way safety regimes, which will be referred to here as “Lehner’s curves.”

Theoretically, there are 10 different travel-way safety regimes: the LTU and the FTU can assume any one of the three types of deceleration. The nine possible combinations of these deceleration types constitute nine safety regimes; a tenth regime is an “endless train” traveling continuously, representing a theoretical limiting case. Of the nine permutations, those in which the FTU assumes a higher deceleration rate than the LTU (e.g., the LTU has normal and the FTU has emergency or instantaneous stopping) are not considered, since they are inherently unsafe and not germane to the analysis. Further, all cases in which the two TUs have the same deceleration type represent the same case, since they result in equal way headways and capacity [see Eqs. (4.32) to (4.34) for $b_1 = b_2$]. Thus one obtains the four feasible safety regimes, *a* to *d*, listed in Table 4.3 in order of decreasing safety and increasing capacity. The only exception to this sequence may occur between cases *b* and *c*. The sequence given assumes that $b_e > 2b_n$, which is typical for most transit modes. For the cases when $b_e < 2b_n$, a regime designated here as *b* has a higher capacity and lower safety than regime *c* (i.e., their order in the set of regimes is reversed). The hypothetical case with continuous train movement (regime *e*) is added for theoretical comparisons.

The five way operating regimes, schematically shown in Figure 4.5, represent an amplification of Lehner’s analysis (which did not include regime *c*). The equations for each regime are presented in the following sections and later used in plotting the Lehner’s curves for different transit systems.

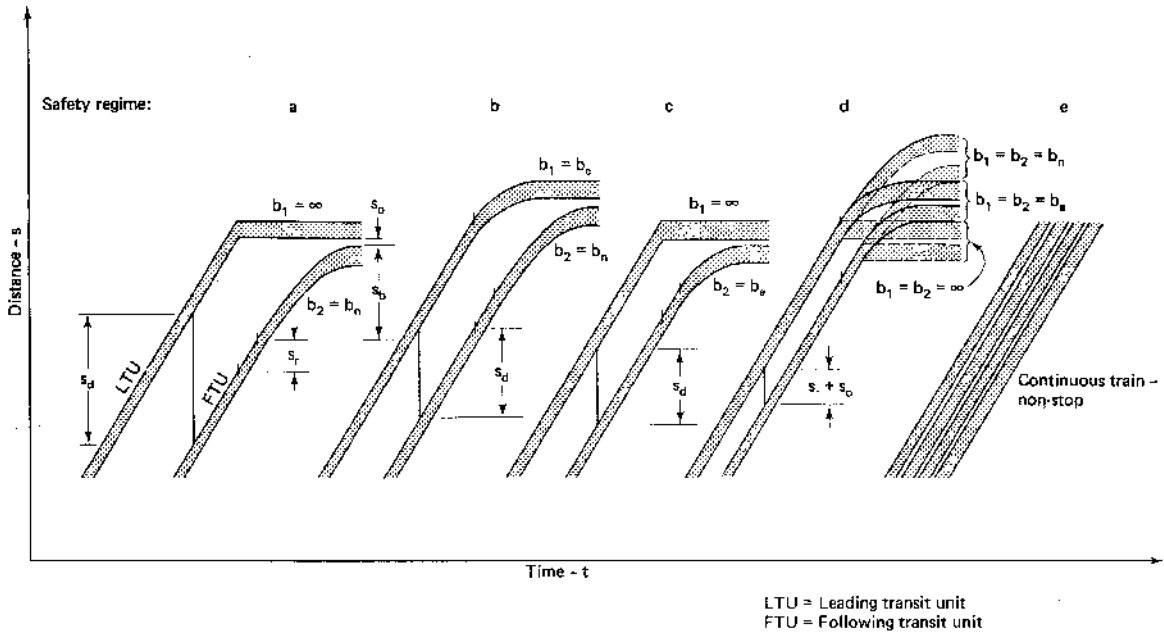


Figure 4.5 The five way safety regimes of successive transit units

4.3.3.1 Equations for the Five Regimes. For each operating regime, the minimum headway is obtained by inserting the appropriate values of b_1 and b_2 into Eq. (4.33); then the vehicle way capacity (c_w) and capacity in spaces/hour (C_w) are derived by Eqs. (4.24) and (4.25), respectively. Through differentiation with respect to speed, the maximum capacities are derived for each case and speeds at which these capacities occur are determined.

Regime a: $b_1 = \infty$, $b_2 = b_n$. This regime provides that even if the LTU were to come to an instantaneous stop, the FTU could stop without collision by applying normal braking; thus not only absolute safety is provided, but passenger comfort is unaffected. The minimum headway is

$$h_{w \min} = \frac{n \cdot l' + s_o}{v} + t_r + \frac{v}{2b_n},$$

$$\left| \frac{h}{s/TU} \right| \left| \frac{n}{veh/TU} \right| \left| \frac{l}{m/veh} \right| \left| \frac{s}{m/TU} \right| \left| \frac{v}{m/s} \right| \left| \frac{t}{s/TU} \right| \left| \frac{b}{m/s^2} \right|$$

(4.35) The way capacity at v^* is:

so that way capacity is expressed as

$$C_w = \frac{3600n \cdot C_v}{(n \cdot l' + s_o)/v + t_r + v/2b_n} \quad (4.36)$$

$$\left| \frac{C_w}{sps/h} \right| \left| \frac{n}{veh/TU} \right| \left| \frac{C_v}{sps/veh} \right| \left| \frac{l}{m/veh} \right|$$

$$\left| \frac{s}{m/TU} \right| \left| \frac{v}{m/s} \right| \left| \frac{t}{s/TU} \right| \left| \frac{b}{m/s^2} \right|$$

Taking the derivative of this expression with respect to v , equating it to zero, and solving for v gives the speed v^* , which yields maximum way capacity (C_w^*):

$$v^* = \sqrt{2(n \cdot l' + s_o)b_n} \quad (4.37)$$

$$\left| \frac{v}{m/s} \right| \left| \frac{n}{veh/TU} \right| \left| \frac{l}{m/veh} \right| \left| \frac{s}{m/TU} \right| \left| \frac{b}{m/s^2} \right|$$

$$C_w^* = \frac{3600n \cdot C_v}{\sqrt{2(n \cdot l' + s_o)/b_n + t_r}}.$$

$$\left| \frac{C_w}{\text{sps/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right| \left| \frac{b}{\text{m/s}^2} \right| \left| \frac{t}{\text{s/TU}} \right|$$

$$(4.38)$$

Regime b: $b_1 = b_e$, $b_2 = b_n$. In this regime, if the LTU applies emergency braking, the FTU can stop by normal braking. However, this would not prevent collision on most systems if the LTU stopped instantly. The regime is therefore not absolutely safe, although in most cases it is acceptable for real-world conditions. The expressions for its headway, capacity, and speed for maximum capacity are:

$$h_{w \min} = \frac{n \cdot l' + s_o}{v} + t_r + \frac{v}{2} \frac{b_e - b_n}{b_e \cdot b_n},$$

$$\left| \frac{h}{\text{s/TU}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{t}{\text{s/TU}} \right| \left| \frac{b}{\text{m/s}^2} \right|$$

$$(4.39)$$

$$C_w = \frac{3600n \cdot C_v}{(n \cdot l' + s_o)/v + t_r + v(b_e - b_n)/(2b_e \cdot b_n)}.$$

$$\left| \frac{C_w}{\text{sps/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right|$$

$$\left| \frac{v}{\text{m/s}} \right| \left| \frac{t}{\text{s/TU}} \right| \left| \frac{b}{\text{m/s}^2} \right|$$

$$(4.40)$$

$$v^* = \sqrt{2(n \cdot l' + s_o) b_e \cdot b_n / (b_e - b_n)}$$

$$\left| \frac{v}{\text{m/s}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right| \left| \frac{b}{\text{m/s}^2} \right|$$

$$(4.41)$$

$$C_w^* = \frac{3600 n \cdot C_v}{\sqrt{2(n \cdot l' + s_o)(b_e - b_n)/(b_e \cdot b_n)} + t_r}.$$

$$\left| \frac{C_w}{\text{sps/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right|$$

$$\left| \frac{b}{\text{m/s}^2} \right| \left| \frac{t}{\text{s/TU}} \right|$$

$$(4.42)$$

Regime c: $b_1 = \infty$, $b_2 = b_e$. This regime provides that if the LTU is stopped instantly, the FTU must apply emergency braking to avoid collision. With slightly lower safety but higher capacity than regime *b* (except when $b_e < 2b_n$), this regime may still be considered satisfactory for the operation of some systems, although not those with automated operation. The expressions for headway, capacity, and optimum speed for this regime are, respectively,

$$h_{w \min} = \frac{n \cdot l' + s_o}{v} + t_r + \frac{v}{2b_e};$$

$$\left| \frac{h}{\text{s/TU}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{t}{\text{s/TU}} \right| \left| \frac{b}{\text{m/s}^2} \right|$$

$$(4.43)$$

$$C_w = \frac{3600 \cdot n \cdot C_v}{(n \cdot l' + s_o)/v + t_r + v/2b_e}.$$

$$\left| \frac{C_w}{\text{sps/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{t}{\text{s/TU}} \right| \left| \frac{b}{\text{m/s}^2} \right|$$

$$(4.44)$$

$$v^* = \sqrt{2(n \cdot l' + s_o) \cdot b_e};$$

$$\left| \frac{v}{\text{m/s}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right| \left| \frac{b}{\text{m/s}^2} \right|$$

$$(4.45)$$

and

$$C_w^* = \frac{3600n \cdot C_v}{\sqrt{2(n \cdot l' + s_o)/b_e} + t_r}.$$

$$\left| \frac{C_w}{\text{sps/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right| \left| \frac{b}{\text{m/s}^2} \right| \left| \frac{t}{\text{s/TU}} \right|$$

$$(4.46)$$

Regime d: $b_1 = b_2$. In this case the term with v in Eq. (4.33) becomes zero. Thus the values of $h_{\min}$ and C_w are the same regardless of what braking rate is used as long as both TUs apply the same rate. This regime is unacceptable in the real world since, in the case of an instant stop of the LTU, the FTU would have to

make an instant stop also (i.e., it would experience a condition identical to collision). Emergency stopping of the LTU would also create a hazardous condition for the FTU.

The expressions for headway between vehicles and way capacity in this case are, respectively,

$$h_{w \min} = \frac{n \cdot l' + s_o}{v} + t_r$$

$$\left| \frac{h}{\text{s/TU}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{t}{\text{s/TU}} \right| \quad (4.47)$$

and

$$C_w = \frac{3600 \cdot n \cdot C_v}{(n \cdot l' + s_o)/v + t_r}$$

$$\left| \frac{C}{\text{sps/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{t}{\text{s/TU}} \right| \quad (4.48)$$

From this expression it can be shown that the way capacity for regime *d* increases nearly linearly with speed and does not have a maximum value in the range of realistic speeds for any system. The curve of C_w as a function of speed is asymptotic to the ratio $3600n \cdot C_v/t_r$.

Regime *e*: No Braking. This condition assumes travel of a continuous train of vehicles (e.g., closed loop) running at a constant speed. Thus it applies to continuous systems rather than to operation with TUs. The concept is useful for analysis, since it represents the theoretical limiting case of way capacity. For this case there is no distance between vehicles ($S_g = 0$), so that way capacity expressed in vehicles and spaces per hour are, respectively,

$$c_w = \frac{3600 \cdot v}{l'} \left| \frac{c}{\text{veh/h}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{l}{\text{m/veh}} \right| \quad (4.49)$$

and

$$C_w = 3600\pi \cdot v \cdot \left| \frac{C}{\text{sps/h}} \right| \left| \frac{\pi}{\text{sps/m}} \right| \left| \frac{v}{\text{m/s}} \right| \quad (4.50)$$

Thus way capacity is in this regime a linear function of speed.

4.3.3.2 Lehner's Way-Capacity Curves. The influence of the operating safety regime on way capacity, defined by the foregoing equations, becomes particularly clear when all these equations are plotted on a single diagram showing way capacity as a function of running speed. Characteristics of the Lehner's curves obtained are best depicted if a rather short single-vehicle TU is observed. Therefore the following data are assumed for the diagram plotted in Figure 4.6:

$$l' = 12.0 \text{ m} \quad s_o = 1.0 \text{ m} \quad b_n = 1.3 \text{ m/s}^2$$

$$C_v = 84 \text{ sps} \quad t_r = 1.0 \text{ s} \quad b_e = 3.0 \text{ m/s}^2$$

Thus $\pi = 7.0$. These values are introduced into Eqs. (4.36), (4.40), (4.44), (4.48), and (4.50) to obtain capacity curves for regimes *a* through *e*, respectively.

The obtained diagram is plotted for speeds up to 120 km/h. It shows that regime *a*, the most important one for application on guided, centrally controlled systems due to its absolute safety, has the lowest capacity; its maximum value of $C_w^* = 55,226$ sps/h is achieved at a speed of $V = 20.9$ km/h. Each subsequent regime with lower safety has a greater capacity and higher optimal speed for maximum capacity except for regime *d* and the hypothetical regime *e*, which do not have a finite maximum capacity.

The productive capacity of different modes, being the product of line capacity and operating speed (see Sections 2.1.4 and 4.1.2), depends on station spacings and various operating characteristics of each individual line. For evaluation of inherent maximum capabilities of a mode, a modified concept can be used. It is *running productive capacity*, the product of line capacity and running (instead of operating) speed (i.e., not including any stops). Running productive capacity can be visualized from the capacity diagram in Figure 4.6: for any given speed it represents the area of the rectangle defined by the coordinates of that point on the

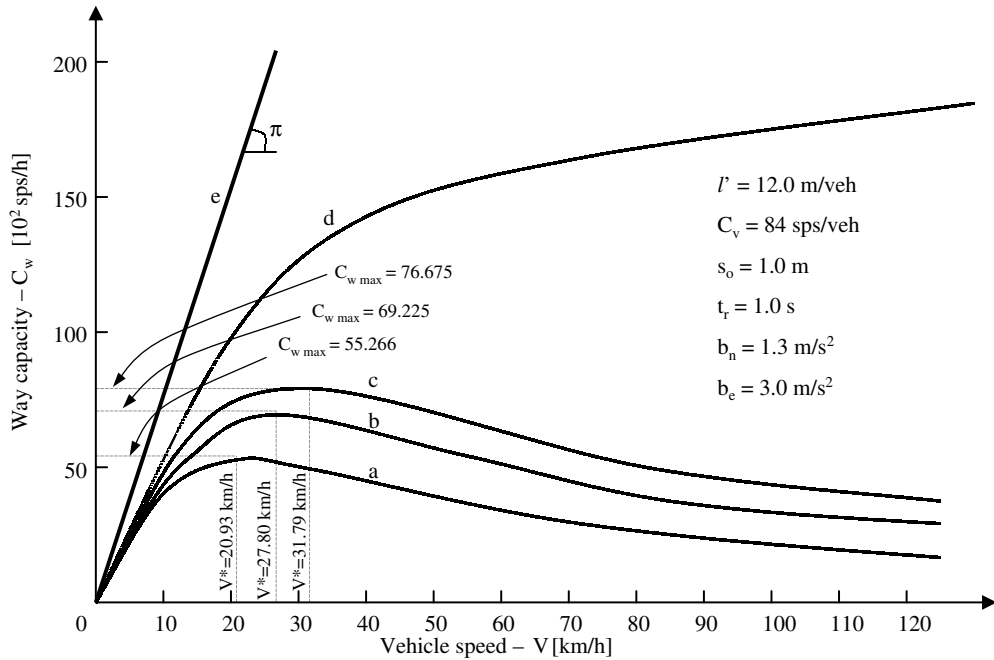


Figure 4.6 Lehner's way-capacity curves: different operating safety regimes for the same vehicle

curve. The diagram shows that the running productive capacity for each regime increases with speed, although at decreasing rates as the operating safety of regimes increases.

4.3.4 Impacts of Train Size and Control Characteristics

Among numerous variations in operations of different transit modes, three factors are of particular significance for capacity. The first and most important is the number of vehicles per TU, or the effect of coupling vehicles in trains. Second is the length of signal control blocks, which are used on most rail transit systems. The third factor is the use of automatic operation on guided systems.

4.3.4.1 Number of Vehicles per Transit Unit. The way capacity of a transit line increases rapidly when longer TUs are operated. The increase can be exactly

computed by the preceding equations. When guided systems operate trains with all cars powered, the dynamic characteristics of trains are virtually the same as those of single vehicles.

Therefore the maximum frequency of TUs on a line, derived from Eqs. (4.24) to (4.27),

$$f_{\max} = \frac{3600 \cdot v}{n \cdot l' + s_{g \min}} \quad (4.51)$$

$$\left| \frac{f}{\text{TU/h}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right|$$

is affected only by the parameter n , to which it is not very sensitive. However, the impact of n on way capacities is quite different. This becomes obvious when way capacities are expressed as functions of n , based on Eqs. (4.24) through (4.29):

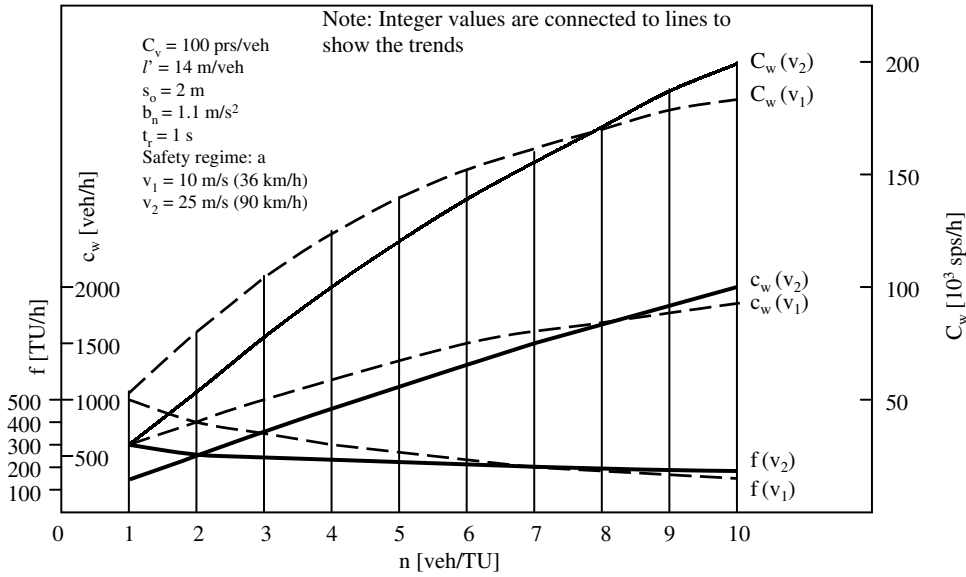


Figure 4.7 Way capacity as a function of the number of vehicles per transit unit

$$C_w = \frac{3600 \cdot v \cdot n}{n \cdot l' + s_{g \min}} \left| \frac{c}{\text{veh/h}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right| \quad (4.52)$$

and

$$C_w = \frac{3600 \cdot v \cdot n}{n \cdot l' + s_{g \min}} C_v \left| \frac{C_w}{\text{sps/h4}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \quad (4.53)$$

The distance that must be maintained between trains is usually much greater than train length: $n \cdot l' \ll S_{g \min}$. Therefore n in the foregoing capacity expression has a much greater influence on the numerator than on the denominator. Thus way capacities increase nearly linearly with the number of vehicles per TU. Since the optimal speed for maximum capacity (V^*) also in-

creases with n (approximately proportionally to its square root), the maximum capacity is even more sensitive to n . With higher capacity at a higher speed, the maximum productive capacity of the line also increases faster than proportionately to the factor n .

The preceding three equations are plotted in Figure 4.7 to illustrate graphically the impact of the number of vehicles per TU (n) on way capacities. To show the influence of speed, each set of bars is plotted for two different speeds. The lowest two sets of bars show the maximum frequency, the middle sets the vehicle way capacity, and the upper two the offered capacity of the line.

The three sets of bars, plotted at different scales, show that the maximum frequency of TUs decreases only slightly as their lengths increase, while way capacity, in both vehicles and spaces per hour, increases sharply with train length. Thus 10-car trains provide nearly eight times higher capacity than one-car trains at a speed of 90 km/h. For the speed of 36 km/h, the ratio of passenger capacity of 10-car to one-car trains is only about 3.6. Consequently, for lower speed, the impact of coupling on frequency and capacity is smaller but still very significant.

While the preceding example was selected to illustrate the impact of operating longer trains on a hypothetical system, the diagram in Figure 4.8 presents $f_{\max}$, c_w , and C_w curves of one- to 10-car trains on a typical rapid transit system. The optimal speed for maximum capacity is also plotted. The diagram clearly shows that operation of trains instead of single vehicles in the real world increases way capacity up to six times.

It is pointed out again that the foregoing equations, diagrams, and numerical examples yield considerably higher capacity estimates than actual transit systems can achieve in operation, not only because they refer to way capacity, while station capacity is critical for most systems, but also because these analyses are based on the assumption that systems operate under continuous control and with no disturbances. The presented diagrams do, however, exactly and clearly show influences of individual mode characteristics—such as

vehicle length, speed, and degree of safety—on capacity, as well as the inherent relationships among different modes in these features.

4.3.4.2 Signal Block Length. The preceding equations are based on the assumption that each TU has exact information about the location and movement of the TU ahead of it at all times. However, on most signal-controlled rail systems, spacings between TUs are detected through block signals, described in Section 6.6.1. As shown in that section, the minimum headways that can be operated with these signals increase with the length of blocks. Since the equations presented in this section apply to zero block length (continuous information), they represent the highest achievable capacity for any given speed. A more general equation for spacing, including any block length D , is:

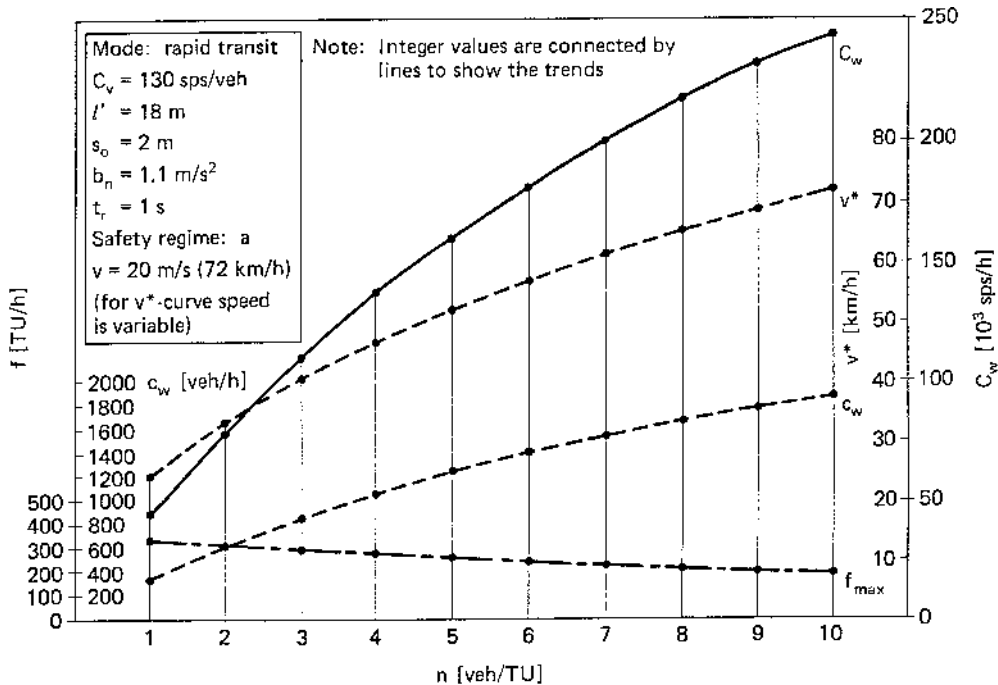


Figure 4.8 Effect of the number of cars per train on rapid transit way capacity

$$s_{s \min} = D \left\{ \left\lceil \frac{s_{g \min}}{D} \right\rceil + 1 \right\} + n \cdot l'.$$

$$\left| \frac{s}{\text{m/TU}} \right| \left| \frac{D}{\text{m/TU}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \quad (4.54)$$

This equation says that to compute minimum TU spacing, the ratio $s_{g \min}/D$ must be rounded up to the next integer. Thus block signal control increases spacing between vehicles by a distance that is at least equal to D (when stopping distance is an integer multiple of block lengths) and at most $2D$, when that ratio is noninteger. The two cases are illustrated in Figure 4.9.

The capacity of most rapid transit systems is also affected by a safety factor K , which is applied to braking rates to compensate for their variations due to different drivers, vehicle maintenance practices, track conditions, and so on. Instead of assuming a normal braking rate b_n in system design, stopping distance is computed assuming a reduced braking rate b_r , defined by a safety factor K :

$$K = \frac{b_n}{b_r} \geq 1. \quad \left| \frac{K}{-} \right| \left| \frac{b}{\text{m/s}^2} \right| \quad (4.55)$$

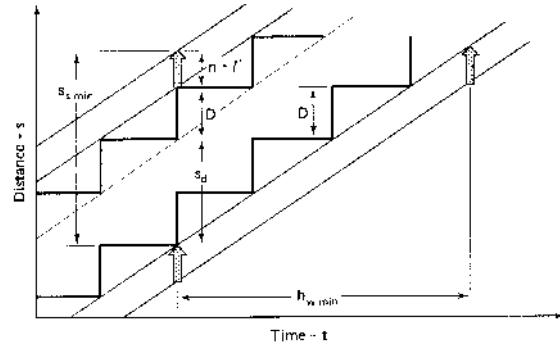
The introduction of K in line-capacity expressions increases headways and thereby safety but decreases line capacity for a given maximum speed.

Consequently, the most general expressions for the capacity of signal-controlled systems are derived from the stopping-distance formula, Eq. (4.32), but including the factor K :

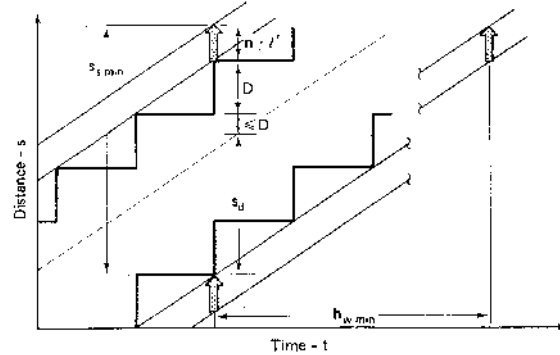
$$s_{g \min} = s_o + t_r \cdot v + K \frac{v^2}{2} \frac{b_1 - b_2}{b_1 \cdot b_2}.$$

$$\left| \frac{s}{\text{m/TU}} \right| \left| \frac{t}{\text{s/TU}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{K}{-} \right| \left| \frac{b}{\text{m/s}^2} \right| \quad (4.56)$$

This value of $s_{g \min}$ is introduced into Eq. (4.27) to derive minimum spacings of TUs. Minimum way headway and way capacity can then be computed by introducing the obtained value of $s_{s \min}$ into Eq. (4.26) and then $h_{w \min}$ into Eq. (4.25).



Case (a): $s_{g \min}/D$ is integer



Case (b): $s_{g \min}/D$ is non-integer

Figure 4.9 Minimum spacings of consecutive TUs for block signal control

4.3.4.3 Automatic Train Operation and Supervision (ATO and ATS). Theoretically, the main effect that automatic train operation and supervision have on way capacity is that they greatly reduce or practically eliminate the reaction time t_r , since electronic reaction substitutes for that of the driver. In practice, automatic control also has other impacts. On one hand, automation is often related to the introduction of shorter block lengths, thus increasing line capacity; on the other hand, with full automation, an extremely conservative safety regime must be applied, at least in the early stages of new system operation. Consequently, the ca-

capacity can be lower than for manual driving with regime *a*. When the automation is fully tested and proven reliable, the same safety regime as for manual driving or even a more liberal one can be applied, resulting in increased capacity. Generally, however, automation increases line capacity more if it is designed to compensate for random delays, so that regularity is increased, rather than through closer spacings among TUs.

4.3.5 Application of Equations to Different Modes

An interesting comparison of the way capacities of different transit modes can be obtained through application of the preceding equations. Six conventional modes, types of vehicles, and technical specifications, representing several real-world systems, as well as three unconventional modes added for comparison, are listed in Table 4.4. The selected models of a standard and articulated bus, LRT, and rapid transit vehicles are used for basic characteristics, with some values modified where it is considered that the capability of a mode can be represented by a value more typical for contemporary vehicles. Thus all systems are assumed

to have a high seat/standee ratio, but because of their low riding comfort, buses are assigned a limited number of standees to ensure passenger stability and circulation. The driver's reaction time t_r is assumed to be 1 s except on fully automated systems, where the liberal assumption of practically instantaneous reaction of the control mechanism ($t_r = 0$) is assumed. Emergency braking rates for rail vehicles are based on actual specifications, while buses are given higher values because of the higher adhesion they possess under most conditions. The highest deceleration rate is assumed for PRT, since all passengers are seated.

Because of their physical and operational characteristics, different modes operate under different safety regimes. Since buses and moderate-speed LRTs operate entirely under the driver's control, their safety regimes cannot be precisely defined, but it can be assumed that buses operate closest to regime *c* and LRT to regime *b*. High-speed LRT is usually signalized, so that regime *a* applies. Rapid transit always operates under regime *a*, which applies also to all fully automated modes.

Two capacity comparisons of the selected transit modes are presented: (1) vehicle way capacity, C_w , obtained by eliminating C_v from the equations for C_w for

Table 4.4 Typical vehicle design and operating characteristics of compared transit modes^a

Item	Unit	Modes		Single						
		Standard Bus	Articulated Bus	Four-Axle LRT Vehicle	Personal Rapid Transit	Two-Car AGT	Two-Car Articulated LRT	Eight-Car AGT	Six-Car RRT	Ten-Car RRT/RGR
n	veh/TU	1	1	1	1	2	2	8	6	10
l'	m	12.0	17.0	14.0	2.3	6.5	24.0	10.7	18.0	21.0
C_o	sps/veh	53 ^b	73 ^b	110	4 ^b	40	190	70	145	175
s_o	m	1	1	2	1	1	2	1	2	2
t_r	s	1	1	1	0	0	1	0	0	0
b_n	m/s ²	1.4	1.4	1.2	1.6	1.4	1.2	1.4	1.1	1.1
b_e	m/s ²	4.0	4.0	3.0	5.0	4.0	3.0	4.0	1.8	1.8
$V_{\max}$	km/h	90	80	80	70	50	90	80	100	120
$v_{\max}$	km/h	25.0	22.2	22.2	19.4	13.9	25.0	22.2	27.7	33.3
Operating safety regime		<i>c</i>	<i>c</i>	<i>b</i>	<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>	<i>a</i>

^aData given are typical for the selected modes with the exception of a few rounded or modified values to eliminate nontypical features. Acceleration rate $a = 0.8 \text{ m/s}^2$ and station standing time $t = 20 \text{ s}$ are assumed for all modes.

^bAssumes seating only.

respective regimes [Eqs. (4.36), (4.40), and (4.44)], and (2) way capacity in spaces/hour, C_w , which is the most important one. It is computed by the same three equations but without modifications. The two diagrams are shown in Figures 4.10 and 4.11, respectively.

The two sets of curves show several way-capacity characteristics of different modes. The greatest vehicle line capacity is achieved by eight-car AGT/APM trains, owing to their higher braking rate and shorter car length than RRT. This mode is followed by RRT with 10-car TUs and then by PRT, two-car AGT, and six-car RRT. In terms of way capacity in sps/h, the relationships are drastically changed. Rail modes with greater TU length and higher linear vehicle capacity Π have by far the greatest capacity. Their maximum val-

ues are reached at higher speeds than for buses. The curve for the hypothetical PRT system shows a much lower capacity than for any existing mode. Comparison of the two diagrams shows that both way capacity and running productive capacity increase with vehicle size and with the number of cars per TU.

The main numerical values from the diagrams in Figures 4.10 and 4.11 are summarized in Table 4.5. The table shows that in capacity and productive capacity, ten-car RRT is far superior to all other modes. It is followed by six-car RRT, eight-car AGT (based on Bombardier C-100 model), and two-car articulated LRT trains, while other systems, operating single vehicles (except an AGT with two), not only lag far behind in capacity and productive capacity but also have

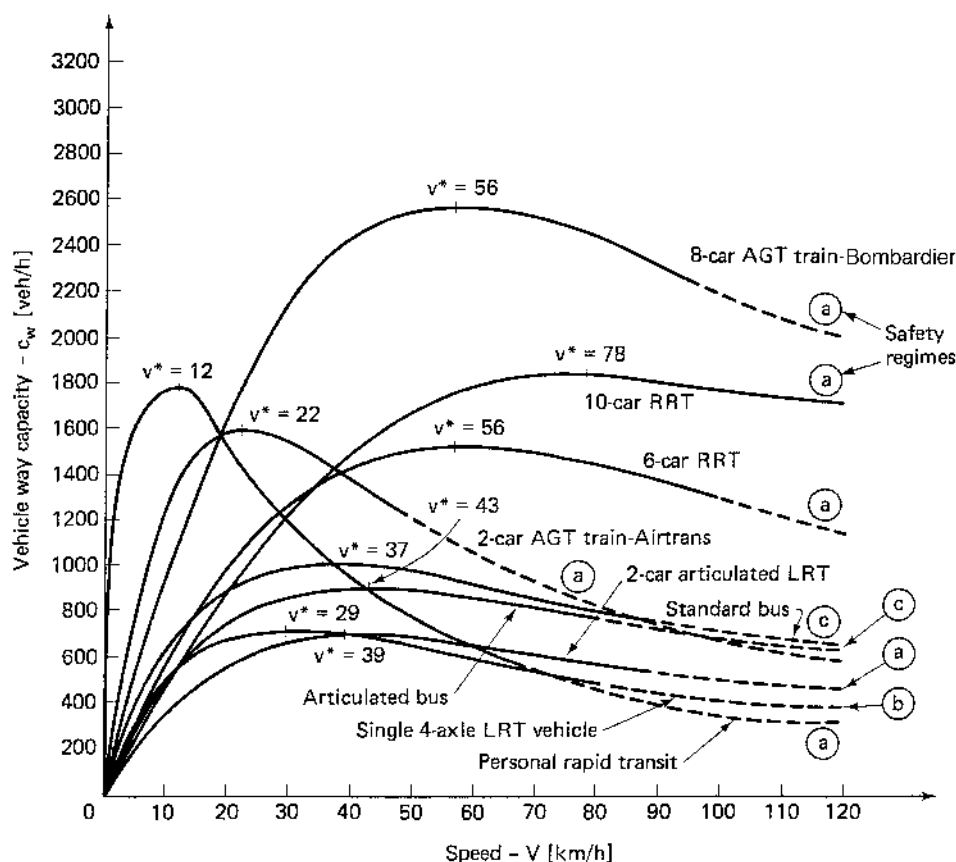


Figure 4.10 Vehicle way capacities as functions of speed: different modes with their typical safety regimes

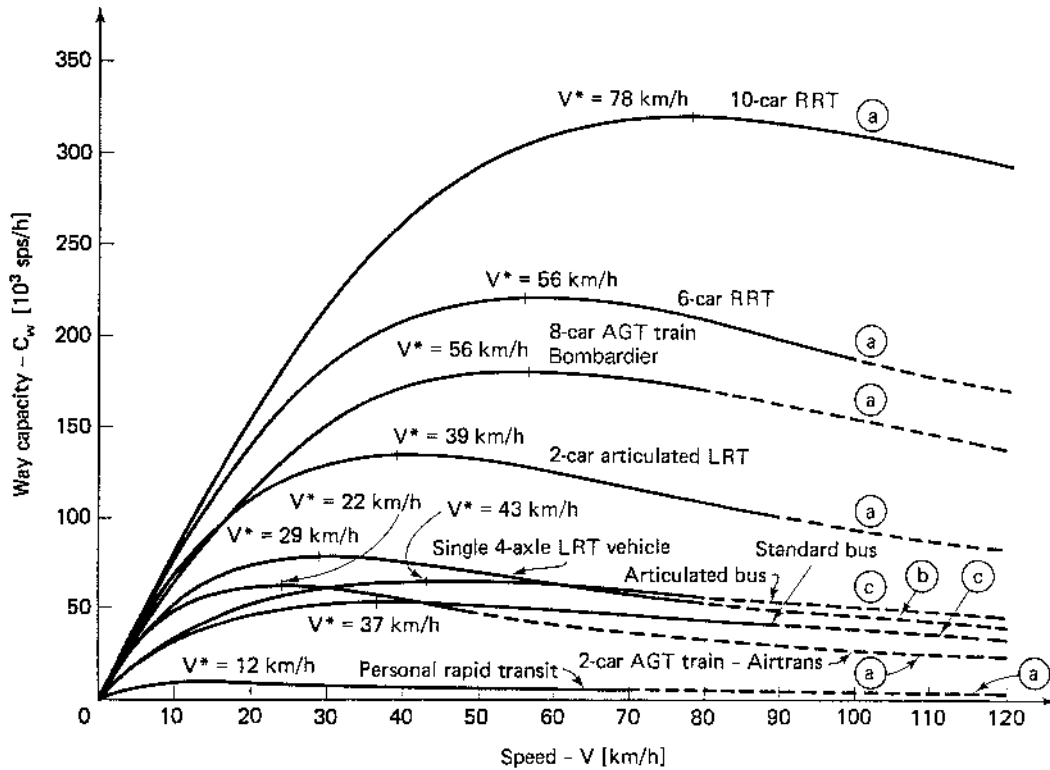


Figure 4.11 Way capacities of different modes for their typical safety regimes

lower optimal speeds for maximum capacity. For example, the standard bus has a maximum capacity at 37 km/h, compared with six-car RRT vehicles at 56 km/h. PRT is the lowest at 12 km/h.

An important conclusion from the preceding analyses is that the line capacity of transit systems should not be considered in isolation. Since it is closely related to other basic characteristics of modes, capacity must always be related to other performance and level of service measures, particularly speed and safety.

4.4 STATION CAPACITY

4.4.1 Significance and Definitions

Stopping of TUs at a fixed location always increases the minimum headway at which TUs can follow each

other with a given regime of safety. For this reason, station capacity is generally considerably lower than way capacity. The only exceptions may occur when stations are designed to accommodate multiple simultaneous stopping of TUs (i.e., when a station actually consists of several stop locations operated simultaneously). Consequently, station capacity governs the capacity of a transit line in the vast majority of cases. Its relationship to the line capacity required to meet the passenger demand is described in the next box.

Headways between successive TUs at a station consist of two groups of elements: (1) time intervals of vehicle motion (i.e., acceleration of LTU and deceleration of FTU), which depend on vehicle dynamic characteristics, operating regime and safety requirements, and (2) standing time, which consists of door opening, passenger exchange, and departure preparation (warn-

Table 4.5 Summary of theoretical capacities of major transit modes from Figures 4.10, 4.11, and 4.15

Mode— Vehicle Type	Safety Regime	n (veh / TU)	Way Capacity						Station Capacity						
			C _v (sps / veh)	h _{min} (s / TU)	f _{max} (TU / h)	c _w (veh / h)	C _w (sps / h)	V _w (km / h)	Running Productive Capacity-P _c (10 ³ sp-km / h ²)	h _{min} (s / TU)	f _{max} (TU / h)	c _s (veh / h)	C _s (sps / h)	V _s (km / h)	Running Productive Capacity-P _c (10 ³ sp-km / h ²)
Standard bus	c	1	53	3.6	1,014	1,014	53,754	37	1,989	30	120	120	6,373	29.7	189
Articulated bus	c	1	73	4.0	900	900	65,700	43	2,825	32	114	114	8,305	24.9	207
Single four-axle	b	1	110	5.0	720	720	79,200	29	2,297	34	106	106	11,732	14.8	174
LRT															
PRT	a	1	4	2.0	1,773	1,773	7,090	12	85	25	146	146	584	5.6	3
Two-car AGT	a	2	40	4.5	805	1,610	64,400	22	1,417	27	131	262	10,490	12.5	131
Two-car articulated	a	2	189	10.0	355	710	134,350	39	5,240	45	80	160	30,758	22.5	692
LRT															
Eight-car AGT (Bombardier)	a	8	70	11.0	324	2,589	181,250	56	10,150	52	69	554	38,800	28.5	1,106
Six-car RRT	a	6	145	14.0	255	1,527	221,470	56	12,402	56	64	386	56,037	32.0	1,793
Ten-car RRT / RGR	a	10	175	19.7	183	1,830	320,888	78	25,029	70	51	514	89,950	44.7	4,021

The relationship between the required capacity on a line and its ability to provide capacity is the following:

- *The highest passenger demand that occurs on any interstation spacing (called the maximum load section, or MLS) represents the critical volume that the line should carry.*
- *The maximum capacity a line can physically offer (in both vehicles per hour and spaces per hour) is determined by the station along the line that requires the longest headway $h_{s \max}$.*
- *Station headway is usually mostly a function of standing time t_s , which in turn depends on the passenger exchange volume (number of passengers alighting and boarding) and station operations.*
- *Consequently, assuming similar design and operating conditions at all stations, the “busiest station” (i.e., the one handling the highest passenger volume) determines line capacity.*
- *The two elements critical for demand and supply of capacity of a line, MLS and the critical station, are independent: the critical station may be located away from the MLS.*

ing, door closing, and departure signaling to the driver). With buses and other street transit vehicles, traffic and signal delays must also be considered, and a much wider distribution of h_s values than with controlled systems must be included in capacity computations. An analysis of TU motion (referring primarily to RRT trains), which is quite complex, is presented in summarized form in the following sections. Station standing time is discussed in Section 4.4.4.2.

4.4.2 Components and Influencing Factors

The following derivation of station capacity equations refers primarily to a single-track, controlled, guided system. Several new concepts must first be defined.

Stopping shadow of a vehicle (or TU) is the distance in front of the vehicle equal to its stopping distance for a given braking rate. As this distance “travels” with vehicle, it creates a “shadow area,” shown in Figure 4.12. Shadow area increases with speed, assuming that all other factors are constant.

Stopping shadow line is the line (i.e., set of points) that the stopping distance “draws” as the vehicle travels. It represents the front of the shadow area. When a vehicle travels at constant speed, its shadow line and the position of its front end are parallel. When it approaches a station and decelerates, its shadow line extends to the far end of the station platform and then

becomes a horizontal line. The path of the vehicle’s front end during braking converges with the shadow line and coincides with it when vehicle is stopped, as Figure 4.12 shows.

In most cases the stopping shadow of the FTU’s front-end and its distance from the rear end of LTU are analyzed. In some cases, however, the stopping shadow line of the LTU’s rear end is also considered. For example, if it is assumed that the LTU may stop with a finite braking rate ($b < \infty$), the distance between the FTU’s front-end shadow line and the LTU’s rear-end shadow line determines the degree of operating safety.

The time interval between the starting of the LTU and the stopping of the FTU at a station consists of several elements, as shown in Figure 4.12. The duration assumed for these elements depends on the critical condition for which the control system is designed. The critical event is the case when, during the LTU’s departure from the station, its acceleration is interrupted by some unforeseen event and the LTU is stopped. If the LTU stops instantaneously ($b_1 = \infty$), the critical curve in the diagram is the path of its rear end; if it decelerates at a finite rate, such as b_e or b_n , the critical curve is the rear-end shadow line for the respective rate. Both curves are shown in Figure 4.12. In no case can the FTU’s stopping shadow line be allowed to intersect the critical LTU’s rear-end line. For

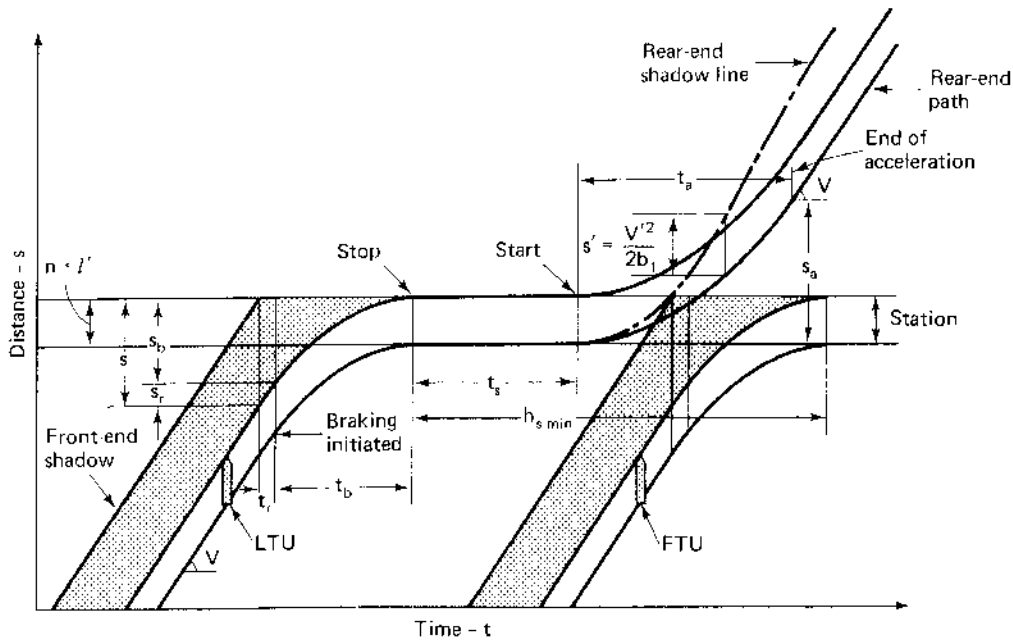


Figure 4.12 Time-distance elements of departure/arrival and headway between consecutive TUs at a station for $b_1 < \infty$

maximum line capacity, the two lines touch each other at the stopping point of the FTU's front end, which is assumed here to be the far end of the station platform (for some rapid transit systems this is correct; on others, the station platform is longer than the TUs).

The distance between the two critical curves (the LTU's rear-end shadow line and the FTU's front-end shadow line) that can be allowed is affected by several elements of line operation, particularly the following ones:

- **Block length:** Finite or zero (moving block—continuous information).
- **LTU acceleration:** The LTU reaches its maximum speed ($v_{\max}$) before it clears the platform, or after it departs from it.
- **Station spacing:** The station spacing is long enough that the TUs can reach maximum speed ($S \geq S_c$), or the FTU must initiate stopping from an acceleration regime.

- **Relationship between consecutive TUs in station:** The FTU is allowed to enter the platform area before the LTU has vacated it, or no simultaneous vehicle occupancy of station is allowed.

Each combination of these conditions introduces changes in the headway and capacity equations. The conditions assumed here are:

- Zero block lengths ($D = 0$);
- The LTU reaches $v_{\max}$ outside the station;
- $S > S_c$; and
- The LTU must clear the station before the FTU enters it.

4.4.3 Capacity Diagrams and Equations

4.4.3.1 Graphical Solution. With the preceding definitions of the basic elements of station operations, it is possible to jointly present the basic diagrams for

a consecutive LTU departure/FTU arrival sequence in a station; their relationship determines the minimum station headway. If it is assumed that the LTU's braking rate is $b_1 < \infty$, the situation is as shown in Figure 4.12: the critical curve is not the path of the LTU's rear end but its rear-end shadow line for b_1 . The minimum headway between the two TUs is graphically obtained by "sliding" the FTU's front-end shadow to the left until it touches the point where the LTU rear-end shadow line leaves the station. This provision assures that even if the LTU must interrupt acceleration and brake to a stop, the FTU still has sufficient distance to stop without collision.

However, some rapid transit systems apply an additional degree of safety. They operate with provision for safe following even in the event that the LTU would have an instant (stonewall) stop and the FTU applies an assumed reduced braking rate [b_r instead of b_n —see Eq. (4.55)]. This provides an additional safety distance. This regime of operation is shown in Figure 4.13. The FTU's shadow for b_r is shown. It represents the set of points at which the FTU's front end would stop if the braking rate applied were only b_r instead of b_n . This shadow is longer than the shadow for b_n by Δs :

$$\Delta s = \frac{v^2(K-1)}{2b_n} \cdot \left| \frac{s}{\text{m/TU}} \left| \frac{v}{\text{m/s}} \right| \left| \frac{K}{-} \right| \left| \frac{b}{\text{m/s}^2} \right| \right| \quad (4.57)$$

The minimum headway in this case is obtained graphically by "sliding" the diagram of the FTU's arrival to the left until the b_r shadow line entering the station comes directly under the point where the LTU's rear-end path is leaving the station, as Figure 4.13 shows. This relationship determines the additional safety distance.

4.4.3.2 Basic Equations. The expression for the minimum headway, shown in Figure 4.13, is

$$h_{s \min} = t_s + t'_a + \Delta t + t_r + t_b \cdot \left| \frac{h, t}{\text{s/TU}} \right| \quad (4.58)$$

While t_s and t_r are known, the other intervals are computed as follows. t'_a is the time of the LTU's acceleration to the point where its rear end leaves the platform (i.e., for a distance $n \cdot l'$ with acceleration rate a):

$$t'_a = \sqrt{\frac{2n \cdot l'}{a}}; \quad \left| \frac{t}{\text{s/TU}} \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{a}{\text{m/s}^2} \right| \right| \quad (4.59)$$

Δt is, as Fig. 4.13 shows, the time of the FTU's travel over distance $(n \cdot l' + \Delta s)$ at speed v :

$$\Delta t = \frac{n \cdot l' + \Delta s}{v} = \frac{n \cdot l'}{v} + \frac{v(K-1)}{2b_n} \cdot \left| \frac{t}{\text{s/TU}} \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{s}{\text{m/TU}} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{K}{-} \right| \left| \frac{b}{\text{m/s}^2} \right| \right| \quad (4.60)$$

Finally, t_b is the braking interval for FTU:

$$t_b = \frac{v}{b_n} \cdot \left| \frac{t}{\text{s/TU}} \left| \frac{v}{\text{m/s}} \right| \left| \frac{b}{\text{m/s}^2} \right| \right| \quad (4.61)$$

Introducing these expressions into Eq. (4.58) gives:

$$h_{s \min} = t_s + t_r + \sqrt{\frac{2n \cdot l'}{a}} + \frac{n \cdot l'}{v} + \frac{v(K+1)}{2b_n} \cdot \left| \frac{h}{\text{s/TU}} \left| \frac{t}{\text{s/TU}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{a, b}{\text{m/s}^2} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{K}{-} \right| \right| \quad (4.62)$$

Thus the general expression for station capacity, based on Eq. (4.12), is:

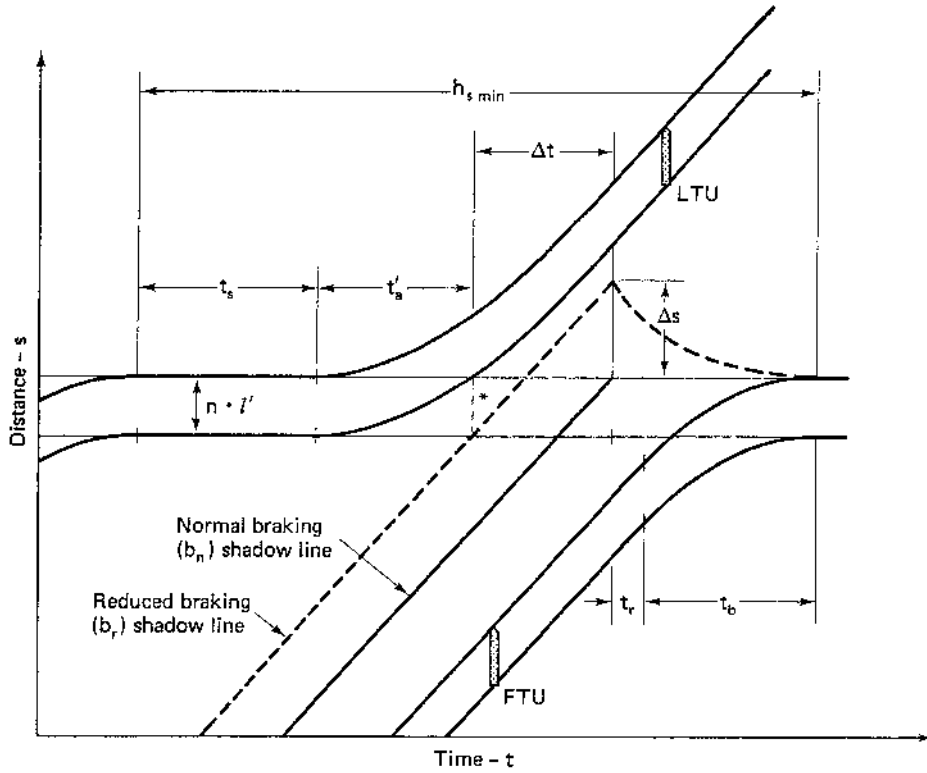


Figure 4.13 Minimum station headway with safety requirements typical for rapid transit systems

$$C_s = \frac{3600 \cdot n \cdot C_v}{t_s + t_r + \sqrt{2n \cdot l' / a} + n \cdot l' / v + v(K + 1) / 2b_n}$$

$$\left| \frac{C}{\text{sps/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{t}{\text{s/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{a, b}{\text{m/s}^2} \right| \left| \frac{v}{\text{m/s}} \right| \left| \frac{K}{-} \right|$$

$$(4.63)$$

The optimal speed for maximum capacity is

$$v_s^* = \sqrt{2n \cdot l' \cdot b_n / (K + 1)},$$

$$\left| \frac{v}{\text{m/s}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{b}{\text{m/s}^2} \right| \left| \frac{K}{-} \right|$$

$$(4.64)$$

and the maximum capacity, at v_s^* , has the expression:

$$C_s^* = \frac{3600n \cdot C_v}{t_s + t_r + \sqrt{2n \cdot l' / a} + \sqrt{2n \cdot l' (K + 1) / b_n}}$$

$$\left| \frac{C}{\text{sps/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{t}{\text{s/TU}} \right| \left| \frac{l}{\text{m/veh}} \right| \left| \frac{a, b}{\text{m/s}^2} \right| \left| \frac{K}{-} \right|$$

$$(4.65)$$

It is reemphasized that these expressions apply only to the conditions specified above. With a different operating regime, such as allowing a simultaneous partial occupancy of the station by the LTU and FTU, mathematical expressions would be somewhat different. Since the assumptions for the case presented here are conservative (the highest degree of safety), virtually all other assumptions would yield shorter headways and higher capacity.

4.4.3.3 Operating Safety Regimes. The relationship between the assumed LTU and FTU deceleration rates, which determines operating safety regimes and through them, way capacity, has a much less significant influence on station capacity. The other operating factors described above are much more important. Yet the previously defined safety regimes can also be applied to station operation. To compare station with way capacity, the same general expression for $h_{s \min}$, Eq. (4.58), must be used. The safety factor K is, however, not included. Expressions for individual time elements in that equation are then:

$$t'_a = \sqrt{\frac{2 \cdot n \cdot l' \cdot b_1}{a \cdot (a + b_1)}}; \Delta t = \frac{n \cdot l'}{v}; \text{ and } t_b = \frac{v}{b_{2n}}.$$

$$\left| \frac{t}{s/\text{TU}} \right| \left| \frac{n}{\text{veh}/\text{TU}} \right| \left| \frac{l}{\text{m}/\text{veh}} \right| \left| \frac{b \cdot a}{\text{m}/\text{s}^2} \right| \left| \frac{v}{\text{m}/\text{s}} \right| \quad (4.66)$$

Thus the expression for $h_{s \min}$ remains similar to Eq. (4.62), but it includes braking rates for LTU and FTU (acceleration rate is always for the LTU only):

$$h_{s \min} = t_s + t_r + \sqrt{\frac{2 \cdot n \cdot l' \cdot b_1}{a \cdot (a + b_1)}} + \frac{n \cdot l'}{v} + \frac{v}{b_2}.$$

$$\left| \frac{h \cdot t}{s/\text{TU}} \right| \left| \frac{n}{\text{veh}/\text{TU}} \right| \left| \frac{l}{\text{m}/\text{veh}} \right| \left| \frac{b \cdot a}{\text{m}/\text{s}^2} \right| \left| \frac{v}{\text{m}/\text{s}} \right| \quad (4.67)$$

The regimes of safety defined in Table 4.3 thus apply also to station operation, but with two modifications: (1) regime d does not have equal station capacities for all values of $b_1 = b_2$, as it does for way capacity, and (2) regime e does not apply, since it requires nonstop operation.

Consequently, for station capacity, regimes a , b , and c remain unchanged; values for braking rates of LTU and FTU, b_1 and b_2 , respectively, are the same as in Table 4.3. For regime d there are only two realistic cases:

- Regime d_1 , when $b_1 = b_2 = b_e$
- Regime d_2 , when $b_1 = b_2 = b_n$.

The braking rates for the five regimes are given in Table 4.3. Station capacities for the five regimes are

obtained by introducing respective values of b_1 and b_2 into Eq. (4.67), and then the obtained $h_{s \min}$ into the equation based on Eq. (4.11):

$$C_s = \frac{3600 \cdot n \cdot C_v}{h_{s \min}}.$$

$$\left| \frac{C_s}{\text{sps}/\text{h}} \right| \left| \frac{n}{\text{veh}/\text{TU}} \right| \left| \frac{C_v}{\text{sps}/\text{veh}} \right| \left| \frac{h}{s/\text{TU}} \right| \quad (4.68)$$

The station capacities for the five regimes are plotted in Figure 4.14, assuming the same vehicle and operating characteristics as for the way capacity curves in Figure 4.6. The diagram shows that impact of b_2 on capacity is significant at higher speed: the two regimes with $b_2 = b_e$ have higher capacities than the three regimes with $b_2 = b_n$. However, the impact of b_1 is negligible.

Comparing Figures 4.6 with 4.14 and 4.11 with 4.15, the following observations can be made about the relationship of theoretical way and station capacities:

- Both way and station capacities are functions of operating speed, but station capacity is somewhat less sensitive to it than way capacity.
- The optimal speeds for maximum capacities are approximately 1.5 to 2.0 times higher for way than for station capacities.
- Way capacities are approximately four times greater than station capacities for all modes, speeds, and safety regimes.

4.4.4 Measures to Increase Station Capacity

Station operation usually determines the capacity of an entire transit line. Therefore line capacity can often be increased by improving the capacity of the station with the longest minimum headways. In addition to the dynamic characteristics of the vehicles and the operating safety regime, the station capacity is greatly influenced by TU capacity and the station standing time of TUs. Measures affecting the latter two elements are described here.

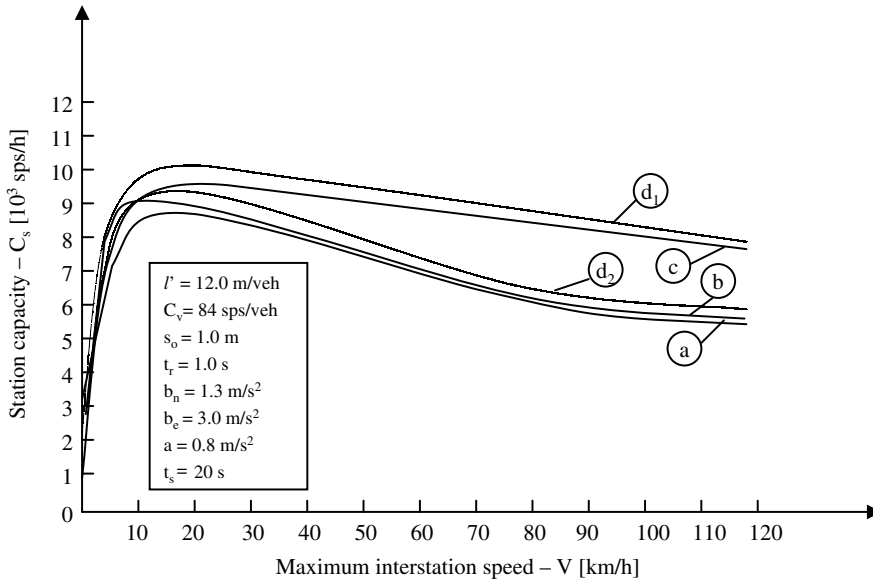


Figure 4.14 Station capacity curves: different safety regimes for the same vehicle

4.4.4.1 Transit Unit Capacity. Since station capacity is a linear function of TU capacity, maximum-size TUs should be operated when high capacity is needed. For a given set of conditions, an articulated bus always provides a higher station (and line) capacity than a regular bus. Similarly, use of an n -car train provides capacity nearly n times greater than operation of single vehicles (see Section 4.3.4.1).

4.4.4.2 Station Standing Time. Every second reduced from station standing time t_s directly reduces headway and thereby increases station capacity. In most cases it is much easier and less costly to shorten headways by decreasing t_s than by improving the dynamic performance of the vehicles. A number of factors influence t_s . Several of them can often be changed to increase station capacity.

The station standing time for vehicles with boarding and alighting via different doors (e.g., most buses) is expressed by:

$$t_s = t_o + \text{Max} (\lambda \cdot p_b, \mu \cdot p_a),$$

$$\left| \frac{t}{\text{s/TU}} \right| \left| \frac{\lambda, \mu}{\text{s/prs}} \right| \left| \frac{p}{\text{prs/TU}} \right| \quad (4.69)$$

where t_o is the fixed time lost during a TU's arrival and departure; λ and μ are the boarding and alighting times per person, respectively, including all available door capacities; and p_b and p_a are the numbers of passengers boarding and alighting, respectively, at the most crowded doors.

For the vehicles with boarding and alighting through the same doors (e.g., RRT, RGR, most LRT systems) the expression is:

$$t_s = t_o + \lambda \cdot p_b + \mu \cdot p_a.$$

$$\left| \frac{t}{\text{s/TU}} \right| \left| \frac{\lambda, \mu}{\text{s/prs}} \right| \left| \frac{p}{\text{prs/TU}} \right| \quad (4.70)$$

"Friction" between boarding and alighting passengers increases the times λ and μ for this type of operation.

The time interval t_o is mostly a function of preparations for the passenger exchange (boarding/alighting) process, such as opening doors, supervision and communication between the platform supervisor (if there is one) and the driver for door closing, and the TU's departure.

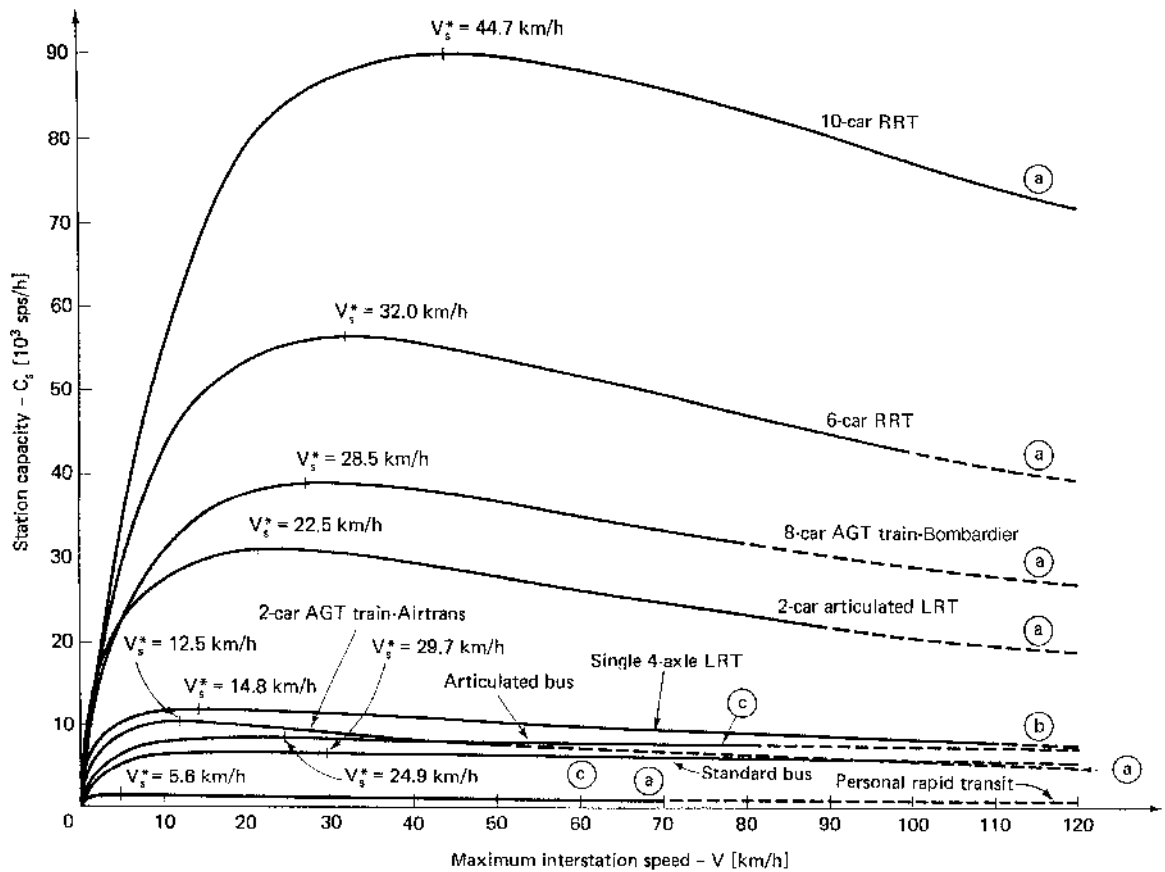


Figure 4.15 Station capacities of different modes with their typical safety regimes

Passenger exchange unit times (λ and μ) which greatly influence t_s at busy stations, are primarily functions of:

- Number of door channels per TU
- Fare-collection method (prior to or at boarding, type of fare, etc.)
- Platform height/vehicle floor-height differential
- Design of doors, adjacent areas in vehicles, and aisles
- One- or two-way passenger flow.

The slowest rates of passenger flow are obtained on buses with single-channel doors (fare collection at boarding, two to three steps, and narrow aisles). Av-

erage boarding times in such cases range from 2.0 to 2.5 s/prs for exact change fares to 4.8 to 5.0 s/prs for complicated fares and up to 6.0 s/prs for passengers with packages. Thus t_s for buses at moderately used stops is 20 to 40 s; with extremely low and high passenger volumes, it can be as short as 5 s or as long as more than 60 s, respectively.

The fastest passenger exchange is found on rapid transit systems that have 16 to 80 door channels (the upper limit is found, for example, in New York and Tokyo on 10-car trains with four double-channel doors per car side), platforms and floors at the same level, and no fare collection at boarding. In these cases λ and μ rates of 1 s/prs are typical, so that even if, because of uneven distribution of passengers to doors along a

train, it is assumed that only half of the channels are used, total boarding rate for the train is as high as 40 prs/s. Because of these extremely high passenger volume exchange rates, t_s on rapid transit systems is usually between 10 and 20 s, but sometimes it is as short as 7 or as long as 25 to 40 s.

The diagram in Figure 4.16 shows t_s as a function of p for a rapid transit station, based on Eq. (4.70). Assuming that the minimum train operating unit consists of two cars and that, as the passenger volume increases, the train is lengthened by additional two-car units up to eight cars, one obtains discontinuities in the t_s line. As the diagram shows, t_s remains within a rather narrow range, since the number of passengers per door remains approximately constant until capacity of the maximum length train is approached. At that time t_s may increase rapidly, and departure control (preventing further boarding) is necessary to avoid excessive delays.

4.4.4.3 Simultaneous Standing of Several TUs.

While RRT always allows coupling of cars to form the maximum-length trains that can be accommodated in

stations, this is seldom possible with other modes. LRT networks often have a convergence of several lines into a trunk line; to handle the resulting high frequency of TUs, trunk-line stations are often designed to accept several TUs simultaneously. With buses, the problem of accommodating high frequency is particularly common, owing to their lower vehicle capacity and the frequent convergence of many lines. Their capacity can be increased by several operational measures.

Stations without bypassing of vehicles have a single lane or track, so that vehicle arrivals and departures must be in the same sequence. Platooning can greatly increase line capacity at the price of a certain decrease in speed. First, forming of platoons at convergence points takes time, particularly if vehicles in each platoon must be in the same sequence to match predetermined stopping locations at stations for different lines. This is the case in the travel direction toward line divergences. Second, station standing times t_s are somewhat longer, since the vehicle with the longest t_s imposes this time on all vehicles in its platoon. The reduction of average headways is therefore less than proportional to the number of vehicles in a platoon.

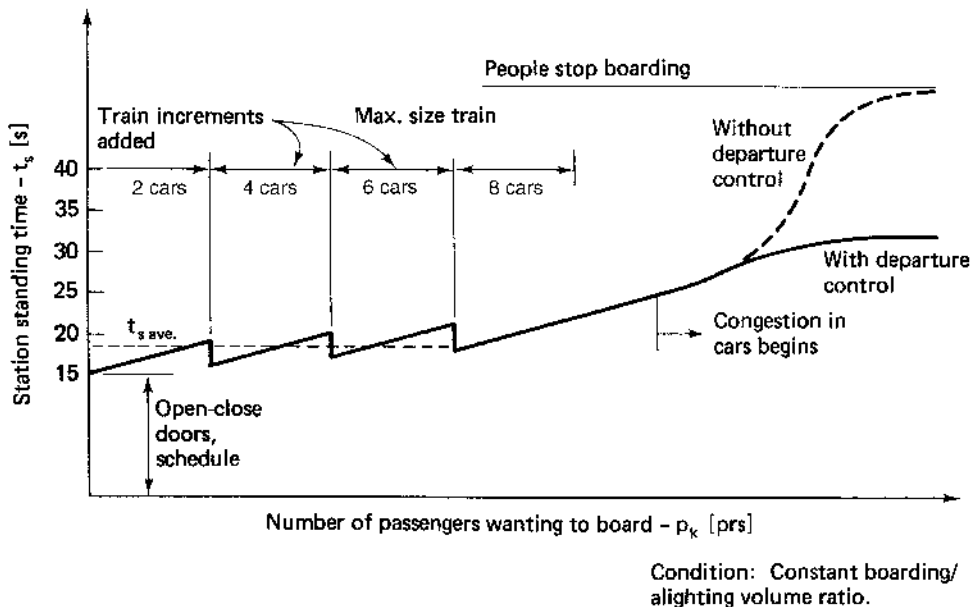


Figure 4.16 Train standing time as a function of passenger volume and train length

Simultaneous standing of two TUs is very common, but three or four are also possible. For example, several LRT underground stations in Philadelphia and Boston have three to four designated locations and an electric information board showing stopping locations and routes of arriving vehicles, so that passengers can wait at their proper platform locations. São Paulo has an operation with platoons of up to five or six buses.

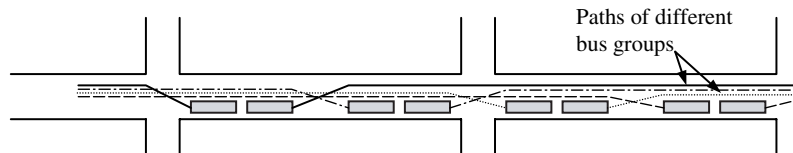
Stations with bypassing of vehicles require considerably larger areas than stations without bypassing: platforms must be longer and the travel way in the station at least twice wider. But they allow nearly independent arrivals and departures of TUs and therefore provide a higher capacity and fewer delays.

In most cases this type of station is used for bus lines. The design that can be used for stations with heavy passenger exchange of many bus routes on a CBD street is shown in Figure 4.17a. Bus routes are divided into four groups, each one using a separate set of stop locations (A to D). Buses using the same lo-

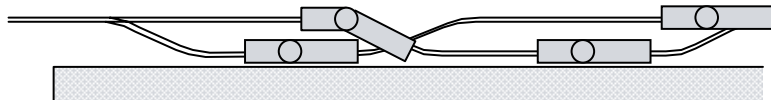
cation set cannot bypass each other, but they can bypass buses stopped at other location sets. This type of facility is most applicable to one-way bus-only streets (transit malls). On streets with heavy traffic volume, mutual interference between buses and other vehicles may significantly reduce the line capacity. Other types of bus stop designs are shown in Figures 5.22 through 5.25.

The same design concept, allowing independent arrivals and departures at two sets of stopping locations, can be used for trolleybus or LRT stations, as illustrated in Figure 4.17b.

Parallel stopping locations on both sides of an island platform (Figure 4.17c) can be used for RRT and other rail systems with doors on both sides of vehicles. These station types allow the fastest arrivals and departures of TUs. Although buses can also have stations with parallel islands (Figure 5.23 and 5.24a), this type of station is impractical for high-frequency operation, since it requires either passenger crossing of roadways

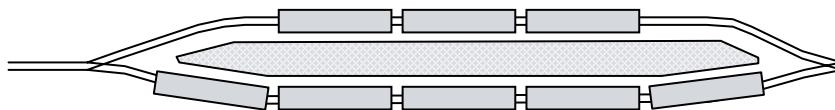


(a) Four sets of bus stop locations along a street. Each set can serve one or more lines (Based on operation in Portland, Oregon)



(b) Trolley bus station with independent arrivals to and departures from two sets of stopping locations (Base on operation in Athens, Greece)

Desirable conditions for cases a and b: one-way transit-only street, minimum roadway width 8.00 m, or a wide avenue without frequent congestion



(c) Rapid transit station with simultaneous parallel stopping at an island platform or for bypassing of local by express trains

Figure 4.17 Transit stations allowing bypassing of vehicles or trains

or one set of stairways for each island with large space requirements and complicated passenger flows.

Time-distance diagrams of TU arrivals and departures at stations with simultaneous standing of TUs are shown in Figure 4.18. Vehicle line capacity of all multiple simultaneous standing operations is computed utilizing the headways between platoons (ptn) of TUs:

$$c_s = \frac{3600n \cdot q}{h_p}, \quad \left| \frac{c}{\text{veh/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{q}{\text{TU/ptn}} \right| \left| \frac{h}{\text{s/ptn}} \right| \quad (4.71)$$

where q is the number of TUs per platoon and h_p the average headway between platoons. This headway consists of different components in each of the described cases. The line capacity is then

$$C_s = \frac{3600n \cdot q \cdot C_v}{h_{p \min}}, \quad \left| \frac{C}{\text{sps/h}} \right| \left| \frac{n}{\text{veh/TU}} \right| \left| \frac{q}{\text{TU/ptn}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{h}{\text{s/ptn}} \right| \quad (4.72)$$

These expressions are deterministic, not taking variations in the h_p into account. The variations can be significant, particularly with street transit services. For example, on heavily traveled streets, bus line capacities may be only 50% of the values that the foregoing expressions give, assuming a fixed minimum value for the platoon headway, $h_{p \min}$.

Off-line stations have at least two tracks or lanes for each direction: one for stopping, the other for passing of express TUs, usually at full speed. This type of stations is used on many RRT and RGR systems in Japan on the Caltrans RGR line south of San Francisco, where Baby Bullet expresses overtake local trains in Chicago (Photo 4.1) and on some busways, such as Transmilenio in Bogota. Deceleration/acceleration of the stopping TUs requires headways somewhat longer than $h_{w \min}$, and t_s of the stopping TUs is extended during the passings of the express TUs, but the latter suffer no delay if schedules are precisely maintained. Therefore capacity of these stations in

terms of stopping TUs (i.e., for boarding/alighting of passengers) is lower than capacity of regular “on-line” stations. The total “throughput” capacity, in terms of TUs passing through that point on transit line, however, can be much higher than capacities of regular stations (i.e., it is between station capacity and way capacity of the line).

An extremely detailed analysis of factors influencing rail transit line capacity and extensive data on actually achieved capacities are presented in Parkinson and Fischer (1996).

4.5 THEORETICAL AND PRACTICAL CAPACITIES OF MAJOR TRANSIT MODES

For a clear review of all the complex concepts of transit line capacity, its components, and influencing factors, a diagram of key interrelationships is presented in Figure 4.19. The diagram contains all the basic concepts from the preceding sections and major factors influencing them. A thorough understanding of these relationships is very important for correct computations of capacity, which is often a major consideration in the choice of modes or determination of basic design features (types of vehicles, station size, operating regime, etc.) of transit systems.

4.5.1 Important Considerations in Capacity Computations

The tendency to simplify the complex concept of line capacity and express it as a single number often leads to erroneous decisions. To avoid them, the following facts should be understood.

First, *transit line capacity is not a single fixed number*; it is closely related to system performance and level of service (LOS), including such factors as speed, reliability, comfort (e.g., sitting or standing), and others. In some cases an increase in the speed, comfort, and safety of a transit line may result in a decrease of its capacity. For example, streetcars following each other on a street at low speed can sometimes carry more passengers past a fixed point than if the line were upgraded into the LRT mode with larger vehicles op-

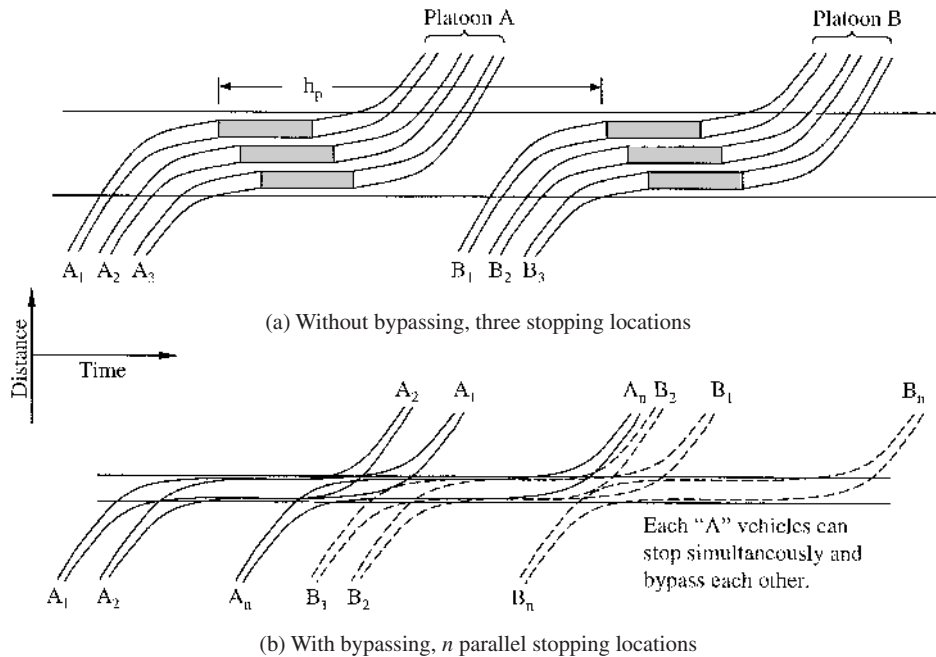


Figure 4.18 Operations of stations with multiple simultaneous standing

erating on mostly separated ROW at higher speed and safety and offering greater comfort (higher seating/standing ratio). Capacities of such diverse modes as RRT and streetcars or regular buses therefore cannot be correctly compared without also considering their operating speeds and other performance and LOS elements.

Second, *operation at capacity does not represent a desirable condition because it tends to "strain" the system to its maximum abilities*. Usually, the most satisfactory operation, considering both LOS and cost criteria, is with volumes that represent not more than about 80% of maximum possible capacity. It is therefore incorrect to consider the capacity of a mode as a required design criterion. The "threshold" of a mode's feasible application is usually several times lower than its capacity: many surface bus lines operate very efficiently with as few as 200 to 600 prs/h, LRT with 1000 to 2000 prs/h, and RRT with 4000 to 7000 prs/h on maximum load sections during peak hours, although the respective capacities of these modes may be about 3000, 10,000, and 30,000 sps/h or higher.

Third, *there is a significant difference between the design capacity (C) (i.e., the ability of a system to offer capacity) and the number of persons actually transported during one hour (C_p)*. The latter may be appreciably lower than the former, owing to fluctuations of passenger volumes within an hour, particularly during peak periods. For example, if 10,000 persons must be transported in one hour by a line offering 10,000 sps/h, fluctuations in demand may cause very long average waiting. To provide transportation service without significant delays, the transit line must have an hourly capacity substantially greater than its actual passenger volume.

Fourth, *way capacity is a different concept from station capacity*, as was shown in preceding sections. It is misleading to compare way capacity of one mode with station capacity of another and present them as respective inherent performance characteristics of the two modes (e.g., buses on freeways without stops with bus or rail lines with stops); such a comparison is valid only when the two modes inherently operate in different ways, such as automobile and transit. Automobiles



Photo 4.1 Express train (center) bypassing a local train (left) at an off-line station on Chicago's Metra system (Courtesy of Joe LeMay)

need not stop, and their way capacity usually governs the capacity of certain facilities, notably freeways. Transit modes, with very few exceptions (e.g., some express bus lines approach way capacity on open freeway, as Figure 4.20 shows, but each line is limited by its station capacity), must stop along their lines, so that with them *station capacity governs line capacity*.

The last and often most important fact is that *theoretical capacities are often quite different from practical capacities*. The capacities computed by formulas, as in the preceding sections (or even those obtained on actual systems but under fully controlled conditions without passengers), often yield values drastically dif-

ferent from those obtained in actual transit operations because of differences in operating conditions.

4.5.2 Review of Theoretical Capacities

The maximum way and station capacities of different modes shown in Figures 4.10, 4.11, and 4.15 are summarized in Table 4.5. The running productive capacities, defined in Section 4.3.3.2, are also computed for the maximum capacity point of each mode and included in the table.

The computed capacities are based on realistic, typical safety regimes for each mode. However, there are

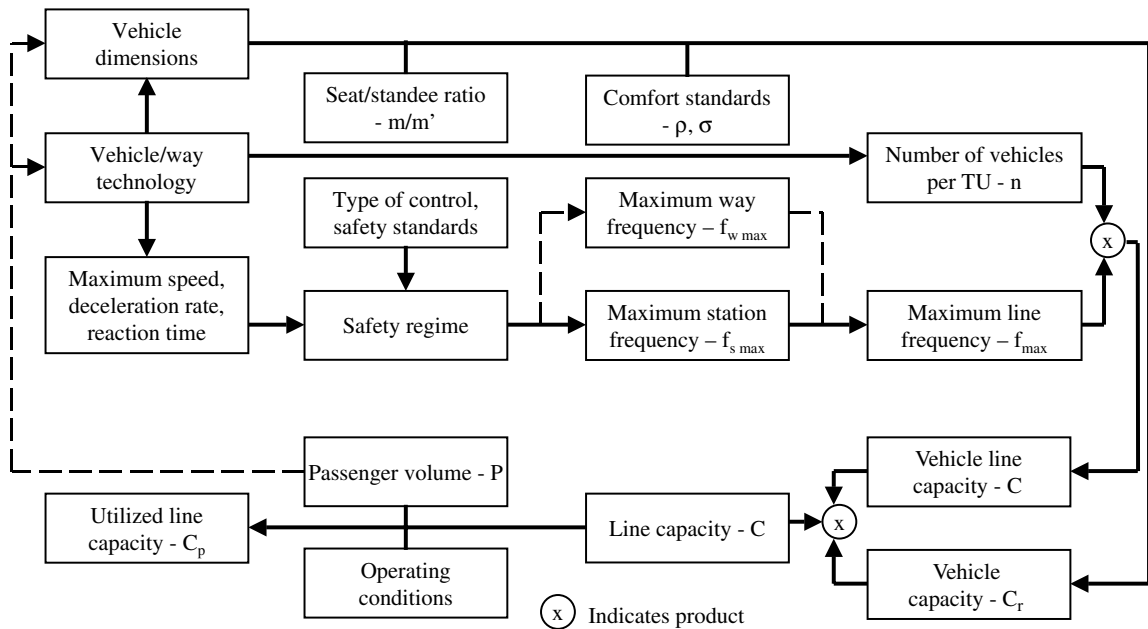


Figure 4.19 Relationship of transit line capacity determinants

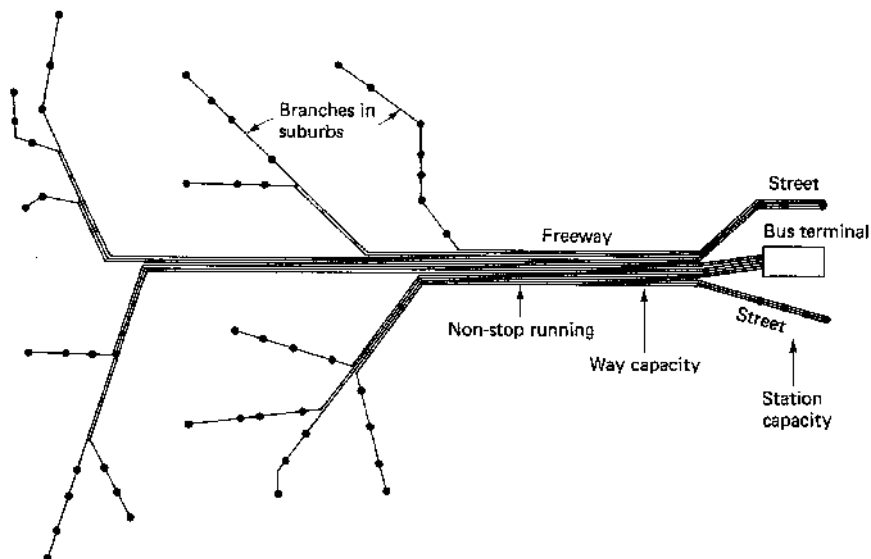


Figure 4.20 Nonstop bus operation on freeway, resulting in high way capacity

several factors in the real world that are not included in these models. First, continuous arrivals of vehicles at minimum headways cannot be achieved at points where different routes converge, and therefore along entire routes, without some delays. Second, variations in standing times at stations, braking and acceleration rates, and so on create irregularities in service (variations of headways), which decrease capacities. For these reasons the theoretical capacities shown in Table 4.5 represent values appreciably higher than those achievable by the same transit modes in the real world. Exceptions to this are street modes, particularly buses and streetcars, operating with double- or triple-location stations not accounted for in theoretical computations.

Although the specific numbers in the table are not adequate for precise analyses of individual modes, they give a useful insight into two relationships: (1) they indicate that way capacity is very much greater than station capacity, so that on all regular transit lines, the latter governs, and (2) the table shows the inherent differences in capacities among modes.

4.5.3 Actual Capacities of Major Transit Modes

Extensive analytical material and actual data about capacities recorded for different modes are presented by Parkinson and Fisher (1996), Levinson et al. (2003), and Kittelson (2003). The sections following here discuss in general as well as some specific examples of record capacities recorded for different transit modes.

It should be mentioned that many capacity records achieved in New York, Paris, London, and other western cities are in most cases not exceeded nor even achieved in recent years, because in most of the industrialized countries rail and other systems have been extended in recent years to increase quality of service, which requires greater area provided per passenger and thus lower throughput capacities.

Record capacities are, however, continuing to be observed in many countries with growing cities and improving transit services, such as Japan, Hong Kong, and many developing countries in Latin America and Asia.

4.5.3.1 Bus Line Capacities. Experience from many cities indicates that frequencies of up to 90 buses/h can be operated on streets with double or triple stop locations if heavy passenger boarding or alighting is not concentrated at a single stop. Such operations are possible without bypassing of buses or special organizational measures. This frequency corresponds to offered capacities of 6000 to 7000 sps/h, or passenger volumes of 4500 to 6000 prs/h.

If large stop areas permit bypassing of buses and dispatching supervision is provided, frequencies of 120 and exceptionally as high as 180 buses/h [Portland (Oregon)] can be achieved. These operations result in offered capacities in the range 9000 to 13,500 sps/h and passenger volumes of some 7200 to 10,800 prs/h, respectively. In all cases buses require at least two lanes per direction. The unique, specially organized operation with up to six-bus platoons in São Paulo exceeds these capacities appreciably, but operating speeds decrease. The Transmilenio Line in Bogota has extensive skip-stop and express-local operations with four lane stations which allow even higher capacities, so that at many locations capacity is limited by intersections at grade and their signal controls.

It should be mentioned that the busways of these BRT systems, in São Paulo and Bogota, represent major physical barriers for pedestrians and separate urban activities along their sides. Pedestrian access to stations is very long and the noise and pollution of buses operating at very high frequencies have contributed to deterioration along some sections of the busways (see Photos 5.24 and 10.3).

4.5.3.2 Streetcar and LRT Line Capacities. Interestingly, the maximum frequencies that can be achieved by streetcars are similar to those experienced with buses except for bus lines with four exclusive lanes: up to 90 TU/h with double stops but without major organizational interventions. With supervision and presale of tickets, frequencies of 120 TU/h have been achieved. A typical case is where two streetcar trains, consisting of three two-axle cars prior to World War II (or two articulated cars in recent years), depart from a streetcar stop at an intersection during each green phase of a 60-s signal cycle. Frequencies of 150

to 180 TU/h were recorded under exceptional conditions (slow, crowded vehicles, little auto traffic) that generally do not exist today.

The quoted frequencies result in offered capacities of some 18,000 and 24,000 sps/h without and with special measures, respectively. Passenger volumes carried are about 15,000 and 20,000 prs/h for the two cases.

Operation of higher-speed LRT systems differs considerably from that of streetcars. Signal control, often used for high-speed LRT systems, does not permit very high frequencies. The minimum headways of LRT systems are shorter than those of rapid transit lines because of shorter blocks, shorter trains, and simultaneous stopping of two trains in stations. However, LRT-line headways seldom average less than 60 to 80 s; the higher values in this range are typical for higher-speed line sections. The reduced frequency is, however, compensated by use of larger TUs: one- to three-car trains of six- to eight-axle articulated cars have total capacities of 160 to 600 spaces. Consequently, LRT systems can offer about the same capacities as streetcars but at considerably higher speeds: between 18,000 and 24,000 sps/h; they can carry 15,000 to 20,000 prs/h, although few systems carry such loads.

Thus LRT systems in most cases do not have higher capacities than streetcars; rather, their superiority over streetcars is reflected in considerably higher operating speeds and therefore higher productive capacities. Moreover, operation with signals offers higher safety, superior riding comfort, and LOS generally.

4.5.3.3 Rapid Transit and Regional Rail Line Capacities. The highest capacities recorded on a rail rapid transit line are in the range 55,000 to 75,000 prs/h. These exceptionally high utilized capacities—recorded in New York City, Moscow, and Tokyo—are followed by capacities from a number of cities, achieving volumes in the range 50,000 to 65,000 prs/h, assuming load factor $\alpha = 0.9$. Like the modern LRT systems, recently built RRT systems in most European and U.S. cities have been designed primarily to provide a high LOS rather than maximum possible capacities. Cities in developing countries, such as Caracas, Hong

Kong, and São Paulo have, however, a great need for high capacities and their RRT systems are designed accordingly. For example, São Paulo RRT has a design capacity of some 60,000 sps/h, provided by trains of six very large cars (21 m long and 3.21 m wide) operating at 90-s headways. Hong Kong achieves similar capacity by eight-car trains operating at 120-s headways. Its *utilized capacity* is estimated to reach 64,000 prs/h.

Some multitrack rail *corridors* exceed these capacities considerably. The Tokaido corridor of the Yamanote Line in Tokyo carries probably the highest passenger volume in the world: during the morning peak hour, RGR and long-distance trains on its four inbound tracks carry approximately 165,000 persons.

Because of the recent trend toward increased length of regional trips, several modern RGR systems have also been designed with very high capacities as well as higher speed and a much higher seat/standee ratio. On some nonelectrified lines, Toronto and Paris operate locomotive-towed trains with 10 bilevel cars, each offering approximately 175 seats. These trains with 1750 seats cannot, however, operate with very short headways. The electrified RER line passing under central Paris has in some respects a record performance. Its 219-m-long 9-car trains, offering 600 seats and some 1900 standing spaces, can operate at 150-s headways. The line thus provides a maximum capacity of over 60,000 sps/h. Operating at an average speed of 42 to 53 km/h, its productive capacity is extremely high: about 2.3 million sps-km/h²; this is actually greater than running productive capacities of most other modes.

Further progress in line control and ATO technology is likely to allow shortening of minimum headways of RRT probably to a minimum of 70 s on some systems (Moscow Metro may be leading in this effort). This will result in further increases in practical line capacities.

4.5.3.4 Review of Major Transit Mode Capacities. Table 4.6 summarizes major transit mode capacity ranges. The highest capacities ever recorded for each mode are omitted because of their limited trans-

Table 4.6 Ranges of actual capacities of major transit modes^a

Mode	Maximum or Moderate Values	Min. Ave. Headway— $h_{\min}$ (s)	Vehicle Line Capacity, $c = fn$ (veh/h)	Typical Vehicle Capacity, C_v (sps/veh)	Maximum Offered Capacity, ^b C (sps/h)	Resp. C_{av}/C_{av} of Regular Bus	Operating Speed at Capacity, V (km/h)	Productive Capacity, ^c P_c (10^3 sp-km/h ²)
Regular or express bus on streets, with or without reserved lane	Maximum Moderate	30 40	120 90	75 75	6,000–9,000 4,000–6,300	1.0 1.0	8–12 ^d 20–40 ^e	75–50 ^d 220–160 ^e
Articulated buses, ROW as above	Maximum Moderate	33 45	110 80	110 110	8,500–12,000 5,000–8,500	1.4 1.3	7–11 ^d 18–36 ^e	90–60 ^d 290–180 ^e
Streetcar on street or curbed median	Maximum Moderate	33 40	110 × 2 = 220 90 × 2 = 180	100 100	14,000–22,000 10,000–16,000	2.4 2.5	8–10 10–14	160 170
LRT on private ROW, regulated crossings	Maximum Moderate	60 80	60 × 2 = 120 45 × 2 = 90	180 180	12,000–20,000 8,000–15,000	2.1 2.2	18–30 20–35	384 316
Rail rapid transit, urban	Maximum Moderate	100 120	36 × 10 = 360 30 × 8 = 240	175 175	40,000–63,000 30,000–42,000	6.9 7.0	22–40 25–45	1,596 1,260
Regional rail, electrified	Maximum Moderate	120 180	30 × 9 = 270 20 × 9 = 180	180 180	30,000–48,000 20,000–32,000	5.2 5.0	25–45 30–50	1,360 1,040
Way capacity of buses on freeways <i>without stops</i>	(Capacity of off-line terminals governs)							

^aThis table presents upper limits of capacities of modes. The first, “maximum” lines, represent capacities that can be achieved with careful design and strict, competent operation; the second, “moderate” lines, are capacities achievable under most conditions without special efforts. Both sets of numbers are realistic for planning new systems. Special conditions and extreme crowding, exceeding all values in this table are not recommended for new systems.

^bUpper values represent rounded products of c_v and C_v .

^cValues for P_c here represent products of mean values of C and V . They are rounded to avoid a false appearance of great precision.

^dRegular buses; P_c values are for the “maximum” and “moderate” values.

^eExpress buses; P_c values are for the “maximum” and “moderate” values.

ferability to other systems. Two sets of ranges are quoted. The first set represents capacities achievable with careful design and strict, competent operating practices. The second set are capacities that can be achieved without special efforts. These are found in a number of cities. It is emphasized, however, that these are offered capacities (sps/h) which are higher than actually utilized capacities (prs/h). In planning transit systems, projected hourly passenger volumes must be increased to compensate for peaking within the hour (through the “peak hour factor”); further, they must be increased to account for vehicle capacity utilization (through the load factor α). These two increases actually convert the projected hourly passenger volume into the offered capacity required to serve that volume. The offered capacity should be used as the design volume for selecting modes from Table 4.6.

The ranges of maximum offered capacities in Table 4.6 show that LRT has approximately 2.2 times greater “moderate” capacity than regular buses for corresponding conditions. RRT, in turn, has 3.1 times greater capacity than LRT, or 7.0 times greater than buses. These ratios are based on the median values of capacity ranges given in the table. They may vary considerably in individual cases.

Ranges of operating speeds and productive capacities are also given for all modes. Since speeds also increase from buses toward RRT, the ratios of productive capacities among the modes are even greater than those for capacities.

4.5.3.5 *Special Cases of Very High Capacities.*

Higher passenger volumes than the quoted transit line capacities have been achieved in special cases. Although these counts are not relevant for planning most transit services, they are useful to know for planning operations on some special facilities.

Way capacity, which is considerably higher than station capacity, becomes relevant on joint sections of several routes that do not have stops or stations. This is sometimes the case with freeways or busways utilized by several routes for nonstop travel between two areas, as Figure 4.20 shows. The best known example is the I-495 approach to the Lincoln Tunnel between New Jersey and New York, with a single contraflow

lane for buses. Way capacities of buses can be three to four times greater than their line capacities. This facility in New Jersey/New York is, however, unique, since its bus passenger volume is about three times higher than such volumes on any other freeway. Actually, no other freeway carries bus passenger volumes greater than those carried in many cities by heavily loaded regular bus lines on streets. The main reason for this is that freeways are seldom built along the directions of major transit travel.

In a few cases LRT systems have sections without stations used by several lines that achieve very high capacities, but these are of little importance for the planning of new lines.

Point capacity, the maximum number of spaces carried past a fixed point in any direction, may exceed the station capacity of rail lines, but this concept is also of little significance. An example of high point capacity is an at-grade crossing of two tracks in the northwest corner of the Chicago RRT “Loop,” which is crossed by more trains than any station. However, this is a unique layout with operational problems and it would not be built on any new system.

Terminal capacity is of considerable importance for many transit lines. For example, a line must often serve as a major carrier of visitors to special events at stadia, fairgrounds, exhibitions, and similar facilities. The special feature of this service is that all alighting or boarding must take place at one station only. This concentration of passengers is more difficult to accommodate than boarding at several stations along a line. However, with special terminal designs and methods of organization, volumes equal to or higher than line capacities can be handled, thus achieving a record number of persons boarded per hour at one station. Good examples of this type of station were found on LRT systems in Brussels (for World’s Fair 1958), Hannover (annual Trade Fair), and Cologne (sport stadium). The Cologne stadium station design is shown in Figure 4.21. Utilizing a loop with eight storage tracks and a boarding area based on the concept from Figure 4.17b, this terminal provides for passenger boarding at a rate of 24,000 prs/h, and dispatching of 48 single eight-axle cars or two six-axle car trains during a 30-min period.

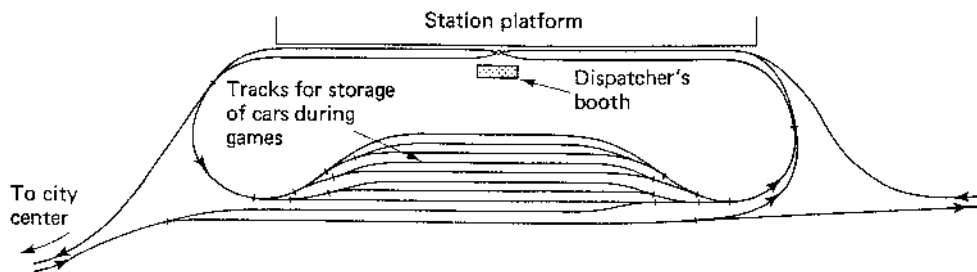


Figure 4.21 LRT terminal station with high boarding/alighting capacity (Sport stadium in Cologne)

Terminals on rapid transit lines with short headways also require careful design and organization of operations. Double-track crossovers before station platforms allow the fastest turnaround of trains, but crossovers beyond the station result in higher reliability of service because train dispatching from stations is not directly affected by arriving trains. When headways are very short (< 2 min), other measures must be used, such as a new driver boarding at the other end of the train, provision of three terminal tracks or splitting the line into two branches to lengthen headways at terminals.

4.6 OTHER QUANTITATIVE PERFORMANCE MEASURES

Capacity data presented in the preceding sections are primarily used for planning and evaluation of transit systems or modes. Several other quantitative performance measures—such as those relating to transportation quantity, work, efficiency, and utilization—are useful for evaluating the operations of any transit system. These measures or indicators can be used at several levels: for entire systems, individual modes, or individual lines; some can be used for financial analysis, others for service quantity, labor utilization, and other aspects of performance evaluation.

Many transit agencies, particularly large ones, regularly perform analyses utilizing a number of performance measures, statistical indicators, and other data. Many of these data are included in the annual reports of transit agencies. Benchmarking studies comparing peer transit systems with respect to their performance and efficiencies are based on many of these indicators.

This section defines and describes selected, commonly used performance measures from all major categories. Their review here is by no means exhaustive; many other indicators may be useful in specific situations.

4.6.1 Transportation Quantity or Volume

The quantity of physical elements of a transportation system is expressed in *units*, while *volume* usually designates the quantity processed per unit of time, such as hour, day, or year. The basic quantities describing transporting capacity and service of a transit system are:

Number of vehicles or *fleet size* is usually given by mode, or further classified by size, number of axles, or other characteristics.

Fleet capacity, or the total capacity of all vehicles in the fleet. Since the capacity may refer either to seats only or to seats plus standing spaces, there should always be an exact definition of this term.

Fleet capacity divided by fleet size gives the *average vehicle capacity*.

Number of lines and *network length* indicate the spatial extensiveness of transit services.

Number of stations/stops reflects accessibility of a transit system; with their geographic distribution, stations define the system's area coverage.

Annual number of passengers, or, more precisely, the number of trips served by the system during one year (or any other period of time) is the basic quantity of utilized transit service. This statistical number may include only revenue trips or all trips; it may represent

the number of trips in individual vehicles—“unlinked trips”—or count trips involving one or more transfers as single, “linked” trips. Naturally the former number is greater than the latter.

4.6.2 System and Network Performance

Various performance measures are sometimes analyzed for entire systems or for individual modes or network sections. Several common measures of system performance are presented here.

Intensity of network service is expressed by the number of space-km offered per kilometer of line per day. It is the ratio of daily space-km service provided and network length. The data presented in Table 4.7

are from industrialized countries during the 1970s, but in most of the given cities they have not increased because networks have been expanded and comfort standards increased. Some cities of developing countries, such as Mexico and São Paulo, would rank among the highest in the table. These data illustrate how this indicator shows differences in service intensities among modes.

Average speed on a transit system or on a network of individual mode must be computed by line, taking into account the intensity of service on each line:

$$V_{av} = \frac{\sum_i W_i \cdot V_i}{\sum_i W_i}, \quad \left| \frac{V}{\text{km/h}} \right| \left| \frac{W}{\text{veh-km}} \right| \quad (4.73)$$

where W_i is the number of vehicle-km operated daily on line i and V_i speed on that line, which may be operating, cycle, or other speed. V_{av} is the average value of the respective speed for all the lines.

Labor efficiency or productivity of different modes can be computed on an average and on a marginal basis, depending on the purpose of the analysis. Each measure is obtained by dividing the number of passengers carried (or spaces offered) during a given period of time by the respective number of employees: total for each service or additional employees needed for a marginal increment of additional passengers. The two usually differ considerably, as the following example illustrates.

In 1972, labor productivity, expressed as daily passenger-km per operating employee per year for the two modes of London Transport, was buses 224,000, rapid transit (“Underground”) 562,000. Thus *average* operating labor productivity on rapid transit was 2.5 times higher than on buses.

During the peak hours, for *additional* passengers, the Underground, with all station and supporting personnel already in place, can carry an additional 750 passengers by adding one driver. Buses can carry 42 passengers per additional driver. Thus, in this case, *marginal* operating labor productivity during peaks on rapid transit is approximately 18 times greater than that on buses. The ratio of operating labor productivities of

Table 4.7 Service intensity on networks of different modes^a

Mode	City	Space-km/km of Network/ Weekday (Both Directions)
Regional rail	Tokyo, JR	900,000 ^b
	Paris, RATP	405,000
	Hamburg (dc traction lines)	340,000
	Philadelphia, SEPTA	28,000 ^b
Rapid transit	New York, NYCTA	915,000
	Toronto	840,000
	Tokyo, Teito	630,000
	Paris, Metro	540,000
Light rail transit	Istanbul	150,000 ^b
	Cologne	105,000
	Stuttgart	100,000
	Hannover	85,000
	Philadelphia, SEPTA CTD	35,000
Streetcar	Hong Kong	300,000 ^b
Trolleybus	Philadelphia	28,000
Bus	Berlin	35,000
	New York, NYCTA	32,000 ^c
	Philadelphia	10,000

^a Offered spaces include seating and standing vehicle capacities. For further discussion of service intensity, see Leopold (1971).

^b Author's estimates.

^c For bus services in U.S. cities, $C_p = 70$ sps/veh was assumed.

the two modes is therefore about seven times greater on a marginal than on an average basis.²

4.6.3 Transportation Work and Productivity

The product of transportation units and the distances they pass—transportation work—is the basic measure of a transit agency's output. Although work does not contain time, its quantity is computed as a total over a time period, usually one year. The most common units of transportation work are as follows:

Annual vehicle-kilometers is the sum of distances passed by all vehicles in a transit fleet during one year. It is usually expressed in thousands or millions.

Annual space-kilometers, the product of annual veh-km and average vehicle capacity, represents the total quantity of service offered by the transit system during one year, usually expressed in millions.

Annual passenger-kilometers, the product of the number of passengers carried and average trip length, is the utilized output of transit service, its final product. Since this indicator includes the distance traveled, it is a better measure of service performed than is the annual number of passengers carried.

Further insight into service performance can be obtained through productivity indicators. While work represents transportation output independent of time, productivity represents the time efficiency with which work is performed. This is illustrated here by an example of line productivity.

Transit line productivity is the product of the number of vehicles operating on a line and their average speed; its unit is veh-km/h. Like other indicators, this one can also be expressed in space- or passenger-km/h.

The difference between work and productivity indicators is illustrated by the following example. Suppose that there are two sections of transit lines, A and B; each one is 9 km long and carries 1000 passengers per hour, but section A has an average speed of 14 km/

h, while section B operates with 28 km/h. The work performed during one hour on each line is the same: 9000 prs-km. However, their productivities differ considerably: on line A it is 14,000 prs-km/h, on line B, 28,000 prs-km/h. Thus productivity reflects the difference in speed, which indicators of work output, being independent of time, do not.

4.6.4 Transit System Efficiency (Productivity) Indicators

As mentioned in Section 4.1.3, a number of different efficiency indicators may be obtained as ratios of various measures of output to resources consumed. Many of these indicators are also referred to as *transit productivity indicators*. The most commonly used efficiency (productivity) indicators, including several outputs and resources, are defined here. Many others may be useful for specific types of analyses.

Vehicle-kilometers/vehicle/year, the total annual veh-km operated divided by fleet size, shows the efficiency of vehicle use for a transit service.

Passengers/vehicle-kilometer, the ratio of annual passengers to annual veh-km operated, is one of the indicators of the intensity of transit service use. The higher the number, the more economically efficient the service is.

Passengers/vehicle/year, or annual passengers divided by fleet size, indicates how efficiently vehicles are used with respect to the number of trips, or how many passenger trips per year are served, on the average, by each vehicle.

Passenger-kilometers/vehicle/year, or annual prs-km divided by fleet size, indicates how much work each vehicle, on the average, performs per year.

Vehicle-, space-, or passenger-kilometers/employee/year is computed by dividing annual work in terms of any one of these three units by the total number of employees (or operating employees only). This indicator reflects the efficiency of labor use or the labor productivity of a transit agency.

Daily passengers/employee, the ratio of weekday ridership to employees, is a similar indicator of labor efficiency or productivity.

²Data supplied by the late Mr. Rockwell, of *London Transport Executive*, in 1974.

Several measures of transit service can be expressed either through indicators of efficiency or through consumption rates, as illustrated by the following energy indicators. When transportation work, expressed in vehicle-, space- or passenger-km, performed during a certain period of time is divided by the quantity of energy consumed during the same period, these energy efficiency indicators are obtained:

The *vehicle-kilometers/kilowatt-hour* (or/Btu) ratio represents the technical energy efficiency of a vehicle, which depends on its technology, design (weight), performance, way characteristics, method of operation, air conditioning, and other elements.

The *space-kilometers/kilowatt-hour* ratio includes, in addition to the above, vehicle capacity. This is the basic indicator of energy efficiency of offered service.

The *passenger-kilometers/kilowatt-hour* ratio represents actual energy efficiency of utilized service or performed work. This indicator is more dependent on vehicle utilization than on its technical characteristics and operating conditions. Another important factor is that its average value for a given mode and type of service is usually much greater than its marginal value for additional passengers.

4.6.5 Consumption Rates and Utilization Indicators

Similar analyses of energy use by transit systems can be performed with energy consumption rate indicators, such as:

The *kilowatt-hours/vehicle-kilometer* ratio (again, seats or passengers may be used instead of vehicles) represents energy consumption per unit of performed work.

Other consumption indicators may include costs, labor, or space consumed per unit of work. The following are two common indicators of this kind.

Operating cost/passenger, usually computed as the ratio of annual expenditures to annual number of passengers, shows the average cost per served trip.

Operating cost/vehicle-kilometer (or space- or passenger-km), is also usually computed on annual ba-

sis. It indicates the cost of transit service per unit of its offered or utilized service, respectively.

Utilization indicators can be applied to a number of different items in transit system operation and service. The most common ones, referring to fleet, capacity and work, and personnel (labor), are defined here.

Vehicle-hours/vehicle/day, the ratio of the sum of the operating hours of all vehicles to fleet size, is a common indicator of vehicle utilization. Strictly, this indicator should be defined as the average percent of hours vehicles are in operation (vehicle-hours operated daily divided by vehicle-hours available—i.e., by fleet size times 24 h), but the average hours of operation per day are easier to use in practice. The same utilization coefficient can be computed on an annual basis.

The *scheduled vehicles/fleet size* ratio shows what percent of the fleet is used for operation during individual periods of day. This indicator reflects both the efficiency of vehicle scheduling and the technical condition of rolling stock. For systems with efficient scheduling and good vehicle maintenance procedures, this coefficient is usually as high as 90% to 95% during peak hours.

The *capacity utilization coefficient* or *load factor* α (defined in Section 4.2.1) is used for several items. It can represent the ratio of the number of passengers in a vehicle to its total capacity or it can be the ratio of passengers carried to capacity offered by all vehicles passing a fixed point on a line during one hour. Both ratios vary along a transit line as well as throughout the day for the same line. The maximum value of α along a transit line is basic for service scheduling.

The *work utilization coefficient* $\bar{\alpha}$ is the ratio of passenger-km carried (utilized service) to space-km operated (offered service). It is computed as the product of number of passengers and average trip length divided by the product of vehicle-km operated and vehicle capacity. This ratio can be computed for an individual run of a single vehicle, for a transit line during a certain period of time (hour, day), or for entire system on annual basis. The higher this coefficient is, the better system utilization is and the more economical its operation. Higher utilization, however, also indicates lower passenger comfort.

Both capacity and work utilization coefficients are used extensively in the analysis and scheduling of transit services. They are shown graphically on a typical diagram of passengers carried/capacity offered for a transit line in Figure 4.22.

The *operating personnel utilization coefficient* η is computed for finding the number of employees required for a given service as well as for analysis of efficiency of manpower use in operating transit system. This coefficient η , or net hours worked as percent of work hours paid, is obtained via the following three different coefficients:

The *attendance coefficient* η_a is the ratio of operating employee on-the-job time to their total paid time. The difference is time lost due to vacation, illness, and other reasons for absence.

The *coefficient of scheduling losses* η_s is the ratio of employee on-vehicle time and on-the-job time. It includes losses due to the timing requirements of schedule and crew assignments. Preparation for the run, travel between garage and line, rest intervals, re-

serve times, and so on are the items included in this coefficient.

The *coefficient of terminal time losses* η_t reflects the time loss due to terminal times. It is computed as:

$$\eta_t = \frac{1}{1 + \gamma}, \quad \left| \frac{\eta}{-} \right| \left| \frac{\gamma}{-} \right| \quad (4.74)$$

where γ is the ratio of terminal time to travel time on a line.

The total coefficient of operating personnel utilization, η , can now be defined as:

$$\eta = \eta_a \cdot \eta_s \cdot \eta_t, \quad \left| \frac{\eta}{-} \right| \quad (4.75)$$

This coefficient represents the ratio of the number of net employee hours for operating vehicles to the total paid operating employee hours.

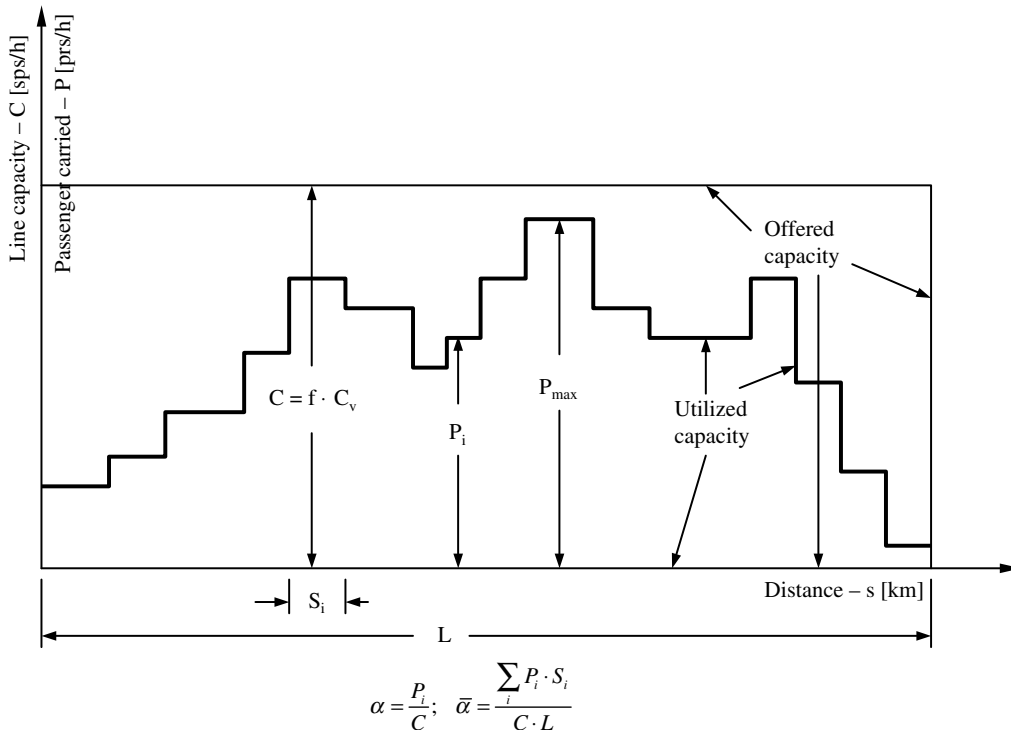


Figure 4.22 Line capacity and work utilization coefficients

EXERCISES

- 4.1.** (Closed book) Define the following concepts:
- a) Spacing between TUs
 - b) Frequency of service
 - c) Vehicle productivity
 - d) Consumption rate
 - e) Train stopping shadow
 - f) Way capacity
 - g) Moving block
 - h) Transit line capacity
 - i) Average speed on a transit network
 - j) Operating personnel utilization factor
 - k) Coefficient of terminal time losses
- 4.2.** Define maximum utilized capacity and maximum offered capacity of a transit line. What is their ratio and how does it affect passenger comfort and economics of operations?
- 4.3.** A metro line operates during peak hours with six-car trains at three-min headways and carries 14,800 prs/h on its maximum load section. The capacity of each car is $C_v = 180$ sps/veh. The minimum headway that can be maintained on an open line between stations with the existing block signals at present operating speeds is 40 s, while the longest minimum headway at a station is 105 s. Compute:
- a) Scheduled capacity of the line, C'_o
 - b) Maximum load factor $\alpha_{\max}$ at present
 - c) Way capacity of the line, C_w
 - d) Vehicle line capacity, c
 - e) Maximum offered line capacity, C
 - f) Maximum load factor $\alpha_{\max}$ if the line operates at its offered line capacity and its passenger volume increases by 20% over the present volume
- 4.4.** Select several vehicles for which data can easily be obtained, such as different automobile models, two different buses, and several rail or other guided vehicles. Compute their linear capacities π and compare them.
- 4.5.** Compute and plot a diagram of way capacity and running productive capacity as functions of speed for an LRT system with two-vehicle trains operating under safety regime b . Its characteristics are as follows: $C_v = 174$ sps/veh, $\ell' = 21.50$ m, $s_0 = 3$ m, $t_r = 1.0$ s, $b_n = 0.9$ m/s², $b_e = 2.8$ m/s².
- 4.6.** Draw a typical diagram of way capacity versus speed for a regular bus line under safety regime c . Then draw general shapes of capacity curves for:
- a) The same line operating under safety regime a
 - b) Articulated buses under safety regime c
- Explain which factors in the capacity equations would be modified by these changes.

- 4.7. Compute vehicle way capacity c_w for a metro line for running speeds of $V_1 = 54$ km/h and $V_2 = 72$ km/h and three different TU sizes: two, four, and six cars. Each car is $\ell' = 18$ m long. Assume safety regime a , $b_n = 1.0$ m/s², $s_0 = 3$ m, and $t_r = 1.0$ s.
- 4.8. Analyze operations on a rail line in your city: obtain its passenger loadings for all station spacings and measure the average standing times of trains at the busiest stations. Find which station is critical for line capacity and explain why. Find the MLS on that line and discuss its relationship with the critical station.
- 4.9. (Closed book) Draw a time-distance diagram of a train departure from a station.
 - a) Show the train in the position where it has just cleared the end of the station platform.
 - b) Supposing that this train is an LTU, show the shadow and path of its FTU entering the station under safety regime a . Show all components of its stopping distance S_d .
- 4.10. List and explain various measures that can be used to increase station capacities of:
 - a) A rail rapid transit line
 - b) A bus line operating on a street

Start with organizational measures; then describe various improvements requiring station reconstruction or provision of an additional lane, respectively.
- 4.11. Define the productive capacity of a transit line. Compute it for several lines in your city. If possible, include different modes by technology, ROW category, or type of operation. Discuss the meaning of the numbers obtained and of compare them.
- 4.12. It is sometimes suggested that reserved bus lanes or busway facilities are justified only when a bus line carries 5000 prs/h during the peak hour; that an LRT line should not be constructed unless it carries 10,000 prs/h; and that a RRT line should transport at least 30,000 prs/h on its maximum load section. Analyze these statements and define all the conceptual errors on which they are based.

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5

HIGHWAY TRANSIT: BUS, TROLLEYBUS, AND BUS RAPID TRANSIT

Buses are the most widely used transit technology today. They are operated in nearly all cities with transit service, in a majority of them as the only transit mode. This chapter focuses on buses; it also includes trolleybuses, which differ from motorbuses in some technical, operating, and cost characteristics. Bus rapid transit (BRT), or upgraded bus systems with partial separation from general traffic, which has become recognized as a separate mode, is presented in Section 5.4. Buses operating as paratransit are covered in Chapter 9.

5.1 FAMILY OF HIGHWAY TRANSIT MODES

5.1.1 Definitions

Highway transit consists of buses (including motorbuses, trolleybuses, and other vehicle types) operating mostly on urban streets with general traffic. Buses are rubber-tired, steered vehicles that can have a variety of technical and operational characteristics. Most buses have single body with two axles and a total of six rubber-tired wheels. There are also articulated models with three axles and up to 10 wheels and double-articulated with four axles and up to 14 wheels. Bus capacity, typically about 70, may vary between 15 (minibus) and 140 spaces (double-articulated bus). By far the most common propulsion is by diesel motor. Electric propulsion from overhead wires (trolleybus) is less common but very efficient under certain conditions (hilly terrain, environmental sensitivity). All other pro-

pulsion types are less commonly used, but their number and diversity are increasing.

The vast majority of buses operate on streets, in mixed traffic. A small but increasing number of cities have reserved and separated bus lanes for heavily traveled routes. The highest ROW type is the busway, a roadway used exclusively by buses. Bus lanes and busways have been increasingly organized or built in many cities of developing and industrialized countries. Major investments and organizational efforts to provide separate infrastructure—busways, separate stations, and priority treatments at intersections—have resulted in upgraded bus services and increased ridership. In a number of North American cities, however, some of the bus lanes and even busways have been converted into high-occupancy-vehicle (HOV) facilities, which have benefited auto users but degraded bus services.

With respect to operations, buses are used for virtually all types of services, from short-haul to regional, from local to express, all-day or peak-period only, as well as for irregular service (see Section 2.1.4). Although each type of service should have an influence on the type of vehicle and ROW, that correlation is not very strong; for example, a standard 12-m-long bus can be found on all types of routes. It is therefore even more difficult to precisely define different modes of bus systems (shuttle, regular, regional, BRT, etc.) than it is to define rail and other modes that have a close interdependence among vehicle design, ROW category, and type of operation. Bus vehicle classifications are

based on propulsion and body design (size), while bus modes are based mostly on type of service and infrastructure when they have separate facilities.

5.1.2 General Characteristics

The most important characteristics of highway transit modes result from their three basic features: ability to operate on virtually all streets, low investment cost (except BRT), and limited-capacity TUs, or single vehicles. Each one gives buses some inherent advantages and some disadvantages.

1. *Ability to operate on most streets* exists because buses (except trolleybuses) contain their own power plants. It gives buses several major advantages over other transit modes. Their *routes can be placed on any street*, as demand requires and other factors permit. Their *stops* can be placed *at many points*. *Temporary reroutings* are also easy. On the negative side, the ability of buses to mix with other traffic makes it *much more difficult to separate buses than is the case with rail and other guided modes* where their operations would require such treatment. Because they “blend” with other traffic and their routes have no fixed facilities, buses have a *weak identity and image*. Another limitation is that as highway vehicles buses are subject to legal regulations of maximum body dimensions.
2. *Low investment cost*: minimal route infrastructure makes *rapid introduction, changes, and extensions of bus routes and stops* very easy. Buses are ideally suited for use on test routes, transitional services during rail transit construction, promotional routes, and so on. Low investment, on the other hand, results in *low permanence* and usually *little influence of bus lines on land use and urban form*.

BRT often requires large stations, special lanes or roadways, and traffic control equipment (signals, signs, barriers, etc.). It sometimes also uses much higher-performance vehicles than standard buses. Since this may involve considerable investment (similar to corresponding rail

lines), *BRT* systems do not have either the advantages or the disadvantages of the extremely low investment characterizing regular buses. Their passenger attraction capability is greater, and they assume a *higher performance/higher cost combination*, which partially overlaps with the lower performance/cost ranges of *LRT* (see Section 2.3.6 and Figures 2.6 and 2.7).

3. *Limited capacity*. *TUs* make buses the *ideal mode for lightly to moderately traveled transit routes*. For services that require *TUs* with capacities of 15 to 60 spaces, buses are usually the most economical mode. When passenger volumes are high, buses are less economical than rail modes because of their limited capacity. Their *labor productivity cannot be increased* by greatly enlarging vehicle capacity, by coupling vehicles into trains, or by automatic driving, as is the case with guided modes on ROW category A. Motorbuses with diesel traction require lower investment than electric trolleybuses and rail systems, but their performance is distinctly lower: internal combustion engine (ICE) traction vehicles have lower acceleration and no energy recovery in braking; they also produce more noise and air pollution, preventing them from operating in tunnels and reducing their suitability to exhaust-free pedestrian areas.

The low investment costs and availability of small vehicles can “stretch” bus applications to very lightly traveled routes, where their characteristics overlap those of paratransit. The “upper end” of bus applications is found, generally, where their advantages of flexible deployment, easier branching, and lower investment become outweighed by the higher labor productivity, performance, service quality (particularly comfort and safety), and higher passenger attraction of rail modes. The range of bus applications is thus quite broad, explaining the use of this mode in all cities with transit.

5.1.3 Bus Transit System and Bus Rapid Transit Concepts

The service quality and role bus transit has in a city depends mostly on the ROW buses use. Their relation-

ship with general traffic is the basic element that influences not only the design of vehicles but also the investment and operating costs of the system as well as its performance. Therefore, prior to the discussion of bus travel ways in the following section, three general types of bus transit systems are defined here.

Conventional bus services in many cities are planned and operated as lines on which bus travel is “flexible”; that is, it operates in mixed traffic with stops at curbs along the way. A common practice, particularly in North America, is to use buses with narrow doors, allowing alighting through any door and collecting fares at front doors only, all resulting in very slow boarding. Bus stops are at every corner, and considerable time is lost due to traffic signals. The stops often have inadequate information for passengers. As a result, conventional bus service often has limited speed and reliability. The conventional bus service on streets is adequate for individual lines and local users. It requires little investment but offers services with weak image and reputation. It is usually not competitive with auto travel.

Bus transit systems (BTS) are bus services planned and operated with vehicles, travel ways, stops/stations and operations that are integrated as efficient transit systems. This type of bus transit has been developed in recent decades to provide high-quality, attractive services in some North American cities such as Portland, Oregon, and in many European cities (e.g., in Germany, Sweden, Denmark, France, and increasingly in other countries).

Bus rapid transit (BRT) is a BTS that has not only coordinated components but also high-quality elements that require considerable dedicated space for lanes, roadways, and stations. These elements involve substantial investments for infrastructure and equipment and enable the system to provide much higher performance than conventional bus and BTS lines. BRT is described in Section 5.4.

This clarification of concepts is fundamental to the understanding of bus services in light of many developments in recent years. Upgrading of conventional buses into BTS became common in Germany (VÖV and VDA, 1979, VDV, 1999), and the need for such upgrading was argued for North America (Vuchic et al., 1994). This and successes of BRT in Curitiba, São Paulo, and Bogota led to the emergence of BRT and

its promotion in North America. However, considerable confusion has developed when the term “BRT” has been used for many improvements that have led to BTS only. This often blurs and downgrades the BRT concept. The introduction of specially designed buses and longer stop spacings on regular streets are measures that can be applied on most bus systems to upgrade them to BTS. However, the designation “BRT” can be correctly used only for the systems meeting all or most of the six characteristics listed in Section 5.4.

It should be mentioned that most of the present efforts to improve buses to BTS have much broader applications in cities than BRT, which is applicable only to a limited number of cities and corridors. The present push for BRT may thus have an indirect but much more beneficial impact through making existing bus services faster and more reliable than through building of new BRT systems.

Because the types of travel ways, i.e., their ROW categories, represent the main component determining system performance, BRT is described in Section 5.4, following Section 5.3, which reviews the entire range of bus travel ways. Bus stops and operations and a review of the all bus modes are covered in Sections 5.5 to 5.7.

5.2 THE VEHICLES

Because of their wide use and short life (5 to 12 years, exceptionally 15 to 20 years), buses are produced in far greater numbers than other types of transit vehicles. Some manufacturers offer a certain number of options in motor power, transmission type, modular body construction, floor layouts, seating arrangements, and other elements. Therefore transit operators usually get less involved in vehicle technology and special design features than they do with rail and other more custom-designed modes. The most important technical characteristics of buses concerning operators and planners are presented here.

5.2.1 Classification by Propulsion Systems

By far the most common propulsion system for buses is the diesel engine, and for trolleybuses the electric

motor. In the last couple of decades, rapidly increasing public concern about air pollution, noise, and vibration has in many countries resulted in the introduction of laws requiring buses to meet rigorous air pollution standards. As a result, a number of bus models have been produced that have greatly reduced negative effects. Buses with some new propulsion systems meet rigorous standards required by U.S. federal, state of California, and European Euro IV clean air standards, produce lower noise levels, and have little vibration.

The maximum pollution levels allowed by government regulatory agencies in the United States and the European Union are given in Table 5.1 for two years to show the trend of increasing standards.

However, in many cases, the significant progress achieved toward more environmentally and passenger-friendly buses that meet these standards has come with considerable increases in the purchase and operating costs of buses as well as additional weight, more complex maintenance, and certain operational difficulties. The process is therefore still continuing.

In many countries and cities, not only in developing countries, where special financing for improved performance are not available, buses still produce objectionable air pollution and noise, which are particularly strong during vehicle acceleration. They are most objectionable in high-density urban centers with dense pedestrian traffic.

Standard bus models as well as the greatly improved new designs and propulsion systems are briefly described here.

5.2.1.1 Diesel Bus. The vast majority of buses in the United States are powered by the six- or eight-cylinder four-stroke water-cooled straight in-line or V-type diesel motor. The power of motors is usually in the range 150 to 300 HP (110 to 220 kW), but some models for express regional lines or routes on hilly streets may exceed this range (Photo 5.1).

Since the mid-twentieth century, the diesel motor has supplanted the gasoline motor in most transit buses except in small units (minibuses) because of its superior characteristics: ruggedness, simplicity, very economical operation due to higher thermal efficiency, and easy maintenance. These features make the diesel motor the most economical onboard power plant for buses presently available. Even so, with respect to performance (acceleration, speed on steep terrain), the diesel



Photo 5.1 A contemporary articulated low-floor diesel bus in Chicago (Courtesy of Kelly Martin)

Table 5.1 United States and European Union government standards for maximum amounts of pollutants produced by urban buses (all pollutants are in g/kW-h; to obtain g/bHP-h, divide by 1.34)

	Carbon Monoxide (CO)	Nonmethane Hydrocarbons (NMHC)	Particulate Matter (PM)	Oxides of Nitrogen (NOx)
U.S. emissions standards ^a				
1998 EPA	20.8	1.74 ^c	0.0671	5.36
2007 EPA	20.8	0.188	0.0134	0.268
EU emissions standards ^b				
Euro III (2000)	2.1/5.45	0.66 ^c /0.78	0.10/0.16	5/5
Euro V (2008)	1.5/4.0	0.46 ^c /0.55	0.02/0.03	2/2

^a Promulgated in g/HP-h, converted to g/kW-h.

^b First number for European stationary cycle (ESC), second for European transient cycle (ETC).

^c For total hydrocarbon.

bus is not as good as a trolleybus of equivalent size and motor rating (see Section 3.3.4). Another disadvantage of the standard diesel bus is its visible exhaust and high output of particulates, vibration, and noise.

A *clean diesel* motor has been developed to reduce the air pollution produced by the conventional diesel motor. The clean diesel uses ultra-low-sulfur diesel fuel. It produces low levels of air pollution, especially of the carcinogenic particulates. The disadvantage of this type of motor compared to standard diesel is the substantially higher purchase cost of buses.

Compressed Natural Gas (CNG) propulsion is provided by a modified diesel motor with spark ignition or a specially built motor. CNG buses carry fuel in large cylinders of considerable weight, usually on the roof. They have been tested and operated in a number of North American, European, and Asian cities. General findings lead to the comparison with regular diesel and clean diesel buses given in the box.

Compared to clean diesel, CNG has the same differences as above except that the two bus models have similar levels of pollutants and the cost difference is much smaller in comparison with regular diesel.

5.2.1.2 Trolleybus. As electrically powered highway vehicles that obtain power via trolley poles from two overhead wires (+ and -), trolleybuses are the only rubber-tired highway vehicles without a self-

contained power source for regular operation (Photo 5.2). Due to electric traction, they have several significant performance advantages over diesel buses, including more rapid and smooth acceleration and deceleration, particularly on gradients (see Section 3.3.3). With recently introduced types of electronic motor control, current models regenerate power during braking, making them even more energy-efficient than earlier models (see Section 3.4.5). They produce extremely low noise and no exhaust fumes. Moreover, trolleybus vehicles are more durable than diesel buses (see Section 3.3.5). Their disadvantages compared to diesel buses are that they require a higher investment and line maintenance costs (for overhead wires). Also, their travel is limited to the network of overhead wires except for short distances or maneuvers, which trolleybuses can negotiate under power from their batteries or propulsion by a small gasoline motor.

Electric battery bus or *electrobus*, a bus with an electric motor powered by batteries, is, with respect to operations, an ideal highway transit vehicle: it combines the excellent performance and lack of air and sound pollution of trolleybuses with an extremely low investment and free movement throughout the street network of diesel buses. Their disadvantages are, however, even more significant. The batteries are very heavy and have a limited capacity for power storage, so that they must frequently be recharged or ex-

CNG compared to regular diesel buses have:

- + Less engine wear (less frequent oil changes)
- + Cleaner exhaust
- + Lower noise production
- = Fuel cost—depends on local conditions
- Higher purchase cost
- Lower power output (approximately by 20%)
- More CO₂ produced due to lower efficiency
- Greater weight, which causes more wear and tear on tires and brakes
- Special maintenance facilities required to prevent fume buildup
- Shorter operating range



Photo 5.2 An articulated trolleybus (Geneva; courtesy of Christopher Puchalsky)

changed. Due to limited power, electrobuses are rarely longer than 10 m. Also, their operating costs are considerably higher than those of diesel buses. For these reasons electrobuses have been used only in special cases, such as on short lines in pedestrian zones or in environmentally sensitive areas.

5.2.1.3 Dual-Mode Bus. An international team of bus designers, with considerable effort developed during the 1970s a bus that has both diesel and electric traction. It can operate on a trunk section of a line in the center city, or in a short tunnel section as a trolleybus and then proceed on streets as a diesel bus. This allows integration of heavily traveled sections requiring clean air and low noise production in the city center with services on extensive branch lines and in low-density suburban areas where investment in over-

head wires would be too costly. Transition between line sections with diesel and electric traction is performed at tunnel entrances by automatic raising and lowering of trolley poles at specially designed funnel sections on overhead wires. This type of vehicles has been operated satisfactorily in Seattle (the tunnel is now being rebuilt for LRT line). The recently built BRT Silverline in Boston utilizes the same technology. A guided dual-mode bus is shown in Photo 5.3.

This dual-traction operation has obvious advantages in combining the low-investment lightly traveled suburban lines with “clean operation” in pedestrian-oriented areas and high-investment tunnel sections in the center city. However, dual-mode buses have two independent drive trains with separate controls, resulting in considerable weight and complexity. To accommodate all aggregates, only articulated buses can be



Photo 5.3 Dual-mode guided bus in Essen (Courtesy of Simon Smiler)

used, and their cost has been approximately two to three times greater than the cost of trolleybuses with similar bodies and operating life spans (15 to 20 years). Due to their high cost and the disadvantages of operating driver-steered buses in tunnels, this bus model has had very limited applications.

5.2.1.4 Hybrid Bus. This bus model has a diesel (sometimes gasoline) ICE, an electric motor/generator, and an electric battery or other energy storage device. A special switching mechanism allows the use of either of the motors or their combination during different regimes of travel. This combination makes for the most efficient use of the two types of motors. Generally, the ICE runs at a much less variable load than in regular buses with ICE propulsion only, while the storage aggregate (battery) supplies extra power when needed. When less power is needed, as in constant-speed travel,

the ICE charges the battery. Braking is regenerative (see Section 3.3.3.3): the kinetic motion of wheels propels the generator, which charges the battery. There are two types of hybrid buses by the arrangement of the basic traction aggregates: series and parallel. Their interconnections and operations under different bus travel regimes are shown in Figure 5.1.

The *series hybrid bus* has an ICE that powers an electric generator. The produced electric energy is used to power the electric motor, which propels the differential and tractive axle of the bus. During the peak power demand in acceleration, ICE power is assisted by battery power. At constant speed, the battery may provide all the power. When the bus is coasting or idling, electric current produced by the ICE-generator combination is used to charge the battery. During braking, the traction motor is converted into a generator and the current produced is also sent to the battery.

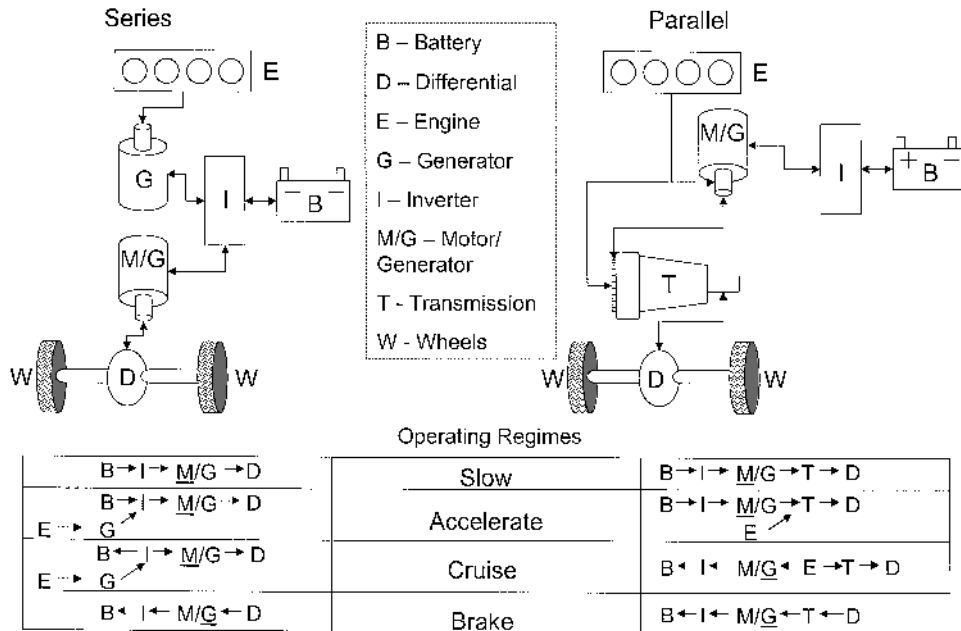


Figure 5.1 Hybrid propulsion system configurations, drive trains, and operation in different regimes

Thus, the ICE does not drive the bus axle directly but only through the electric traction motor.

The *parallel hybrid* has both the ICE and an electric motor powering the vehicle axle, each alone or both in tandem. During coasting or standing, the ICE can power the motor as a generator and charge the battery. In braking, the bus axle also propels the generator and the produced current charges the battery.

Like the dual-mode bus, the hybrid bus is designed with the capability of using both its ICE and electric motor for propulsion. However, while the dual-mode bus can use either the ICE or electric motor (from its power supply line) one at a time, the hybrid bus can use both propulsion units in tandem, and it has a battery or other storage medium that can supply power to the electric motor for traction (although not as powerful as the dual-mode bus drawing current from the power line). The ICE propulsion of the generator and regenerative braking charge the battery. Thus, the hybrid bus utilizes the three aggregates interconnected in a complex manner to optimize both power for accel-

eration or regeneration in braking, so that each can always operate close to its optimal regime.

The hybrid bus has shown very promising results in the testing and operations of sizable fleets in several cities and some national parks (see the following box). They have high efficiency, but that efficiency is obtained at the cost of more complex aggregates and their interworking mechanisms.

5.2.1.5 Other Propulsion Systems. Several other propulsion types have been used for buses. The most significant are the following:

Ethanol, biodiesel, and liquefied petroleum gas (LPG) buses use modified diesel motors and produce considerably lower emissions than regular diesel. Ethanol and biodiesel involve mixing fractions into regular diesel fuel, while LPG requires special pressurized tanks.

Propane gas, stored in bottles in liquefied form, is used for adapted diesel motors. This propulsion is cleaner than that of the common diesel motor because

Tests with several fleets to date have shown the following features of the hybrid bus as compared to regular diesel:

- + Optimal combination of ICE and electric motor provides better performance than ICE alone.
- + Combination of fuel and electricity results in lower cost of power.
- + Much less air pollution and noise production.
- Higher purchase price (approximately 20% to 30%, but this difference may decrease with larger orders).
- Greater complexity and weight of the propulsion system.
- More sophisticated maintenance due to greater complexity of design.

propane burns with less residue than oil. The motor is also quieter and has less wear. The disadvantages of propane diesel motors are a somewhat lower power output and the need for special caution in propane storage. Generally, propane has been superseded by compressed natural gas (CNG) propulsion.

Gasoline (Otto) motors dominate as the propulsion type for small buses (minibuses) because of their lighter weight and lower cost than diesel for small power output.

The *inertial energy bus (IEB)* has been developed with several different propulsion, charging, and design concepts. An early version of the IEB, the Gyrobus with a large flywheel, was developed about 1950 by the Swiss firm Oerlikon and used in several cities until 1969. Garrett Corporation developed and tested a somewhat different version of the IEB for rail vehicles. However, all these tests found that the flywheel, with several tons of mass, represented a substantial additional load on the vehicle and required very precise controls and safety devices. The Phileas model, developed by Advanced Public Transport Systems in the Netherlands as a prototype for testing many new technical concepts, has both a flywheel and battery option. Ultracapacitor, a high-powered battery, and several other storage devices have also been tested on different bus models.

In summary, at present the diesel motor is still the dominant bus propulsion system in most cities around the world. However, the trend is toward the increased use of hybrid, clean diesel and several other variations

of buses that are more energy efficient and “cleaner” with respect to air pollution, noise, and vibration than diesel buses. The main problem these models are facing is the higher purchase cost and, in most cases, more complex design and aggregates, requiring sophisticated maintenance, as well as, in some models, lower vehicle capacity. Despite their discontinuance in many cities during the 1950s and 1960s, particularly in the United States and United Kingdom, trolleybuses continue to be used in over 200 cities in the world.

5.2.2 Classification by Body Type

Vehicle size and body characteristics are largely independent of the propulsion type. Some manufacturers produce diesel buses and trolleybuses with identical bodies and practically equal weights. Consequently, the following description of vehicles are grouped by bodies regardless of their propulsions.

Technical data for different bus and trolleybus types, including models from several countries, are given in Table 5.2. Major categories of buses by their body type and main features are described here. To fully explain the roles of different bus types, the merits of vehicle size are presented first.

5.2.2.1 Optimal Bus Size. The general factors influencing optimal applications of large versus small transit vehicles, described in Section 2.2.2, are somewhat related to transit mode. Applied to buses, they

Table 5.2 Technical data for selected models of different bus types

1. Type	—	Midi	Standard	Standard	Standard	Standard	Electric	Hybrid	Articulated	Double articulated	Double decker
2. Manufacture	—	Bluebird	Nova	Scania	Nabi	Neoplan	Neoplan	New Flyer	Neoplan	Vanhool	Volvo
3. Model	—	Ultra LF	Nova LFS ^a	CN94 UB 4x2	40-LFW	Trolleybus	AN460/LF CNG	DE60LF	18.28	AGG300	B7L-5700
4. Overall length	m	9.14	12.40	11.99	12.19	12.19	12.19	18.80	24.79	24.79	10.34
5. Front overhang/ wheelbase ^a	m/m	2.27/3.99	2.97/6.20	2.65/6.00	2.18/7.01	2.17/7.11	2.17/5.80/7.70	2.17/5.80/7.70	2.17/5.64/7.26	2.72/5.79/7.15/6.45	5.70/2.27
6. Width	m	2.59	2.59	2.55	2.59	2.59	2.60	2.59	2.59	2.55	n.a.
7. Min. turning radius	m	n.a.	11.16	19.68	13.41	13.11	11.80	13.11	13.11	12.00	9.00
8. Height	m	3.10	3.12	3.00	2.90	2.92	3.35	3.35	2.92	3.28	n.a.
9. Floor height	m	0.66	0.37	0.34	0.81	0.37	0.39	0.39	0.37	0.83	n.a.
10. Boarding (step) height, kneeling	m	0.25	0.27	0.32	0.38	0.30	0.32	0.32	0.30	0.33	0.25
11. Number of doors	—	2	2	2	2	2	2-5	3	4	4	2
12. Capacity: seats /total	—/—	19/n.a.	41/n.a.	n.a.	40/n.a.	33/n.a.	60/96	65/n.a.	72/130	72/130	n.a.
13. Motor power	kW	149	209	169	n.a.	—	246	n.a.	n.a.	265	158
14. Fuel tank capacity	L	227	473	300	473	—	557x2	606	606	300	270
15. Weight: tare/ gross	ton	n.a./12.0	n.a./18.0	n.a./19.1	13.1/18.5	n.a./19.7	19.8/29.0	n.a./30.7	n.a.	n.a.	n.a.

^a One wheelbase for regular buses, two for articulated, three-axle ones.

are as discussed here and presented on a diagram in Figure 5.2.

1. *Line capacity*, required to meet passenger volume, increases nearly linearly with vehicle size. For a given volume, larger buses cause less congestion and offer higher service reliability. For example, 2000 prs/h can be transported on a typical urban street much more reliably and at a higher speed by articulated buses carrying an average of 67 persons at 2.0-min headways than by standard buses carrying 50 persons each operating at 1.5-min headways. Minibuses carrying only 25 persons and averaging 45-s headways would have serious backups, delays, and lower speeds, which could be avoided only by providing two lanes and supervisory personnel at all bus-stop areas.
2. *Service frequency* is desirable for passengers, but above 20 to 30 departures per hour it is fully satisfactory.

3. *Vehicle maneuverability* decreases with vehicle size. Large vehicles are less convenient and slower on routes with many turns, narrow lanes, and so on. A 16-m-long articulated "push" bus is less maneuverable than a standard 12-m-long single-body bus.
4. *Riding comfort* increases with the vehicle size on single-body buses, but may be lower with articulated and double-decker buses.
5. *Operating costs* per unit of offered capacity (space-km) decrease as vehicle size increases. This is mostly due to higher labor productivity, but lower energy consumption per space, costs of vehicle maintenance, and other items also contribute.

The selection of bus size is usually a complex task because the relative importance of these factors varies with local conditions. Thus, in some cities or on some bus lines, maneuverability is an important factor

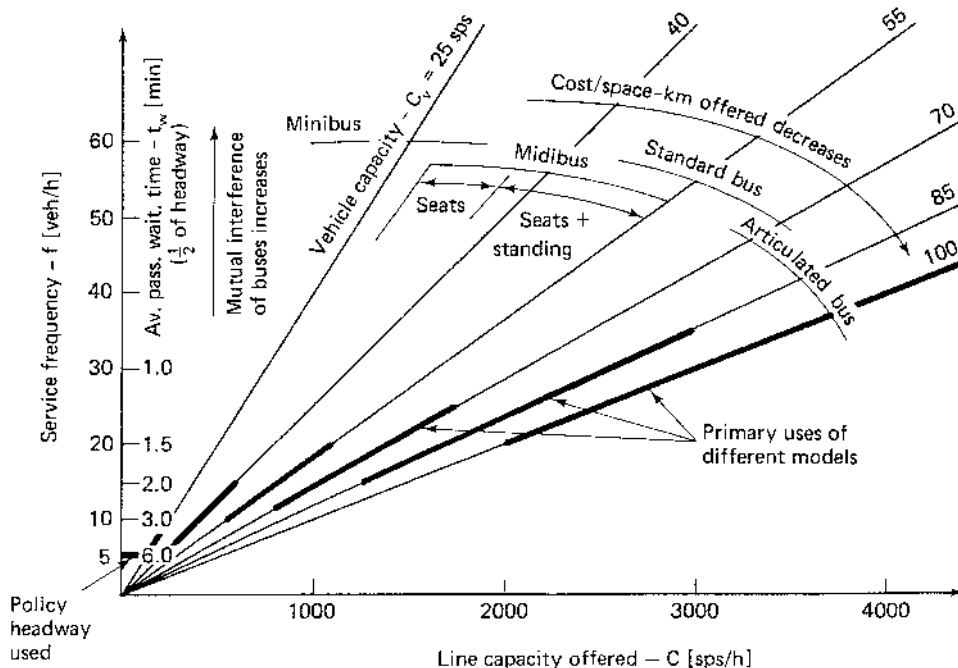
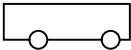
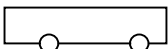
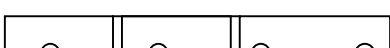
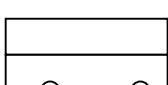


Figure 5.2 Influences of passenger volume, service frequency, and unit costs on optimal bus size

Table 5.3 Different bus vehicle types

Type	Sketch	Length (m)	Capacity	
			Min / Max Seats	Total
Minibus		6–7	12/20	30
Midibus		8–10	16/30	50
Standard bus		10–12	35/55	85
Articulated bus		16–18	40/75	130
Double articulated bus		22–24	40/80	140
Double-decker bus		10–12	60/95	125

against use of the maximum size buses: many European cities find 11-m regular and 16.5-m articulated buses preferable to the standard-length buses (12 and 18 m, respectively) or extra-long 15-m standard buses, which require special permits owing to their wider turning paths. Often, however, operating costs and service reliability (as affected by line capacity) are the dominant factors. Therefore, with increasing demand, as soon as headways are reached that guarantee minimum waiting time (3 to 6 min), line capacity should be further increased by introducing larger vehicles rather than higher service frequency, which causes higher operating costs and decreases reliability. These relationships are plotted on the diagram in Figure 5.2.

In summary, for schedules based on policy headways (required service frequency), smaller vehicles result in lower cost (primarily fuel and maintenance); for schedules determined by passenger volumes, larger vehicles offer both lower operating costs (particularly labor) and higher service reliability.

Since the optimal bus size is a function of passenger volume, a larger bus is preferable for peak rather than off-peak hours. Forced to select for practical reasons a

single bus type for all hours, the operator must analyze the trade-off between the following:

- Lower operating costs of smaller buses during off-peak hours
- Lower operating costs and higher LOS of larger buses during peak hours

Maneuverability, comfort, and other factors must also be considered.

Table 5.3 presents a review of the basic bus types by body and wheel characteristics, body length and capacity.

5.2.2.2 Minibus. As the smallest type of bus (it can accommodate standees, which vans and limousines cannot), a minibus is a 6- to 7-m-long vehicle with 12 to 20 seats and a total capacity of 20 to 35 spaces. It has two axles, four or six tires, and often a maximum speed of only 40 to 70 km/h (some models can achieve 100 km/h). A typical minibus used in developing countries is shown in Photo 5.4. The layout of a minibus is plotted in Figure 5.3.



Photo 5.4 Minibus in Mexico

Minibuses are commonly used for three different types of service: (1) Paratransit or dial-a-ride services within low-density suburban areas; (2) Feeder service to major transit, usually rail lines and stations; (3) Shuttle services between two points, such as train stations or airports and hotels, campuses or residential complexes where high frequency is required for low-to-moderate passenger volumes, and (4) CBD circulator (Photo 5.5). In the first type of application, where minibuses serve rather long trips, they require small doors and maximum possible seating capacity. The feeder and shuttle lines usually have buses with wide doors, a low floor, and a minimum number of seats to efficiently serve short trips and heavy passenger exchanges. In industrialized countries, minibuses are seldom used for regular transit services because of their high operating costs and low comfort (see Section 5.2.2.1).

Another major application for minibuses is for regular transit services in cities with little or no government regulation of transit services, as is the case in many developing countries. In this function they carry more passengers in some cities than any other mode of transport. The advantages of such minibus services are that vehicles are usually operated by their owners, avoiding standard wages for drivers. Due to their small capacity, minibuses operate in great numbers, offering frequent services and few stops along the line. Thus, passengers enjoy frequent and fast service, but the

comfort, safety, and reliability of these vehicles are often below the standards required from transit services. Operating with group taxis, vans, midibuses and buses, they cause congestion and very chaotic traffic conditions, as further discussed in Chapter 9.

Minibuses usually have gasoline motors or, exceptionally, diesel motors. There are no trolleybuses of this type.

Midibuses, shown in Photo 5.6, have 8- to 10-m-long bodies and 15 to 30 seats. They are used for regular transit in many small and medium-sized cities as well as for lightly traveled lines, usually in suburban areas of large cities. Their domain is between those of minibuses and standard buses.

5.2.2.3 Standard Bus. The most common type of transit bus and trolleybus, usually considered as standard, is a single-body vehicle with two (exceptionally three) axles, six wheels, and a capacity of 50 to 80 spaces (Photo 5.7). The maximum number of seats is about 49. However, in many recently designed bus models—with low floor, an area in the back occupied by air conditioning and exhaust control equipment, accommodations for wheelchairs and spacious seats—the capacity has been decreased considerably. Many such models have only 28 to 35 seats and a total capacity of 60 spaces.

Basic dimensions of a standard bus and their symbols are shown in Figure 5.4. The legal size of highway vehicles determines the bus width and length. In the United States, bus width is 8 or 8.5 ft (2.44 and 2.59 m), depending on the laws of different states; in most European countries it is 2.50 m. The length over bumpers is usually in the range 33 to 40 ft (10.1 to 12.2 m); in Europe 12 m; and for special routes, 15 m (Photo 5.8). The dimensions of 8.5 ft and 15 m require special permission for individual cities or bus routes.

The turning geometry of a standard bus is shown in Figures 5.4 and 5.5. Its main equations (all symbols are distances in meters or feet) are as follows. When the outside wheel path radius, R_w^o , is known, the inside wheel path radius, R_w^a , is:

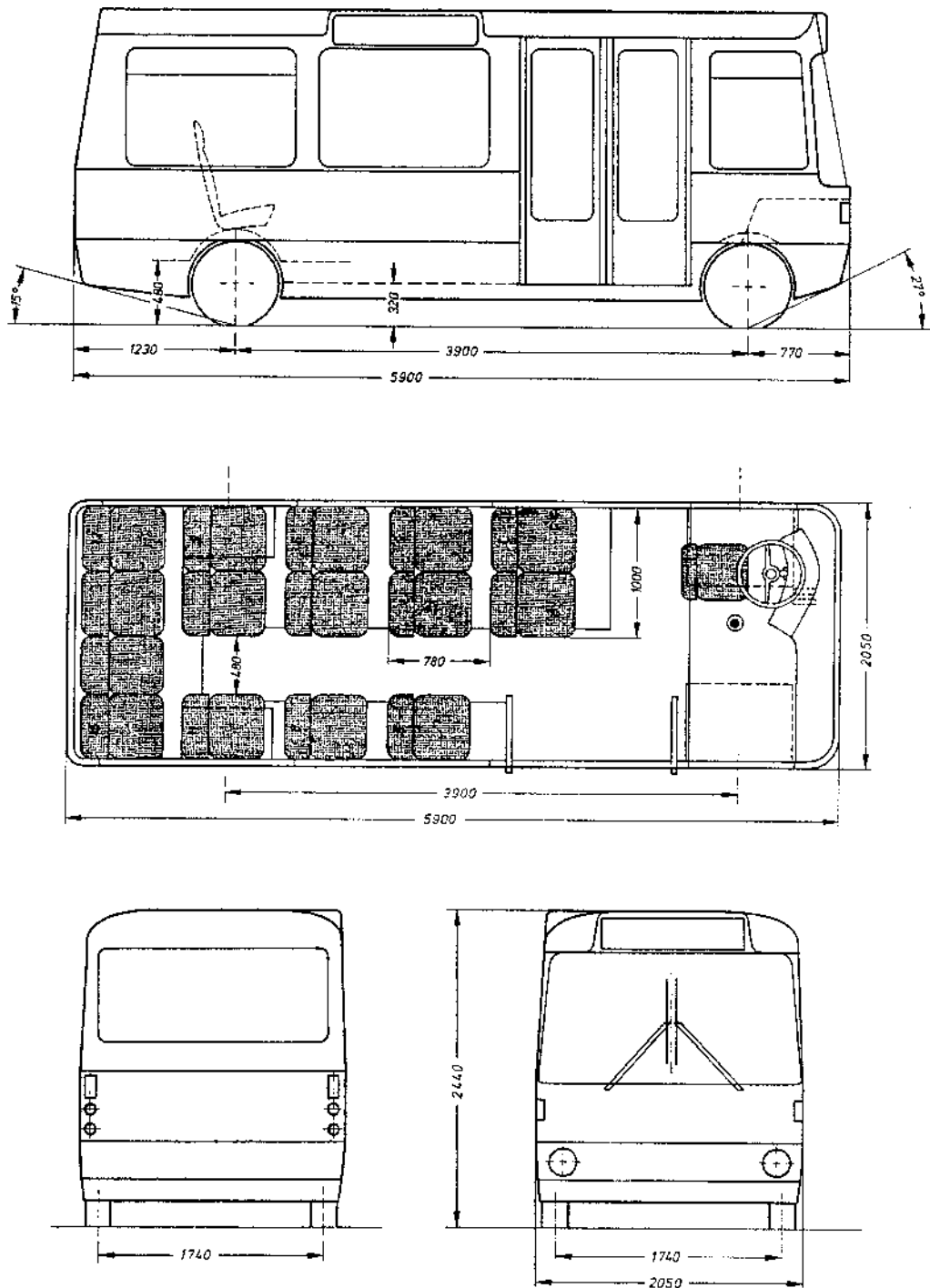


Figure 5.3 Layout of a minibus



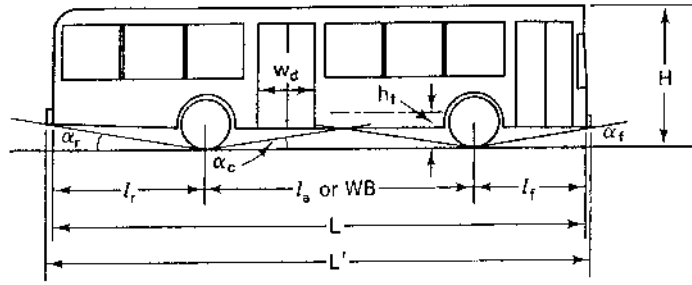
Photo 5.5 A contemporary minibus (Long Beach)



Photo 5.6 Midibus in Budapest

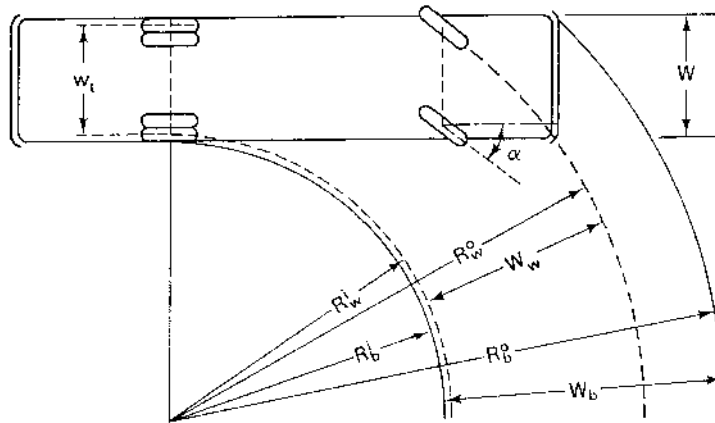


Photo 5.7 Standard U.S. urban low-floor bus (New Flyer D40LF) at RRT transfer station (Frankford Terminal in Philadelphia; courtesy of Michael Pompili)



Body dimensions:

H = Vehicle height	l_r = Rear overhang	W = Body width
h_f = Floor height	L = Body length	α_c = Center clearance angle
l_a or WB = Wheelbase	L' = Length over bumpers	α_f = Front clearance angle
l_f = Front overhang	w_d = Door width	α_r = Rear clearance angle
	w_t = Wheel tread	



Turning dimensions:

R_b^i = Inner body clearance	R_w^o = Outer wheel path	
R_b^o = Outer body clearance	W_b = Body clearance width	α = Turning angle
R_w^i = Inner wheel path	W_w = Wheel path width	

Figure 5.4 Basic dimensions of a standard bus and its turning geometry

$$R_w^i = \sqrt{R_w^{o2} - l_a^2} - w_t \quad (5.1)$$

When the outside body path radius, R_b^o , is known, R_b^i and W_b are, respectively:

and the width of vehicle wheel path is:

$$W_w = R_w^o - \sqrt{R_w^{o2} - l_a^2} + w_t \quad (5.2)$$

$$R_b^i = \sqrt{R_b^{o2} - (l_a + l_f)^2} - W \quad (5.3)$$



Photo 5.8 Three-axle bus in Hamburg (Courtesy of Malcolm Crowe)

and

$$W_b = R_b^o - \sqrt{R - (l_a + l_f)^2} + W. \quad (5.4)$$

Since the rear axle accepts most of the motor weight and the rear overhang is longer than the front overhang, the weight distribution of standard buses is usually about two-thirds on the rear and one-third on the front axle.

5.2.2.4 Standard Trolleybus. The body of a typical standard trolleybus is generally the same as that of a diesel bus except that the trolleybus has two trolley poles for its contact with overhead wires. The same is true for the articulated bus and trolleybus. As Figure 5.6 shows, trolley poles have lateral flexibility, so that a trolleybus can travel up to 4.5 m or more than one lane to the left or right from the lane directly under its wires.

5.2.2.5 Articulated Bus. The first successful articulated bus/trolleybus vehicle was designed in Germany during the 1950s. Its use spread quickly in many European cities. In the United States, with federal assistance, several European models (Ikarus, Leyland, M.A.N, Neoplan, and Volvo) were imported during the 1970s. Following their successful testing, a number of large cities have been using articulated buses, mostly on heavily traveled lines.

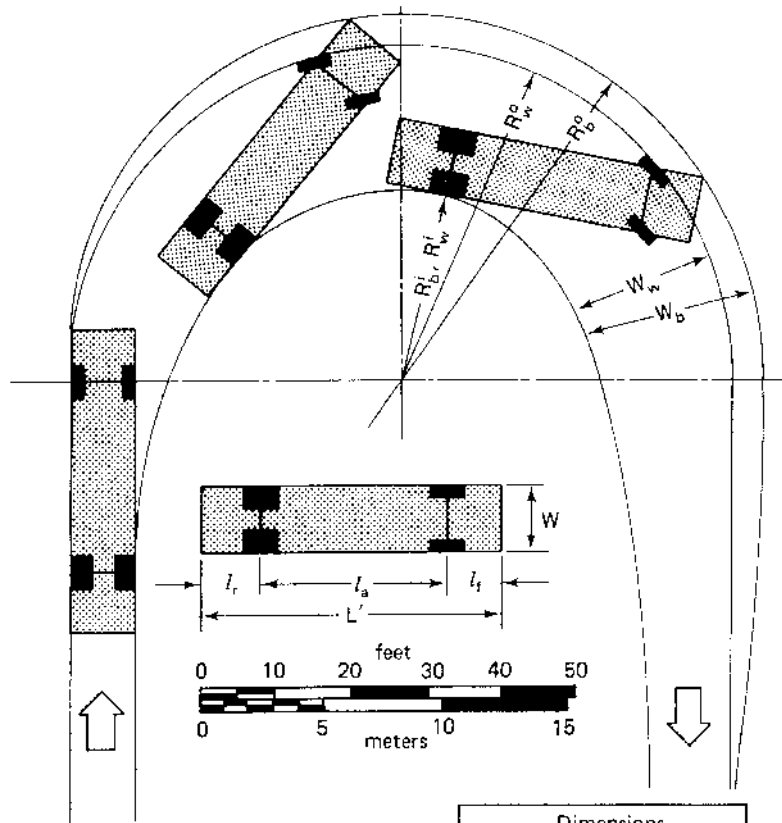
An articulated bus (Photo 5.9, and also Photo 5.2) is a long bus with two bodies connected by a joint that

has a single, continuous interior but allows the vehicle to “bend” while turning. It has two axles under the front and one axle under the rear body section. The joint is suspended on the rear overhang of the front body section. The articulation joint usually allows bending of the two body sections of up to ± 40 to 45 degrees horizontally and ± 10 degrees vertically, as shown in Figure 5.7. Its overall body length is 16 to 18 m, the latter being the legal limit of length of articulated highway vehicles in many countries. This limit has been increased in a few countries to allow the use of double-articulated buses with lengths up to 24 m. The total capacity of articulated buses is usually 100 to 120 spaces, the number of seats is 35 to 55 (there are models with as many as 75 seats but lower total capacity).

Several factors make the articulated buses/trolleybuses attractive for use. Their higher labor productivity—one driver serves more offered spaces—results in lower operating cost per space-km than that of standard buses. Their introduction is most logical on lines where there is a need to provide higher passenger capacity: less crowding during peaks and seats for most passengers during off-peak hours. With the growing need for higher passenger comfort, this factor is increasingly common. Finally, larger vehicles utilize street space better and increase line and street capacities.

A slight disadvantage of articulated buses is lower riding comfort in their rear section because it is supported by the overhang of the front section. This causes magnified motions and discomfort in sharp turns or on poorly maintained streets.

In spite of their 50% greater length, some articulated buses have the same turning radius and a narrower turning path than standard buses. This is the case with articulated bus models that have rear wheels steered in conjunction with the front ones, but in the opposite direction, at approximately a half of their turning angle, as shown in Figure 5.8. Thus the paths of the rear wheels (which are single) fall within the paths of the front and middle axle wheels, allowing the bus to make any turn a standard bus can make. An exception is in the beginning of its turn, when the articulated bus makes a larger outward swing with its rear overhang than the standard bus. The maneuverability and safety of 16.5- to 17.0-m-long articulated

**Notes:**

Dimensions shown are composite for different vehicles. No individual vehicle, including the one shown, has all extreme values.

Some low-floor bus models exceed the shown turning dimensions.

Dimensions		
Symbol	Feet	Meters
l_f	7.0	2.13
l_a	25.0	7.62
l_r	8.0	2.44
L'	40.0	12.19
W	8.5	2.59
$R_b^i = R_w^i$	23.2	7.07
R_w^o	42.0	12.80
R_b^o	47.1	14.36
W_w	18.8	5.73
W_b	23.9	7.28

Figure 5.5 Minimum turning path for a U.S. standard bus

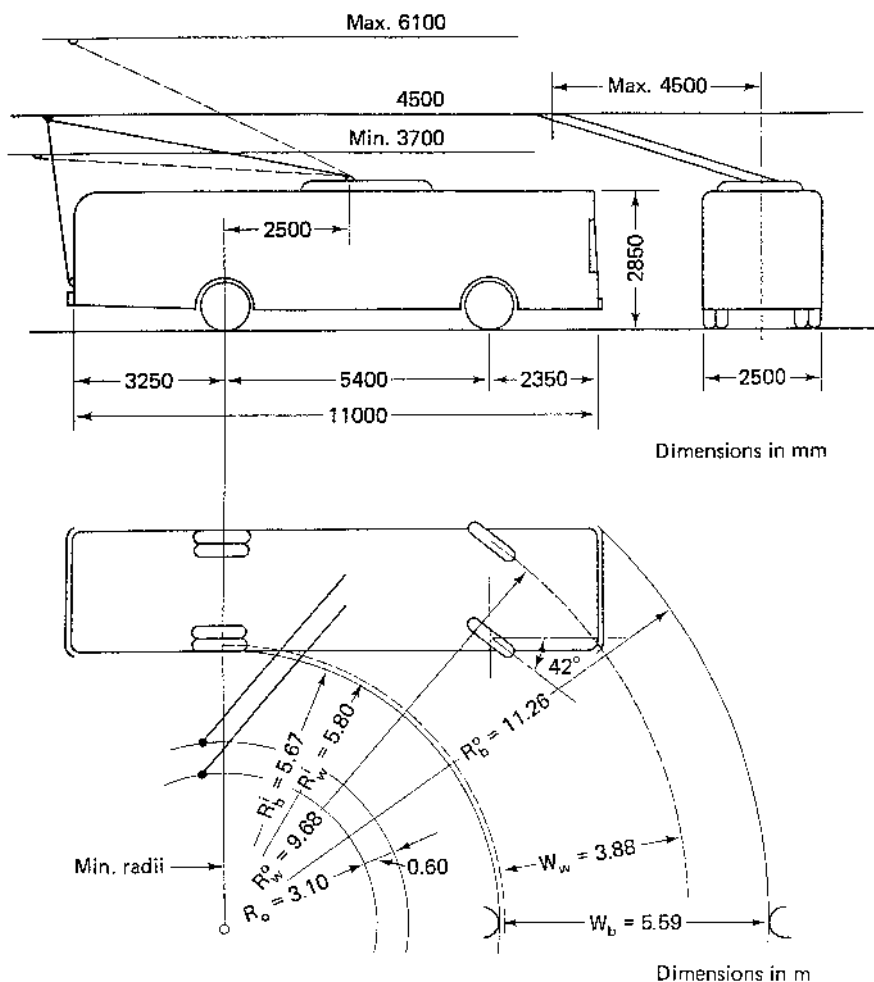


Figure 5.6 Basic dimensions of a standard trolleybus, its overhead wires, and the geometry of sharpest turn (Model 9-Tr; Skoda, Czechoslovakia)



Photo 5.9 Low-floor articulated bus with wheelchair ramp lowered (Courtesy of Edmonton Transit System)

buses with this type of steering have generally been satisfactory, but the 18.0-m-long (maximum allowed) buses with a steered third axle have had somewhat lower safety record because the rear body has a tendency to swing in the curve at higher speeds (Booz Allen 1974).

Another articulated bus design now most commonly used, has engine located in the rear, propelling the third axle, which has double wheels without steering. This design has more stable and comfortable ride, although it requires a wider turning path than the bus with trac-

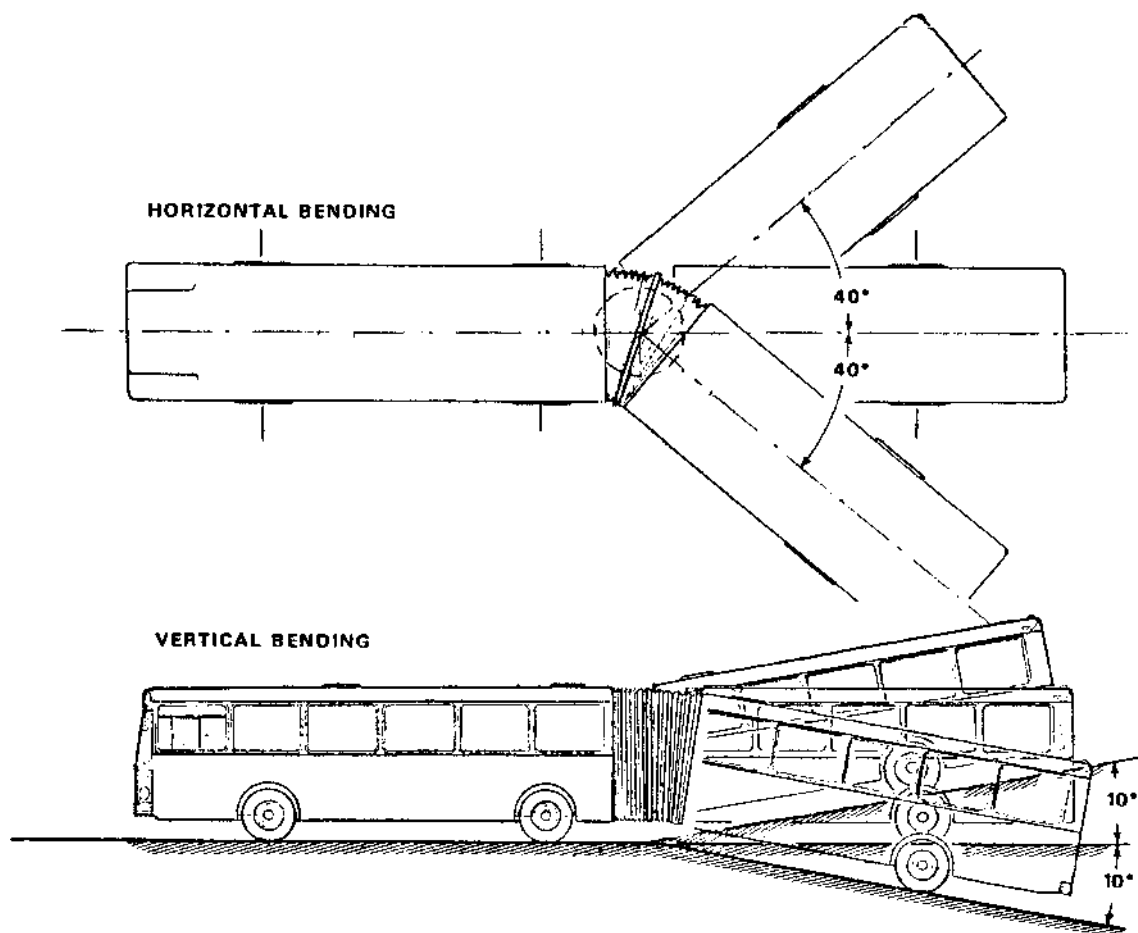


Figure 5.7 Bending ability of articulated bus (Source: Booz Allen Applied Research, 1974)

tion on the second axle and steered third axle, as shown in Figure 5.8. Placement of the engine in the back has become necessary with low-floor buses that do not have sufficient space under the floor. This “push bus” design has replaced most but not all buses with a steered third axle. A wider turning path, however, requires particular attention for pedestrian safety at intersections.

To obtain an operating speed similar to that of standard buses, articulated buses must have a comparable ratio of vehicle capacity to the number of door channels. Therefore they typically have three to four double-channel doors. Another requirement is that they

either have a conductor (applicable in countries with low labor cost) or self-service fare collection system, common in most European countries and increasingly introduced in North American cities. This fare collection method allows simultaneous boarding/alighting on all doors, so that heavy passenger volumes can be handled without major delays. Naturally, only the self-service fare collection leads to a higher productivity of articulated buses in terms of labor as compared with standard buses.

Although articulated buses and trolleybuses perform best on straight streets and flat terrain, they also operate successfully on narrow streets of many cities

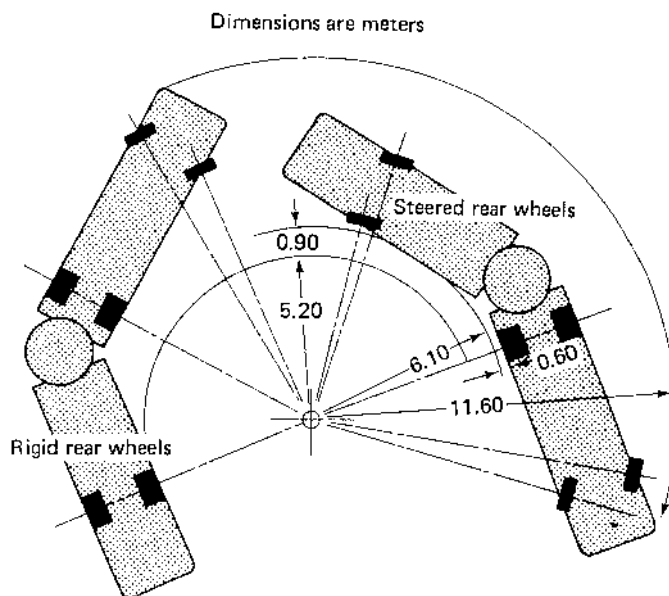


Figure 5.8 Turning paths of articulated buses (Source: Booz Allen Applied Research, 1974)

Briefly stated, an *articulated bus* compared with a *standard bus* provides:

- + Higher line capacity
- + Higher labor productivity (lower cost per space-km)
- + More spacious vehicles
- Somewhat wider path and more complicated turning geometry and terminal maneuvers
- Sometimes lower acceleration and climbing abilities (depending on motor power)

(e.g., Salzburg) and have demonstrated satisfactory performance on hilly terrain (Belgrade, Pittsburgh). However, a few cities did find articulated buses poorly suited to operation on streets with heavy traffic. Consequently, the main factors for their introduction are required capacity and operating costs per space-km: their inherent advantage over standard buses in both of these factors makes articulated buses the optimal vehicles for many heavily traveled lines.

5.2.2.6 Double-Articulated Bus. The highest-capacity bus vehicles have three body sections, two articulations and four axles, arranged as 2+1+1. These double-articulated buses, shown in Photo 5.10, reach a length of 24 m and provide even greater capacity and labor productivity than articulated buses. Due to their considerable length and the different paths of the wheels, most models have wide turning paths, so that they can generally be efficiently used only on



Photo 5.10 Double-articulated bus in Curitiba (Courtesy of Jaime Lerner)

lines with mostly straight alignments and no sharp turns or steep gradients. Their primary use is on long, straight, heavily loaded lines, such as BRT lines with exclusive bus lanes.

The double-articulated bus has the same comparisons with the standard bus as the articulated bus, but to an even greater degree.

5.2.2.7 Double-Decker Bus. The double-decker (Photo 5.11a) is the primary bus type in most large cities in the United Kingdom and in many other British Commonwealth countries. Berlin also has a large fleet of 12-m-long double-deckers with two stairways (Photo 5.11b). Some other cities—such as New York, Paris, Stockholm, and Vienna—have used them at different times, but those uses remained rather limited or temporary.

Double-deckers are buses with two floors (decks) connected by one or two stairways. They are usually 4.00 to 4.45 m high, 9 to 12 m long, and have two, exceptionally three, axles. Thus they do not take more

street space than standard buses but provide more passenger space, which is used mostly for seating capacity. The upper deck allows only sitting (because of the low ceiling and vehicle sway), while the lower deck often accommodates a limited number of standees. Thus the total capacity of double-deckers is between 65 and 100 spaces (i.e., only slightly greater than for standard buses, but with a smaller share of standees).

Most buses of Transport for London, the best-known double-decker fleet in the world, have been only 10 to 11 m long, typically accommodating 66 seated and 22 standing passengers. The main reason for use of the relatively short double-deckers instead of longer single-deck buses in British cities are the narrow, frequently congested streets, which make the flexibility of short vehicles very important. The models used in Berlin, Hong Kong, and most other cities outside the British Commonwealth are generally larger, often 12 m long.

In recent years, London has undertaken energetic measures to improve its traffic conditions and make



(a)



(b)

Photo 5.11 a. Double-decker bus: a symbol of London (Wright Eclipse Gemini; © Martin G. Layton); b. 12-m long double-decker in Berlin

transit more attractive and efficient. The successful introduction of road pricing in 2005 was accompanied by many improvements of bus services. This includes introduction of an articulated (“bending”) bus type, named “Bendy,” which has shorter stop dwell times than double-deckers and provides higher capacity on the reserved bus lanes introduced on many streets. This drastic change from double-decker to articulated buses

results in very different passenger accommodations: more standing but much faster and easier boarding and alighting; less scenic view than from the upper deck but no climbing of circular stairways, etc. These innovations are still being evaluated in London.

One of the limitations of double-deckers is their height. Although legal height limits are seldom a restricting factor [in most of the United States, they are

13 ft 6 in. (4.12 m), the lowest is the District of Columbia: 12 ft 6 in. (3.81 m)]. Introduction of double-deckers in a new city is often restricted at some locations by low overpasses, traffic signals, or tree branches. Despite their apparent low lateral stability, that is not a problem, since double-deckers are designed with a low center of gravity and tested for different passenger distributions on a special machine that gradually tilts the bus. With respect to comfort, the upper deck does experience an increased vehicle sway, but—on well-maintained streets—it does not exceed the level acceptable to seated passengers. The view from the upper level is an attractive feature of double-deckers. Tourists in London, Hong Kong, and Berlin often find riding double-deckers an excellent mode of sightseeing.

The flow of passengers in double-deckers is constrained not only by the stairway but also by lower ceilings than in regular buses. Ceiling height is always lower than normal on the upper deck and sometimes also in the lower deck. Outside views of a double-decker bus are shown in Figure 5.9.

Consequently, double-deckers are best suited for routes with long trips rather than with heavy passenger interchange. Their effectiveness depends, as in the case of articulated buses, on the speed of boarding/alighting, which is a function of fare collection method, internal passenger circulation, step heights, and door widths.

The former labor cost disadvantage of two-person crew double-deckers has been eliminated by the introduction of self-service and smart-card fare collection, which enabled one-person operation. For example, very efficient operation of 12-m-long double-decker buses has been achieved in Singapore where self-service fare collection with smart-card payments is used. At entry, passenger's smart card is charged with the maximum fare on the line; when passenger exits, he or she registers the smart card again and, if the trip is shorter, the card is given back the difference in the fare. Thus, passengers register their cards on entering and leaving, providing a passenger load count on the bus along the line. Passenger boardings and alightings are fast because all four door channels can be used for both.

Finally, in evaluating double deckers, tradition and passenger habits are also important: in some cities these buses have not proved attractive to riders, while in others, double-deckers are very popular. In London, the red double-deckers are such a strong city symbol that many other cities purchase second-hand "Londoners" to enhance their local tourist attractions. For a summarized comparison see the following box.

5.2.2.8 Guided Buses. Potential advantages of enabling buses to be guided are the following:

- Dual-mode—steered and guided operation—allows such vehicles to operate in both modes

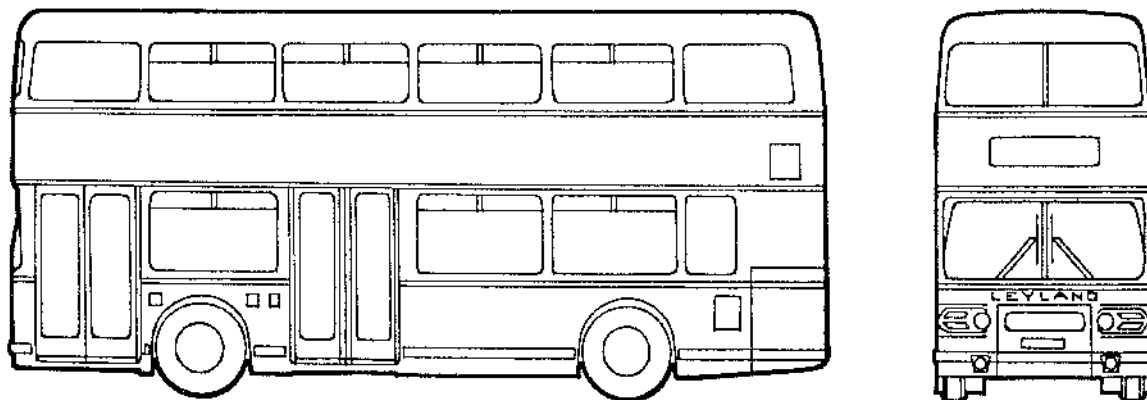


Figure 5.9 Double-decker bus: side and front views (Leyland B-15, 1978)

Double-deckers, compared with *standard buses*, have:

- + Higher capacity, particularly seating, for the same vehicle length
- + An attractive view for passengers on the upper deck
- + Little disturbance on the upper deck from passenger movements—particularly useful for longer trips
- Greater vehicle height, requiring higher clearances
- Inconvenience of ascending and descending the curved stairway during bus movement
- Less direct supervision of the upper deck (possible by driver via a periscope)
- More constrained passenger circulation, making double-deckers less convenient for routes with heavy passenger interchanges
- Need for special maintenance shops

with their relative advantages on different sections of the same line.

- Sections of bus lines with guidance require narrowed right-of-way and provide greater safety than conventional roadways (busways), allowing higher running speeds.
- Buses can be brought to a stop location so precisely that high-floor buses can “dock” to a high platform with a small gap only (used on some BRT systems).

A number of technical inventions have been used to develop guided buses. The guidance mechanisms used can be grouped in three categories:

1. Mechanical, where the bus has two small horizontal wheels that can be extended in front of the bus’s front wheels. Line sections with guidance have two 20-cm-high concrete curbs that provide guidance for the two horizontal wheels. The driver extends the guiding wheels prior to entering the roadway section with curbs and retracts them for running on streets.

By far the best-known guided bus has been the O-Bahn model, developed by Mercedes Benz in Germany about 1982. This system was built on a test line in Essen, Germany, on a long transit line in Adelaide, Australia (Photo 5.12), and on short sections in Mannheim, Germany, and Leeds, United Kingdom. For a

description and detailed evaluation of the O-Bahn concept, see Vuchic (1985).

2. Electronic, where the bus follows magnetic impulses from markers at every 4 to 5 m in road surface (Phileas Bus) or from a wire buried in the roadway, or a bus using optical guidance follows a painted line through image processing (Civis Bus).
3. Optical, when the bus has a scanner that follows a line painted on the street pavement.

Mechanical guidance has the advantage that it provides positive physical guidance not affected by snow, ice, or optical or magnetic failures: the guidance does not depend on wheel adhesion. Its reliability has been proven in several applications on regular transit lines. Electronic guidance has not been used on heavily traveled transit lines, but it has been proven reliable for precise vehicle guidance in approaching high platforms or curbs at bus stops. Optical guidance requires surface free from obstacles.

Comparisons of BRT with alternative transit modes for several cities (e.g., with rail rapid transit in Lima, Peru, and for the bus tunnel in Seattle, Washington) have shown that the closest competitor of the guided bus is actually BRT rather than LRT.

In comparison with LRT, the guided bus involves a lower investment cost and can have extensive branches from a trunk line without requiring transfers. However,



Photo 5.12 Guided bus in Adelaide (Courtesy of Alex Wardrop)

Compared to BRT, the guided bus has the following advantages (+) and disadvantages (–):

- + Requires narrower ROW.
- + Guidance provides higher safety and allows greater running speeds.
- + Entry of other vehicles is physically prevented, eliminating need for enforcement.
- Lower capacity because of inability of buses to overtake each other.
- Lower reliability because vehicle breakdown blocks the guideway.
- Higher investment cost due to precise tolerances of the roadway and its foundations.

the guided bus also has all the inferior features of buses compared to LRT: much lower TU and line capacities and the disadvantages of ICE as compared to electric traction: lower dynamic performance, inability to operate in tunnels, less comfortable ride, less spacious vehicles, and lower attraction of passengers.

Applications of O-Bahn may be expected in the situations where there is ROW with restricted width and in cities where the pressure to invade busways by other traffic is great and police enforcement is inadequate. O-Bahn physically prevents entry by other vehicles and thus eliminates the need for police enforcement. Net-

works with several branches converging on a single trunk can also be appropriate for O-Bahn use.

In attempts to increase safety, reduce ROW width, and overcome the weaker image of buses as compared with rail vehicles, due to their lack of visible guidance and path, several groups of vehicle manufacturers developed new designs of rubber-tired vehicles with steel wheel guidance along a single rail. They have been tested by RATP in Paris since the late 1990s.

- Bombardier has led the group that developed the Guided Light Tramway (GLT) system, which has been chosen by the cities Nancy and Caen.
- The Translohr guided bus has been developed by Lohr Industrie.
- The Civis, with optical guidance, developed by IrisBus and Matra, has been introduced in Rouen;
- The Italian Ansaldo group has developed a system called Stream, which combines guided traction with ground-supplied electrical power for trolley-buses.

These “Tram on tyres” vehicles incorporate different guidance technologies (two types of steel wheels guided by a single rail in the centerline of the travel lane); operation with guidance and off-line with steering; single- and double-articulated bodies with lengths up to 26 m but width of only 2.20 m; axles under articulations (as on rail vehicles) to reduce interior narrowing by the joints; traction by electric motors, ICE, and batteries for off-line travel; and a number of other features.

5.2.3 Propulsion, Equipment, and Performance

Several important functional requirements for bus performance have had major influences on bus vehicle designs in recent decades. First, heating/ventilation/air conditioning—HVAC equipment—has become standard and very sophisticated, occupying considerable space. Second, legal requirements for reduced engine emissions have led to the development of new types of motors and the addition of exhaust filtering devices. On some buses, that takes up nearly 1 m or

8% of body length. Third, low-floor buses have required the relocation of many technical components that were formerly placed under the floor. Finally, many bus models specially designed for BRT operations have new body shapes, spacious interiors, doors on the left instead or in addition to the right side, and multiple doors (both reduce seating capacity) sophisticated computer controls, etc.

5.2.3.1 Motor and Drive Train. It is mechanically possible to connect the motor via a drive train, utilizing universal joints with powered axle(s) from nearly any location in the bus. Therefore motor position is mostly determined by the requirement not to occupy internal vehicle space and reduce capacity, the need for easy accessibility for maintenance, and considerations of weight impact on traction and vehicle stability. A number of different positions of the motor exist, among which horizontal takes the least space.

Most contemporary buses have the motor located at the rear end, partly under the last row of seats, accessible from the back. North American designs usually have the motor in transversal or angular position, mounted in a compartment that occupies 50 to 80 cm of vehicle length behind the last row of seats. On some bus models, the floor is raised with a 6% to 10% slope from the rear door toward the back to provide adequate space for the motor compartment. A step in the aisle is found in these models, often referred to as 70% low-floor buses.

Since the rear axle carries more weight than the front axle (the ratio is usually about 2:1), it always has double wheels and is powered by the drive train via a differential, commonly with a ratio between 4:1 and 6:1. With three-axle vehicles, only one of the rear axles may be powered (the other then has single wheels); or a special drive train is used that goes from the transmission box through the first differential into the second and powers both axles.

The trolleybus motor is typically mounted longitudinally under the floor in front of the rear axle. Connection with the rear one or two axles is usually the same as that for buses except that there is no transmission. When an auxiliary ICE is provided, it is placed in the rear.

The transmission is automatic on all North American and most European transit buses. Common designs have three-, or four-, or sometimes five-speed transmissions. The greater complexity of more gears in some applications is considered more than compensated by lower fuel consumption and better performance of the bus due to more precise “fitting” of its motor operating regime to travel conditions.

The exhaust pipe below the bus at its rear end was objectionable because it released gases into the breathing area of pedestrians in streets. This has been alleviated by placing exhaust pipes overhead in the rear. Combined with a catalytic muffler and a particulate trap for pollution control and dilution with cool air prior to exhaust, this design results in a reduced negative impact of emissions on the street environment.

Standard buses have air brakes acting via wheel drums. Hydraulic brakes are common on minibuses. Motor braking is used on some diesel buses for retardation to low speeds.

Trolleybuses utilize motors for braking much more extensively and effectively than ICE buses. Their basic braking is dynamic (see Section 3.3.4), supplemented by air brakes at low speeds when the dynamic braking fades out. Both are controlled by the same pedal. With chopper motor control, regenerative braking has become standard, resulting in a substantial reduction of energy consumption (in the range of 20% to 40%) through the return of current generated by braking.

Suspension is provided either by leaf springs or by air springs. The latter, used on most current models in industrialized and some developing countries, have the advantage of maintaining constant floor level regardless of load. An air compressor, serving air-brake cylinders, also provides air for the springs. The inflow of air is regulated by leveling valves, which allow more air when load increases and release air as load decreases. Since air suspension has a tendency to sway the vehicle body, radius rods are attached to front and rear bulkheads to dampen lateral and longitudinal sways.

Contemporary buses have air suspension, which provides a soft and comfortable ride over reasonably well-designed and maintained roadways. However, in

many cities, frequent bus turns, stops, and maneuvers, drainage inlets in the curb lanes commonly used by buses, and inadequate maintenance of streets often make standing passengers in these vehicles uncomfortable.

5.2.3.2 Performance. With the power of diesel motors in the range of 150 to 330 HP, buses have power-to-weight ratios between 18 and 30 HP/t. Since a diesel motor cannot deliver more than its rated power, buses with low power-to-weight ratios can have either a high acceleration rate or high maximum speed (by different transmission ratios) but not both. Also, power for auxiliary aggregates, particularly air conditioning, may drain enough power to decrease bus performance. These additional loads or the need to operate on freeways or steep streets sometimes leads to the use of motors with greater power.

Because of these limitations and the high cost of providing adequate power for all aspects of vehicle performance, most buses are designed either for regular service on streets with good acceleration capability, or for express service on freeways with high-speed capability. Buses for cities with hilly terrain are usually designed for better climbing ability at the expense of high speed. The engine performance curves of two buses are shown in Figure 5.10.

Data on acceleration and jerk characteristics, customarily given for rail transit vehicles, are seldom supplied by bus manufacturers. Only the times needed to reach several different speeds from a standing position are sometimes quoted. Measurements in different cities show that typical acceleration rates of buses are in the range 0.7 to 0.9 m/s², but some models may perform outside of this range. Tests have shown the following characteristics of bus traction performance:

- The maximum acceleration rates are reached for a short period of time only; then they fall off rather rapidly.
- Acceleration rates are affected significantly by bus loading: a full bus achieves less than 70% of the acceleration rate achieved by empty bus.
- Air conditioning reduces the acceleration rate by some 10% to 15% on both empty and loaded buses.

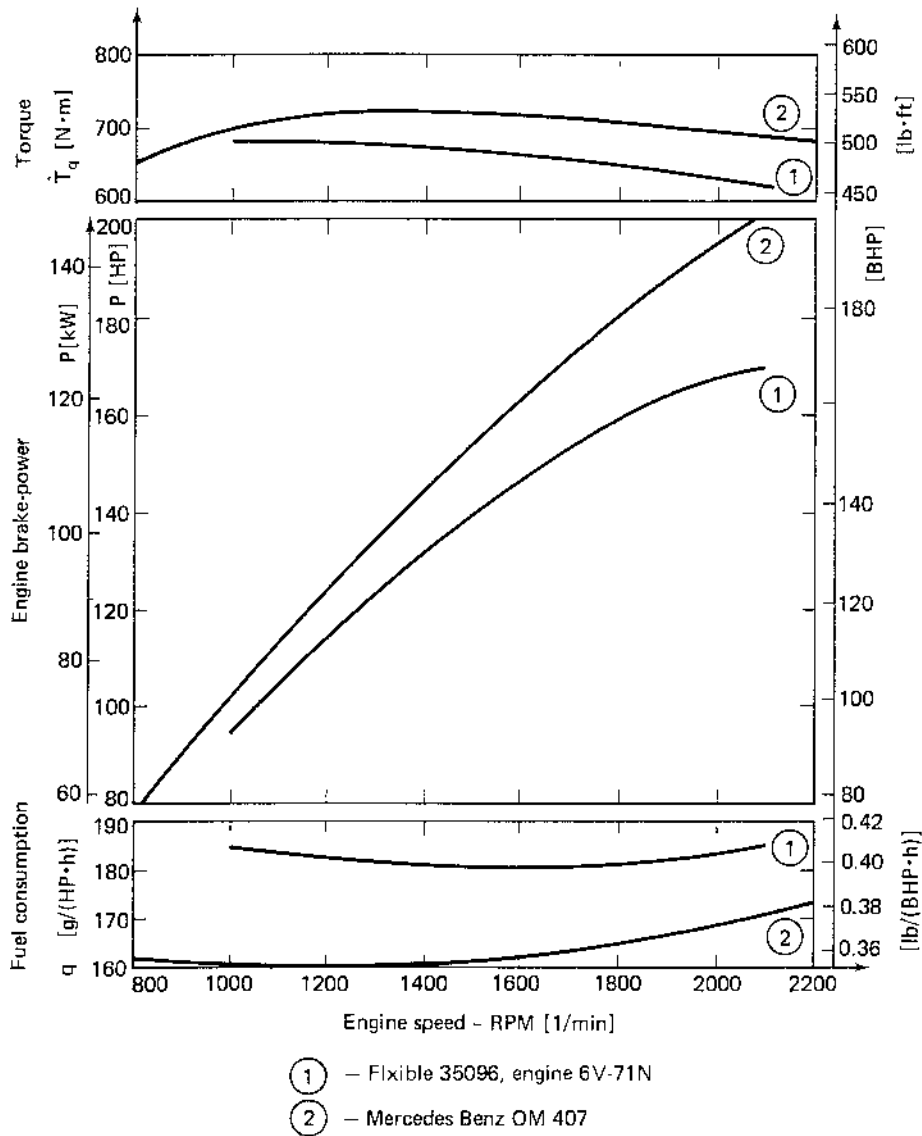


Figure 5.10 Bus engine performance curves

Trolleybuses have excellent performance: high and smooth acceleration and braking. Combining the ability of the electric motor to deliver higher than rated power for a limited period of time with rubber-tire adhesion, the trolleybus is capable of providing higher acceleration rates than either ICE buses or rail vehicles. Moreover, all electrically powered vehicles experience

less effect of load than ICE buses and no effect of air conditioning. Thus, for comparable performance, a trolleybus can have a motor with at least 20% to 30% lower rated power than a diesel or other ICE bus.

The maximum technical speed of buses can be as high as 100 km/h (O-Bahn in Adelaide), but transit buses can very seldom utilize such capability. They

usually have maximum speeds of 60 to 95 km/h. The upper values are adequate for buses operating on free-ways in U.S. cities, since on many of these the speed limit is 88 km/h (55 mph). Some regional services also use intercity buses.

The braking rate in normal operation with a well-trained driver is approximately uniform. For emergencies, all buses have excellent performance: under all except very slippery (ice) conditions, they can decelerate at rates as high as 3 to 6 m/s² (i.e., well in excess of what standing passengers safely tolerate).

5.2.4 Body Structure and Form

There are two basic types of bus body structure. The classical one is with a chassis as the main structural part. Consisting of steel beams and crossbars, the chassis rests on axles via a suspension system. The motor and vehicle body are mounted on it. The other currently used type of structure is monocoque, or integral construction, with a self-supporting body and no chassis.

The body consists of a structural skeleton and double walls made of steel or aluminum plates. In addition to covering structural parts, double walls provide safety, insulate heat and noise, and house conduits and some auxiliary equipment.

Some recently developed bus models, such as *Com-pobus*, use boron-carbon fiber and other aerospace materials, resulting in very significant weight reductions (as much as several tons), with benefits of higher energy efficiency.

5.2.4.1 Vehicle Exterior. Design of the bus exterior must satisfy both functional and aesthetic requirements. The exterior of a modern North American bus is shown in Photo 5.1. Several aspects have particular importance.

- Large “panoramic windows,” introduced on many European bus models during the 1960s, have now in most countries replaced the small windows designed for seated passengers that were “fashionable” from the 1930s into the 1970s. They are preferred for better passenger visibility and good bus appearance. This and many other new design

features, including accessibility for physically impaired passengers, were first tested on the federally sponsored “Transbus” project in the late 1970s and then introduced widely in the United States to comply with the requirements of the federal 1991 Americans with Disabilities Act (ADA).

- The windshield is often curved or tilted to provide good visibility and reduce glare for the driver. Horizontal curving (“wraparound” form) allows good streamlining of the vehicle body.
- Adequate signing for bus line number and destination must be provided on all vehicle sides. This item is very deficient on many bus designs, but its importance is particularly great for buses, to improve the weak identity of their service and the orientation of its passengers. A set of good destination sign designs is shown in Figure 5.11.

5.2.4.2 Doors and Steps. Boarding and alighting from buses involves steps and therefore affects passenger convenience; accessibility by persons with strollers, the elderly, and the disabled; and dwell times at stops, which in turn directly affect operating speed and operating cost.

The ratio of vehicle capacity to door channels is the basic design factor for determining the number and width of doors. This ratio should be smaller for lines with short trips and heavy passenger exchange (e.g., intracity lines) than for long commuter lines. Some standard buses for busy routes in European cities have three double-channel doors and a capacity-to-door channel ratio as small as 12:1 (including standees). Most common European designs have two double-channel doors and a ratio of about 20:1.

In North America, double-channel doors on buses were virtually unknown until the 1980s because domestic bus manufacturers offered nearly exclusively single-channel doors. Most standard U.S. transit buses with only two single-channel doors had capacity-to-door channel ratios of 35 to 40:1, which cause extremely slow operation when these buses are heavily loaded. Even with only a seated load, the ratio is about 25:1. The argument for this design was that fare-collection control allows only a single channel for boarding. This was not valid, since PCC streetcars have

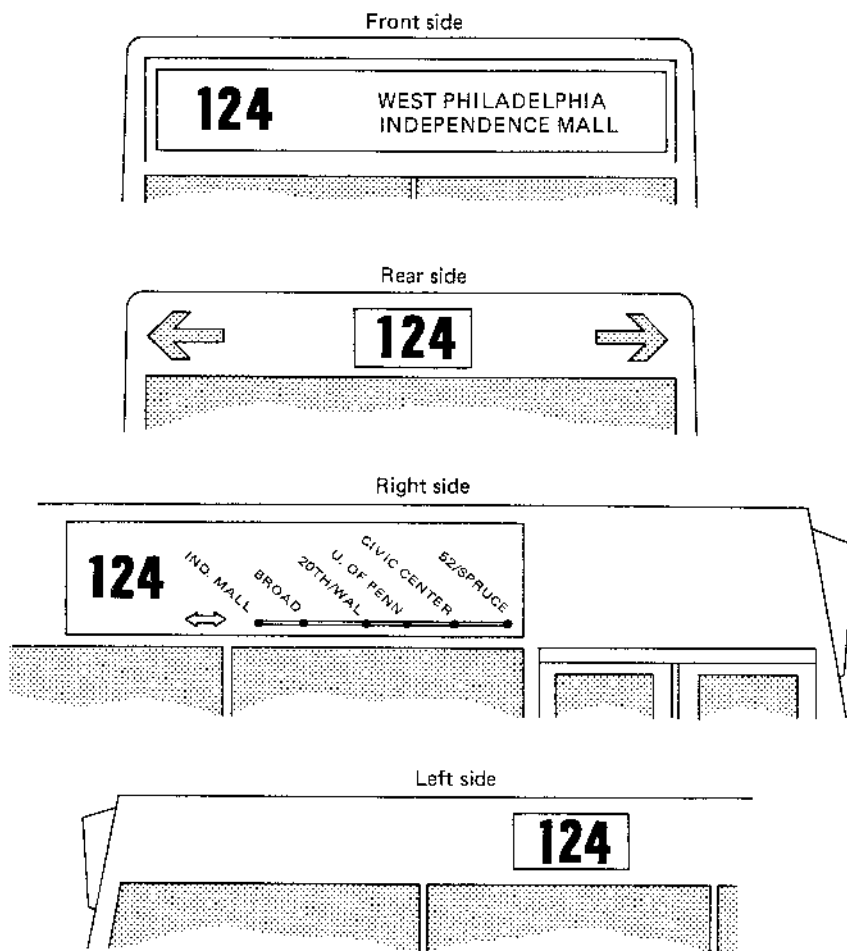


Figure 5.11 Destination sign designs (Design by Hamburg-Consult, Germany)

always had double-channel doors with the same fare-collection method.

Increased use of flash tickets (passes) and the introduction of self-service fare collection in a few cities (standard in many European countries) make double-channel boarding even more efficient. However, the great benefits from faster boarding are often overlooked by transit operators. Door widths of 26.5 to 32.5 in. (673 to 825 mm), still found on many buses in North America, have boarding/alighting rates of 1 to 4 seconds per person (s/prs) (Kraft & Bergen 1974), depending on whether fare is collected, the type of fare, baggage carrying, and so on. With complicated

fares, boarding time may be as long as 6.0 s/prs. Double-channel doors (Photo 5.12) with widths between 1200 and 1400 mm are used in many overseas cities and on many recent models, particularly on BRT systems such as those in Brazil and Colombia, as well as in an increasing number of North American cities. They allow up to twice faster boarding/alighting rates when one channel is used by passengers paying complicated fares and the other one for passage by those with prepaid tickets or passes.

The fastest, simultaneous boarding and alighting is achieved with prepaid fares through double-channel doors with floor and platform at the same level. This



Photo 5.13 A European low-floor articulated bus (MAN, Munich; courtesy of Peter Specht)

is achieved with low-floor buses and raised curbs or with high floors and high platforms on BRT systems with precise docking of buses to high platforms.

For articulated buses, it is particularly important to maintain the same capacity-to-door channel ratio as for standard buses. For them, one double-channel door for boarding and two double-channel doors for alighting represent the minimum required for efficient operation on most urban transit routes. On longer suburban lines, a total of four or five channels may be adequate.

5.2.4.3 Low-Floor Buses. Major efforts were made in Germany and the United States (Transbus project) during the 1970–1980 period to develop buses with floors 32 to 40 cm above ground, instead of the previous floors 70 to 90 cm high, which required three steps. Among the problems to be solved were the

placement of the motor and other aggregates in the very back of the bus, the design of smaller wheels with brakes that did not overheat, minimizing impacts of wheel compartments that protrude through the floor into the bus interior, and others. Since the 1990s, these low-floor buses have become standard in Germany and other European countries (Photo 5.13) as well as in an increasing number of North American cities (Photos 5.14 and 5.15).

Figure 5.12 shows cross sections of buses with different floor arrangements. The conventional high-floor bus has three steps; a low-floor bus has a single step or nearly horizontal boarding from a 20-cm-high curb; the same bus with a “kneeling” capability, a mechanism that tilts the bus body about 10 cm lower; and a bus that has high floor and no steps, but operates on special BRT lines with high platforms, allowing horizontal boarding. This last design results in most con-



Photo 5.14 Low-floor trolleybus by New Flyer in Vancouver (Courtesy of Martin Parsons)

venient boarding, but it requires precise docking of the bus and limits its use to lines with high platforms only.

Low-floor buses greatly facilitate boarding for all passengers and for the disabled in wheelchairs (a much simpler plate instead of a complicated lift is all that is required). Their disadvantages are their higher complexity and sensitivity to roadway quality, their higher investment cost, and lower comfort of seats placed over the protruding wheel compartments. In most cases low-floor buses are designed with fewer seats, requiring replacement of conventional buses by a greater number of low-floor models. However, the trend is to increase the required investment to obtain the advantageous superior features of low-floor buses, particularly faster boardings and meeting the ADA or similar requirements.

5.2.4.4 Vehicle Interior and Capacity. The initial consideration in the design of a transit vehicle interior is to maximize the percent of gross area to be used by

passengers. In addition to the driver's area and door areas, the motor compartment and wheel protrusions may reduce utilization of the gross bus area. By placement of seats on the wheel protrusions, many contemporary bus designs have reduced the areas that are unusable for passengers and driver.

The next important consideration is the number and arrangement of seats, which is based on the trade-off between passenger circulation and seating capacity. For bus lines that seldom have standees, the maximum number of seats, with 2 + 2 arrangement, should be provided. With bus widths between 2.44 and 2.59 m, a wall thickness of 8 to 10 cm, and seat widths of 43 to 48 cm, only about 50 cm remain for aisle width. This dimension is not sufficient for easy circulation when there are standees, particularly while the bus is moving. Two double seats should therefore not be used for lines that carry standees, even if only during peak hours. A 2 + 1 seating between the two doors is a better layout for such service. For very high passenger



Photo 5.15 Interior of a U.S. articulated bus (Silver Line in Boston)

volumes, single seats (1 + 1) in the entire vehicle are preferable, since they offer the highest total capacity. Several seating variations in a standard bus are shown in Figure 5.13.

Although the size and design of seats is not necessarily directly related to vehicle technology, many transit buses have seats with minimal acceptable dimensions: area per seat of this type is usually between 0.30 and 0.35 m². More comfortable seats take a larger area.

While the seating capacity is precisely known, standing capacity is a function of the assumed areas per standee. For this area the values of 0.10 to 0.15 m²/space are used for structural design (loading) of the vehicles. A realistic value for crush loading is

about 0.20 m²/space, which is close to the value of 2 ft² (0.186 m²) per space used by some transit operators. Wherever available information has permitted, vehicle capacities quoted in this book are based on 0.20 m²/space. For acceptable comfort levels, the area per standee of 0.25 to 0.35 should be used. The highest value, assuming comfortable standing and easy circulation, is 0.33 m²/space or 3 prs/m².

Transversal seating is more comfortable than longitudinal because people are more sensitive to lateral than to forward/backward forces. Since transverse seats also give more privacy, they are used wherever possible. For the comfort and safety of standees, buses should have so many stanchions and holding bars that a person can catch one from any standing location.

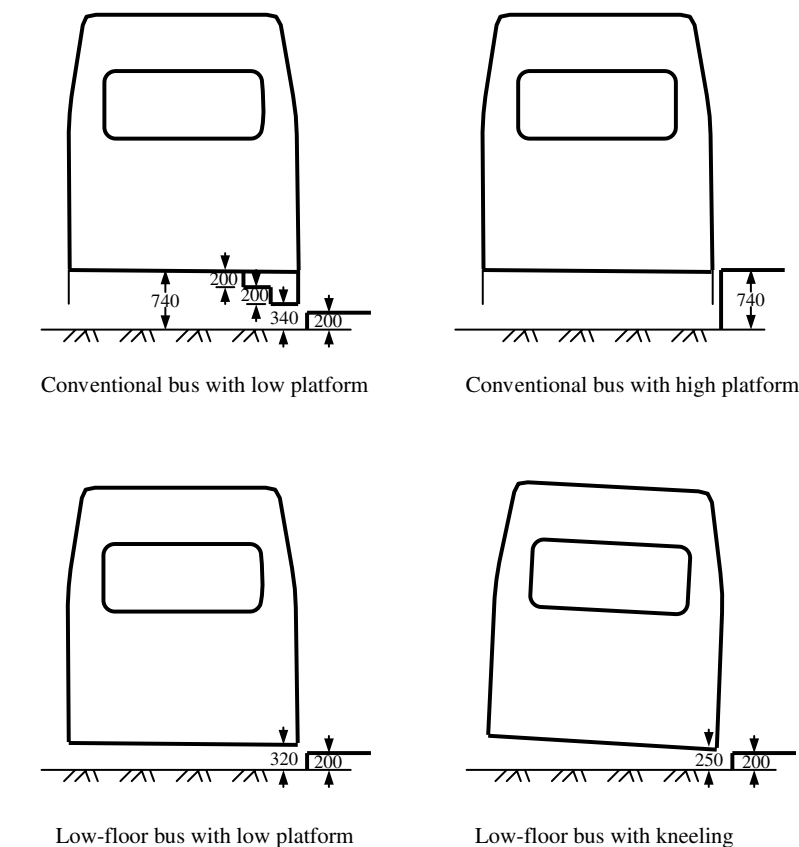


Figure 5.12 Different buses by floor heights (Source: Müller-Hellman et al., 1999)

Additional requirements for design include adequate heating and ventilation or air conditioning, lighting, good visibility from the bus, emergency evacuation features, and others.

5.2.5 Review of Bus Models, Characteristics, and Design Trends

The preceding review of bus vehicle types by body size and form, propulsion, high and low floor, and other features shows that there have been numerous developments in bus technology in recent decades. The basic bus types by body form and size were shown in Table 5.3. Variation in body length, doors, and interior layouts are shown in Table 5.4. Transit operators there-

fore have a much greater choice in selecting optimal vehicles for their specific conditions than they did a couple of decades ago, when the industry, particularly in North America, was dominated by a few standard vehicle designs.

A number of prototype buses have been developed to test new designs and aggregates. The Transbus program in the United States and VÖV bus prototypes in Germany during the 1970s led to the eventual development of low-floor buses. An international committee worked on the development of a dual-mode bus. Various industry groups in Brazil, France, and the United States developed very diversified prototypes that included such concepts as several propulsion systems, steering of all wheels (Neoplan and Phileas), automatic guidance, spacious interiors, and many others. Gener-

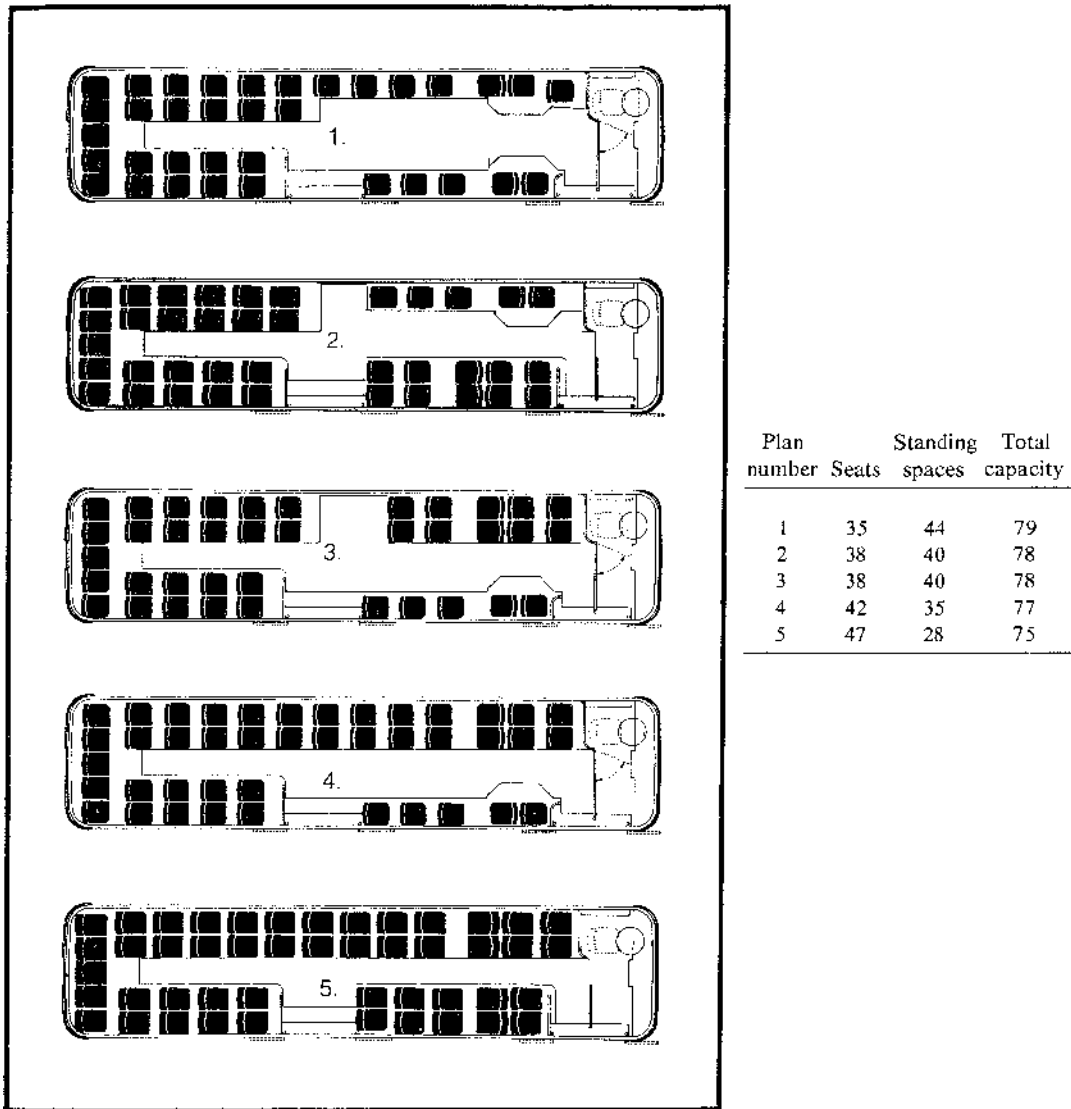
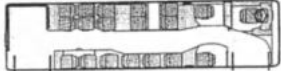
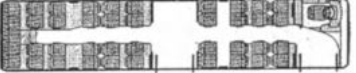
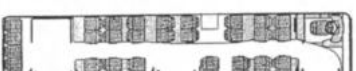
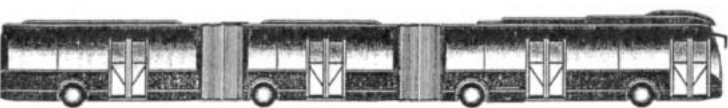


Figure 5.13 Various seating plans for a standard bus (Courtesy of Kassbohrer Fahrzeugwerke GmbH, Ulm, Germany)

ally such diversified models do not become standard vehicles because their diversity imposes very high costs and complexity in operations, which are not needed for any one specific application. However, individual features that are found useful lead to their adoption on some new bus models. Thus, the inven-

tions like dual-mode (diesel and electric) and many guided buses have had very limited applications, but new propulsion systems and improved accessibility have been adopted for many new models. Different types of low-floor designs are still in the phase of testing under different conditions.

Table 5.4 Different buses by body size, doors, and seating arrangements (Van Hool)

<i>Model</i>	<i>Layout</i>	<i>Length (m)</i>	<i>Capacity</i>	
			<i>Seats</i>	<i>Total</i>
A308		9.50	18	45
				
A320		12.00	41	65
				
A300		12.00	35	60
				
AG300		18.00	49	85
				
AGG300		24.80	72	130
				

As in all inventions of new vehicles and new transit modes, two critical questions in their feasibility and adoption are:

- Technical feasibility.
- Benefits versus the increased purchase and operating costs compared with the best present models. For example, buses with many new features which have a cost several times higher than standard models (such as \$1.5 to 2.0 million, compared to \$0.5 million for articulated buses) are not likely to be adopted except in very special cases.

Parallel with these efforts in bus technology development are innovations in the operational regimes of buses on the streets and special ROW types in many cities.

5.3 TRAVEL WAYS

A vast majority of buses operate on urban streets with no special fixed facilities except bus-stop signs and benches or shelters. In recent years in many cities, there has been a growing recognition of the fact that the level of bus service depends mostly on the type of ROW facilities, leading to the introduction of bus lanes and busways, i.e., elements of BTS and BRT.

5.3.1 Geometric Elements

The standard and minimum desirable widths of lanes on which standard buses operate are, respectively, 12 and 10 ft (3.66 and 3.05 m) in America, 3.50 and 3.00 m in most other countries. Operation on narrower lanes is possible, but only with reduced speed and safety. Curb radii at intersections where buses make right turns should desirably be 10 m but not less than 7 m (approximately 30 and 20 ft, respectively). Single-lane roadways, such as ramps in freeway interchanges, should be 5.50 m (18 ft) wide if passing of a standing vehicle is required, 3.75 m (11.5 ft) without passing. Two-lane roadways for buses traveling at moderate speeds should be 7.30 m (24 ft) wide; high-speed (freeway-type) operation exceeding 70 km/h requires

a median separation or a physical divider such as a guard rail and 5.50-m width for one lane and a shoulder on each side. For speeds below 40 km/h, as in pedestrian malls with bus roadways, a total width of only 6.50 to 7.00 m for both directions is often used.

Rights-of-way for BRT may consist of only one regular lane but a widened section of up to 10 m width per direction in stations where overtaking and maneuvering are routinely performed. On open sections between stations, bus roadways may be one or two lanes wide, sometimes with narrow shoulders. The entire busway thus may be from 8 to 18 m wide. Station areas for each direction are sometimes staggered to reduce the entire width along the busway corridor to a single lane in one direction and a double lane and station platform width in the other, with a total width of approximately 12 to 15 m.

Bus facilities designed with provisions for eventual conversion to LRT or other rail transit modes usually do not need any extra width, since rail modes require a narrower ROW than buses. In stations, the difference in width is even greater if bus service is frequent and requires two lanes per direction (one is for overtaking standing buses). Station length is determined by the maximum length of future LRT trains or by the number of bus stopping points required, whichever is longer.

Both diesel buses and trolleybuses can operate on very steep streets in areas without snow and ice. In San Francisco, both modes operate on gradients of up to 19%, but diesel buses at speeds of only 5 to 8 km/h, and their 300-HP engines produce considerably greater than usual motor noise and exhaust emissions. On the same slopes, trolleybuses with only 105- to 125-kW (140- to 170-HP) motors achieve up to three times greater speeds and produce no additional noise—and, of course, no air pollution along a route. In areas with snow and ice, the maximum gradient for both modes is 6% to 8%, even if an adequate snow removal service exists.

5.3.2 Operation in Mixed Traffic

Bus operation on urban streets and arterials requires virtually no investment, allows nearly any bus routing,

but has adequate reliability only if auto and other traffic on the same streets does not have frequent delays. Since buses are vulnerable to traffic congestion and must make passenger stops along their way, bus operating speed is always lower than the travel speed of private automobiles on the same facility. Thus buses in mixed traffic (Photo 5.16) cannot be competitive with autos with respect to travel speed. They can attract a substantial share of choice riders only where there are other disadvantages to auto use, such as limited capacity and high charges for parking.

On streets with smooth traffic flow, buses may use any lane; when they have very frequent stops or where traffic flow is heavy, they usually stay in the right curb lane. This tends to discourage other traffic from that lane, but it also often reduces possibilities for mutual overtaking of buses.

Bus use of freeways can be very effective where transit routes follow freeway corridors. Provided that freeways are not chronically congested, bus speeds can be substantially higher than in street running. Buses can usually use any freeway lane, but if they stop at closely spaced interchanges, they tend to remain in the right-hand lane.

Several cities (e.g., Los Angeles, Houston, Washington, DC, Minneapolis) have made major efforts to utilize their extensive freeways networks for buses. Some of these efforts have brought significant increases in transit ridership, particularly in commuter travel: radial trips during peak hours. Most of these services are commuter transit, operating in peaks only, sometimes one-way in reversible lanes, rather than regular transit. However, three factors present severe limitations on usefulness of freeways for buses, or for any other transit mode:

- Transit demand was never considered in selecting freeway alignments.
- Areas through which freeways go are usually auto-oriented. As a consequence, most efficient alignments for transit routes seldom coincide with freeways.
- Transit stations on freeways can be few (usually in interchanges only) and they often involve difficult access for pedestrians.

For these reasons it is only in some cases possible to have a regular transit line serving a freeway corridor and with stops on the ramps of interchanges. The most common use of freeways by buses is for long express lines with few if any stops on that section. Typically, commuter transit lines have local street running in the suburbs and in the city center, while they use freeways for their middle sections with express running. Similarly, lines connecting airports with the CBD or those approaching cities via major bridges (San Francisco from the north and east, Philadelphia from New Jersey, New York City from New Jersey, and many others) use freeways for their express sections very efficiently.

The usefulness of freeways for buses depends greatly on their treatment. Special facilities (stops, ramps) and preferential treatments discussed in the following section can increase it considerably.

5.3.3 Bus Preferential Treatments

Following many decades of treating buses like any other vehicles in mixed traffic (Vuchic et al. 1994), preferential treatment for buses over other vehicles on streets, freeways, at intersections and interchanges has now begun to be introduced in an increasing number of cities, stimulated by the BRT concept.

5.3.3.1 Purposes and Significance. Equal treatment of all vehicles in streets—including public and private, high and low capacity, passenger and freight—is an illogical and inequitable anachronism that often results in increased cost and travel time to *all* participants in urban travel. An extremely important but often ignored fact is that the purpose of passenger transportation is to move *people*; movement of vehicles is a means toward that goal but not a goal in itself. Furthermore, it is always desirable to perform a given amount and quality of transportation by a *minimum number of vehicles*. The growing recognition of this fact is having a major impact on the treatment of different modes and therefore on urban transportation policies. Once equal rights are given to all traveling *persons instead of vehicles*, a standard transit bus should be given between 5 and 50 times greater im-



Photo 5.16 Bus travel in mixed traffic suffers from low speed and poor reliability (Courtesy of James Aslaksen)

portance than a private auto, 3 to 15 times greater than carpools, and 2 to 8 times greater than vanpools. In addition to this, public transport should be favored over private because it provides a basic transport service to the *entire population*, it is more economical, and it has much lower negative side effects per person-km.

Bus preferential treatments bring significant benefits. Increased travel speed is the most obvious, but increased reliability and improved image of bus service are often equally significant. Reduced operating cost, improved safety, and several other benefits are also often realized. On the cost side is the investment for regulatory devices and the need for continuous enforcement. Impact on other traffic varies with local conditions. On very narrow streets the increase of congestion may be so great that the favoring of buses is unacceptable. However, the introduction of bus lanes on multilane streets may decrease congestion because of the greater uniformity of vehicles in each lane. In such cases the benefits of bus preferential treatment may easily outweigh its costs.

The ultimate significance of bus preferential treatments is that the service improvements resulting from it usually change the competitive position of transit with respect to the auto. As mentioned above, the lack of competitiveness by buses in mixed traffic was demonstrated by the fact that bus transit had a continuous loss of passengers in the United States even during the period of heavy conversion from streetcar to bus services, 1945–1965. The same trend was recorded in the United Kingdom and France when tramways, including many with ROW B, were replaced by buses on ROW category C.

Following the misdirected trend of using “bus flexibility” to mix buses with general traffic, cities began to rediscover the importance of segregating transit, be it rail or bus vehicles, by separation and preferential treatments. Once buses are physically separated, their service can become competitive with some auto trips and attract a number of auto drivers. In many North American cities, improvements of bus services have resulted in sharp reversals of downward passenger trends: Madison, Wisconsin; Portland, Oregon; and Vancouver, Canada are some of the cities that increased ridership by 10% to 30% annually for several years by introducing preferential treatment combined with new vehicles, improved networks, marketing, new fare structures, etc. Similar results were experienced in Paris, London, and many other European cities. Consequently, *bus preferential treatment is the basic prerequisite for improving bus competitiveness with respect to the auto and creating a BTS.*

In some cities certain other categories of vehicles are allowed to use bus lanes. While mixing buses with any other mode decreases their efficiency and image, in some cases such a combination may be necessary and feasible without significant negative impacts; in others, impacts would not be justified or acceptable. Table 5.5 presents a review of impacts and compatibility of four different types of vehicles that are allowed to share bus lanes in some cities: taxi, bicycle, HOVs and trucks. As the table shows, the feasibility of buses sharing their lanes with these modes decreases in their sequence, from taxis—least objectionable, to trucks—highly incompatible.

Table 5.5 Impacts on bus service on permitting other vehicle classes into bus lanes

Vehicle Class	Lower Safety	Lower Reliability	Physical Incompatibility	Strengthening Competitors	Weakened Image
Taxis	x	x	—	xx	x
Bicycles	xx	x	xx	x	—
HOVs	x	xx	x	xx	xx
Trucks	xx	xx	xx	—	xx

— = minor impact; x = significant impact; xx = major impact.

Source: Vuchic 1994.

5.3.3.2 Obstacles to Applications. Despite their underlying logic, equity aspects, and social benefits, preferential treatments of buses are still underutilized in many cities, mainly for two reasons (Vuchic et al. 1994).

The first reason is the deeply rooted belief that streets are best utilized when the greatest number of *vehicles*, not *people*, travel on them. Many traffic engineers still feel that bus lanes can be “better utilized” if empty spaces between buses are filled by autos. The major reductions in reliability and identity of bus services caused by such a mix are seldom considered. Many auto drivers, predictably, tend to share this opinion, so that the introduction of bus lanes often faces formidable opposition.

The second reason is that separating buses from other traffic is physically and organizationally not simple. A bus lane in the street, unlike the curbed grass or gravel median with LRT tracks, appears ready for use by all highway vehicles and is very tempting to auto drivers: marginal cost (imposition, delay) of a bus lane use by any other vehicle is usually very low, so that compromise in exclusive bus use is very easy; its prevention requires energetic and permanent enforcement, which many cities cannot provide. In cities and countries with chaotic traffic conditions, bus lanes often either cannot be introduced or cannot be maintained as such.

The problems of turning traffic, driveway accesses, and deliveries must be satisfactorily solved prior to bus lane introduction. Exclusive physically separated busways, which require a considerably higher investment, are operationally greatly superior to the lanes on regular streets, since their physical separation eliminates interferences and the need for enforcement.

The most serious limitation of reserved bus lanes is the fact that this policy is under jurisdiction of street traffic authorities, who sometimes favor general traffic and are not inclined to favor transit. Regulation of urban streets is often subject to decisions by political bodies or courts rather than transportation experts. Many bus lanes and busways in U.S. cities have been downgraded to mixed use by such political or judicial bodies, which give short-term conditions much greater

importance than the long-term aspects of optimal intermodal systems.

5.3.3.3 Priorities at Intersections. Since intersections cause most traffic delays, speeding up bus travel through them is of particular importance for bus line operating speed and reliability.

As a basic element of transportation policy, general priority should be given, wherever possible, to streets that have transit service. At unsignalized intersections, cross streets should have “yield” or “stop” signs. At signalized intersections, signal split should be such that it gives a lower volume/capacity ratio, and therefore fewer delays, to the street with transit than to the streets crossing it. Such a split corresponds more closely to the ratio of the number of persons transported rather than of the vehicular volumes on the two streets.

Bus lanes make it possible to give buses partial or full preferential treatment of several kinds: *leading* or *lagging green* (extended green interval preceding or at the end of the green phase), separate on-call phase, or full override (the last is extremely rare for buses). These special treatments may reduce bus time lost at signals, give them a start before other vehicles, or allow them to make turns (usually left) prohibited for other traffic.

Full potential benefits from bus preferential treatments at intersections can be achieved with *special bus (or transit vehicle) signals* that do not apply to other vehicles. The common special transit signals, initially introduced in Germany and now used internationally, have a white vertical line for “go” and white horizontal line for “stop.” Actuation of bus signals can be done either by a radio signal from the bus or by an inductive loop in the pavement. Whereas standard loops react to the presence of any vehicle, some signal actuation systems “inquire” and receive, from specially equipped vehicles, a coded response that identifies them. Transit bus detection and identification systems, increasingly using global positioning systems (GPS) technology, are used to give them preferential treatment (special or extended signal phases) even when they operate in lanes with mixed traffic.

Regular bus lanes (RBLs) on streets often have problems with turning movements at intersections. With curb RBLs, right turns by other vehicles and left turns by buses create weaving maneuvers. The same problem arises with left turns by other traffic and right turns by buses with center RBLs. Various solutions can be used for this problem. For example, right-turning vehicles can be allowed to share curb RBL in intersection approaches. However, this can be done without impeding buses only if the turning volume is light and turns are fast (i.e., seldom delayed by yielding to pedestrians). There is an increasing use of low-cost intelligent transportation systems (ITS) devices to clear turning traffic prior to bus arrival. Where volumes are heavy and turns slow, they should be rerouted elsewhere in the street network or separated from buses by special signals. However, the best solution for all turning movements, regardless of their volume, is provided by a special design and signal installation called a *bus gate*, shown in Figure 5.14. This design has been in operation in Wiesbaden and a few other German cities for many years.

As the figure shows on the example of an intersection of one-way with a two-way street, a set of presignals (1 in the figure) is located on the street with RBL prior to its main signals (2), forming the “bus gate.” The length of the gate is about 30 to 40 m, depending on the number of lanes and maneuverability of the buses. The phases of signals 1 are advanced by several seconds in relation to signals 2, so that the gate area is emptied during phase IIa, prior to its red phase (I in the figure). During phase I, the bus-lane signal (IB) is green, allowing buses to proceed from the presignal into any lane up to the signals 2. Phase II starts by changing IB to red, 1 to green, and a few seconds later, 2 to green. Buses are thus the first vehicles to enter the intersection. All vehicles can make either turn without weaving with other traffic. This signal phasing (I, II, IIa in the figure) thus does not affect the capacity of regular lanes, since their green times remain the same and full progression is provided through signals 1 and 2. Buses have protected turning movements and position ahead of other traffic. The only disadvantage is that the buses arriving at the presignals during phase II must wait until the beginning of the next phase II

to cross the intersection, thus suffering a delay longer than phase I.

A small variation in signal timing can eliminate this delay to some buses through a slight reduction of the green time for other traffic. This alternative timing, shown in the figure as phase IIb, represents an “overlap” of phases I and II: as signals 1 turns red, 1B becomes green and signals 2 remain green for a few more seconds than is necessary to empty the cars from the gate area. Thus one or two buses that arrived at IB during the phase II can proceed through the intersection prior to phase I, again with fully protected turns. Clearly, whenever bus volume is substantial and it is possible to subtract some 5 to 8 seconds from other lanes on either intersection approach without excessively deteriorating their level of service (LOS), signal phases I, II, IIb represent the optimal operation. An even better solution is when buses are equipped so that they can actuate the signals; then the normal signal operation can be with phase IIa, but the buses approaching during phase II can call for phase IIb instead.

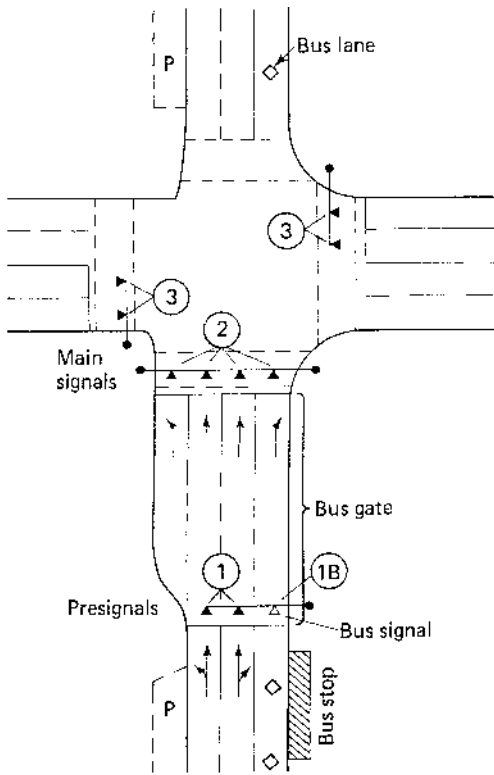
5.3.4 Bus Lanes on Streets

The most important preferential measure for buses is the longitudinal separation of travel ways. It can be provided in different forms with respect to types of lanes, alignment, and degree of separation from other vehicle categories (Photo 5.17).

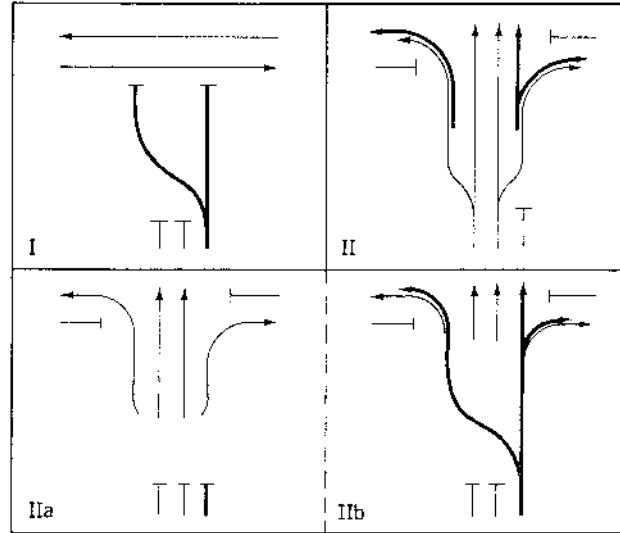
The numerous reasons for preferential treatment of buses, discussed in Section 5.3.3.1, can be divided into two categories:

- Greater importance of public transport due to its basic role in the city, its greater efficiency, and fewer negative side effects
- Much higher occupancy of public than of private vehicles

Since many reasons for bus lane introduction cannot be easily quantified, the following analysis, utilizing a combination of quantitative and qualitative factors, can be used for the evaluation of bus lane justification.



(a) Intersection layout



(b) Signal phases (IIa and IIb are alternates).

Phase \ Signals	I	II	IIa	IIb
1	R R	G Y	R R	R R
1B	G Y	R R	R R	G G
2	R R	G G	G Y	G Y
3	G Y	R R	R R	R R

(c) Signal face indications plan

Figure 5.14 Bus-gate intersection approach control allowing all bus and auto turning movements

The basic factor to be analyzed is the relationship of the number of persons carried by buses versus those carried by autos. The most conservative warrant should be that a bus lane is justified when buses carry as many people as autos carry per lane in the remaining lanes. The volume of buses required for this warrant is:

$$q_B \geq \frac{q_A}{N - 1} \cdot \chi \quad (5.5)$$

where q_A and q_B are hourly volumes of autos (including trucks as passenger-car equivalents) and buses, respec-



Photo 5.17 Regular bus lane on a street (Courtesy of Thor K. Haatveit)

tively; N is the total number of lanes per direction; and X is the ratio of average auto to bus occupancies.

Values of X vary among locations and during different times of day. During peaks, auto and bus occupancies may be 1.2 and 60 (for standard buses); during off-peaks, 1.5 and 15, respectively, so that X would fluctuate between 0.02 and 0.1. Figure 5.15 shows the bus volumes that justify bus lanes for several

values of N and X . However, in most cases bus volumes somewhat lower than those shown would already justify reserved lanes for the following reasons:

- Introduction of a bus lane is likely to cause some diversion of travel from auto to bus, so that a lower q_A and higher q_B would apply than those for existing conditions.
- It is desirable to favor transit over auto travel for the above-mentioned reasons.
- Permanently reserved lanes are the basic element of BRT: they have the advantages of better identity, simpler regulatory devices, and less confusion. This justifies in many cases retaining bus lanes required during peak hours during the entire day—i.e., also during periods when bus volumes are lower than the diagram shows.

There are several types of bus lane layouts in street. The easiest introduction and most effective operation of bus lanes is on streets that have three or more lanes per direction. Ideally, on such streets right turns should be prohibited or regulated by special signals, unless they are very light, and curb parking should be elim-

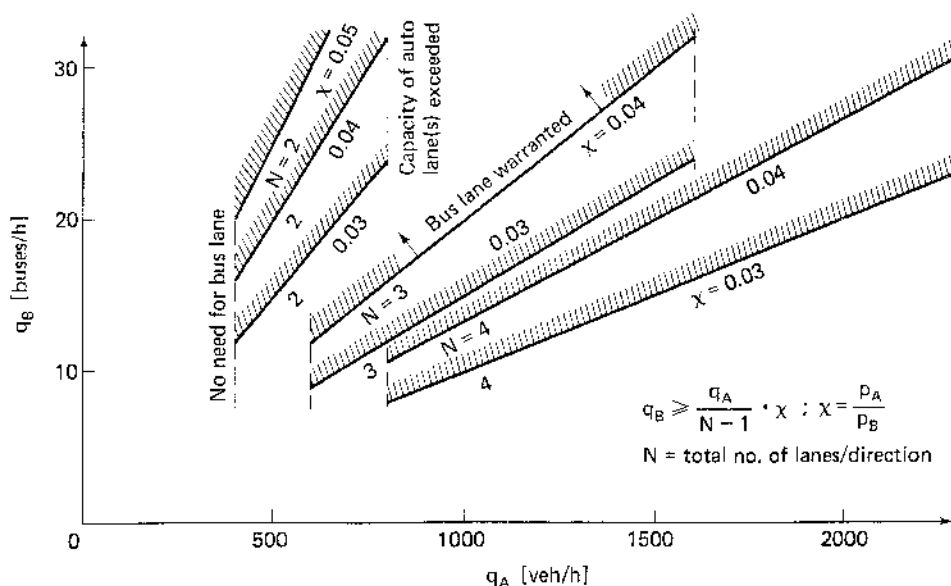


Figure 5.15 Travel volume warrant for bus lane introduction

inated. Then buses can have one lane and other traffic two lanes. However, even where only two through lanes are available, one can be reserved for buses. The other traffic has one lane and, on the rare occasion of vehicle breakdown in it, can use the bus lane for bypassing the blockage.

Separation of buses decreases turbulences in traffic flow and therefore often increases speeds of not only buses but also of the auto traffic in other lanes. A disadvantage of bus lanes is, however, that they tend to discourage mutual overtaking of buses from different lines, which reduces their delays: they usually only follow each other, as do streetcars. However, on multilane bus streets, as in Portland, Oregon, and Bogotá, Colombia, overtaking is common.

Several types of lane arrangements before and after bus lane introduction are shown in Figure 5.16. The most common cases are with conversion of curb parking or one of the driving lanes into a bus lane. Typical layouts of streets with bus lanes [regular bus lane (RBL), contraflow bus lane (CBL) and exclusive bus lane (EBL)] and their intersections are presented in Figure 5.17. The main features of each are described here.

RBLs, usually curb lanes, are the most common type of bus lanes on streets. Their introduction, naturally, requires prohibition of parking and stopping. Turning traffic at intersections requires special solutions, as described in the following section.

Curb RBLs are convenient, since they allow easy stopping of buses for passenger boarding/alighting, but they are usually slower than other lanes because of “marginal friction”: closeness to curb, trees, poles, and pedestrians. Most important, their effectiveness is greatly dependent on the enforcement of driving, stopping, and parking prohibitions, adequate provision for deliveries outside that lane, accesses to driveways and parking areas, and so on. For this reason RBLs cannot be effectively used in cities with inadequate enforcement of traffic controls and chaotic street conditions.

CBLs, having the opposite direction from other lanes on the same street, must be located along the curb to the left from the main travel direction (see Figure 5.17b). The opposite direction of CBL operation strongly discourages any encroachment of other traffic,

so that less enforcement is needed than with RBL. Yet, to prevent potentially dangerous head-on situations, CBLs must be marked more conspicuously than RBLs: double yellow lines, signs, and sometimes overhead lane signals are used.

To further ensure safety, it is desirable that CBLs be used only where bus frequency is high (20 to 40 buses/h), so that a bus is in view of other drivers at most times. Another potential safety hazard is to pedestrians who may step into the lane, not expecting vehicles traveling the “wrong way” on a street perceived to be one-way. This may be a serious problem where pedestrians cross at midblock locations; it may therefore be necessary to install a light fence or chain along the curb.

In planning CBLs, signal timing must be carefully examined. If buses travel against a set of coordinated signals (“green wave”), their delays may be minimized by selecting a convenient sequence of near-side and far-side stops.

Center lanes or *curbed medians*, the most common location for LRT tracks, can also be used for center RBLs. Such lanes are faster and safer than curb RBLs, but pedestrian islands must be provided at all stops for safety and convenience. It is desirable wherever possible to separate lanes on their entire length by curbs, as shown in Figure 5.17c. This type of facility requires either elimination of left turns for other traffic or a three-phase signal control that separates left turns from bus movements. The curbed lanes in median designs, the highest type of bus lanes in streets, were virtually unknown in North America, but they have been given major attention with the efforts to develop “rail-like BRT” systems.

Buses sometimes share reserved LRT ROW (Amsterdam, Belgrade, Munich, Pittsburgh–Mt. Washington Tunnel). These joint ROW are usually somewhat wider than those for LRT alone (see Figure 6.28) because of the lower precision of bus steering. The benefits from increasing the passenger volume which the facility carries can be significant: opening of the Mt. Washington Tunnel to buses (through reconstruction, paving, and installation of a ventilation system) more than doubled the passenger volume carried through the facility. The problems may occur with joint use when

Standard	Curb-to-curb width ^a		Before	After
	m	ft		
Regular (curb) bus lanes				
Minimum	12-15	40-50		
Acceptable	15-20	50-65		
	20-24	65-80		
Desirable	>24	>80		
Contraflow bus lanes				
Minimum	9-12	30-40		
Acceptable	12-17	40-55		
Desirable	>17	>55		

^aConversions between meters and feet are approximate. P — parking lane B — bus lane

Figure 5.16 Street cross-section rearrangements for bus lane introduction

headways are short, or on steep gradients, when different dynamic characteristics of the two modes cause some mutual interference. Consequently, each potential joint LRT-bus ROW must be analyzed separately. In some cases it may bring significant improvements of bus services through their separation from other traffic; in others, the problems of different ROW width re-

quirements, station designs, and mixed operations of the two technologies with different dynamic characteristics may outweigh the benefits.

Bus (transit) malls, sections of streets with bus and pedestrian traffic only, have been opened in several North American and European cities [Minneapolis, Portland, Vancouver, Lyon (a trolleybus mall), and

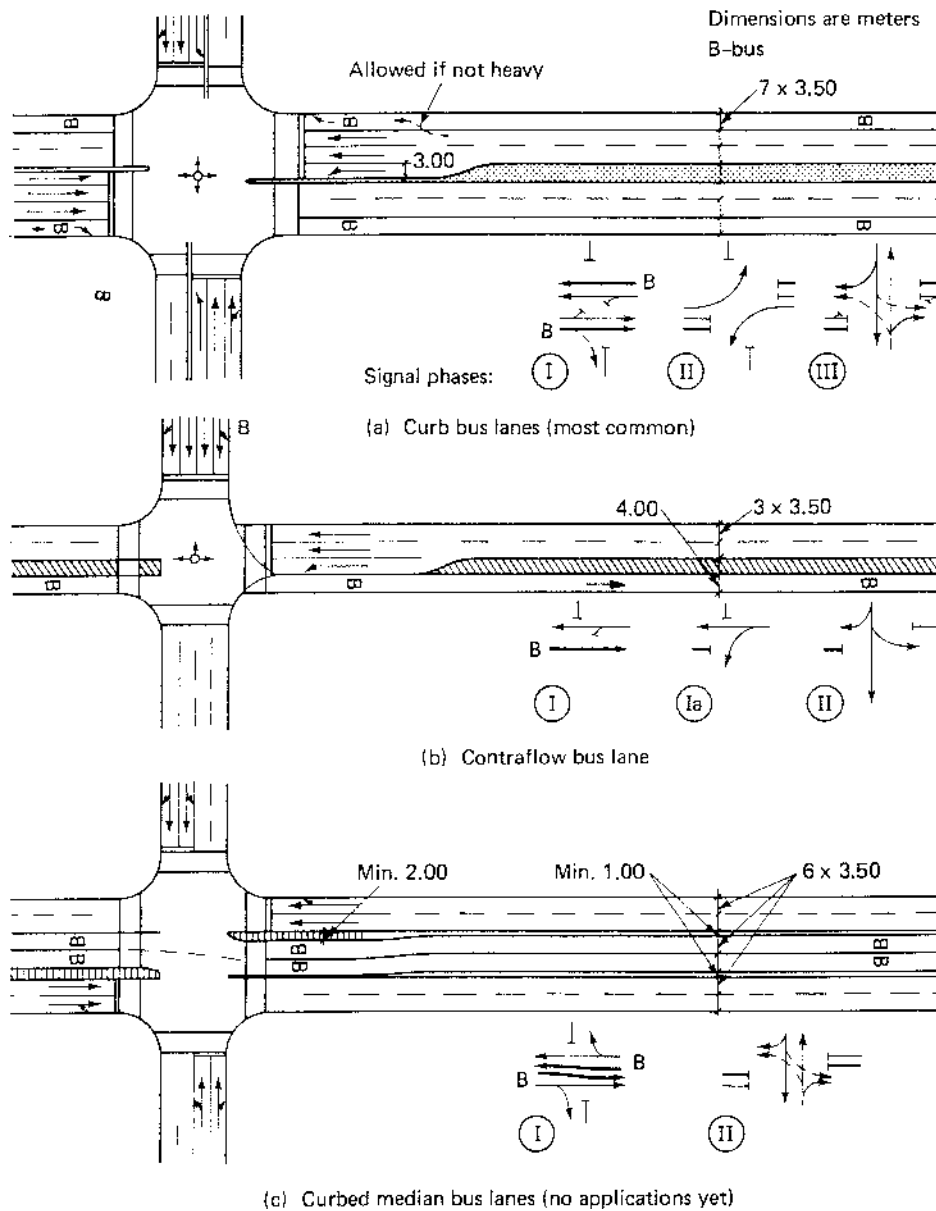


Figure 5.17 Different types of bus lanes

Trier] with good results. Conversion of overloaded, usually chronically congested streets in CBDs or other activity centers into bus malls is functionally an efficient solution: it allows direct transit service to and

from the areas with the highest density of trip generation without the usual problems of traffic congestion. Well-planned bus malls provide an improved street environment and induce increased transit usage.



Photo 5.18 Shirley Highway HOV lanes in the Washington, D.C. Area (Courtesy of FHWA/DOT)

However, two potential problems require particular consideration in planning of bus malls.

First, noise and exhaust produced by buses can be very intensive where bus frequency is high. In Portland, where some 160 to 180 buses pass through each one of its two malls (a pair of one-way streets) during the peak hours, they have caused citizens' complaints. In Philadelphia such complaints contributed to the closing of a bus mall—its conversion into a one-way regular street.

The second problem is that buses cannot be as fully integrated with pedestrians as LRT vehicles; they must have a curbed roadway, while rails can be flush with pedestrian area. Pedestrian movements across the bus roadway are therefore discouraged or prohibited outside designated crossings. For safety reasons, speed limits of all transit vehicles in pedestrian malls are usually between 25 and 40 km/h. Lane widths of about 3.25 m (11 ft) are thus adequate even for two-way operation.

Enforcement of prohibition of other vehicles from bus malls is essential and easier to perform than with other types of bus lanes. The problems exist in cities

with lenient police departments, which allow various official vehicles or even their own vehicles to use the mall for regular patrolling purposes, degrading the pedestrian character of the facility.

5.3.5 Bus Operations on Freeways

The main purposes for giving buses preferential treatments on freeways are the same as those for arterial streets, discussed in Section 5.3.2 (Photo 5.18). As in preferential lanes on streets, there are three forms of bus lanes on freeways:

- *Reserved bus lanes (RBL) or diamond lanes*, one per direction or one reversible lane for both peak hours, used for commuter bus lines.
- *Contraflow bus lanes (CBL)*, one or two lanes opposite to the flow on one roadway separated by lines, curbs, rubber cones, or overhead signs serving buses in the prevailing direction (Photo 5.19).
- *Exclusive bus lanes or busway (EBL)*, physically separated facility for two-way bus travel at all times.



Photo 5.19 Contraflow bus lane in London (Courtesy of Simon Smiler)

All these three types of bus facilities were introduced in a number of cities as early as the 1970s.

Often called “diamond lanes,” RBLs are marked by diamond symbols on the pavement and on signs and separated by double yellow lines and sometimes rubber cones. Since entering and exiting traffic uses outer lanes for considerable distances around interchanges, a diamond lane that provides full separation from other traffic must be the inside lane (i.e., next to the median). An exception is when most buses use the freeway only between two widely separated interchanges, as on the San Francisco–Oakland Bay Bridge (Photo 5.20).

To get to the center lane, buses must weave across two to four traffic lanes. Diamond lanes therefore cannot be used along bus routes with stops. They are practical only for long express traffic routes, usually radial toward the CBD.

Where suitable conditions exist, diamond lanes on freeways represent a very economical way of increas-

ing freeway capacity and favoring transit travel. The greatest obstacle to their introduction is the fact that they often increase congestion in other lanes, leading to protests from motorists (such protests led to abandonment of the diamond lane on the Santa Monica Freeway in Los Angeles in 1977). With a systems approach to transportation policy in a metropolitan area, however, overcoming this obstacle to introduction represents a long-term asset: bus lanes can be an effective auto-use disincentive tool. Another problem is the need for continuous enforcement: a bus lane is always physically available and tempting for motorists using the other, congested lanes.

CBLs are used on radial freeways with heavily directionally unbalanced peak-hour traffic. One or two lanes of the roadway opposite to the peak-hour flow are converted into *CBLs* for the peak direction travel.

The best known freeway *CBL* is in New Jersey on the I-495 approach to the Lincoln Tunnel leading to Manhattan. An extraordinarily high number of buses



Photo 5.20 Regular bus lanes through the toll plaza area on the San Francisco Bay Bridge. Each bus carries during peaks more persons than all cars which can be seen in two of the adjacent lanes (Courtesy of FHWA/DOT)

(up to 485 per hour) converging on this freeway section are routed via special ramps and entrances during the morning peak hours into a single lane of the out-bound roadway, leaving two other lanes to the out-bound traffic. The lane is marked by overhead lane signals and separated by short rubber posts, which are placed at the beginning and removed at the end of the morning peak period. Because of chronically heavy congestion during these hours, introduction of the CBL resulted in a travel time saving of approximately 15 min for each bus, despite the moderate speed (about 55 km/h) on this 4-km-long section without stations!

The conditions on the Lincoln Tunnel approaches from both sides are unique in that moderate speeds and extremely high frequency of buses make operation of a single freeway lane in the contradirection reasonably safe (Link 1975). However, if buses in contraflow lanes operate with headways of 3 to 5 min or longer, the protection safety of such operation from incidental entry of vehicles in the opposite direction must be carefully ensured.

CBLs on freeways can, in cities with extensive freeway networks, bring a major improvement of bus services during peak hours; however, CBLs always represent a short-term improvement, rather than a permanent solution.

The concept of EBL and physically separated busways in freeway alignments was first introduced during the 1970s in several North American and other cities, such as Ottawa, Pittsburgh, Washington (Shirley), Los Angeles (El Monte), and Lima. They were very successful in attracting new riders and creating an improved image of transit. However, many of these busways were seriously downgraded by their conversion into high-occupancy vehicle (HOV) lanes or roadways in North America. While Ottawa and Pittsburgh retained their distinctive busway facilities, most other U.S. cities allowed opening busways to HOVs. HOVs were initially defined as vehicles with four or more (4+) persons. Then the definition was relaxed to 3+ persons. Finally, some cities, like Minneapolis, adopted 2+ as the definition of HOVs, which represents all

vehicles except single-occupancy vehicles (SOVs and trucks). The HOV facilities resulted in the degradation of bus services and weakening of their image (Vuchic et al. 1994).

Compared with EBLs, HOV lanes provide greater total transporting capacity at low additional investment cost: their introduction usually involves only construction of some ramps and posting of regulatory and informational signs. Operation of HOV lanes can be adjusted to ensure that occurrences of congestion are minimized by changing the definition of HOVs. For example, if allowing cars with 3+ persons creates congestion, the limit can be raised to 4+ persons, thus reducing the traffic volume below congestion levels. The significance of impacts of other vehicle classes on buses varies with local conditions, but all these impacts are negative.

The desirability of mixing other HOVs with buses can be correctly evaluated only if all of the positive and negative consequences of such operation are carefully analyzed for each particular facility. These can be summarized as shown below.

The significance of each of these factors varies among locations, so that in some cases allowing other

vehicle classes in EBLs may bring a total of more benefits than losses, or vice versa. Generally, the more vanpool and carpool users are diverted from single-occupancy cars, the greater the benefits; the more of them are former bus passengers, the greater the losses. However, it is important to note that allowing these classes is always harmful to transit: buses can only lose from it, while all the benefits are accrued by their competitors, private autos. *With respect to the policies of auto-use disincentives and favoring of transit, which many cities consider or use, changing of EBLs into HOV facilities is directly counterproductive.*

Preferential entry is another measure that can improve use of buses on freeways. Such entry can be provided either by exclusive ramps (e.g., Manhattan approaches to the Lincoln Tunnel in New York), or by allowing buses to bypass car queues on metered ramps. The latter is achieved by bringing a bus lane to the ramp merging area, past the signal that meters automobile flow, as shown in Figure 5.18. Thus, while auto entry is held up by the signal, causing the buildup of a queue, buses can bypass the queue and enter freeway lanes without delays (Photo 5.21). Since the frequency of buses is usually negligible in comparison with vol-

HOV facilities compared with exclusive bus facilities result in:

- + Reduced travel time for high-occupancy auto passengers.
- + Decreased congestion on parallel regular lanes or roadways: some reduction of travel time of other auto users.
- + As a result of the preceding two changes, increased productive capacity of the entire facility.
- Decreased performance (reduced speed, reliability, safety) of buses due to increased traffic volume and nonuniform vehicle flow composition.
- A loss of the distinct advantage of public transport (buses) in performance and LOS, which full separation gives it over private transport (autos).
- As a consequence of the preceding two factors, some diversion of passengers from buses back to autos, particularly to vanpools and carpools.
- Additional loss of passengers due to their “stealing” by auto drivers from bus stops to form “ad hoc carpools”: direct loss of bus revenue and service.
- A requirement for a wider roadway: minimum of two lanes per direction.

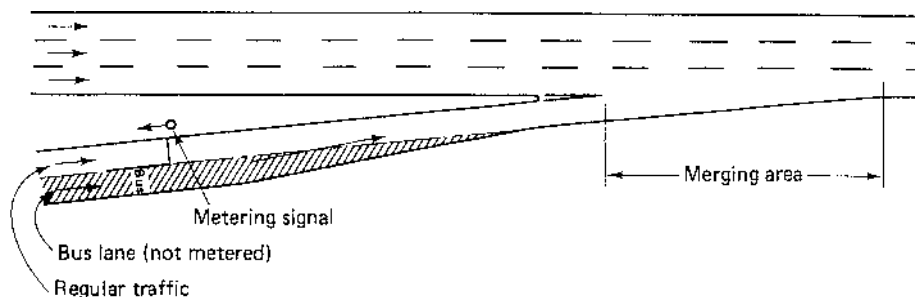


Figure 5.18 Bus preferential entry: "que jumper" on freeway ramp

umes of autos, direct entry of buses does not have a significant adverse effect on traffic flow on a freeway.

Preferential entry is very useful for heavily used interchanges during peak hours. It does not, of course, protect buses from congestion along the freeway.

5.3.6 Busways

Busways, grade-separated roadways used exclusively by buses, have been built for sections of bus routes in several cities. Their typical cross sections are shown in Figure 5.19. Most of them are within freeway rights-of-way; a few have independent alignments.

Busways, representing the highest type of ROW for buses, have several positive characteristics. They do not require the introduction of new technology with separate installations (as rail modes do). They can be built for any section of existing bus lines where suitable physical conditions and service warrants exist and can be utilized incrementally, similar to the improvements of individual sections of LRT ROW. They can be used by many bus routes converging from a large area and speed up their operations along heavily traveled corridors. The implementation period for busways is shorter than for rail lines, while their cost depends mostly on ROW type and location.

Busways leading to a center city have a limitation in that their effectiveness depends on the street distribution of buses. Because sections of lines utilizing streets have much lower capacity, speed, and reliability, they represent the ceiling for the performance and LOS

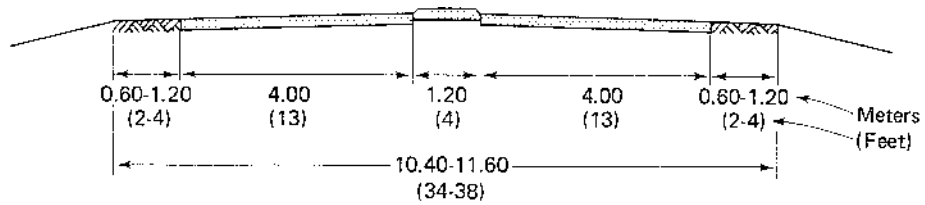
that can be utilized on busways themselves. This "bottleneck" phenomenon can be only partially alleviated through provision of RBLs on streets. Grade-separated ROW, used often for rail modes in central cities, cannot be effectively applied for buses because of their intensive noise and exhaust generation, particularly in station areas (deceleration and acceleration), where waiting passengers are affected. These problems have been avoided in several cities—such as Guadalajara (Mexico), Seattle, and Boston (Silver Line)—through the use of trolleybuses or dual-mode (diesel/electric) articulated buses in their short tunnels under the central business district (CBD). In Guadalajara and Seattle, these were temporary solutions, later converted into LRT lines. Boston uses dual-mode buses, which involve much higher purchase and operating costs than regular buses and trolleybuses, as a permanent solution. Brisbane has a wide bus tunnel with a special ventilation system.

Another problem with bus operation in tunnels is that highway vehicles require considerably wider cross sections of tunnels, particularly in station areas, and yet they offer much lower speeds and line capacities than rail modes. Thus, bus tunnels are both more expensive and less efficient than rail tunnels.

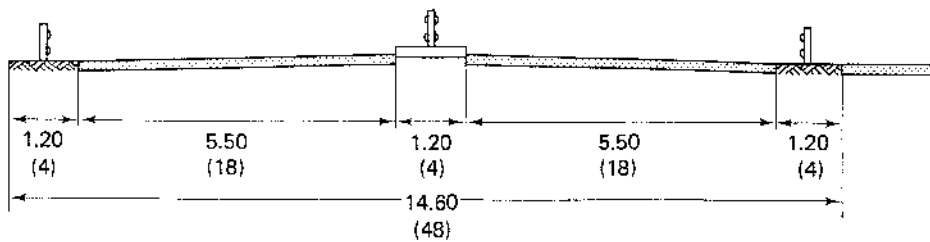
Most busways in freeway alignments have another serious limitation: they have few and sometimes no stations along their entire lengths, so that most of their corridors have no service although large numbers of buses go through them. This deficiency is caused by the fact that the busways have usually been added to



Photo 5.21 Bus bypassing backed-up cars on a freeway ramp (North Vancouver) (Courtesy of B. E. Sullivan)



(a) Minimum dimensions for moderate speeds (≤ 70 km/h). Mountable median can be crossed to bypass stalled bus



(b) Fully protected lanes for high speed operation (up to 90 km/h = 55 mph)

Figure 5.19 Cross section of exclusive busway

freeways after the corridor, ROW width, and basic freeway design had been determined, so that busway alignment and design are often severely constrained. Busways following independent alignments do not have these limitations, so that they can serve the areas they go through. Examples of such facilities are the busways in Pittsburgh and Ottawa.

5.4 BUS RAPID TRANSIT

Conventional or regular bus service, consisting of buses operating on streets in mixed traffic and stopping at curbside stops, has very little infrastructure, and its performance depends largely on traffic conditions. The image of regular bus service is therefore usually not very distinctive and it is often mostly oriented to regular, predominantly captive users.

5.4.1 Definitions of Bus Transit Modes

In response to the increasing need for higher performance and more attractive transit services that can be competitive with autos and reduce street congestion, numerous improvements of bus services have been introduced in recent decades. Now there is a broad range of physical and operational characteristics of bus systems, which culminated in the recent introduction of the bus rapid transit (BRT) concept. There is a considerable discussion about the definition of BRT as a transit mode. The tendency to call any bus system with partial use of bus lanes, with new types of vehicles, or with some buses skipping a few stops as BRT is not only confusing but damaging to the image of BRT mode.

Discussions about characteristics of bus transit as a mode range from its downgrading as a system with low attraction used mostly by captive riders, to overestimation of BRT as a mode comparable to rail rapid transit. This frequent confusion can be reduced if buses are defined as three different modes. Although their definitions were given in Section 5.1.1, they are presented again here at the introduction of the BRT to clarify their relationships.

- *Regular or conventional bus (RB)*: A bus transit system consisting of buses operating with fixed schedules on streets in mixed traffic (ROW category C) and curbside stop locations equipped with signs and sometimes with passenger protection and information facilities.
- *Bus transit system (BTS)*: A bus mode developed as a coordinated system with significant improvements in its components for higher operating speed, reliability, and efficiency. Upgraded components may include provision of bus lanes, stops with greater spacings designed for fast boarding due to self-service fare collection (SSFC), multi-channel doors, low-floor buses, and others.
- *Bus rapid transit (BRT)*: Bus transit designed as an integrated system of distinct buses and a separate infrastructure with considerable independence from other traffic, allowing higher speed, reliability, and safety than BTS.

Although it is not possible to precisely define the distinction among the three bus modes, which may differ in many physical components and operating practices, the six components listed in the box below are used as the basic elements that a system must have to be considered a BRT.

The most important among these six elements is the first, provision of a separate ROW, usually category B.

5.4.2 Evolution of BRT as a Mode

The creation of improved and high-performance bus systems, defined here as BTS and BRT, respectively, is a result of a long series of innovations in technology and, particularly, operations of bus systems and their relationship with other traffic. It is useful to review this evolutionary process because it took place in many cities and countries and included innovations that have been successful as well as others that failed.

Many cities that operated extensive bus services in mixed traffic realized that they had a need to introduce transit systems offering much better performance than regular buses but requiring lower investment costs

BRT must have the following elements:

1. Predominantly ROW category B or A not shared by other modes such as taxis or HOVs, and only limited line sections, if any, with ROW C.
2. Distinctive lines with frequent, reliable service and regular headways during all daily hours.
3. Distinct stops or stations with good passenger protection, information, and fare-collection equipment, allowing fast passenger exchange, which are spaced at least 300 to 600 m apart in the central city and at greater distances in suburban areas.
4. Bus vehicles of distinctive design, with a large door channel-to-capacity ratio, low floor, or high platform for fast passenger exchange at stops and stations.
5. Bus preferential treatment at all major intersections.
6. Use of intelligent transportation system (ITS) technology for monitoring vehicle locations and movements, passenger information, and fare collection.

than rail rapid transit. That led to the development of several medium-capacity or, more precisely, higher-performance systems than RB. While LRT was created by upgrading streetcar systems and automated guided transit (AGT) was developed as a new mode based on fully automated control, numerous attempts were also made to develop an upgraded bus system that could meet the requirements of higher capacity, reliability, and quality of service. BTS and BRT represent modes created by a coordinated set of upgraded elements of bus systems, many of which have been described in the preceding sections.

It is interesting that the massive replacement of streetcars by buses which took place during the 1930s and then the 1950–1970 period in the United States and other countries led to several basic misconceptions about the nature of transit services, which then resulted in serious downgrading of their service quality. The large losses of transit passengers occurred due to not only lower attraction by buses compared to rail vehicles but also due to the types of lines and services buses offered. Five misconceptions about transit services that were introduced with buses are described and corrected here (see also Vuchic 2005, Chapter 12). Their adoption in many bus systems led to the development of regular bus systems that are noncompetitive with auto travel.

Misconception I: *Buses are flexible so that their routes can be easily changed and they can operate better in mixed traffic than on fixed ROW.* This led to abandonment of category B rail ROW and their replacement by buses operating in mixed traffic, category C.

Fact I: Ability to change routes is an advantage. However, the fact that buses can operate in any traffic lane does not mean that they do not need separation. Replacement of B by C category degrades transit service regardless of vehicle technology.

Misconception II: *Transfers are not tolerable; they discourage people from using transit.*

Fact II: Although not desirable, transfers are fully acceptable if they are made convenient and result in faster and more reliable travel. The best transit systems (New York, Paris, Toronto) involve extensive intra- and intermodal transfers. Acceptance of transfers is demonstrated by the large demand for park-and-ride by high-quality rail transit systems (Boston, San Francisco, Washington).

Misconception III: *Buses should offer convenience of easy access by frequent stopping along their routes.*

Fact III: Stop spacings should be a compromise between convenient access of short spacings and higher speed and economy of service, which longer spacings ensure. In virtually no case is stopping at

every intersection in cities with short blocks optimal. Stops can be spaced at short distances only where passenger demand is so low (e.g. in suburban areas) that every bus bypasses most of them.

Misconception IV: *Transit should consist of flexible buses on streets and fully separated rail rapid transit.*

Fact IV: This planning misconception was dominant in many countries (the United States, the United Kingdom, France, Spain, Japan) during the 1945–1975 period, and it resulted in serious damages to cities that built “bipolarized transit,” leaving a large gap between traditional buses and metro systems. A recent upsurge in the development of medium-capacity modes—including BRT, LRT and AGT—has clearly demonstrated the need for a “family of modes” instead of two extremes only (see Section 2.3).

Misconception V: *Flexible transit lines and schedules are needed.*

Fact V: The vague term “flexibility” has been falsely proclaimed always to be a major objective in transit planning and operations. It has been used to criticize rail as “inflexible” and to imply that transit services that are changeable in alignment and schedules are always desirable.

Concepts opposite to “flexible” are *permanent, reliable, durable, efficient, and simple*. These are desirable features for most transit services (Vuchic 1971). Upgrading of traditional bus services usually consists of network redesign to have fewer lines and more permanent lanes and stops. One of the reasons for the success of BRT systems has been that they are permanent due to their infrastructure, as opposed to changeable routings and stopping patterns. Lightly traveled feeder lines remain flexible, but not the higher-performance BRT lines.

As a result of these misconceptions, many bus services have consisted of buses operating in mixed street traffic with curbside stops and little infrastructure. In many U.S. cities, the obsolete practice of buses stopping at every corner still exists. This type of service is subject to traffic conditions and therefore has operating speed and reliability that are not competitive with travel by automobile. Moreover, bus line networks in many cities consist of a very large number of overlap-

ping routes. With little coordination among routes with different headways, these services tend to be oriented to regular passengers on individual routes; they do not represent an open transit system that is easily accessible to any traveler in the city.

Extreme cases of unreliable bus services that do not offer easy travel on a transit network are those in cities with competing, unregulated bus companies, found in many developing countries. In addition to a lack of convenient transfers, such services do not offer integrated fares or information about the use of the entire system. With such operations, major corridors are typically served by many different routes, but lightly traveled streets have unreliable service with long and irregular headways.

Consequently, bus services, particularly those without intra- and intermodal integration, are not capable of satisfying the needs of cities for an attractive and efficient medium-capacity transit system that is competitive with car travel and thus can ameliorate traffic congestion.

To meet the need for more efficient and attractive bus services, a number of studies have used a systems approach to define and propose upgraded bus systems (e.g., Levinson 1975, Midgley 1977, VÖV 1979, Vuchic 1981, Vuchic et al., 1994). This approach defines the basic goal of transit system performance: to provide convenient and attractive transit service that is competitive with auto travel for many trip categories, economically efficient, and suitable to the environment of livable cities. To achieve this goal, improvements must be made to physical components, including vehicles, ROW and stops, as well as to the bus system/network form and operations.

These studies and projects have generally recommended and led to the corrections of the mentioned misconceptions, such as the introduction of bus lanes and busways; operation of fewer but higher-frequency, reliable lines; fewer stops of higher quality; and easy transfers among coordinated bus lines as well as with rail modes.

The most important of these innovative projects deserve careful attention because they indicate which projects can be efficiently introduced and which face obstacles. Major innovations and upgrading efforts are

briefly described and analyzed here, designated as advancements (+), various experiences (~), and setbacks (−).

- + **Exclusive bus lanes and busways** were already built during the 1970s in a number of cities. The best-known successful busways were built in North America in Ottawa, Pittsburgh, Washington, DC, area (Shirley), Los Angeles County (El Monte Freeway). In Latin America they were introduced in São Paulo (Comonor Project), Lima, Mexico City (Ejes Viales), and Curitiba. They were followed by the construction of an O-Bahn (guided bus) line in Adelaide and busways in Brisbane, Australia, and in several French and British cities.
- + **Bus vehicle design** has had very significant advances: new vehicle types, such as the articulated bus, double-articulated bus, low-floor bus; also increased comfort, large windows and improved appearance, hybrid and other cleaner engines, etc.
- + **Applications of intelligent transportation systems (ITS) for upgrading bus services** have already been significant, and there is considerable potential for their wider use in BTS and BRT operations, passenger information, and safety.
- + **Introduction of BTS and, particularly, BRT as system concepts** have led to the fundamental change of treatment of bus services. Instead of conventional operation of buses on streets with minimum infrastructure, a systematic planning and operation of buses as a higher-quality, coordinated system has improved existing bus services and created the new BRT mode, which maximizes separate facilities and gives buses a distinct image.
- ~ **The commuter busways** concept was adopted in several U.S. cities in place of busways for regular BTS services. The extensive systems of busways in Houston, Seattle, the Washington DC area–Shirley HOV facility, and many others are unidirectional roadways which provide efficient commuter services to and from downtowns, but they do not represent regular, all-day transit systems which constitute an integrated network.
- ~ **Bus lanes on streets** have faced a similar problem to busways: pressure always develops to let other vehicles, such as taxis, HOVs, delivery trucks, and others into bus lanes. In recent years in the United States, even HOV facilities on freeways are under attack by the SOV motorists who see free-flowing lanes next to the congested lanes in which they are traveling.
- ~ **Progress with priority treatments at intersection** has been very slow. Although the technology for signal and other priorities has existed for decades, even today—in cities like Boston, Baltimore, and Los Angeles—buses with 80 persons and LRT trains with 300 to 400 persons are treated at intersections with the same rights as cars with an average occupancy of 1.3 persons. Priorities for buses are operationally and politically even more difficult to implement than for rail systems because of their full technological compatibility with street traffic. For example, bus priorities at signalized intersections along the South Busway in Miami have been suspended following several accidents, and there have been claims that the highly successful Metro Rapid BTS line on Wilshire Boulevard in Los Angeles has a negative impact on traffic flow at intersections. This criticism is based on the obsolete concept that the capacity of streets and intersections is measured in the number of vehicles rather than the number of passengers.
- ~ **Guided bus or O-Bahn** (see Section 5.2.2.8) has had largely unfulfilled expectations with respect to implementation. The Adelaide system has been successful but remained the only major facility with that technology. Even in the Seattle and Brisbane bus tunnels, where such a system had potential, guided buses were not introduced.
- ~ **Interactions with surroundings and impacts on the served areas** have varied. Good coordination between transportation and land-use planning in Curitiba and Ottawa enabled BRT systems to have positive impacts on land devel-

opment around major stations and along the served corridors. In São Paulo, on the other hand, the corridors along the highest-capacity bus/trolleybus lines have deteriorated economically and environmentally due to the intensive noise, pollution, as well as physical and visual separation of the two sides of the avenues. The lines carry very large passenger volumes (in excess of 20,000 prs/h) but have a much lower image than the BRT systems in Curitiba and Ottawa.

- **Downgrading of busways:** the concept of HOV lanes or roads was introduced in the United States during the late 1970s. Although such lanes logically favor more efficient vehicles with greater numbers of passengers and result in the increased productivity of highways, this concept has led to the **conversion of most busways into HOV facilities**. This change benefited carpools and vanpools, while the bus users experienced a distinct degradation of service and image of BTS. Moreover, the new phenomenon of “ad hoc carpooling,” performed at the ramps of former busways, resulted in direct “stealing” of transit passengers. The decrease in transit ridership eventually resulted in a reduction of bus services. Today, several cities allow all vehicles with two, three, or more persons to mix with buses in the former exclusive busways. Thus, in the United States, busways have virtually disappeared, the exceptions being Pittsburgh, Miami, and very few other cities where they are owned by the transit agencies. This has been a distinct setback for the BTS concept.
- **Many bus priority measures have been diluted or eliminated** due to inadequate police enforcement as well as political pressures (Philadelphia, Chicago, Mexico). The bus lanes on Santa Monica Freeway, evaluated positively by detailed professional studies, were eliminated in 1977 by a legal action—i.e., by a judge who was a layman with respect to urban transportation. A city council sometimes forces the elimination of transit priorities or enforcement of regulations of parking and turning vehicles.

- **Deregulation of bus transit**, as in Great Britain, has resulted in the breaking up of bus systems and made their technical and organizational upgrading much more difficult or even impossible. For example, in Mexico City, the replacement of most bus services by deregulated minibuses during the 1990s practically destroyed reserved bus lanes and other BTS features.

Most of the physical and operational elements of BTS are described throughout this chapter, in sections on bus vehicles, ways, stations, etc. Physical and operational components developed specifically for BRT systems are reviewed in further text of this section.

5.4.3 Vehicles

The development of BTS and BRT concepts has greatly stimulated innovations and the diversification of bus vehicles. Although there is no sharp division of bus vehicle designs and features among the three bus modes (RB, BTS, and BRT), there is a distinctive difference between typical buses for each one of these three modes. For example, a 12-m-long bus used for regular bus lines can be used on most BTS lines. However, the more advanced features that each bus system has, the more efficient its operation on higher-performance lines. For lines with large passenger volumes or for desired spaciousness and comfort, articulated buses are superior to single-body tow-axle buses.

The following is a review of bus vehicle features that are required or most effective for application to BRT systems.

5.4.3.1 Body Size and Structure. Since the size and capacity of a bus depends on the required line capacity, passenger comfort (seat/standee ratio), and desired service frequency, BRT lines are usually served by articulated buses because they serve heavily traveled lines and require high passenger comfort. In some cases, like the Los Angeles Metro Rapid BTS (Photo 5.22), regular buses are used in combination with articulated units to provide higher service frequency than



Photo 5.22 Los Angeles Metro Rapid bus service (Courtesy of Chaffee Y.B. Yiu)

would be available by articulated buses only for the given passenger volumes.

BRT lines in developing countries, which handle very large passenger volumes, use in most cases articulated buses. Curitiba, which has a very well designed BRT network and facilities, uses double-articulated buses on its major trunk lines with few turns at intersections and running in streets.

5.4.3.2 Floor Height. There has been a clear trend toward low-floor buses in all three systems, conventional, BTS and BRT. In some countries, high-floor transit buses are now seldom being ordered. The benefit of easier boarding/alighting generally outweighs the increased complexity of vehicles and loss of four to eight seats because of protruding housings for wheels. However, some BRT systems use a different solution: high-floors on vehicles without steps designed to dock precisely with high-level platforms. This design greatly improves the boarding/alighting process at the price of preventing the vehicles from using any bus stops and lines that have street-level platforms. Thus, these high-floor buses are designed ex-

clusively for one or more given BRT lines and they are incompatible with other bus lines.

5.4.3.3 Steering and Guidance. Most articulated bus models now have only the first axle steered. Although the turning path of such buses is wider than that of buses with steered first and third axles, fixed third-axle wheels allow placement of the motor in the rear and provide a somewhat more stable ride. Double-articulated buses, however, have the fourth axle steered to avoid an excessively wide turning path.

Many other steering arrangements have been developed and tested; for example, a two-axle bus with rear axle wheels that are also steered. An extreme case has been Van Hool's prototype double-articulated Philadelphia bus with all eight wheels steered, resulting in different capabilities and problems in steering than those of standard buses. This design has not been adopted for any other bus models.

With respect to bus guidance, the well-known O-Bahn model was developed by Mercedes Benz in Germany and demonstrated in Essen. It has then been proven on a long line in Adelaide as feasible and ef-

ficient, but its guidance technology has not been used on any BRT system lines so far. Different methods of bus guidance are used on many BRT systems for access of buses to the station platforms, particularly where high platforms and high-floor buses are used. At such stations articulated buses with several doors must “dock”—i.e., stop parallel to the platform at a distance of 10 to 25 cm. This can be achieved in several ways:

- As the bus approaches the platform, the driver slows down to 10 to 15 km/h and travels at that speed to the location where the bus doors match the platform doors or openings. This requires no special technology but results in considerable time loss at every station. In some cases (Curitiba) gangplanks are lowered from the bus to bridge the gap.
- Electronic guidance from an underground cable in the station area. The driver takes over steering again when the bus departs.
- Optical guidance: painted lines on the pavement are scanned and detected by the bus, giving it precise steering.
- O-Bahn-type guidance, which the bus enters when approaching the station and leaves when departing. This guidance is somewhat more complicated, but its physical components prevent any other vehicles from entering the bus lane, which may be a problem with other systems if the bus lane is not physically fully protected.

5.4.3.4 Doors, Seats, and Capacity. With respect to doors—their number, width and locations—there is a rather sharp distinction between regular bus, BTS, and BRT modes. Although conventional buses in many countries, including North America, still follow the obsolete design of two single-channel doors, one of the basic differences BTS introduces is the use of double-channel doors, two on regular and three or four on articulated buses. All BRT systems also have a larger number of doors because short station dwell times are required for the high capacity and speed that BRT systems must have.

In addition to multiple door channels, BRT systems in most cases have prepaid fare collection, so that each

door can be used for both boarding and alighting, further reducing dwell times.

As for the ratio of seats, aisle widths, and total vehicle capacity, there is no difference among the three bus modes: Some BRT vehicles have been produced with very spacious seats and aisles, implying that BRT provides high comfort. Actually, such designs offer high comfort at the cost of lower total capacity and higher vehicle purchase and operating costs. On many BRT lines that are heavily loaded, like most of those in Latin American cities, the most efficient vehicle design is for fewer and less comfortable seats and maximum standing capacity. Under such conditions maximum design capacity actually results in less overcrowding of vehicles during peak hours. Consequently, line capacity and passenger comfort depend more on the ratio of served passengers and design line capacity than on the specific mode. BRT often offers greater line capacity but not necessarily greater passenger comfort than regular bus lines.

5.4.3.5 Vehicle Propulsion. In addition to the desire to make BRT a higher-quality transit system than regular bus, BRT lines with high-frequency operation make clean and quiet engines (hybrid or others) even more desirable than on regular bus lines.

5.4.3.6 Vehicle Form and Aesthetics. As an element of the distinct image that BRT systems should have, their buses are usually built with a distinct design or color scheme. Several recent models have been given rather exotic shapes with the appearance of large, rather bulky vehicles (Photo 5.23). Although such “fashionable” designs usually do not outlast tastes that change with time, it can be expected that BRT vehicles will look distinct from regular buses and will sometimes vary among the lines (at the expense of no possibility for shared fleets for entire networks).

5.4.4 Infrastructure: Lines and Stations

As discussed in Section 5.3.4 and shown in Figure 5.17, BTS lanes are usually placed along street curbs. This facilitates bus stopping at stops, but the lanes are



Photo 5.23 BRT in Las Vegas: bus with rail styling. Optical sensor above windshield for automated close docking (Courtesy of NeiTech.)

slow and right-turning vehicles often impede buses. With the goal of making BRT lines a distinct transit system with priority over general traffic, their exclusive lanes are placed in most cases in a central position (Figure 5.17c), following the experience of LRT lines. This position provides for faster travel of buses, although it requires special design of stations and regulation of turning movements at intersections.

Bus station designs depend on the passenger volumes, their access to stations on islands in the middle of the street, and method of fare collection. In cities with self-service fare collection, separate stops/stations can be provided for each direction and stop areas do not have to be fenced off. With full payment control—i.e., the need to fence off the boarding platforms—the design is much more difficult and takes more space. Pedestrian access must be channeled via one or two pathways from intersections or overpasses to a set of fare gates. In most cases high platforms must be used not only for faster boarding but also to prevent direct pedestrian access from the street.

Since installation of high platforms on the two sides of the two lanes would require high structures along the street median, it is logical to use a single center platform serving buses in both directions. However, such platforms require that buses have doors on their left-hand sides (in countries with driving on left, doors are on the right), so that specially designed vehicles must be used. These typical BRT lines with the most efficient boarding/alighting arrangement therefore have specially designed buses which cannot branch out to other lines. The stop dwell times are, however, minimized, reducing the average headway between vehicles and maximizing their capacity.

This type of station design—with fare gates and the boarding/alighting process on four to eight door channels on each bus—is used, for example, on the Insurgentes BRT line in Mexico City. Articulated buses stop one at a time and proceed through signalized intersections at the rate of one bus per signal cycle. At intersections where signal cycles of 90 s are used, this operation can reach approximately 5000 prs/h: if each

one of the 40 signal cycles per hour is used by a bus with a capacity of 120 spaces and assuming occupancy close to 100%, this results in a line capacity of 4800 prs/h.

Line capacity can be further increased with provision of two berthing locations along the station platforms and two lanes per direction through the station areas, which allows mutual overtaking of buses and operation of local and express services. With this type of facility, such as TransMilenio (Photo 5.24), record line capacities have been achieved.

Another method for increasing frequency of buses and line capacity is operation of bus convoys or platoons. This concept, designated “Comonor,” was theoretically prepared and then applied in the late 1970s on the 9 de Julho Avenida in São Paulo, which carried hundreds of buses per hour in a very chaotic manner at average speeds of only 10 km/h (Szasz et al, 1978). At the beginning of a trunk bus line, which later divides in three groups of branches, a wide street roadway was built with three parallel lanes designated A, B, and C. Buses stop in individual lanes according to the group of branch lines they belong to.

Special controller releases groups of buses, each one consisting of one or two buses from each group strictly in the A–B–C sequence. Thus organized convoy travels and stops at each stop with designated lo-

cations for two buses from each group—A, B, and C. The standing of all buses in each convoy is thus simultaneous as the convoy travels together along the trunk line. At points where different routes separate, buses diverge from the convoy.

Theoretical analyses showed that under ideal conditions this operation could reach 450 buses per hour and carry 27,000 prs/h. A carefully prepared demonstration achieved much higher capacity than the previous unorganized operation could produce: a flow of 300 buses per hour which carried 12,000 persons at an average speed of 19 km/h. This innovative organization of convoy operation was thus very successful in increasing bus line capacity, reliability, and speed. The great difference between the theoretical and achieved capacity—27,000 versus 12,000—is typical for any transit facility, as discussed in Sections 4.3–4.5). In this case it was caused by many random events, such as uneven dwell times of buses at stops (where the longest one dictates the travel of each convoy), sometimes dispersal of a convoy, uneven bus loadings which resulted in considerably lower average (40, representing seated load only) than theoretical maximum of 100 persons per bus, etc.

Another example of high capacity of bus lines was developed in Portland with a great number of bus routes overtaking each other in bus stop areas, as de-



Photo 5.24 TransMilenio BRT (Courtesy of TransMilenio BRT, Bogotá, Colombia)

scribed in Section 4.5.3.1. Overtaking of buses requires two lanes per direction along the entire street and allows orderly operation of 185 buses per hour on many bus routes sharing the same trunk line.

5.4.5 Operations and ITS Applications

One of significant improvements of bus services that has been achieved by the introduction of the BRT mode has been that it reversed the trend toward deregulation of bus services and their operation by many companies with diverse vehicles, operating practices, driver training, as well as with different fares and, typically, inadequate passenger information systems. BRT requires bus operations with prescribed schedules and stopping patterns, easy transfers, joint fares, as well as uniform vehicle paint scheme and insignia. This coordination and uniformity creates more efficient operations and a higher quality of service for passengers and results in higher passenger attraction.

Most BRT systems are operated by a single agency, but in some cases various operators have been included when they fulfilled the requirements for coordination and integration of operations, fares, schedules, etc. The centralized control system typically uses some ITS elements. The most common are listed here.

- The automatic vehicle location (AVL) system, based on GPS or other technologies, is often used by control centers for bus dispatching, coordination of transfers among bus lines, interventions when delays occur, and other events.
- Priority or preemption at signalized intersections.
- Silent alarm for the driver and other security devices.
- Passenger information systems for pretrip and on-board information for forthcoming stops, transfers, etc., automated or transmitted from the driver or from the control center.
- Announcements of next bus arrivals at stations.

All these and many other ITS elements are actually used by all types of bus lines, but most commonly they are used on BRT systems to provide high service quality.

5.4.6 Review and Evaluation of BTS and BRT

A brief review of several selected BTS and BRT systems is presented here to illustrate the diversity of applications and designs of these modes, followed by an overview of their present and potential roles in different types of cities and functions.

5.4.6.1 Selected Case Studies. Following the numerous attempts to upgrade bus transit systems since the 1970s, with some successes and some setbacks, as described in Section 5.4.2, the BRT mode has recorded a number of effective implementations and obtained very positive publicity in many countries since the 1990s. A review of implemented BRT systems reveals a great variety of systems distinguished by the roles they are designed to achieve as well as by their functional and design characteristics.

In North America, **Ottawa** developed one of the first BRT systems with an excellent combination of reserved rights-of-way, from reserved lanes in center-city streets and on sections of freeways to specially built busways. The network consists of trunks on exclusive bus facilities (Photo 5.25) as well as extensions to branches on streets where traffic congestion is not a problem. A number of stations are designed for easy transfers among lines and surrounded by high-rise residential buildings.

The Ottawa BRT system has been successful because of comprehensive planning and the ability to provide bus lanes and priorities at intersections in center-city streets. A very high density of buses on the core trunk sections requires good operational controls to minimize loss of speed and delays in these areas.

Pittsburgh has also been successful in maintaining exclusive busways and prioritized treatment of buses on many streets. This has been possible because the transit agency owns the busways and has full control over them.

In a number of other cities, such as Seattle, Minneapolis, and Washington, DC, initially reserved busways have been converted into HOV roadways and lanes, which has downgraded the quality of bus services as well as their image. Such systems do not meet most of the essential requirements of BRT systems.



Photo 5.25 Ottawa BRT (Courtesy of Steve Brandon)

Houston and several other cities have built extensive exclusive bus lanes used as reversible facilities serving commuter buses inbound in the morning and outbound in the afternoon. These systems represent efficient commuter transit but not a permanent, high-performance regular BRT because they do not provide service for any other than radial peak-hour trips.

The main obstacle to the introduction of BRT systems in many U.S. cities has been very strong political pressure of highway interest groups and, often, city traffic engineering departments to maximize the flow of vehicles rather than the flow of people. Downgrading of bus facilities into HOV roadways and lanes, which may look in the short run as an easy way to increase the vehicular capacity of streets, prevents the development of distinct, independent, and competitive transit systems such as BRT.

Opposition is also often encountered by store owners and residents when introduction of BRT requires elimination of curb parking along an arterial street.

The concerted program of the Federal Transit Administration to encourage implementation of BRT as

independent systems has led to extensive planning and implementation of several BTS and BRT lines in North America. Several examples, such as new bus lines in Los Angeles, Vancouver, and Cleveland, deserve mentioning.

In **Los Angeles**, a new systems approach to bus lines planning and operations resulted in the abandonment of misconceptions described in Section 5.4.2 and application of contemporary principles for efficient bus services. **Wilshire Boulevard**, the busiest corridor in the city, was served by traditional bus services: numerous bus lines with different headways and frequent delays operated by conventional buses with narrow doors, frequent stops with slow boarding, and long waits at signalized intersections. They were supplanted by **Metro Rapid Buses**, distinctly painted, attractive low-floor buses with double-channel doors (see Photo 5.22) operating as expresses with widely spaced stops that are better designed and equipped than local stops. Signal priorities at intersections and several other ITS control and information elements have been introduced. With fewer stops, faster passenger exchange,



Photo 5.26 Los Angeles Orange Line BRT (Courtesy of James Aslaksen)

easier transfers among lines, and less time lost at signals, travel times were shortened by up to 25%.

These technical and organizational innovations created a very different service and image. In addition to increased speed and reliability, the new service was given distinct symbols and Metro Rapid designation. Although it does not have a separate ROW because the conditions did not allow that on Wilshire Boulevard, this (and several later introduced) Metro Rapid lines are not BRT but typical BTS systems. They demonstrate that it is possible to upgrade many conventional bus services with contemporary systems concepts at low investment cost and achieve very significant results. The introduction of the Metro Rapid Buses re-

sulted in increases of ridership by 42%, about one-third of this increase being new riders, old riders making more trips, and riders diverted from other services.

In the San Fernando Valley, northwest of the Los Angeles city center, a new 22.9-km-long BRT **Orange Line** was opened in 2005. It feeds the rail rapid transit Metro Red Line at its North Hollywood terminal station. Specially designed low-floor articulated buses operate on ROW category B with signal priorities at intersections (Photo 5.26). The line has only 13 stations and an operating speed of 32 km/h, and it carries 22,000 weekday passengers (2006). It provides a much better service than did the set of bus lines operating in mixed traffic on streets in that corridor which it re-

placed. The investment cost for this project was \$390M, or \$17.0M/km.

The successful introduction of several Metro Rapid BTS lines and the new BRT Orange Line in the Los Angeles area is paralleled by continuing downgrading and efforts to save the once successful **El Monte Busway**. Built as an addition to a freeway, El Monte was one of the nation's early attempts to introduce a high-performance bus system that could become a BRT system. However, instead of its further upgrading by improving service regularity and reliability, this facility became subject of decisions by the state legislature which, under strong pressures by auto lobbies, voted to convert El Monte into an HOV facility with 3+ occupants; then another law decreased this requirement to 2+ occupants, causing collapse of the bus lanes as well as the general lanes. Repeal of this law followed but created an occupancy limit that varies by direction and hour of day. Thus, instead of being upgraded into a BRT line following successes of similar systems, El Monte has become a politically regulated, inefficient facility that favors buses at certain hours on weekdays but has no image similar to BRT in any way.

Vancouver, Canada, is known for its energetic policies of transit development, which have created numerous innovations since the 1980s. Among these have been the fully automated driverless LRRT, locally designated as "Advanced LRT" or ALRT SkyTrain, SeaBus Ferry serving as the main transit link between northern suburbs and center city, new LRT and regional rail lines, and an extensive trolleybus network. The transit agency operates four BST lines, designated as BeeLine, although only one (98B) has reserved lanes. One of these, connecting the SkyTrain Broadway Station with the University of British Columbia campus, has been particularly successful. Although without separate ROW or signal priorities, the line has been supported by strong pro-transit policies: reduction of university parking and provision of transit passes by the university. The line provides three types of service: local trolleybus (route 9), express with few stops (99B) and nonstop between the two terminals 12 km apart (99S). The line has achieved a weekday ridership of over 70,000 passengers.

Cleveland has considered many designs for its planned BRT line on once heavily traveled Euclid Av-

enue and selected several features from the BRT systems in Latin America: center station platforms and high-floor buses with left-side doors. The investment of this line is very high (about \$25 million/km), but that expenditure was justified by the expectation that it would act as a catalyst for urban redevelopment.

As Europe and North America produced many studies of possible improvements in bus systems, several cities in Latin America have pioneered the implementation of BRT systems. There is a considerable difference between these two groups of BRT systems. European and North American systems have as a major goal the provision of high-performance, high-quality service that is competitive with auto travel. Facing high labor costs, transit systems in industrialized countries are designed for maximum productivity of employees. In Latin America and many other less industrialized countries, provision of high transporting capacity is usually the dominant goal, while comfort standards can be considerably lower and labor intensity is not as much of a problem. Several BRT systems typical for Latin America are briefly described here.

Curitiba, Brazil, built one of the best-known BRT systems in the world. It is a result of long, farsighted city planning that integrated transportation planning. Thus the Curitiba BRT is a result of comprehensive planning of a transit network coordinated with the activities and densities it is designed to serve. The BRT trunk lines represent the spines of high-density urban developments and they are integrated with secondary network of branches, tangential lines, and community buses.

The BRT lines have a single lane per direction (Photo 5.27), but some busy stations have an extra lane for overtaking of stopped buses. Stations with high platforms are on each side of the busway. Buses have plates that bridge the gap when buses stop. Fare-collection turnstiles are on one or two access paths from platforms, so that all fares are collected offboard. Several types of buses, including double-articulated ones, are operated on different categories of lines by the passenger volumes they serve. At major stations, two articulated buses can board simultaneously.

The Curitiba BRT system is remarkable in several respects. First, it represents not only an efficient transit system network but also an integral part of a city with



Photo 5.27 Curitiba BRT (Courtesy of Jaime Lerner)

coordinated urban design and transportation policies that favor transit and a livable urban environment over domination of street and highway traffic. The population is aware of these policies, supports them, and considers transit as the basic and favored mode for travel in the city. Therefore, in Curitiba, buses are the mode for all citizen categories rather than serving mostly those who have no other means of travel.

São Paulo developed one of the first high-capacity BRT systems. Its Comonor Project opened during the 1970s and was followed by other, similar bus systems. These preceded high platforms with bus docking and horizontal boarding but utilized several other concepts for achieving very high line capacities. These innovations included bus platooning with multiple simultaneous stopping, overtaking of buses in some stations, use of buses and trolleybuses, and a number of others.

São Paulo BRT lines were claimed to achieve capacities over 20,000 prs/h, although these numbers

were based on theoretical models without well-documented actual field counts. These achievements are somewhat offset by two deficiencies. First, to protect the two lanes carrying very frequent buses in the middle of a multilane avenue, a physical divider—concrete or wire fence—is built between the two bus lanes, physically and visually dividing the two sides of the avenue (Photo 5.28). This and nearly continuous noise and exhaust from buses has had depressing impact on the quality of life, economic viability, and the environment of the entire corridor. Second, unlike the rail rapid transit in the same city, which is used by all population groups, the buses tend to be used predominantly low-income groups and captive transit users.

The TransMilenio BRT system in Bogotá, Colombia, was designed with the experiences of Curitiba and São Paulo in mind. It is situated in an extremely wide corridor in the median of a divided arterial street that, in some sections, also has service roads. The BRT



Photo 5.28 São Paulo BRT

facility has long sections with four lanes to maximize capacity and allow bypassing stopped buses at stations (see Photo 5.24). The line also has some branches with two lanes. The buses have high floors and dock along high-platform stations. Passenger access is at most stations from overpasses on one side of the station, and fare-collection turnstiles are located on them.

Simultaneous boarding of two articulated buses, each with six door channels, provides for the operation of short headways. The busway has intersections at grade, which are another element determining line capacity.

There have been claims of line capacity as high as 35,000 prs/h and 800,000 prs/day, but these figures are theoretical. Such a peak hourly volume would require average headways of about 12 s, which exceed considerably the actual physical limitations of any bus line with intersections at grade.

The character of the corridor the TransMilenio line serves is quite unique. The highway is very wide, and construction of the BRT facilities was one component of intermodal planning and design that also included roadways, intersections, bikeways, and pedestrian paths. Extensive pedestrian facilities have been built, and many stations have access via pedestrian overpasses and ramps. They are well designed, but walking access paths are extremely long. In many cases the closest points of pedestrian destinations are several hundred meters long. The high attraction of passengers

by this line shows that the city has a great demand for travel, which was previously not served by fast and reliable transit services.

Insurgentes Avenue BRT in Mexico City is an excellent example of how a basic policy giving transit the priority it deserves by the number of people it serves can be used to improve the chaotic situation that had been created by unregulated minibuses when they were introduced some 15 years earlier. It has been realized that the inefficient and unattractive unregulated minibus transit can only be improved if transit buses are treated as a system and given separate infrastructure (exclusive lanes and stations). High-capacity articulated buses were introduced and operated under centralized control. They have a distinct image. A 17-km-long line along Insurgentes Avenue, one of the busiest corridors, is served by a fleet of 80 articulated buses with high floors and six-channel doors. Buses stop, one at a time, along centrally located island stations. Passenger access to the stations is, however, from one intersection only, making pedestrian paths from many points rather long and indirect. Buses are brought to the platform by drivers manually without problems, but at a very low speed along the entire station, resulting in considerable increases in travel times.

The line is supported by traffic engineering measures (left-turn prohibitions at intersections) and police enforcement, which is not fully satisfactory, so that delays occur. Despite these and some other design shortcomings, the success of the line was obvious when, immediately after its opening, passenger volumes reached capacity during many periods of day. The line capacity, with one fully loaded bus (crush capacity of about 120 prs) loading at the station and proceeding through intersections during each 90-s signal cycle, amounts to about 4800 prs/h. For comparison, if this volume were served by the 24-space minibuses used extensively in Mexico City and an unrealistic load factor of 1.0 could be achieved, the minibuses would have to operate at an average headway of 18 seconds, resulting in a very chaotic regime, particularly at stations and intersections. On the other hand, an LRT line in the same alignment would have required substantially higher construction cost, but operation of two-

articulated-car trains would result in three times greater line capacity, preventing the serious overcrowding that now occurs and may well increase.

5.4.6.2 Present and Potential Roles of BTS and BRT Modes. The treatment of bus services as systems and their upgrading into BTS and BRT is part of a broad trend of diversification of transit systems. It is specifically a part of the effort that has taken place since the 1970s to “fill the gap” between the low-investment/low performance conventional bus services in mixed traffic on streets and high-investment/high-performance metro systems. In this role of medium-capacity mode, BRT has joined the LRT and AGT modes, both of which have also been developed in many different forms and functions in recent decades.

In the phase of promotion and enthusiasm that is common for the development of new concepts or modes, the BRT system is now often presented as the mode that can provide optimal solutions for nearly any conditions. A professional evaluation, based on evidence and experiences from many cities over the recent decades, gives a more precise and realistic evaluation of the BTS and BRT modes. It is summarized as follows.

In many countries, such as most of central Europe, from Norway to Switzerland and from France to Austria, most bus services have been upgraded and integrated so that they represent the BTS mode. They have bus lanes and special signals on many streets; stops are spaced 300 to 500 m apart; buses have at least two double-channel doors, and they are used for boarding and alighting because self-service fare collection is used. Intramodal and intermodal transfer points and schedule coordinations are common at many points of the network; central control supervises bus movements, and abundant well-designed information systems and maps are provided for the public. Thus, BTS is already used extensively in these countries.

In many cities in the United States, the United Kingdom, Japan, and other countries, conventional bus services still have many of the features defined in Section 5.4.2 as misconceptions: buses operate in mixed traffic without any priorities and have frequent stops

at which passengers board and alight through single-channel doors and are delayed by fare collection. Great numbers of overlapping routes are operated with incompatible headways, transfers among routes or different modes are not integrated physically nor operationally, information is inadequate, and the image of bus services is accordingly much lower than in cities with BTS services.

Bus services in many U.S. cities that have some or many of these deficiencies could be greatly improved by their upgrading to BTS, which should be much easier and cheaper than building BRT systems with much more expensive infrastructure and special vehicles. The problem is, however, that upgrading conventional bus services by introducing of BTS elements is often very difficult, although it does not require major investments, because it depends on the municipal transportation policies. It has been remarked, in several large U.S. cities, that it is easier to obtain hundreds of millions of dollars for the construction of a subway system than to convert lanes in CBD streets from general traffic and parking to exclusive bus lanes. Traffic departments in many cities still oppose priorities to transit because they claim that they “decrease capacity”—computed by vehicles per hour—instead of persons per hour.

An even greater problem is faced in cities where members of the city council are so “protective” of residents in their localities that they oppose the closing of any stops or speeding up of buses, although this would bring a clear upgrading of bus service. There are cases where a city council or even state legislature (see above, the case of the El Monte facility) decides for some highways which lanes can be used for buses exclusively or for which categories of HOV, and at what time periods. This micromanagement of technical features of transit systems by a body of nontechnical persons pursuing their political interests prevents the upgrading of any transit system. Buses are, however, much more vulnerable than rail systems, which have tracks on physically different ROW rather than on public streets.

Opportunities for upgrading conventional buses into BTS in U.S. cities are much more numerous, wide-

spread, and with broader positive impacts than the introduction of BRT systems on individual lines with separate infrastructure.

As in the case of rail systems, there is a considerable difference between the forms and roles of BRT systems in developing versus developed countries. In the former, BRT has the primary role of providing sufficient transporting capacity for a low capital expenditure in a short period of time. Quality of service—including comfort, reliability, safety, and system image—is important but secondary to the need to transport large volumes of passengers. In developed countries, however, the speed, reliability, and quality of service are of primary importance, while the degree of line capacity required is generally much lower than in developing countries. In industrialized countries, particularly in the United States, transit tends to be oriented mainly toward captive riders unless its service is competitive with auto travel. That is a very demanding requirement, because travel by private car is usually subsidized in many indirect and direct ways.

With respect to economic efficiency, BRT is more advantageous in developing countries because the cost of drivers' wages and benefits is much lower than in industrialized countries. On heavily traveled lines, rail is also more advantageous because of its lower operating costs, due to much higher driver productivity.

The potential for the development of BRT in some developing countries is considerable, because the need for increased transit system capacity is great and urgent in many cities and urban corridors. The prerequisites for successful BRT development in developing countries can be summarized as follows.

- A policy of upgrading transit must be strong and effective.
- Multilane roadways or exclusive ROW for busways must be available or possible to acquire. This is often a very difficult problem, particularly in central cities, where the only solution to the provision of high-capacity transit is to construct tunnels and use rail systems. The construction of four-lane busways would in most cases require acquisition of large surfaces and be incompatible with a pedestrian-oriented environment.

- Financing for the investment in and operation of a BRT system must be provided or contributed to by the government.
- There must be a good organization for implementation and, particularly, for operational and police control of the BRT system. This requirement is difficult to meet in many countries.

The potential for development of BRT in the U.S. cities and other developed countries generally involves medium-performance systems, which, together with LRT and AGT modes, provide much better service than regular buses and require much lower investment costs than metro systems. BRT actually represents the first step in that sequence of transit modes, so that it can be introduced in some cities that need significant transit improvements but does not justify the effort of introducing the LRT technology or the higher technology of AGT systems (e.g., Eugene, Oregon).

The feasibility of BRT introduction depends on the basic policies toward transit, availability of financing for its construction, and ability to organize and control a BRT system. Its role is limited by the availability of ROW and ability to control them from intrusions into their lanes by other types of vehicles. This is often a problem not only in daily operations but also in the long run, because the permanence of the entire BRT system usually depends on the prevailing policies and their permanence: the "flexibility" of all bus systems makes them dependent on the administrative and political support that is provided.

In relation to LRT, BRT generally represents a lower-investment/lower-performance mode. It is therefore superior to LRT for the "first step" in upgrading bus services. As the passenger volume increases—and passenger attraction is important—LRT is increasingly more advantageous. An interesting analysis by Bruun (2005) shows that for conditions typical of new bus and LRT systems in U.S. cities (radial corridors with sharp peaks, exemplified by LRT and buses in Dallas), operating costs for LRT become distinctly lower for volumes on the order of 2000 prs/h. The advantage of LRT increases further with passenger volume because LRT has distinct economies of scale, while bus operating costs per offered space do not decrease with vol-

ume. AGT is another step in investment level, but it is less compatible with the pedestrian environment than LRT.

The comparison of differences among these modes must not be limited to investment and operating costs. The relationship of each mode with the surroundings is in this case quite different. A busway, particularly if it is operated with short headways, is generally not feasible in pedestrian areas for several reasons. First, steered vehicles on curbed roadways are not compatible with flat pedestrian surfaces. Second, due to lower capacity, the frequency of buses is much greater than of longer LRT vehicles and trains. And third, the noise and exhaust of buses are objectionable in areas with high pedestrian concentrations. LRT, on the other hand, operates very well in pedestrian streets and malls. However, if the area is very active and LRT operates with high frequency, tunnels can be built.

Buses have been placed in tunnels in several cities, but with major interventions. In Guadalajara, Mexico, trolleybuses were operated and later replaced by an LRT system. As mentioned in Section 5.3.5, the bus tunnels in Seattle and Boston (for the Silver Line) involved much higher construction costs than tunnels for rail systems, because buses need much larger areas. They also necessitated dual-mode (ICE and electric motor) buses. Such vehicles involve very high investment and operating costs. The Silver Line articulated buses (Photo 5.29) cost \$1.5 million, exceeding the cost per unit of area of LRT vehicles. This is excessive for a bus that has lower performance and a life span about 2.5 time shorter than that of rail vehicles. Moreover, bus travel in the tunnel of the Silver Line is very uncomfortable and limited to speeds of 40, 25, and 10 km/h on different sections. From the systems point of view, it does not make sense to invest hundreds of millions of dollars in very large tunnel installations, like those in Seattle and Boston, and then operate buses instead of much more efficient, comfortable, and higher-capacity rail vehicles. The tunnel in Seattle also requires additional investments for reconstruction to accommodate the addition of LRT.

AGT, on the other hand, can operate in tunnels, but it requires entirely separated ROW, which is more in-

trusive and with less accessible stations than LRT and buses can have.

BRT systems can be designed to be similar to rail vehicles (several authors in Bosch (2002) referred to the efforts to make BRT “rail-like”). However, most such efforts—including vehicle design, propulsion, ROW, and station design, etc.—involve increases in investments. In such cases, the investment costs of BRT become very similar to those of LRT, so that BRT loses the advantages of lower investment and yet does not match the level of service and passenger attraction offered by LRT.

Consequently, BRT and LRT are more complementary than competitive. The two modes have domains, BRT with a lower investment/lower performance level than LRT and AGT, and with a number of other factors varying and giving relative advantages to one or the other depending on local conditions.

5.5 STOPS, STATIONS, AND MAINTENANCE FACILITIES

The locations and designs of bus stops, stations, maintenance shops, and garages have a major influence on operating efficiency (speed, reliability of service, dead-heading travel) and on passenger convenience (area coverage versus travel speed).

5.5.1 Bus Stops on Streets

The planning of stops along a bus route involves three major aspects: spacings, locations, and stop designs.

5.5.1.1 Spacings. As a compromise between shorter passenger access to closely spaced stops and the higher operating speed of lines with widely spaced stops, the spacings of bus stops should be inversely related to the ratio of passenger origins and destinations to volume of passengers traveling through an area. Stop spacings should be such that, on the average, buses stop at distances of 400 to 600 m, in exceptional cases somewhat closer, but in no case below 300 m. Average spacings shorter than 300 m, common for many U.S. cities, are acceptable only as demand stops



Photo 5.29 Boston Silver Line

(buses do not stop when there is no request for boarding/alighting) on lightly traveled routes. The use of such spacings on regular bus routes heavily degrades service quality (speed, comfort) and negatively affects ridership. Moreover, frequent stops make it economically and physically difficult to provide adequate facilities, such as shelters, benches, and information signs. Further analysis of bus-stop spacings can be found in Vuchic (2005, Chapter 2).

5.5.1.2 Locations. There are three types of locations for transit stops along streets: near-side (NS), at an intersection before crossing the cross street; far-side (FS), at an intersection passed the cross street; and

midblock (MB), away from intersections. It is common in many cities to adopt one type of stop location (usually NS) and use it throughout the city. However, such uniformity of stop locations is seldom justified. The only significant advantage of it is that passengers become accustomed to a standard location. With properly marked stops, however, the problem of passenger confusion does not exist. Since several different factors influence the choice of locations, variations among stop locations along a street, particularly NS and FS, can often bring considerable advantages in terms of higher bus speeds and passenger comfort.

Major factors influencing the choice of stop locations are land uses (buildings generating transit trips)

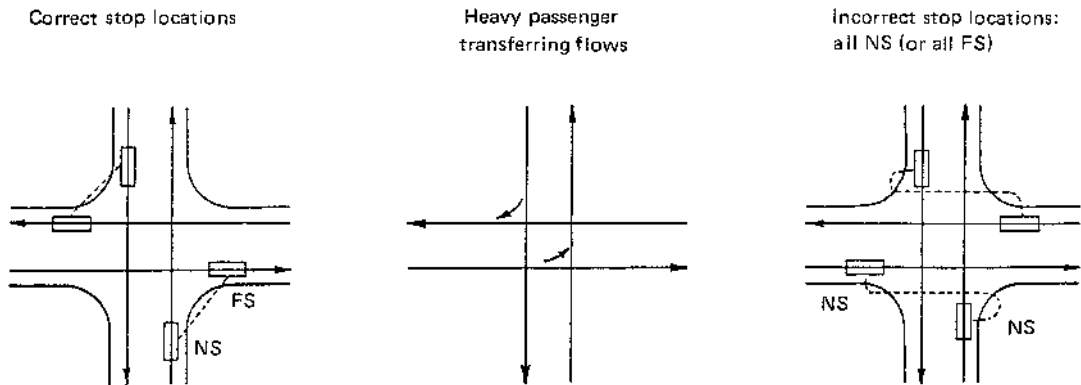


Figure 5.20 Impact of bus stop locations on convenience of passenger transfers between intersecting routes

traffic signal coordination, passenger access—including transfers from other routes, vehicular and pedestrian traffic conditions at intersections, and geometry of bus turning and stopping.

Signal coordination is often a major factor, since it can strongly influence bus speeds. A simple rule, known as “von Stein’s law of transit stop locations,”¹ is that on a street with coordinated signals, alternate stops (NS-FS-NS, etc.) result in the shortest delays. This rule is simple to explain. A bus (or any other transit vehicle) can leave an NS stop at intersection 1 only during a green phase (i.e., within a “through band” on the signal timing diagram). It therefore arrives at intersection 2 during its green phase. With an NS stop there, the bus would have to stop and risk being “caught” by the next red phase. With an FS stop, the bus passes intersection 2 within the band (i.e., with the platoon of vehicles). Thus at intersection 2, FS is clearly better than NS. Since stopping at the FS may delay the vehicle, so that it falls out of the band, it is better that the following stop, at intersection 3, be NS, so that the bus may utilize its waiting at the red signal for passenger exchange at the stop. Further travel follows the same sequence of events, making alternate stops the optimal pattern. (Additional discussion of the

relationship between transit stops and signal coordination is given in Vuchic 2005, Chapter 2).

Passenger access and convenience are maximized when stops are located where waiting passengers are well protected from traffic, have sufficient space for circulation, and do not impede the pedestrian flow on the sidewalk. The stops should be located at intersecting points of two or more bus routes so as to minimize the walking distance required for transfer between buses, as shown in Figure 5.20.

Traffic conditions must also be considered in selecting stop locations. Minimum bus interference with the turning movements of other vehicles, ability of the bus to merge into traffic, and visibility at pedestrian crossings are the most important items to be considered at each bus stop location. In general, the NS location causes the least amount of interference when the cross street is one-way from right to left or when the number of vehicles that turn right from the transit street is small. For the opposite conditions, an FS stop is preferable.

The *geometry of bus maneuvers* may in some cases influence stop locations.

Most of these factors favor either NS or FS stops over MB stops, which require the greatest curb length, cause longer walking to cross streets and transfer points, and may encourage jaywalking. The MB stops may be optimal only in special cases: where a major trip generator is in the middle of a block, where traffic

¹ Developed and first applied by Wolfgang von Stein on LRT lines in Düsseldorf in the mid-1950s.

or geometric conditions at intersections make stops inconvenient, or where buses turn left onto a street where an FS stop cannot be placed.

In conclusion, the blanket use of only one type of stop is usually not the best solution. Selection among the three types should be made for each individual route based on the factors discussed above.

5.5.1.3 Design. The simplest type of bus stop is where buses travel and stop in the curb lane. Although such stops are convenient for passengers and require the least maneuvering, they block a traffic lane for other traffic. Their applications should therefore be limited to reserved bus lanes or locations where other traffic is light and buses usually make short stops.

A better location for bus stops is outside driving lanes: this provides greater safety and less interference with other traffic. The most common such stops are located in parking lanes and in special bus bays, as shown in Figure 5.21. Any one of the pavement markings or textures in the figure may be used. Because of the high axle loads of buses, the bays should have heavy-duty pavement.

Stops in parking lanes are common on streets with curb parking. They occupy a curb-lane section in which parking is prohibited by signs, pavement markings (Figure 5.21a), or a specially contoured curb, as in Figure 5.21b. For all permanent parking lanes, this design is the best because it eliminates the problem of illegal parking in the stop areas. Bringing the curb across the parking lane to the travel lane is the most favorable arrangement for bus access and passenger boarding from the curb when impedance of traffic by the standing bus is acceptable.

Bus-stop bays are particularly useful on streets with one lane per direction or on heavily traveled multilane arterials where stopping in a driving lane causes major delays and disruption of traffic flow.

The problem of buses having difficulties pulling from bus bays into a travel lane, common to many bus stop designs, is solved most efficiently by a traffic regulation that traffic in the travel lane must yield to buses starting from bus-stop area when they indicate departure by left-turn blinkers. This regulation should also

be displayed at conspicuous locations along the line and on the backsides of buses.

The total lengths of bus bays for each type of stop (NS, FS, and ME), consistent with the standard U.S. literature, are given in Table 5.6. Assuming straight curb tapers (6:1 for approach, 4:1 for departure), these values are desirable. With S-shaped curbs, better fitted to bus movement, and buses with smaller turning radii than the typical U.S. 40-ft (12.2-m)-long buses, shorter dimensions may be used, as Figure 5.21d shows (the values in parentheses approximate those from the table).

5.5.2 Stations and Terminals

Bus stations are off-street areas or buildings with stops for several bus routes. Terminals are, strictly speaking, end stations of one or more bus routes; however, the term is sometimes used for any large station with passenger facilities, such as waiting rooms, ticket offices, and so on.

Bus stations are usually built at transfer points among several bus routes (e.g., in a timed transfer network in low-density areas) or between bus feeders and rail lines. Since buses serving a central city are usually dispersed throughout a network of streets, CBD bus transit terminals exist only in cities with special conditions, such as termination of routes from another jurisdiction (e.g., the AC Transit Terminal in San Francisco, Port Authority Bus Terminal in Manhattan, and intermodal terminals at both ends of the 16th Street Bus Mall shuttle in Denver). Bus stations and terminals must be on sites with good accessibility from major highways and arterials and, naturally, extensive service by intracity transit routes.

The number of berths (bus loading points) in a bus station depends on the number of routes, the peak-hour headways on each line, schedule coordination, reliability of operation, and dwell times of buses. Routes with headways below 3 to 5 min usually require at least two berths, since bus delays often cause the dwell times of two buses to overlap. Headways between 5 and 10 min allow use of one berth if dwell times are

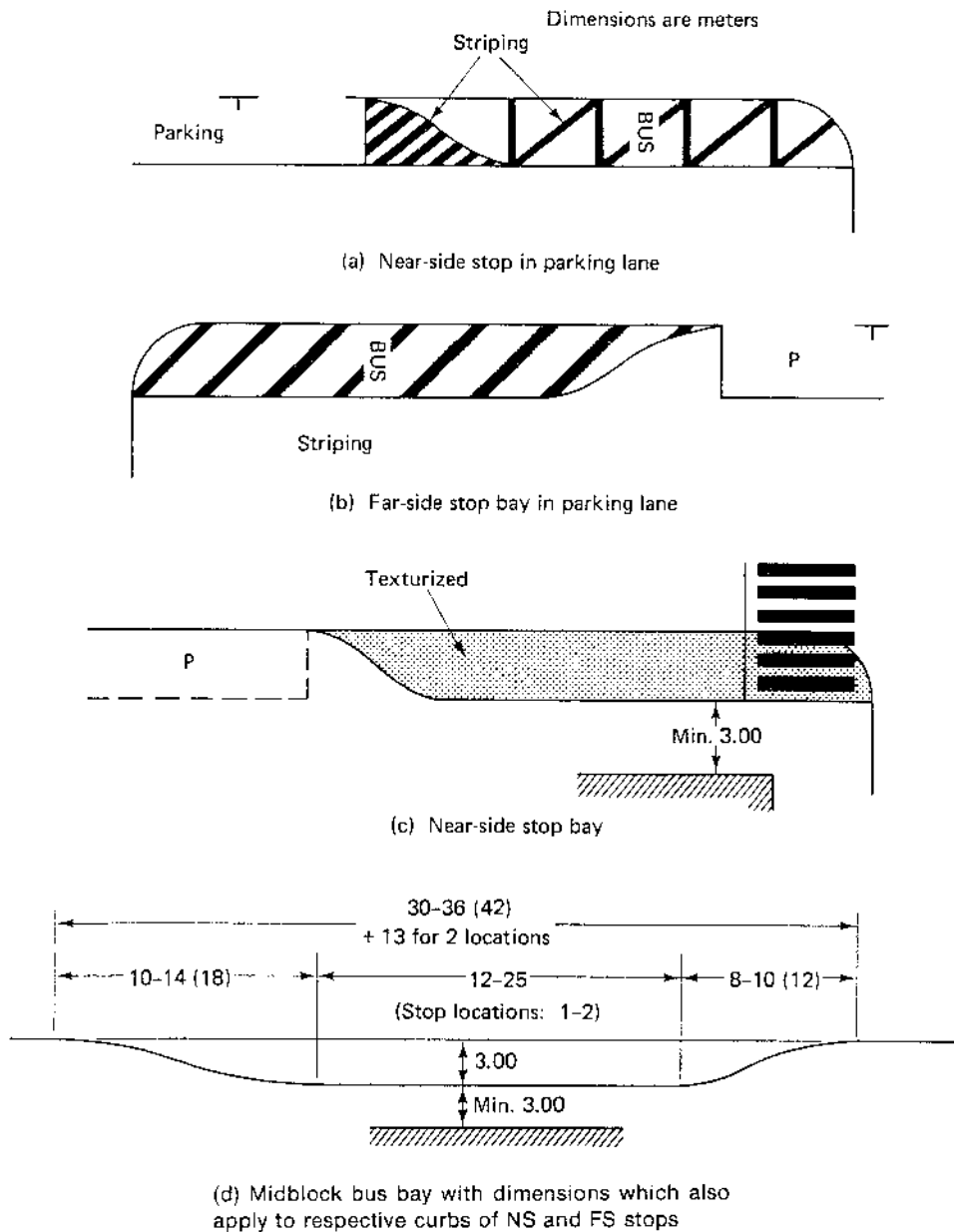


Figure 5.21 Different designs of bus stop areas and bays

Table 5.6 Desirable curb lengths for different types of bus stops (m)^a

Approximate Bus Length	One-Bus Stop			Two-Bus Stop		
	NS	FS	MB	NS	FS	MB
7.50	27.5	19.5	38.0	36.0	28.0	46.5
9.00	29.0	21.0	39.5	39.0	31.0	49.5
10.50	30.5	22.5	41.0	42.0	34.0	52.5
12.00	32.0	24.0	42.5	45.0	37.0	55.5

^aNote: The values given here are recommended in the U.S. literature. Tests performed by MARTA (Atlanta) show that considerably shorter dimensions can also provide satisfactory operation (see Figures 5.21 and 5.24).

short compared to the headways and delays. Some berths may serve several routes with long headways if their schedules ensure staggered arrivals and dwell times.

Multiple bus stops along a curb (on a street or in a station) can be designed for three different cases with respect to bus arrivals/departures:

1. Not allowing any overtaking
2. Allowing independent departures but not independent arrivals
3. Allowing independent arrivals and departures

As Figure 5.22 shows, stops for the first case occupy a curb length equivalent to a bus length (L') plus 1 m for distance between stopped buses. For the second case, a distance of 6 to 8 m between vehicles is required for both regular and articulated buses. In the third case, the arrivals are the more critical maneuvers and require distances of 8 to 11 m for standard and 10 to 13 m for articulated buses. The specific values within this range depend on the length and minimum turning radius of the bus, steering design of articulated buses, and the desired speed and facility of operation.

Sawtooth curb design (Figure 5.22c and Photo 5.30) is adjusted to the geometry of bus arrivals and departures. This design geometry allows faster and easier bus maneuvers and takes a shorter distance per stop location than does straight curb for the same vehicle. The sawtooth design has become common for bus feeder locations in recently built rail transit stations in U.S. cities (Cleveland, Washington, Atlanta).

In designing bus stops, the trade-off between operating flexibility and curb length required must be evaluated. Independent arrivals and departures are always desirable for flexible operation; however, they require 50% to 80% greater curb length than do stops without overtaking. The greater length involves longer walking distances and requires more shelters.

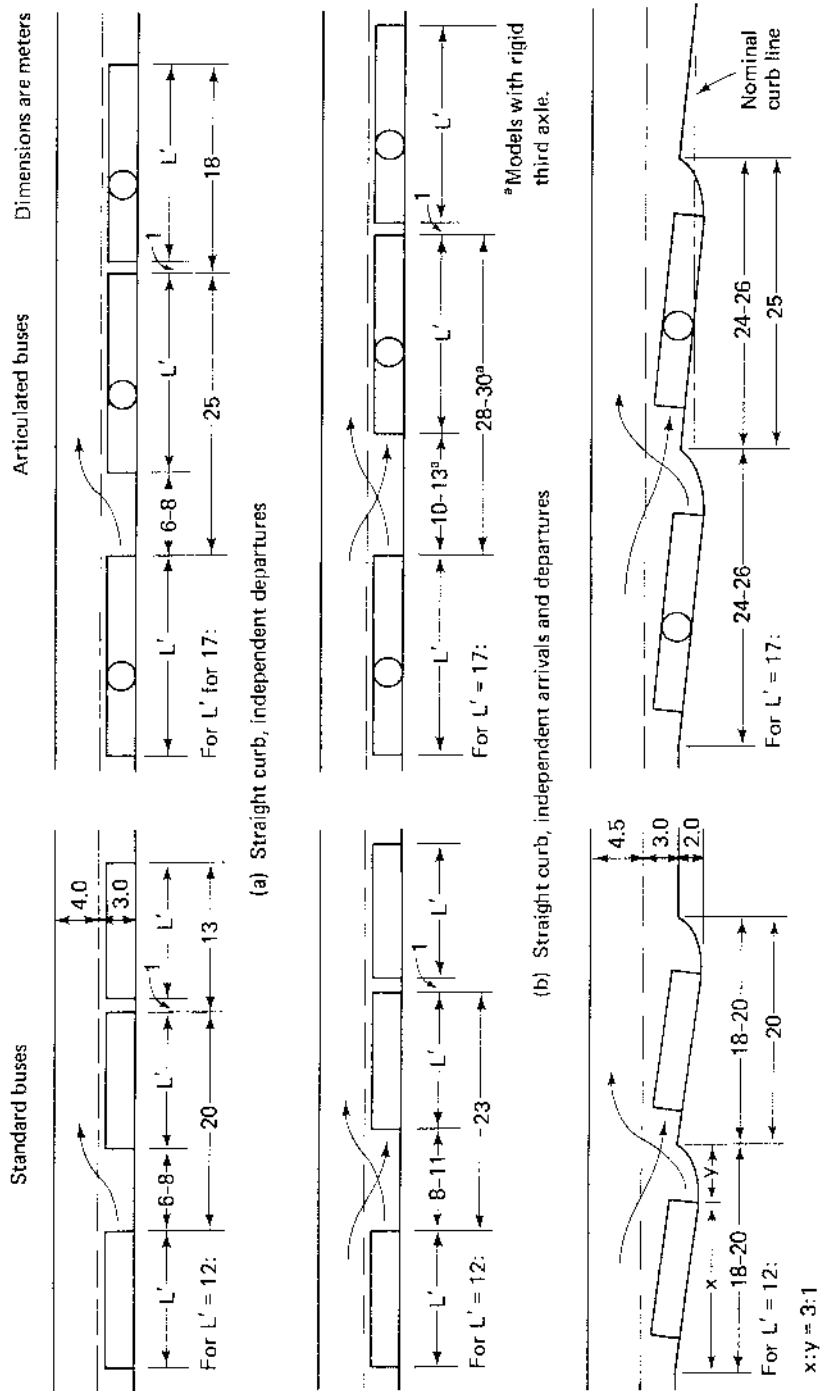
Another layout of bus stops is shown in Figure 5.23 and Photo 5.31: a series of parallel islands separated by single-lane roadways. This layout is efficient for major terminals with many lines. For example, Toronto uses island stops for bus/trolleybus/LRT feeders to RRT at major transfer stations.

The most common are the designs of islands at angles of 45, 60, and 90 degrees to the access roadways. As the values tabulated in Figure 5.23 show, the sharper the angle, the larger the dimensions.

At stations with parallel island stops, the relationship between pedestrians and vehicles must be carefully planned. For moderate bus frequencies and pedestrian volumes, crossings of bus lanes in front of vehicles is acceptable; for large volumes, it is desirable to provide stairways or escalators to a pedestrian under- (or over-) pass leading to the terminal building or rail transit station. This design, applied to several RRT and RGR stations in Toronto and Munich, provides good safety and convenience: passengers descend into an exclusive pedestrian mezzanine area, which can have various amenities. However, the stairways, shown in Figure 5.24a require wider islands: instead of 1.50 m, their minimum width increases to 3 to 4 m.

Bus berths from which buses must back out are seldom used for transit; in some countries (e.g., Germany) they are prohibited by law for safety reasons.

The best layout for pedestrian safety, comfort, and convenience is with bus stops around a major rectangular or oval island. As the sketches of several such stations in Figures 5.24 and 5.25 show, this arrangement allows passengers to transfer among all bus routes (e.g., at timed transfer points) or between buses and trains at rail transit stations (via stairways from the island) without crossing a roadway. The station is thus a complete "pedestrian zone." The pedestrian crossings shown in the figures provide connections with adjacent streets. However, in some cases the crossings



(c) Saw-tooth curb, independent arrivals and departures

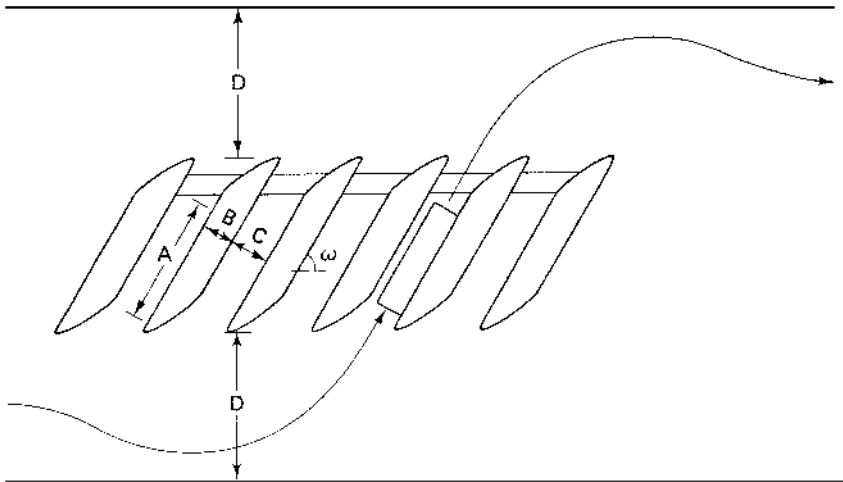
Figure 5.22 Design of different types of bus stops



Photo 5.30 Sawtooth bus stop design (Courtesy of AC Transit)

may be omitted and pedestrian access even prohibited in order to make the island a “ticketed area” (i.e., area restricted to passengers who have paid fares). They can then transfer between buses and trains without fare payments and control.

The central island also has excellent operating features. The circular roadway allows buses to unload passengers at one location, move to a waiting area, and then return to the same or to another stop location for boarding. Moreover, these stations can be used by routes passing through as well as for the terminating routes with buses simply “looping” around the island and returning to the same direction.



Meters				
ω	A	B*	C	D
45°	$L' \text{ or } 2L' + 1.00$	1.50–3.00	3.25	8.00–10.00
60°	$L' \text{ or } 2L' + 1.00$	1.50–3.00	3.50	10.00–12.00
90°	$L' \text{ or } 2L' + 1.00$	1.50–3.00	3.75	12.00–14.00

*For stairs or escalators leading to a pedestrian mezzanine 1.50–2.50 m should be added.

Figure 5.23 Design dimensions for island bus stops



Photo 5.31 Bus terminal with parallel islands in Hong Kong (Courtesy of Carl Uebelhart)

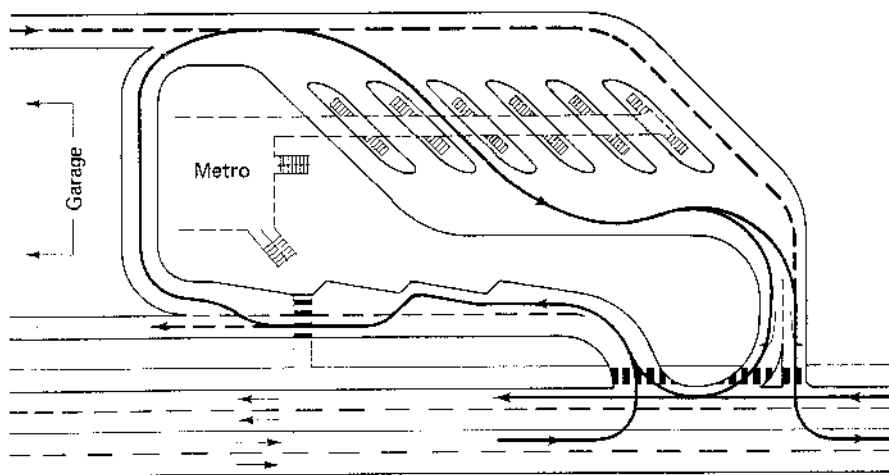
5.5.3 Garages, Storage Facilities, and Maintenance Shops

The number and capacities of bus garages for large transit agencies are determined on the basis of network extensiveness, fleet size, methods of vehicle maintenance, land availability, and various local factors. The basic trade-off is between the economies of scale in the operation of large garages and shorter travel time to and from lines (deadheading) associated with a greater number of smaller garages distributed to several peripheral locations. Large transit agencies usually have garages with capacities of 180 to 250 buses.

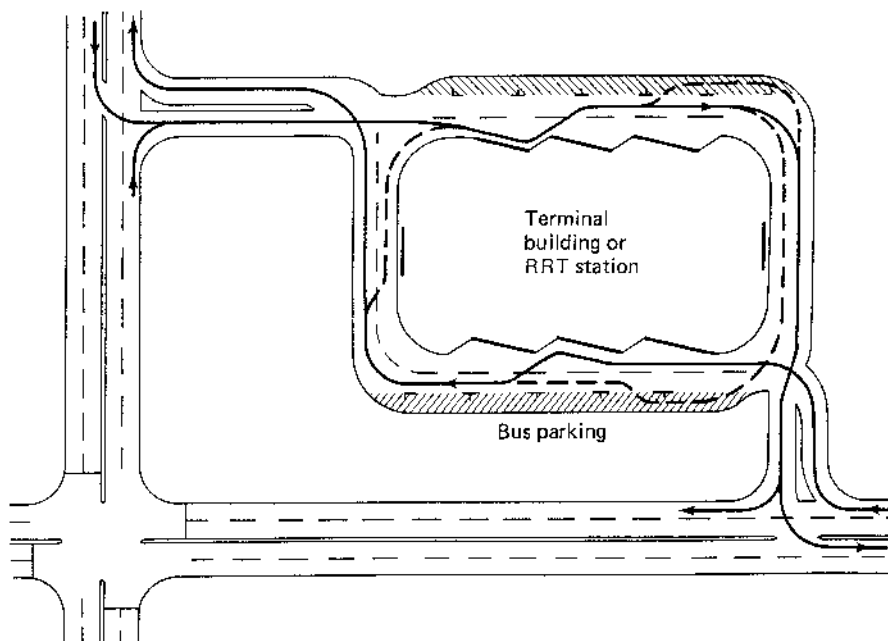
The largest area is required for bus storage. Each standard, 12-m long bus occupies an area of $12.5 \times$

3.10 m^2 plus 60% for aisles, or 62 m^2 per space when buses are parked and driven out in the same sequence. For independent access to any space, area may amount to 80 to 100 m^2 .

Bus storage facilities can be of two types: a garage or an open-air, fenced-off yard. Storage in garages requires approximately 30% to 50% higher investment costs and usually ventilation and heating. Open-air storage yards, on the other hand, must be equipped with external or internal (installed in buses) equipment for preheating engines and interiors in cold weather. The advantage of lower investment is further offset by exposure to weather, shortening of vehicle life, and sometimes higher wages for maintenance personnel.

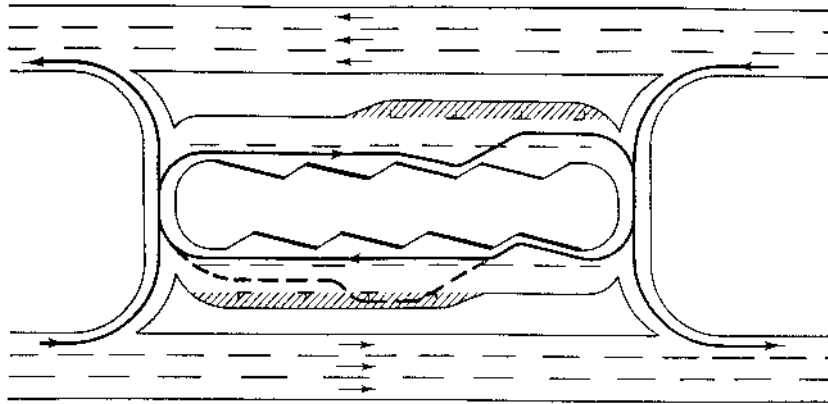


(a) Bus-rail transfer station with island stops

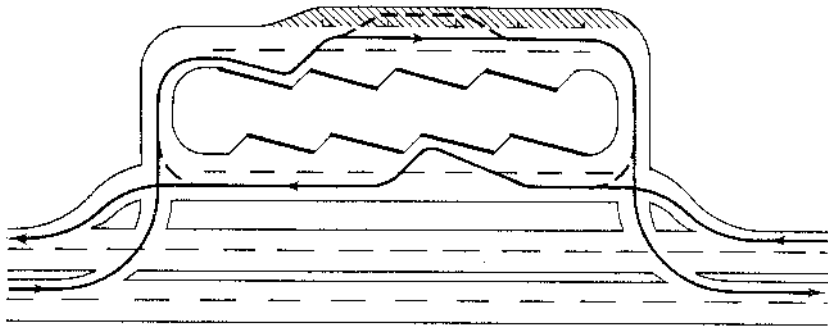


(b) Central island station in quadrant of an intersection

Figure 5.24 Different types of major bus stations and terminals



(a) Parallel station between a pair of one-way streets



(b) Parallel station on the side of a two-way street

Figure 5.25 Oval island stations parallel with streets

(A detailed comparison of these two types of storage is given by Mouzet 1975.) A plan of a bus and LRT garage with maintenance shops and open-air storage yard in Cottbus, Germany, is shown in Figure 5.26.

The maintenance hall requires about two to three pits or hoists per 100 buses. A washing facility, body repair, and spare parts magazine are also required. Usually, each garage has a control or dispatching center. For the personnel, management offices and a cafeteria are provided, sometimes on a different floor to reduce the total land area of the garage. A plan and operational flow of a typical garage is shown in Figure

5.27. Small garages have only service and washing facilities.

Major repairs and general overhaul of vehicles, if performed by the transit agency, are always centralized at one location. The size of the repair facility depends on the extensiveness of these operations, which varies among agencies. At one extreme, some large transit agencies (e.g., Transport for London, RATP-Paris) used to perform general overhaul of their vehicles as a continuous process at a rate of several buses per day in extremely large workshops resembling bus manufacturing plants. At the other extreme, some agencies

KOMBINIERTER BETRIEBSHOF BUS/STRAB - COTTBUS - COMBINED LIGHT RAIL AND BUS DEPOT

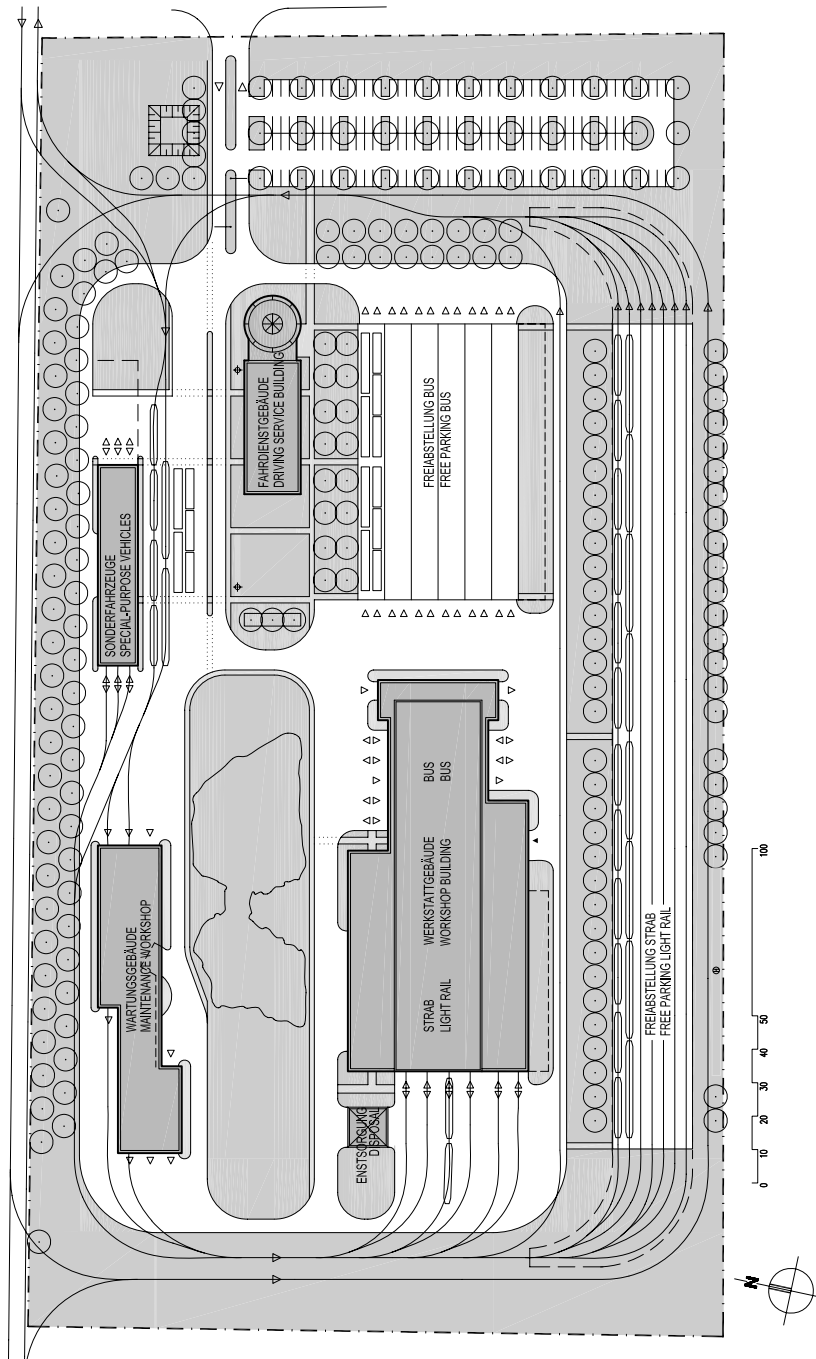


Figure 5.26 Plan of a bus/LRT maintenance shop and open air garage in Cottbus, Germany (Courtesy of VDV and Gesterling, deVries, Wurster, and Partner)

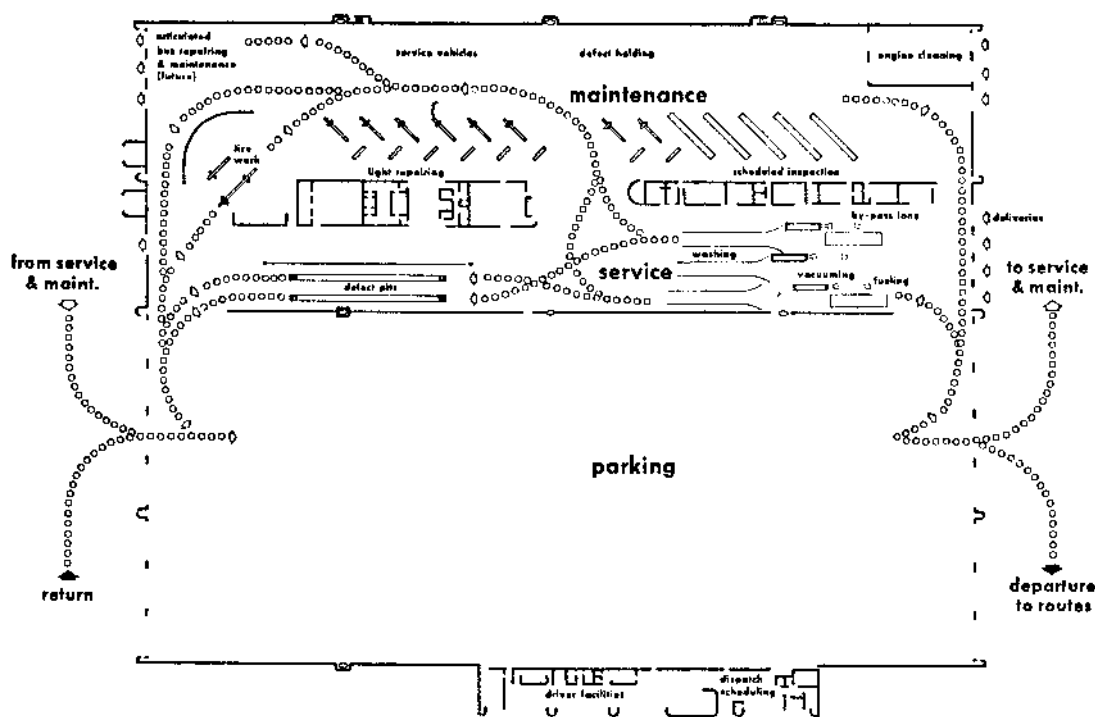


Figure 5.27 Floor plan and flow of operation in a bus stop (Courtesy of Twin Cities Area Metropolitan Transit Commission and Smiley, Glotter Associates, Inc.)

operate their buses only until they reach the age at which general overhaul is needed, then sell them and buy new ones. The latter procedure eliminates the need for overhaul facilities and requires only those needed for small and medium-size repairs. This saving is at least partially offset by the higher total vehicle purchase cost or depreciation.

5.6 OPERATIONS, PERFORMANCE, AND COSTS

The safety, steering, speed, comfort, and reliability of bus travel depend greatly on the vehicle design, street and traffic conditions, and capability of the driver. Physical or electronic guidance can assist on some sections, but fully automatic driving is not feasible because it requires fully controlled ROW, which buses do not have. Moreover, full automation of bus driving

would not bring any economic benefit as long as the drivers was retained.

5.6.1 Operations and Types of Service

The regularity of transit operations depends considerably on the control of bus movements. Control centers that monitor movements of transit vehicles, traditionally used for rail vehicles through their signal systems, are now used for bus systems also, with deployment of automatic vehicle location (AVL) systems, which utilize a number of technologies, including the recording of buses as they pass fixed points and radio scanning ("inquiring") each vehicle every few seconds about its location. Now most common are satellite-based communication technologies utilizing the Global Positioning System (GPS). These information systems are combined with a computer aided dispatching

(CAD) program. An integrated CAD/AVL system can be used to show on computer monitors time-distance diagrams for each transit line with graphical presentation of scheduled and actual travel, thus indicating the on-time or disturbed travel of individual vehicles. This information allows dispatchers to follow movement of each vehicle and intervene, when possible, to recover delays, reroute vehicles, etc.

These reporting and control systems, although unable to change most traffic conditions on streets, are very useful in increasing the regularity of bus services through improved coordination among vehicles on a route as well as the provision of preferential treatment and various other interventions.

Buses can provide extremely diversified types of service. Their primary domain is operation on regular transit routes with low-to-medium passenger volumes, but many other types of service are also common, such as short-haul routes in high-density areas as well as long low-volume suburban routes. These may be individual routes, feeders to rail transit, or components of an integrated timed transfer network. Buses are also the most convenient mode for express service with low-to-moderate volumes, particularly on alignments where a freeway can be utilized for part of the route. On the high end of passenger volumes, buses can carry large passenger volumes utilizing two lanes per direction. Such intensive operation on ROW C is very irregular and unreliable on busy urban streets. Since the 1970s, however, starting in Portland, São Paulo, and Curitiba, the concept of BRT has been developed with provision of ROW B for buses and stations that have two lanes per direction for overtaking (see Section 4.4.4.3).

In addition to regular transit, buses are used for many commuter services (commuter bus and subscription bus), where their domain overlaps with some paratransit modes, and for special services (charters, special events).

5.6.2 Performance Characteristics

Performance of bus services varies greatly with type of operation and ROW category. Thus operating speeds

may be as low as 8 km/h on short-haul routes on congested streets with frequent passenger stops or as high as 50 to 70 km/h on express routes utilizing uncongested freeways with few or no passenger stops en route. Most typical bus routes on urban streets operate with overall speeds of 15 to 20 km/h during off-peak hours. During peaks, speeds of only 8 to 14 km/h are typical.

The *reliability* of bus service, usually measured as a percentage of arrivals at the terminus with less than 4 min delay, also depends primarily on traffic conditions along the route. Since these conditions are variable, the reliability of bus services is seldom measured with the precision typical for rail systems.

Buses have good reliability under certain conditions, including emergencies. For example, if streets are blocked, bus routes, unlike rail, can be quickly and easily relocated. Further, buses are not affected by temporary power failures. On the negative side, buses are highly sensitive to traffic conditions, since the vast majority of bus routes operate on ROW category C. Inclement weather affects buses much more than rail modes, not only physically (reduced adhesion) but also through increased congestion of surrounding traffic. Consequently, bus services in congested urban areas with a reliability of only 50% to 70% are not rare, particularly during peak hours. In small cities and outlying suburban areas, reliability is often considerably higher and less affected by peak hours, but it seldom approaches values above 95%, typical for systems with ROW categories B or A.

The *frequency* of bus services must be higher than the frequency of rail modes serving the same passenger volume with the same type of operation (stopping regimes) because of the smaller capacity of buses.

The *capacity* of bus modes is discussed in Chapter 4, *energy consumption* in Chapter 3.

The *safety* of buses varies greatly among different transit systems, depending on traffic conditions and local operating practices. In general, passenger safety on bus systems is substantially higher than safety in private autos but lower than on rapid transit systems, owing both to fully controlled ROW and the number of automatic safety devices that the rail mode has.

The speed, frequency, capacity, and safety of trolleybuses are quite similar to those of buses, since both modes generally operate under the same street conditions. The reliability of trolleybuses is somewhat lower because of their dependence on overhead wires.

5.6.3 Service Quality and System Impacts

The *riding comfort* of buses in straight running on well-maintained streets is excellent. When buses operate in heavy traffic and maneuver frequently, vehicle sway and high jerk rates often make standing uncomfortable. Circulation inside buses is easy when 1+1 or 2+1 seating and wide doors are provided, but buses with 2+2 seating cannot accommodate many standees without uncomfortable crowding.

The *area coverage* that bus services can provide is more extensive than that for any other fixed-route transit mode. Trolleybuses are more constrained because of their wires but are still better than rail modes in this respect.

The *identity* of bus services is very poor because of lack of fixed facilities. This deficiency can be partially overcome by extensive and precise public information. Trolleybuses have a considerably better identity because of their overhead wires.

The *direct impacts* of buses are both positive and negative. The absence of guideway, wires, and so on makes bus routes totally unobtrusive. However, their noise and air pollution are often objectionable, particularly at terminals and stops, due to engine idling and frequent accelerations. It should not be forgotten, however, that although the objectionable impacts of a bus are more intensive than those of one private auto, they are usually many times less intensive than the impacts that would be produced by the autos needed to carry the same number of persons.

The *long-range impacts* of buses are seldom tangible. Owing to their lack of fixed facilities and the flexibility of routes, bus services do not have a strong impact on land use. However, the presence of adequate bus service in an area is an important factor in maintaining its economic and social viability. Without tran-

sit service, deterioration and blight are more likely to occur.

5.6.4 Costs

The *investment cost* for most bus services consists mainly of vehicle purchase (or depreciation) costs. Fixed facilities for street operation consist only of pavement markings, bus-stop signs, benches, and shelters—except when special lanes and signal equipment are used for priority treatment. The construction of bus lanes and busways, however, requires an investment of much greater magnitude. In all cases, garages and maintenance facilities must also be included in the bus system investment costs.

As of 2006, the prices of standard diesel buses are in the range of \$300,000 to 330,000, depending on particular features such as air conditioning, seating, body design, and the size of the order. Articulated buses are priced in the range of \$450 to 500,000. Clean diesel, hybrid, and other special propulsion systems tend to increase the price by 20% to 40%; but with increased sales of hybrid buses, their price may decrease. Buses with 70% low floor are about 10% more expensive than standard ones, but due to their smaller number of seats, the per seat cost of low-floor buses may be 20% to 25% higher than that of comparable standard buses. Specially designed buses, such as dual-mode for the Silver Line in Boston, have prices as high as \$1.6 million.

Costs of fixed facilities for buses vary greatly with their characteristics. For example, signal priorities may involve a minor adjustment of a fixed-time signal or an entirely new computer-controlled installation that “recognizes” buses. Conversion of a regular street lane into a reserved bus lane usually does not involve high cost; but construction of a separate busway, particularly when a separate ROW must be acquired, is usually substantial, on the order of \$8 to \$20 million/km. Grade-separated busways require a much higher investment. This is particularly the case with tunnels, which can reach or exceed the construction cost of rail systems. For example, the BRT tunnels in Seattle and Boston (a section of the Silver Line) have such large

profiles that the volume and complexity of construction more than offset the lower cost of bus roadways as compared with that of rail tracks and electrification. The Silver Line tunnel section had a cost estimated at about \$500 million per mile (\$310 million per kilometer), or as high as the most expensive rail tunnels.

Operating costs are usually broken down into the following components: transportation, or direct costs of operating buses (mostly drivers' wages and fringe benefits as well as fuel); vehicle maintenance and garages; general and administration; marketing and advertising; taxes and licenses; and insurance. In industrialized countries, the first item, transportation, is the largest component, amounting to 45% to 65% of total operating costs, and it is often the main cause for wide cost variations among different transit systems. For 2005, U.S. cities reported operating and maintenance costs in the range of \$80 to \$120 per vehicle-hour. These costs are considerably lower in the developing countries with low labor wages. Costs per vehicle-km depend very much on operating speeds, so that they are higher in large cities with greater traffic congestion and heavy passenger volumes.

5.6.5 Trolleybuses: Characteristics and Applications

The overall characteristics of the trolleybus mode are rather similar to those of diesel buses, but physical differences between the two technologies do bring some significant distinctions. In summary, trolleybuses have the following characteristics.

Steering control and vehicle bodies are practically identical for trolleybuses and buses. However, electric propulsion gives trolleybuses performance characteristics similar to those of rail modes: powerful traction and fixed alignments. The combination of rubber tires with electric propulsion provides trolleybuses with two excellent qualities: good performance and low negative environmental impact. Their high but smooth acceleration and grade-climbing ability are very much appreciated by passengers. Their extreme quietness (trolleybuses produce less noise than any other transit

mode) and absence of air pollution are popular with both the riders and the population in the areas served. The only negative impact may be aesthetically poor overhead wire networks at junction points, where they are often elaborate.

Disadvantages of trolleybuses include the costs of installation and maintenance of overhead wires and incidental dewiring of trolley poles. The ability to temporarily change alignment depends on vehicle design: trolleybuses with auxiliary ICE motor can travel several blocks without wire contacts. The most serious drawback is the approximately 50% higher price of trolleybus than bus vehicles. The approximately 50% longer life of trolleybuses (15 to 20 years versus 10 to 12 years for buses) compensates somewhat for this difference, however.

Operating costs of trolleybuses depend largely on the price of electricity. Energy costs for the operation of trolleybuses are in some areas higher, in others lower than those for the operation of diesel or other ICE buses. Many cities willingly pay the higher costs of trolleybuses because they consider it worthwhile for the superior features of trolleybuses, such as better performance, environmental friendliness, and use of electricity, which can be generated from any primary energy source.

This review of their characteristics shows that most of the advantages of trolleybuses concern passengers and the population in the areas served, while most of their disadvantages affect operators. When a transit agency is in financial straits, it is inclined to reduce its costs by converting trolleybus lines to buses, thus sacrificing the largely intangible, although not insignificant, benefits to the public.

This dichotomy of public and operator's interests with respect to trolleybuses has had a major impact on applications of this mode. During the 1930s and 1940s, when transit ridership was high and investment funds were available, trolleybuses were introduced in many cities. With increasing volumes of autos on urban streets and continuous attempts to accommodate them and with decreasing ridership and the disappearance of investment funds, massive conversion of trolleybuses to diesel bus services took place. In Great Britain,

which had trolleybus systems in many cities (including 1500 vehicles in London alone) at the time of World War II, this mode has been completely eliminated. Most trolleybus services have also been discontinued in Denmark, the United States, and other countries.

During the 1960s, it did not appear that trolleybuses could retain any significant role in urban transportation. However, several developments since 1970 led to a change in attitude toward this mode. The influencing developments have been:

- The introduction of public financial assistance to transit, which led to increased attention to quality of service rather than only minimum cost.
- Emphasis on improving the environment, which led to recognition of the excellent features of trolleybuses with respect to noise and air pollution.
- Reduced dependence on oil through use of electric propulsion became an important factor: recent trolleybus models with thyristor chopper control may allow absolute reduction in energy consumption over buses.

As a result of these developments, conversion of trolleybuses to buses was stopped and new vehicles have been purchased in recent decades by several U.S. and Canadian cities which operate this mode.

About year 2005, trolleybuses are operated in over 200 cities in the world, among them five U.S. and two Canadian cities. Eastern European countries use this mode extensively, as do some Asian and Latin American countries. Renovation and some network expansion is taking place in some European and North American cities (Athens, Bern, Luzern, San Francisco, Seattle, Vancouver). Advanced vehicle models have been produced in recent years in several countries, including Switzerland, Austria, Czechoslovakia, France, Russia, and Belarus.

Primary conditions that make trolleybuses advantageous in a comparison with buses are one or a combination of the following:

- Hilly terrain (Belgrade, San Francisco, Seattle).
- Importance of low noise and no air pollution (e.g., historic cities such as Athens and Salzburg).

- Moderate to heavy passenger volumes (Athens, Milan, São Paulo).
- Use of electricity preferred to oil (performance, reduction of oil imports, etc. Switzerland, east European countries, Russia, China).
- Municipal ownership of electric power supply systems.

Although no major resurgence in the use of trolleybuses appears imminent, the downward trend in trolleybus use has generally stopped. It is likely that this mode will retain a significant role and enjoy popularity in a number of cities.

5.7 PRESENT AND FUTURE ROLES OF HIGHWAY TRANSIT MODES

Buses are the most widely used transit mode today. In the United States, buses carried (in 2003) approximately 60% of transit passenger trips and 44% of transit passenger-km. About 77,000 bus and 700 trolleybus vehicles are operated by nearly 2000 agencies and companies (APTA 2005). The vast majority of these are conventional bus services operated on streets in mixed traffic with elements oriented to captive riders. Typically, buses have single-channel doors and stops are provided at every corner, often with few amenities and inadequate passenger information resulting in frequent and long stops and low operating speeds. Priority treatments for buses at intersections are applied in few cities. Buses therefore offer service with lower speed and comfort than the auto. This results in the inadequate utilization of bus services: in most U.S. cities, bus patronage consists predominantly of captive riders. Only in large cities do buses carry a significant number of noncaptive or choice riders.

Another problem with bus transit is that many cities of both developing and some industrialized countries, including the United States and Europe, have bus networks that are extensive but with low service quality (long and irregular headways, inadequate information for passengers, inconvenient transfers). This type of services is often overextended and therefore underutil-



Photo 5.32 Guided busway in freeway median (Essen)

ized. In many cities of developing countries, this condition is further complicated where there are many jitneys, which create a chaotic condition without any systematic information for passengers or coordination of services. Another common problem is that bus fleets in many cities consist of only one bus model, such as the standard 12-m long bus or one type of minibus.

Great efforts to develop new technological features and designs of buses have been positive, although the results of these efforts have varied. Some innovative designs, such as low-floor buses and hybrid propulsion, have had very good results. Others have not fulfilled expectations. For example, the guided bus, of which O-Bahn is the best-known example (Photo 5.32), has found very limited applications; its main competition is not LRT but buses on busways. The articulated bus with a guiding rail (Photo 5.33) has been tested for

many years. In both cases the dual-mode features bring some attractive benefits, but the trade-off in vehicle complexity and various operational problems often cancel them, preventing the introduction of these new concepts.

Since the mid 1990s, however, there has been increasing awareness of the need to upgrade conventional bus services into bus transit systems: coordinated networks with fewer lines but higher performance (higher speed, frequency, and reliability), fewer but better-equipped stops, preferential treatment at stops and intersections, improved bus designs such as low-floor vehicles, and a stronger image. Upgrading of this kind has resulted in substantial increases in bus patronage and an improved image of transit in the city. Excellent example of this type of improvements is the Metro Rapid bus service on Wilshire Boulevard in Los Angeles and the Insurgentes Line in Mexico City (Photo 5.34a & b). Both of these lines have limited features (limited preferential treatment and protection from other traffic), and yet they are so much better than the preceding obsolete types of operation that the ridership response has been excellent.

An even more revolutionary development has been the introduction of BRT. The provision of ROW category B, exclusive lanes for buses, stations with spacings of 400 to 500 m and off-vehicle fare collection, specially designed buses, use of ITS and other advanced components, upgrade these systems into a semirapid transit mode, which is much more efficient and competitive with cars than conventional buses. These improvements are reflected in significant increases in ridership.

The present strong interest and publicity given the BRT is useful because it provides the attention and necessary public support for transit innovations, primarily in cities that need better service than conventional buses offer but the introduction of LRT is not yet justified. However, the vast majority of bus services will continue to be of the conventional type, providing basic service on streets, which would need many improvements to become BTS systems. Such improvements as buses with double-channel doors, increased stop spacings, and priorities for buses on streets can



Photo 5.33 Double-articulated trolleybus with guide-rail embedded in street

Conditions favoring the introduction of improved bus services and increase of their ridership can be summarized as follows:

- Urban transportation is treated as one intermodal system and transportation policies are aimed at achievement of balance among modes.
- Public is informed about implementation of system-wide measures to improve bus (or transit) services and the resulting increased speeds, and improved reliability and quality of services.
- There is recognition of the need to favor public over private transport in entire urban areas.
- Vehicle priorities are based on the basis of the number of passengers they carry.
- Measures are undertaken to improve utilization of existing streets and other transportation facilities.
- Transit management, public information, and marketing are continually monitored and improved.
- There are disincentives to the use of private cars, such as parking controls and rates.
- Increasing price of oil and further strengthening of clean air requirements.



Photo 5.34a BRT Insurgentes Line in Mexico City: high-floor bus at a station (Courtesy of Christopher Puchalsky)

be beneficial to many more cities than new BRT systems. Introduction of these innovations will continue to depend on local transportation policies. In most cities, a major obstacle to improvements is the fact that transit agencies get insufficient support from police and traffic authorities. In cities with good intermodal co-

ordination and policies favoring transit, introduction of elements for BTS and construction of some BRT systems is much more likely to take place than in cities without such practice. An overview of likely factors influencing future role of bus/trolleybus modes is given in the box.

EXERCISES

- 5.1. List and explain the positive and negative characteristics of regular bus transit owing to the fact that this mode requires very low investment and can operate on most streets.
- 5.2. Compare the trolleybus with the motorbus from the point of view of passengers and residents along the streets where these vehicles operate.
- 5.3. Which negative characteristics of diesel buses led to attempts to develop inertial energy buses? Why has that propulsion system not been successful?



Photo 5.34b Insurgentes Line station access (Courtesy of Christopher Puchalsky)

- 5.4.** Present a methodology for the evaluation of two or more bus vehicle capacities for a given set of operating conditions. Assume that all buses have the same performance.
- 5.5.** A standard bus has the following dimensions:
- | | |
|-------------------------------|----------------------------|
| Front overhang $l_f = 2.10$ m | Track width $W_t = 2.20$ m |
| Wheelbase $l_a = 7.10$ m | Body width $W = 2.50$ m |
- a) Draw the bus in a curve with an outside wheel path radius of $R_w^o = 11.00$ m and show both wheelpath and bodypath widths (W_w and W_b).
- b) Derive the equation for a bus's outside body radius R_b^o , as a function of l_a , l_f , R_w^o , W , and W_t .
- c) Compute R_b^o , R_w^i , wheelpath width W_w , and bodypath width W_b , and check the results of computations on your drawing.
- 5.6.** Compare articulated with standard buses and define a set of conditions under which the former are most likely to be superior to the latter.

- 5.7. Why is riding comfort in the rear section of articulated buses inferior to the comfort in the front section? Why would that comfort be improved in the articulated bus with a powered third instead of a powered second axle, and what are the other advantages and disadvantages of this model compared to the more standard model with second-axle powering?
- 5.8. Several cities have made major efforts to introduce regular bus transit lines on freeways with stops along the way. Yet there are very few such lines in successful operation (i.e., attracting substantial patronage). Why?
- 5.9. Describe dual-mode bus (ICE–electric) and explain its operational advantages and disadvantages as compared to regular buses.
- 5.10. Select one of the two basic types of hybrid buses, with series or parallel power trains. Explain its set of components and then describe how the power train works during each one of the following travel regimes: full accelerations and travel at constant maximum speed.
- 5.11. Several busways have been converted into HOV lanes (e.g., Shirley in Washington, El Monte in California). List all the effects that this type of conversion has on bus services and patronage.
- 5.12. Define and describe the bus transit system, as distinguished from conventional bus.
- 5.13. Discuss the design, operation, and spacing of bus stops typical for conventional (regular) bus, BTS and BRT modes.
- 5.14. List and briefly describe measures that can be taken to increase the reliability of bus service on urban streets. Include the physical features of buses, streets, operations, and control.
- 5.15. What measures can be undertaken to improve the *identity* of bus services?
- 5.16. Review the design and operations of one bus line in your city. Evaluate its operations and define the elements (if any) that should be improved to make the line a BTS type.
- 5.17. Define the differences between a BTS and BRT line.
- 5.18. Which conditions favor construction of a BRT line? Include factors concerning line alignment and ROW availability, travel demand and distribution (dispersed or concentrated), competing or alternative modes in the city, operating costs, particularly labor, traffic discipline and its enforcement and others.
- 5.19. Why have the attitudes toward trolleybuses, which were very negative during the 1960s, greatly improved in recent years?
- 5.20. If a city wants to increase usage of its highway transit modes and attract auto drivers to it, what are the most important measures it should undertake with respect to bus operations on streets, auto travel and parking, and public information/marketing?

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6

RAIL TRANSIT: STREETCARS, LIGHT RAIL, RAPID TRANSIT, AND REGIONAL RAIL

Transit modes utilizing rail technology cover a broad range of performance/cost characteristics. The “family of rail transit modes” comprises four basic modes—streetcars/tramways, light rail transit, rail rapid transit/metro, and regional rail—which range from single-vehicle streetcars operating in mixed traffic to 10-car trains on high-speed, highly automated metro or regional rail systems, with nearly continuous transition between these two extremes. Because of their common basic technology, all rail modes are described in this chapter. In addition to standard rail systems, rubber-tired rapid transit, used in several cities, is also included because of its close similarity to conventional rail systems in all physical and operational characteristics.

6.1 FAMILY OF RAIL TRANSIT MODES

Basic characteristics, definitions, and a review of trends in development and applications of rail modes are presented here, leading to the description of their physical and operational characteristics.

6.1.1 General Characteristics

Most of the characteristics that distinguish rail from other transit modes are caused by four different features typical for them: external guidance, rail technology, electric propulsion, and ROW separation. The differences among rail modes can also be largely

traced to the types of these features each one has. Rapid transit has all four features with exception of several rubber-tired systems; some streetcars have little ROW separation, and some regional rail systems utilize diesel instead of electric propulsion; both exceptions account for differences in characteristics of these modes. Based on the analyses from Chapter 2, the impact of each of the four features on mode characteristics is defined here.

6.1.1.1 External Guidance. Rail vehicles are physically guided by their way (track); the driver's only function in vehicle travel is to control its speed. The external vehicle guidance gives rail modes the following characteristics: they require *minimum ROW width*; they have *superior riding quality* as compared to non-guided modes, *greater permanence*, and *stronger identity*, which are particularly important factors in *high passenger attraction* and *impact on urban development*. External guidance also permits utilization of *electric traction*, which offers superior operational and environmental characteristics as compared to other methods of traction. The guidance is also a necessary, but not sufficient condition, for the *operation of trains* and for *full automation of vehicle travel*, two features that can result in significant reductions of operating costs and make operation of short trains at high frequency economically feasible. On the negative side, the guided systems usually require *higher investment costs* than steered (highway) modes, and they *restrict*

movement of their vehicles to the guideway network only.

Consequently, *as a result of external guidance*, rail modes are characterized by high performance and LOS and by low operating costs per unit of offered capacity in high-capacity ranges. The guidance requires higher investment costs than those required for steered modes and limits their services to the extent of the guideway (rail) network. It is pointed out, however, that most of the investment cost difference between various rail and bus systems in specific cities is caused by different ROW types, performance, and LOS characteristics; only a fraction of these cost differences is caused by the guideway itself. Most of the operating-cost differences in favor of guided modes in high-capacity ranges

(for comparable system performance and LOS) are caused by the economies of train operations made possible by the external guidance.

6.1.1.2 Rail Technology. Flanged steel wheels running on two steel rails provide both support and guidance for rail vehicles in a unique, extremely simple manner. Because of the flanges and the conical shape of their riding surfaces, each wheel is guided via a single contact point (actually a small area) with the rails.

This comparison shows that rail technology represents an appreciably superior mode to all other presently operational guided technologies under normal conditions. Only special conditions, such as very steep

Briefly stated, *rail guidance technology* has the following characteristics:

- + *Simple basic mechanism*; four to eight wheels per basic vehicle and two simple steel rails.
- + *The simplest, fastest fail-safe switching of all guidance technologies.*
- + Since steel-on-steel contact produces extremely low rolling resistance (about 10 times lower than rubber tire on concrete), rail modes require the *lowest energy consumption per ton weight* of all currently operational transit modes for any given dynamic performance. This advantage increases with speed, so that rail is the only technology for high-speed ground transportation using wheels (regional rail and high-speed intercity lines).
- + Rail is the only guidance technology that allows not only *at-grade crossings* but also *on-street running*.
- + Its simplicity and ruggedness give rail technology *low maintenance requirements and high durability*.
- + It is *more capable of coping with adverse weather conditions* (rain, ice, and snow) than are rubber-tired technologies, making rail modes most reliable for operation in severely cold climates.
- + Modern rail vehicles provide virtually the ultimate in *stable, smooth riding comfort*.
- *Investment cost of rail lines is higher than that for guided buses but lower than the cost of other guidance technologies, such as RTRT, AGT and Maglev.*
- The *lower adhesion coefficient* of steel-on-steel than rubber on dry concrete surfaces gives two relative disadvantages to rail technology: rail systems *cannot negotiate as steep gradients* as can rubber-tired systems, and they *must be operated with a higher degree of safety* because of their longer stopping distance.
- Although modern rail vehicles run quietly on straight sections and mild curves, when *negotiating sharp curves, rail vehicles produce more noise than do rubber-tired vehicles.*

gradients or running on old elevated structures, which produce noise and would be very costly to reconstruct, may make other guided technologies superior to rail.

6.1.1.3 Electric Propulsion. With the exception of some regional rail systems utilizing diesel traction, all rail transit systems are electrically powered. The characteristics of electric propulsion, described in Section 3.3.4, can be summarized as follows. Its advantages include *excellent dynamic performance of vehicles*, especially smooth and rapid acceleration; *clean, durable, low-maintenance motors with very low negative side effects*, particularly *low levels of noise and absence of air pollution*; and the *possibility of energy recovery during braking (regeneration)*. On the negative side, electric propulsion *requires substantial investment* in fixed power supply facilities and *limits vehicle travel* to the extent of electrified lines only. Moreover, a *regional power failure may paralyze the whole system* rather than individual vehicles.

Since the performance advantages of electric propulsion are extremely significant, electrification is highly desirable wherever travel demand is such that its investment can be justified.

6.1.1.4 Right-of-Way Separation. The fundamental influence of ROW separation on transit mode characteristics was discussed in Chapter 2. It was shown in Figures 2.5 to 2.7 that ROW category determines, more than any other characteristic, the investment required and performance obtained by different modes. This correlation is most clearly shown on the family of rail transit modes: most of the differences among SCR, LRT, and RRT are caused by their different ROW categories (C, B, and A, respectively).

Several unique features of rail modes have a direct relationship with their ROW category. First, its *lack of movement flexibility* makes rail technology inferior to steered modes for operation in mixed traffic (ROW category C). Second, it is *easier to achieve separation within streets (category B)* for rail than for bus transit modes: curbed, unpaved tracks are distinct from other lanes and are not tempting to auto drivers, as are bus lanes and busways. Third, *rail is the only guided tech-*

nology that allows operation across or along streets. This “dual-mode” feature enables some rail modes (mostly LRT) to utilize all three ROW categories on the same lines, giving them high flexibility of alignment and operating efficiency. Fourth, *guided technologies are superior to steered ones for operation on ROW category A*; buses are less suitable for such lines because their most important advantage—ubiquitous mobility—is irrelevant; in most other characteristics, such as capacity, safety, speed, and so on, they are inferior to guided modes. Finally, *ROW category A is, together with physical guidance, a necessary condition for the operation of long trains (four cars or more)*, speeds exceeding 80 km/h, as well as for fully automatic train running (without crews).

In review, rail technology is generally inferior to bus modes on category C ROW, but its advantages increase with ROW separation; on transit lines with ROW category A, with the exception of some short-haul services, rail is the superior technology.

6.1.1.5 Summary of Rail Transit Characteristics.

All rail modes have the characteristics resulting from guidance and rail technology, and most have those caused by electric propulsion. For the rail modes that also have partial or full ROW separation (LRT, RRT, and RGR), it can be stated that they represent transit modes with the highest overall performance of all modes but that are limited in their network extensiveness because of high investment costs. Consequently, although they cannot be efficiently utilized on low-demand routes, rail modes are usually the optimal choice where high demand exists. The point at which rail modes become superior depends, however, not only on the demand, but on the availability of partially or fully separated ROW, requirements in terms of service quality and performance, characteristics of alternative means of travel, and external effects, such as compatibility with pedestrian-oriented areas in cities and desired impacts on land-use developments.

The higher service quality and much stronger identity of rail than bus transit modes, particularly when they utilize separate ROW, have a major impact on transit ridership and on the overall role of transit in the

city. Thus a major study of rail transit (Pushkarev and Zupan 1982) found that per capita *bus* travel in U.S. cities with rail transit is the same or slightly higher than in cities served by bus transit only. This indicates that rail systems increase total transit usage, in the long run, by the number of trips they serve. In other words, introduction of an LRT or metro line usually generates more transit trips on all modes than it diverts from the bus lines it replaces.

In cities that utilize buses only, transit usually has a considerably less important function than in the cities that have modern rail transit systems. This different role can be observed through several factors. Rail lines typically offer a simple, easily understood type of service with short headways during most daily hours. Connected by convenient rail and bus transfer stations, they comprise an integrated network with high LOS.

Because of their permanence and ability to attract human-oriented urban development, rail transit stations tend to influence investment and land-use development in their vicinity. For example, it is well-known and visually obvious that the construction of BART and Muni Metro had a strong influence and physically enabled very intensive growth and intensification of livability of the San Francisco CBD. Washington Metro was the critical force for development of many suburban activity centers such as Arlington and Ballston. Similar developments are taking place under the influences of LRT systems built since 1980 in Calgary, Dallas, and Denver. Similar examples of interdependence between rail transit and urban development are found in many cities around the world, such as Paris, Singapore, Stockholm, Tokyo, and Toronto.

Finally, the greater complexity of rail modes, a negative feature in many respects, has one very positive side. The planning, construction, and operation of rail transit require considerably higher expertise than bus transit; as a consequence, agencies utilizing rail modes usually have a higher degree of transit expertise than those utilizing buses as the sole transit mode. This is an overlooked but very important factor for urban transportation planning and the role that transit plays in the city in general.

6.1.2 Definitions and Characteristics of Individual Rail Modes

On the basis of the main features that define transit modes—ROW type, technology, and operational/service characteristics—rail systems can be classified into four modes: streetcars/tramways (SCR/TW), light rail transit (LRT), rail rapid transit (RRT), and regional rail (RGR). Each mode offers a different range of physical characteristics, performance, and cost, as shown in Chapter 2. In some, there is an overlap between modes, which sometimes causes confusion with respect to definitions of concepts and terminology. Following the descriptions of all four modes, their technical characteristics are systematically presented in a table, allowing easy definition of each one.

6.1.2.1 Streetcars/Tramways. Streetcar (SCR) systems consist of one, two, and occasionally three rail vehicle trains operated mostly on streets in mixed traffic but sometimes also with limited separation from street traffic by preferential treatment or separate ROW. Streetcars have excellent dynamic characteristics and riding comfort, but their reliability and operating speed depend greatly on the conditions along their lines: if they run on narrow streets with congested traffic, their performance can be unsatisfactory, while on wide streets with little traffic interference or with various preferential treatments, SCR service can be very good.

A typical SCR/tramway vehicle has four to six axles and a length of 14 to 21 m, seating about 20% to 40% of its 100 to 180 total passenger-space capacity. In recent years many tramway systems in central and western Europe (Bordeaux, Budapest, Milan) have introduced 35 to 53 m long multiarticulated low-floor vehicles with five to seven body sections, with capacities up to 350 spaces. Because of the predominantly shared ROW, tramway services generally have operating speeds of 15 to 30 km/h. A modern low-floor articulated tramway is shown in Photo 6.1.

SCRs offer superior riding comfort and a more distinct image than highway transit modes. However, they involve considerably higher costs on lightly traveled lines. Moreover, they may have operational problems



Photo 6.1 A modern streetcar (Siemens Ultra-low-floor model in Vienna)

in congested mixed traffic. The need for route extensions in expanding cities and the delays SCRs encountered in congested streets have led to their extensive replacement by buses, particularly at times when transit was given no priority treatment. They were the main transit mode until the 1950s, but then they were eliminated from many cities in several countries. However, they have retained an important role in cities of many European countries (Russia, the Czech Republic, Switzerland, Austria) as well as in cities elsewhere, such as Melbourne, San Francisco, and Toronto.

In addition to the replacement of SCRs by buses and trolleybuses, their role has also diminished because of conversion of this mode into higher-quality LRT or substitution by RRT systems. The transition to LRT was in most cases gradual, and precise distinction be-

tween the two modes is often difficult to make; yet it will be shown that characteristics of a typical SCR line differ considerably from the characteristics of typical LRT lines.

Since the late 1990s, however, there has been a rebirth of streetcars in a number of U.S. cities in different functions, which can be classified into three groups, following general sequence of their development:

- First, several cities with modern LRT systems—such as San Francisco, San Jose, and San Diego—began to operate some classical streetcar vehicles in center city portions of their LRT networks, usually as shuttles or loops. The main role of these lines is creation of a special pedestrian/historic atmosphere and tourist attraction.

- Second, several cities have built new lines for classical streetcar vehicles only. The function of these lines is usually similar to that of the first category, but they are independent and longer, often serving an active commercial corridor or CBD with other major activity centers. Lines in this category have been built in Montgomery, Alabama; Tampa, Florida; Seattle, Washington; Kenosha, Wisconsin; and a number of other cities.
- Third, in the most significant category, have been entirely new streetcar lines that have lengths of several kilometers (miles) and have primarily a transportation function, carrying substantial passenger volumes throughout the day but also giving the service and areas served a special character and tourist attraction. Several excellent examples of this category deserve mention. Line F in San Francisco is unique in that it is served by a variety of classical streetcars acquired from many North American and European cities. Its daily ridership is 16,000 persons. Portland, Oregon, has built a new streetcar line independent of its LRT network that serves a long downtown corridor and is featured as a “mascot” of several new housing and business developments. Tacoma has such an independent line in its CBD. New Orleans has been developing a network that incorporates the oldest historic St. Charles streetcar line; it is a symbol of the city and serves an attractive neighborhood, a line in the French Quarter and one on its main artery, Canal Street. The latter line is functionally an LRT, but with cars designed as classical streetcars. Washington, DC, is also building new streetcar lines.

Further projects for streetcars in all these three categories exist in a number of cities in the United States and several other countries.

6.1.2.2 Light Rail Transit (LRT). Consisting of electrically powered, high-capacity, quiet vehicles with high riding quality operating in one- to four-car trains on predominantly separated ROW, rights-of-way this mode has in the last 40 years become an important member of the family of transit modes. Actually, in many countries, LRT is the fastest-growing rail transit

mode. As a transit mode, LRT is in the semirapid transit group; by its performance/cost characteristics, LRT falls between SCR and RRT modes.

LRT systems typically have articulated vehicles with two to seven articulated sections and four to ten axles or, in some designs, also several single-suspended wheels (Photo 6.2). They operate as single or multiple-unit trains of up to four four- or six-axle, or two eight-axle cars. Articulated LRT vehicles range in length from 18 to 42 m; one such vehicle can accommodate up to 250 persons, 20% to 50% of whom are seated. LRT vehicles have high acceleration-deceleration capabilities (1.0 to 2.0, emergency braking 3.0 m/s²). Their maximum speeds depend on the designs of individual systems: they are usually in the range 70 to 80 km/h, but there are models capable of achieving 100 to 125 km/h. Operating speeds of LRT are typically between 18 and 40 km/h.

LRT is characterized by great variety in its physical components and operational features, as their brief description here shows. A particularly useful feature of LRT is that it can use many different types of alignment on the same line: travel in tunnels, in street medians, and through parks and pedestrian zones; have high and low platforms at different stations; even be driven by drivers and then switched to fully automatic operation on category A line sections (San Francisco).

Many LRT lines have floors 0.80 to 1.00 m high and three or four steps from low station platforms. Or low-floor cars can have virtually level boarding from 20-cm high curbs. Accessibility for the disabled may be by a lift, via a ramp, or direct for level boarding.

LRT systems usually operate mostly on ROW category B, sometimes on category A, and exceptionally on short sections of ROW category C. The two reserved ROW categories, B and A, generally amount to 70% to 90% of the total network length. It is common practice to first separate the most critical sections in the central city or on congested arterials, so that most sources of service disturbances are eliminated. Thus LRT in some cities utilizes tunnel sections to penetrate the congested areas of the city, a factor that greatly enhances the quality of service they offer in very high density areas. Under some conditions, LRT penetration into the busy CBD area is on an at-grade alignment



Photo 6.2 LRT: a six-axle low-floor vehicle in Cologne (Siemens K4500; courtesy of Sybic)

through pedestrian areas. In medium-sized cities such arrangements often contribute to the livability of pedestrian zones. Outside the central core area, LRT is usually placed on ROW category B. On some new LRT systems, such as those in Denver and Baltimore, outlying LRT alignments utilize long sections of ROW category A on the surface, while Dallas and Portland also have long tunnel sections. This flexibility in alignments, stops, stations, and type of operation allows a staged upgrading of a rail network to a new ROW without interruptions of service and with immediate utilization of new route sections. Such staging permits investment to be tailored to local conditions, the desired service quality, and the availability of capital funds.

Reserved ROW, particularly in congested areas, allows LRT to have average network operating speeds of 20 to 45 km/h, but individual lines may be considerably above this range. On exclusive ROW sections, single streetcars used to operate at frequencies of up to 120 vehicles per hour. Present LRT systems operate much longer TUs at frequencies not exceeding 30 to

45 TU/h, offering similar capacities of up to 18,000 to 20,000 prs/h at much greater speed and reliability than unsignalized streetcars used to achieve.

LRT networks are characterized by fairly good coverage of central areas (in tunnels, aerial ways, or on at-grade separated rights-of-way) with extensions branching out at-grade on a number of radial routes. Station spacings in central cities average 400 to 800 m, but many recently built LRT lines in North America have regional character with considerably longer station spacings: San Diego, 1650 m; Los Angeles, 1900 m; Dallas, 2200 m; and the intercity Trenton–Camden RiverLine in New Jersey, 2880 m. Park-and-ride (P+R) and kiss-and-ride (K+R) access modes are increasingly utilized, particularly on new North American LRT systems such as those in St. Louis, Los Angeles, and Sacramento.

Light rail rapid transit (LRRT) is the highest-performance form of LRT. Its basic distinction is that it has a fully separated ROW, category A (Photo 6.3), or only a few grade crossings with full preemption. This permits the vehicles, very similar in size and de-



Photo 6.3 Light rail rapid transit: Docklands Light Railway in London (Courtesy of Stephen Knight)

sign to regular LRT vehicles, to have a considerably higher maximum speed. Thus vehicles on SEPTA's Norristown line in Philadelphia can reach 110 km/h, and some runs are scheduled with an operating speed of 57 km/h. This line has high-level platforms and a third-rail power supply, typical RRT features. The intercity LRT RiverLine in southern New Jersey, which operates mostly on railroad tracks with fully protected street crossings (ROW category A), has operating speeds of 45 to 55 km/h.

In a number of cities with LRT networks there are individual lines that are LRRT—i.e., they have entirely separated ROW. Lines of this type exist, for example, in Gothenburg, Sweden, and Frankfurt, Germany. Among new LRT systems, LRRT lines have been increasingly built. The Scarborough Line in Toronto, Green Line in Los Angeles, and the Airport Line in St. Louis are fully separated LRT lines, while such

lines in Vancouver, London–Docklands, and Copenhagen have been fully automated to take the advantage of exclusive ROW. This feature, fully automated operation, is expected to be frequently used in the future, so that the LRRT mode will have an increasing role in urban transportation.

6.1.2.3 Rail Rapid Transit (RRT). This mode is also called metro and heavy rail. In many respects, RRT, including rubber-tired rapid transit (RTRT), represents the optimal transit mode for a high-capacity line or network service. It has a fully controlled ROW without any external interferences. Simple guidance, electric traction, and fail-safe signal control allow the maximum speed possible with given station spacings. These rail modes also provide excellent passenger comfort, high efficiency in energy utilization, high reliability, and virtually absolute safety. Operation of a

train with up to 10 long four-axle cars by one person results in a capacity and labor productivity much higher than with any other mode except that which its “big brother,” regional rail (RGR), can achieve. Off-vehicle fare collection, high platforms, and simultaneous boarding/alighting through up to 40 double-channel doors allow this mode to provide total boarding/alighting rates 3 to 5 times greater than those of LRT, and 10 to 20 times greater than those of buses, assuming the ultimate capabilities of all these modes.

With its fully protected ROW and physical and operating characteristics, RRT is the mode most conducive to fully automated train operation of all existing and proposed modes. Many recently built metro systems (Photo 6.4) have many automated elements: unmanned stations, automated train operation, and central control of the entire lines or networks. Following the AGT mode, for which operation of trains without crews is a required element of economic/performance feasibility, several metro systems without crews have been introduced since the late 1990s. The best-known examples are the Lyon Metro Line D, Paris Metro Line 14, and the Singapore Northeast MRT Line. This trend is likely to continue and accelerate.

RRT requires the greatest investment of all modes (primarily because of its entirely grade-separation

ROW and large stations), so that its primary applications are in heavily traveled corridors. It should be borne in mind, however, that where heavy passenger volumes must be served by a high-performance, high-LOS system, RRT requires substantially lower investment and lower operating costs per passenger than any other technology. Also, on existing RRT systems, the marginal cost of providing additional capacity is much lower than that on any other mode: San Francisco BART can offer some 1500 additional spaces per train operator. The corresponding figure for the Philadelphia PATCO Line is 780; LRT can offer 150 to 720, a bus system 70 to 140. A detailed comparison of the productivities of different modes is given in Section 4.3.

The typical modern RRT vehicle, 16 to 23 m long and 2.50 to 3.20 m wide, is operated in TUs of 1 to 10 cars. Vehicle capacities range between 120 and 250 spaces; seats represent anywhere from 25% to 60% of vehicle capacity. Operating speeds range from 25 to 60 km/h, with peak-hour frequencies between 20 and 40 trains per hour. Recorded capacities of RRT lines with stations have been as high as 62,000 prs/h per track (New York). Some of the recently opened systems (Tokyo, São Paulo, Hong Kong, R.E.R. in Paris) have been designed for capacities of the same magnitude. The maximum seated capacity of RRT is approxi-



Photo 6.4 Rapid transit: Washington Metro (Courtesy of WMATA, photo by Paul Myatt)

mately 30,000 seats/h, but most systems operate with maximum volumes in the range of 8000 to 25,000 sps/h.

Rapid transit is usually placed in tunnels in central urban areas, while aerial structures, embankments, and some sections at grade (with street over- or underpasses) are common for suburban and outlying areas. The Moscow Metro is rather unique as a large network nearly entirely in tunnels; the RRT network in Manhattan is also mostly underground, giving the name “Subway” to the entire system, although many lines in other boroughs, particularly in the Bronx and Queens, are elevated. RT systems in Cleveland and Miami, on the other hand, run on portions of railroad ROW and aerial structures and have no tunnels.

Old elevated RRTs with steel structures are usually noisy and bulky, and they have a negative impact on the surroundings. New RRT structures are entirely different. Referred to as “aerial” structures, they are built from prestressed concrete and have considerably lower negative environmental impacts. Their use is likely to increase when the population realizes from experience with lines such as the San Francisco BART and the Washington and Miami metros that the objections to elevated structures do not apply to the aerials.

Most RRT lines in U.S. and Canadian cities are predominantly radial with only limited coverage of city centers, Manhattan, Boston and Montreal being an exception. On the other hand, many modern European RRT systems, as well as those of Tokyo, Seoul, and Mexico, have been designed with networks covering large central areas, thus offering service for medium and short trips in addition to the longer urban or regional trips. Area coverage in the suburbs is often aided by bus and LRT access modes. In North America P+R and K+R facilities are used extensively, while many Japanese cities use the bicycle, a far more economical access mode, as the main means of access in addition to walking. In part, this supplementary vehicular access is required because of low population densities and the longer station spacings of RRTs in these areas. Generally, average trip lengths on RRT systems are greater than on surface transit: 5 to 10 km is their typical range.

6.1.2.4 Regional Rail (RGR). Representing local services of long-distance railroads, RGR systems have the highest technical and operating standards of all transit modes. Most of these systems are operated by railroad agencies on their ROW, which are grade-separated, in some cases with signalized grade crossings in outlying areas. Traction is mostly electric, although in many North American cities (Boston, most Chicago lines, Toronto) it is diesel. Their large high-speed vehicles (Photo 6.5), operated individually or as multiple-unit or locomotive-hauled trains, offer excellent riding comfort. The service is characterized by long average trip lengths (the U.S. average is 35 km), long station spacings, high speed, and reliability.

Most RGR networks consist of a number of lines radiating from the CBD with stations located at suburban town centers. In addition to walking, bicycles, and bus feeders, K+R and P+R are used as access modes. Central city stations are often combined with intercity rail stations, but they are limited in number and provide little downtown coverage. Serving predominantly suburb-to-CBD commuter travel (therefore the designations “suburban” or “commuter railroads”), RGR often has heavily peaked and highly directional passenger volumes. Lines that offer regular headways (20, 30, or 60 min) throughout the day have, however, reasonably high off-peak and weekend travel also. Good examples of RGR systems are found in Chicago, Glasgow, London, Moscow, New York, Philadelphia, Sydney, Zürich, and many other cities.

RGR systems in some European and most Japanese cities are, however, considerably different in character. The RGR systems in Berlin, Copenhagen, Tokyo, and Vienna are also operated by railroad agencies on their tracks and have high technical standards, but they have many stations in the city and offer service frequencies similar to those of RRT. Their passenger volumes are less peaked, since they serve many noncommuter and non-CBD-oriented trips. Actually, by their type of service, these systems represent transit systems with extensive area coverage (particularly Berlin), more similar to RRT than to typical “commuter railroads.”

In recent decades, with the spatial growth of cities, the trend has been toward development of the latter,



Photo 6.5 Regional rail: Bilevel cars on Los Angeles Metrolink (Courtesy of James R. Greene)

RRT-type RGRs. With alignment, station spacings, and speed similar to commuter rail, these systems have frequencies of service and CBD distributions similar to RRT: they actually represent a bridge between the two modes. Some of the existing RGR systems have been reorganized into this type by construction of tunnel connections between radial lines, improving CBD coverage: the Munich S-Bahn, Paris R.E.R. and Philadelphia RGR systems are good examples. Manchester has built a similar network connection, but with LRT character and introduction of LRT rolling stock on the entire connected lines. Systems built in recent decades with this character and operated by transit authorities are the San Francisco BART, Philadelphia PATCO, and Frankfurt S-Bahn systems. These modern RGR systems have given metropolitan regions with many satellite communities an excellent high-performance

regional transportation network integrated with local transit.

Serving rather long trips, most RGR systems provide a much higher share of seats for their passengers than other transit modes. Their large cars have very high seating capacities: up to 128 seats in single-level cars, as many as 185 in double-decker cars. The latter type of car was used in a few cities, such as Chicago, Toronto and Paris. Since 1980, double-decker cars have been introduced in cities of many countries, such as the United States, Canada, France, Germany, Japan, and Australia. Many new RGR systems, such as those of Los Angeles, Zürich, and Seattle, use only double-deckers for their entire fleets.

Operating speeds of RGR services average anywhere between 30 and 75 km/h, with maximum running speeds of up to 130 km/h. The labor productivity

of RGR can be very high, although some older systems still use obsolete operating practices and have a labor force greatly in excess of what this mode would require with contemporary vehicle designs, fare collection, and other operating methods. The underutilized potential of these RGR systems can be traced to such labor practices, frequently to disinterested management, insufficient financial assistance from public sources, and the resulting inadequate maintenance and lack of modernization or progressive thinking in general.

It is because of the inherent high performance of this mode that even the inefficiently run systems provide an extremely valuable service in metropolitan areas. Yet their basic advantages and durability should not be an excuse for wasteful practices and underutilization of the full potential of this mode.

6.1.2.5 Tram-Train Mode. This is the convenient, popular, although not technically correct name for a system that combines urban LRT and intercity railway tracks (thus it should be called LRT/intercity mode). The growth of metropolitan areas and increasing travel between central cities and surrounding suburbs and towns has led to the development of this dual-mode rail transit system. LRT vehicles are designed with dual voltages (or diesel motor) and equipped for signal control on railway lines. They operate on transit lines in the city, then use connecting tracks to go on railway lines into suburban areas, sharing tracks with intercity trains operating at speeds as high as 200 km/h and with freight trains.

Introduced first in Karlsruhe, Germany, tram-train service has been extremely successful, resulting in passenger increases of 30% to 60% on some previously RGR lines. This has led a number of other cities to adopt the tram-train concept. The city of Saarbrücken has built an entirely new LRT line operating on ROW categories B and C in the city center, then going on German and French railways tracks to Sarreguemines, a city in France (Photos 6.6a & b). Interest in the United States has been equally strong, but the extremely strict Federal Railroad Administration rules about the buffeting strength of all cars sharing railroad tracks with trains is still an obstacle that awaits resolution. The only allowed track sharing between LRT

and railroad equipment in the United States is with time separation, i.e., strict division of time into periods when each mode can operate alone. In other countries, these safety standards or superior ones have been achieved by implementing modern electronic safety systems.

6.1.2.6 Review of the Family of Rail Transit Modes. The four basic rail transit modes are not distinctly separated from each other. The distinctions between SCR and LRT systems as well as between RRT and RGR are particularly complex. The clearest difference is between LRT and RRT: full grade separation is a characteristic that distinguishes RRT and gives it higher performance than LRT, as well as many distinct technical features, such as high-level platforms, third-rail power supply, operation of long trains, and fully automatic fail-safe control.

The overlaps of characteristics and exceptional features often cause confusion in definitions of modes. The fact that it is difficult to define whether the San Francisco BART is a RRT or RGR mode, that the Norristown Line in Philadelphia has a unique combination of LRT and RRT features, and that one RRT system (Chicago) has grade crossings illustrates the reasons why transit modes cannot be defined with absolute rigor. However, these kinds of exceptional cases should not confuse the clear distinctions among characteristics of the four basic rail modes.

Technical characteristics of the four modes are given in Table 6.1. For clarity, a review of their basic technical and operating features is shown in a graphical form in Figure 6.1. These exhibits show the great diversity in characteristics of different rail modes. Statements describing rail transit as a single mode, such as that "Rail transit is expensive and its application is limited to a few cities," represent erroneous generalizations. The broad ranges of rail transit characteristics make these modes suitable for application under a great variety of conditions. The highest-performance rapid transit—automated, high-capacity systems like BART—is not applicable to other than large metropolitan areas; but lower-performance types of RRT or LRT can be the optimal modes for many other, medium-sized areas. Moreover, *if the goal of a transit*



Photo 6.6a Tram-train in center city Saarbrücken

system is to attract auto users by a high level of service, rail modes are often the lowest-cost and most efficient systems of all available alternatives. This presumes, of course, that the comparison is made taking into account passenger attraction abilities and total, positive and negative, effects of alternative modes, including the indirect effects, for the entire planning period. Actually, such comprehensive analyses of different alternative modes were performed when rail systems were selected in all U.S. and most other cities in recent decades.

6.2 ROLLING STOCK

Rail technology allows use of a great variety of vehicles with respect to axle arrangement, body type, dimensions, and dynamic performance. Major differ-

ences among vehicles are caused by characteristics of different modes.

Tramways and LRT vehicles usually have their body widths limited by conditions in street operation and their distances between truck centers limited by sharp curves; they must also have powerful magnetic brakes for compatibility with other traffic. Legal limits on vehicle length either do not apply to rail vehicles or are quite liberal because their guidance and body articulation result in narrow precise paths in negotiating curves. RT, being an independent system, has vehicles designed together with the selected alignment and clearance standards for lines. Regional rail has the largest dimensions and the highest speed because it complies with railroad standards, which are higher than those of transit systems.

Another set of factors influencing vehicle design are those imposed by local conditions (passenger volumes,



Photo 6.6b Tram-train on mainline railway track from Saarbrücken to Sarreguemines

station spacings, topography, climate, etc.). Standardization of vehicles is highly desirable from the economic point of view for both manufacturers and operators, and there have been examples of manufacturers of standardized vehicles for different cities: Brill, St. Louis Car, GE, and others built and PCC SCR vehicles in the United States between 1935 and 1950; the Czechoslovakian Tatra produced some 10,000 vehicles for tramway systems in East European countries between the early 1950s and the 1990s; Siemens (Germany) and Bombardier (Canada) made vehicles that operate in many cities in West Europe and North America. However, because of the very long life of rail vehicles (desirable 25 to 30, but often 40, 50, or even 60 years) and due to the independence of transit systems in individual cities, there are often considerable variations among vehicle designs for different cities.

6.2.1 Rail Vehicle¹ Types and Basic Components

The characteristics of different vehicle types can be best reviewed through a systematic classification of vehicles by their basic features.

6.2.1.1 Vehicle Classifications. The features by which rail vehicles can be classified include vehicle *powering, type of propulsion, type of operation, body type and wheel/axle arrangements, number of levels or decks, and floor heights*. Definitions of vehicles with these features are given here. Common basic transit units are described in more detail in Section 6.2.5.2.

¹ Rail vehicles are often referred to as “cars”; the two terms are used here synonymously, according to their most common use.

Table 6.1 Technical, operational, and system characteristics of rail transit modes^a

	<i>Streetcar/Tramway</i>	<i>Light Rail Transit</i>	<i>Rapid Transit</i>	<i>Regional Rail</i>
Vehicle/train characteristics				
Minimum operational unit	1	1 (4 to 10 axles)	1–3	1–3
Maximum train consist	3	2–4 (6 to 8 axles)	4–10	4–10
Vehicle length (m)	14–35	14–54	15–23	20–26
Floor height	Low/high	Low/high	High	High/low
Vehicle capacity (seats per vehicle)	22–40	25–80	32–84	80–175
Vehicle capacity (total spaces per vehicle)	100–250	110–350	140–280	140–210
Fixed facilities				
Exclusive ROW (% of length)	0–40	40–90	100	100
Vehicle control	Manual/visual	Manual/signal	Signal/ATC	Signal
Fare collection: self-service or:	On vehicle	On vehicle/at station	At station	At station/on vehicle
Power supply	Overhead	Overhead	Third rail/overhead	Overhead/third rail/diesel
Stations				
Platform height	Low	Low or high	High	High or low
Access control	None	None or full	Full	None or full
Operational characteristics				
Maximum speed (km/h)	60–70	60–120	80–120	80–130
Operating speed (km/h)	12–20	18–50	25–60	40–75
Maximum frequency				
Peak hour, joint section (TU/h)	60–120	40–90	20–40	10–30
Off-peak, single line (TU/h)	5–12	5–12	5–12	1–6
Capacity (prs/h)	4000–15,000	6000–20,000	10,000–60,000	8000–45,000
Reliability	Low-medium	High	Very high	Very high
System aspects				
Network and area coverage	Extensive, good coverage	Good CBD coverage, Branching common	Predominantly radial: good CBD coverage	Radial, limited CBD but good suburban coverage
Station spacing (m)	250–500	350–1600	500–2000	1200–7000
Average trip length	Short to medium	Medium to long	Medium to long	Long
Relationship to other modes in addition to walking	Can feed higher-capacity modes	P+R, K+R, Bus feeders	P+R, K+R, Bus & LRT feeders	Outlying: P+R, K+R, Bus feeders; center city: walk, bus, LRT, metro

^aListed are typical ranges of existing systems; exceptional values may be outside the ranges

Characteristics	Type \ Mode	Tramway - Streetcar	Light Rail	LRT	Rapid Transit	Regional Rail
Right-of-way separation	None Some Grade crossing only Full	—	—	—	—	—
Max no. of cars/train	1-3 4-10	—	—	—	—	—
Station platform	Low High	—	—	—	—	—
Power pick-up	Overhead Third rail (Diesel)	—	—	—	—	—
Vehicle travel control	Driver/visual Permissive signals Forced stop signals Automatic	—	—	—	—	—
Max. vehicle speed	≤ 70 km/h 71-100 km/h > 100 km/h	—	—	—	—	—

Figure 6.1 Basic characteristics of rail transit modes

• By powering:

- A *powered (motor) car* has some or all axles powered and can operate alone or coupled in a train.
- A *powered trailer* is a powered car without driver's controls; thus it is operational only in "consists" (operating units) with cars that have driver controls. This car type is used on some RRT systems (Paris, Mexico, San Francisco).
- A *trailer* is an unpowered car towed by a powered car or locomotive, or it may be semipermanently coupled to two powered cars in an operating unit (RRT and RGR).
- A *locomotive*, a powered non-passenger-carrying vehicle, is used to tow or push trailers.
- A and B cars are powered vehicles that share many components with each other and can only operate together, as a *married pair*. Each one has driver's controls at one end only.

All vehicles, powered and trailers, have braking capabilities.

• By type of propulsion:

- An *electric vehicle* is powered by electric (AC or DC) motors (vast majority of rail transit vehicles). A *linear induction motor (LIM)* is used on a few guided transit systems.
- An *ICE vehicle* is powered by a diesel or similar type of internal combustion engine (in rail transit used only on some RGR and a few LRT systems).
- *Hybrid vehicles* are powered by a combination of ICE, electric, and other motor types.

• By type of operation:

- A *single unit (SU)* is a single, usually four-axle uni- or bidirectional powered car that can operate alone or in a train consist.
- A *married pair (MP)* and a *three-car unit* are transit units with cars that share mechanical and electrical equipment. Commonly used for RRT and RGR systems, these units are made of, respectively, two (A and B) and three (A, B, and C, the last being a powered or unpowered

ered trailer) semipermanently coupled vehicles which are not operational alone (see Section 6.2.5.2).

- *A powered car with trailer* is a consist used mostly for SCR systems.
- *Locomotive/trailer car* consists, typical for long-distance trains, are used on some RGR systems, mostly the nonelectrified ones. Called *push-pull consists*, they are bidirectional trains that can be driven from the locomotive or a driver's cab in the last car.
- *A multiple-unit (MU) train* is a consist of several powered cars (SU, married pairs, or other types) that are controlled by one driver. All RRT systems have MU capability, but the term is used primarily when LRT and RGR are operated in this manner to distinguish them from train consists with trailers.
- *By body type and axle/wheel assemblies:*
 - *Single-body vehicles* can have two or four axles. A vast majority of RRT and RGR, and a decreasing number of SCR and LRT vehicles, are four-axle, single-body types.
 - *Axles* are placed in pairs in rail trucks/bogies; *single axles* and *single-suspended wheels* are used in some low-floor vehicles.
 - *Articulated vehicles*, used on most SCR and LRT systems, have two to five (exceptionally seven) bodies connected by joints into a continuous interior through all body sections. The joints allow vehicle bodies to bend in curves horizontally and vertically with respect to each other. Most articulated vehicles built until about 1990 have body joints fixed on a truck, so that a two-body vehicle has three trucks and six axles (Photo 6.7), or a three-body vehicle has four trucks and eight axles (the latter type has not been used in North America).

Recently-built LRT vehicles have middle trucks carrying a short body section with joints suspended on its overhangs, so that vehicles with six axles have three bodies with two articulations, or eight-axle vehicles have up to five

bodies and four articulations (Photo 6.8). Some low-floor six- and eight-axle vehicles have different types of single-axle and single-wheel designs.

- *By number of decks/levels:*
 - *Double-decker cars* were used on most British tramway systems; at present they are used in Hong Kong. *Bilevel cars*, used increasingly on RGR systems, have two full or partial decks with two sets of stairways connecting them.
- *By floor heights:*
 - *High-floor cars* have floors at 0.8 to 1.2 m above top of rail (TOR) and either steps or high platforms at stations.
 - *Low-floor cars*, as are many LRT and some RGR cars, have floor at 0.20 to 0.40 m above TOR and no steps.

In addition, SCR vehicles can be *unidirectional* (one set of controls, doors on one side, etc.). All other rail vehicles are *bidirectional*, with symmetrically designed sides and ends for running in either direction.

6.2.1.2 Axle Arrangements and Purpose of Trucks. The smallest rail vehicles have two axles held in a mutually parallel position by a chassis. The vehicle body rests on the chassis. Suspension between axles and body is usually achieved by leaf springs. Since the wheelbase distance between the axles is critical in negotiating curves, the length of two-axle vehicles, including long overhangs, seldom exceeds 10 m.

Two-axle vehicles were widely used for tramways in many European as well as in some U.S. cities. Although simple and very economical, this vehicle type has been superseded by larger multi-axle vehicles because of their higher capacity, speed, and comfort. At present, virtually all RRT and RGR vehicles have two two-axle trucks (i.e., four axles), but some articulated tramway, LRT, and RGR vehicles have various arrangements of axles and wheels.

A typical rail transit vehicle, as Figure 6.2 shows, consists of two basic components: vehicle body and trucks (bogies). The body contains the passenger section, driver's stand or cabin with driving controls, and various mechanical and electrical equipment, located



Photo 6.7 Six-axle LRT vehicles at a high-platform station on the Metrolink system in St. Louis



Photo 6.8 Eight-axle LRT vehicle in Montpellier (Courtesy of P. L. Guillemin)

mostly under the floor or on the roof of low-floor models. The trucks contain axles with wheels, motors, brakes, and other mechanical and electrical equipment. Power pickup equipment is on the trucks for a third rail and on the roof for an overhead power supply. The most important vehicle dimensions are designated in Figure 6.2.

The truck frame holds two axles fixed in a parallel position, but some models allow certain axle turning that produce less friction of flanges and less noise on curves than do fixed-axle trucks. At the center of most truck frames is the centerplate—a joint that supports the body but allows horizontal rotation of the truck with respect to it. Thus the vehicle body rests on two truck center points. In addition, both the body and the trucks have sliding surfaces on the sides of the centerplate over which the body is supported against excessive lateral roll. There has also been increasing use of

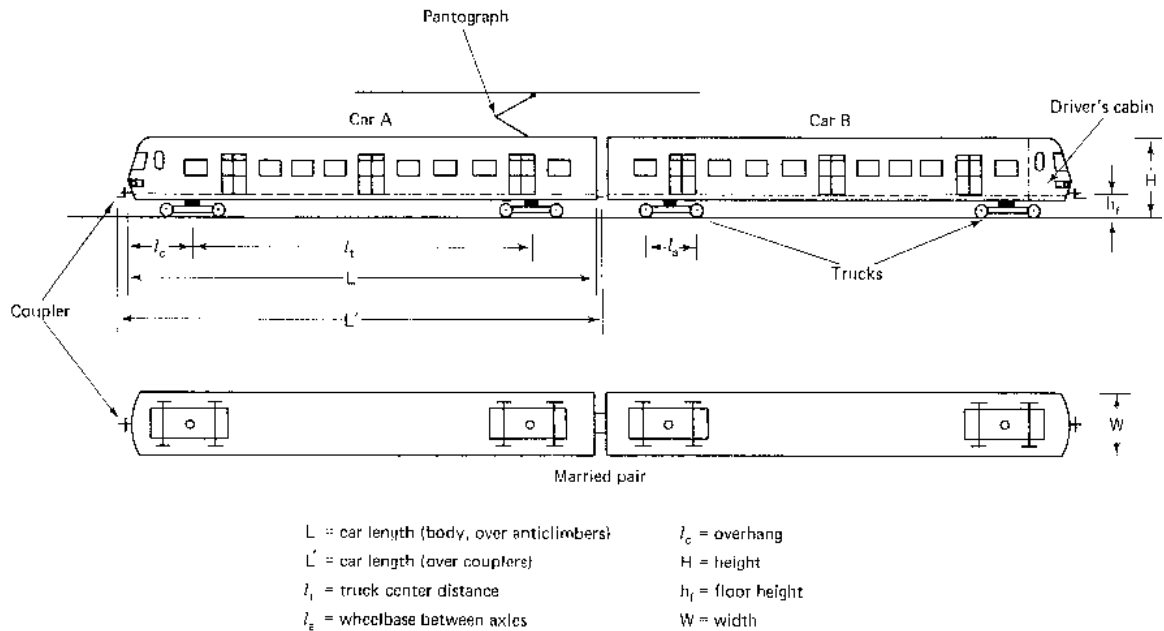


Figure 6.2 Rail vehicle components and dimensions

four-point suspension (i.e., with side bearings only and no centerplate).

Trucks have several purposes. First, they eliminate mechanical constraints on vehicle length. With two-axle vehicles, the wheelbase ℓ_t —the distance between fixed axles limited by the track curvature the vehicle is required to negotiate—determines the maximum possible vehicle length. With four-axle vehicles, the wheelbase is very small (between the two axles in a truck), so that it allows negotiation of sharper curves than for two-axle vehicles and the use of any body length that the free profile along tracks permits. Each rigid body is supported by two trucks, which may be as far apart as the body clearances in curves and axle loadings (weight per axle) allow. Even longer vehicles can be used with articulated bodies. The differences in the turning geometry of the basic two, four-, and six-axle rail vehicle types are shown in Figure 6.3. Second, vehicle weight is better distributed: although heavier, vehicles with more axles have lower axle loadings, thus reducing track maintenance requirements. The third factor is that the geometry of vehicle support via

trucks is such that only half of every shock an axle receives is transferred to the vehicle body. This is shown schematically for both horizontal and vertical displacements in Figure 6.4. Finally, trucks permit the provision of two to three suspensions between axles and body supports, resulting in a softer ride. Multiple suspension may require dampers to avoid excessive and unpredictable responses of the vehicle to dynamic forces.

These features, despite the additional mechanical complexity and weight the trucks involve, represent a considerable advantage for vehicles with four or more axles. As a consequence, vehicles with trucks can be longer, with greater capacity, and have better riding quality than two-axle vehicles: this is true not only for rail but for all guided technologies.

6.2.2 Trucks and Mechanical/Electrical Equipment

Steel wheels provide both support and guidance for rail vehicles. Weight is transferred via the flat (“cylindri-

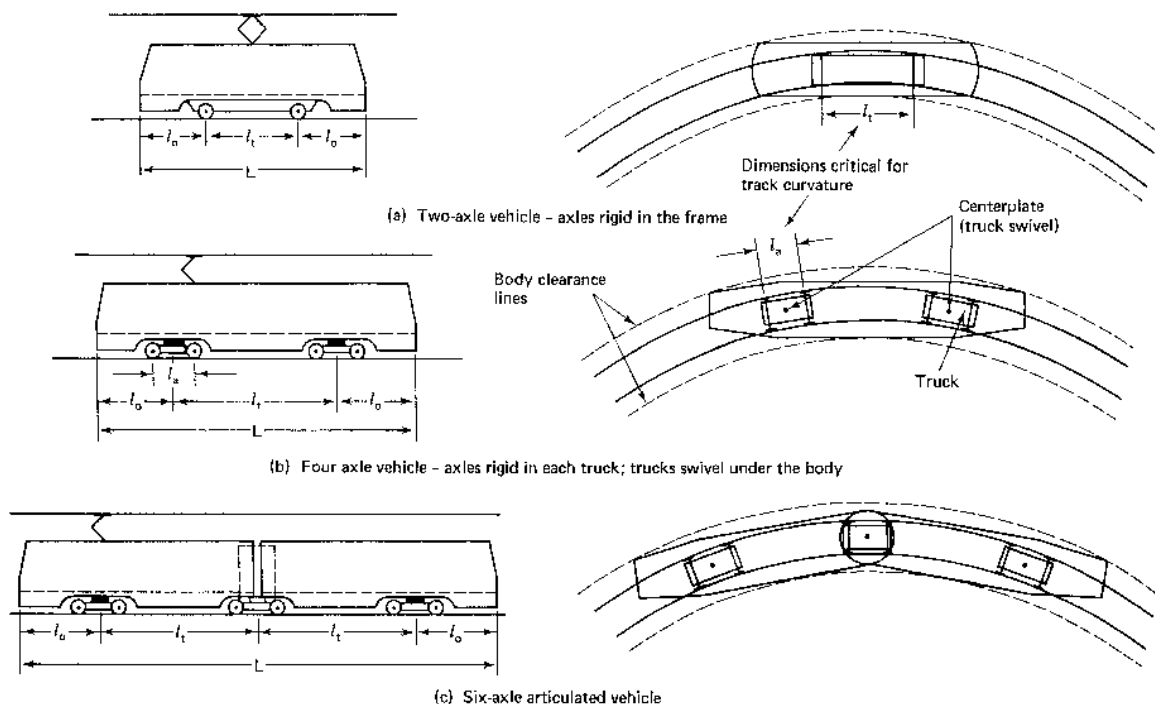


Figure 6.3 Basic types of rail transit vehicle profiles and positions in curves

cal”) or slightly tilted (“conical”) wheel periphery surfaces. Guidance is provided by the conicity of the wheels and contacts between wheel flanges and inside rail surfaces. Some transit vehicles have sandwich-type wheels with a layer of rubber between the center part and the outside tread of the wheel, so that there is no direct metal contact between the steel tire and the axle except for a jumper wire to provide contact for return current. These resilient wheels have very low noise and vibration and dampen shocks without any increase in the extremely low rolling resistance of steel wheel/steel rail contacts.

The wheels are rigidly attached to solid axles, which support the truck frame. Axle bearings can be located inside or outside the wheels, supporting the frame via a set of springs—leaf, coil, or rubber-insert type. The bolster, housing the centerplate that supports the vehicle body, can also be supported by a set of springs. In many vehicle designs, the leaf and coil

springs are supplemented or substituted by air springs or bellows, which have the special feature of maintaining constant body elevation under all loads (increased load automatically calls for higher pressure in the air springs). This is particularly important for vehicles of RRT and other systems with floors and platforms at the same level to ensure safe and fast boarding.

The types and “softness” of suspension influence riding comfort and vehicle sway, which determines its required cross-sectional free profile critical for platform edge position and tunnel profile.

6.2.2.1 Motors. Vehicles on many electric rail transit systems have all axles powered. This provides high performance, i.e., high speed and high acceleration and braking rates even on gradients exceeding 4%, because their total weight is also adhesion weight. However, some RRT and RGR systems operating on lines with

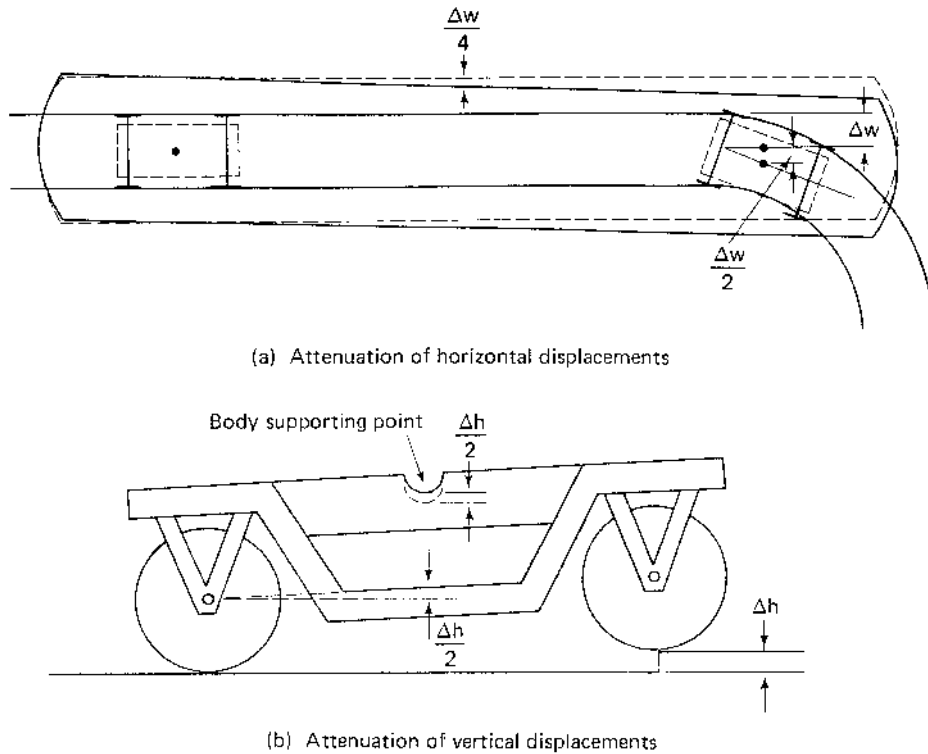


Figure 6.4 Truck geometry increases riding comfort

gradients not exceeding 4% require less power, so that they have a combination of powered and unpowered axles and even basic three- or four-car train units with some trailer cars. On such lines, this design provides satisfactory performance at lower investment and operating costs.

On LRT systems, trailers are seldom used, but most articulated cars have some unpowered trucks. However, the car bodies are designed so that unpowered trucks, which are usually under body joints, carry only 20% to 30% of the total vehicle weight, while adhesion weight is about 70% to 80%. Therefore, even with an unpowered truck, these cars can negotiate 6% or even 9% gradients (San Francisco Muni).

RRT and LRRT vehicles with propulsion by a linear induction motor (LIM) (see Section 3.4.6.1) have very different truck designs for two reasons. First, LIMs

have flat form; they can fit in a lower truck and allow a lower vehicle body profile. Second, since wheel adhesion is not used for traction and braking, LIM-propelled vehicles can negotiate steeper gradients (although with higher energy consumption) than conventional rail vehicles.

Most common design of powered trucks of RRT and RGR vehicles is with two motors, each powering one axle and lying either parallel with it or perpendicular to it, with corresponding types of gearing. Truck designs and motor configurations on LRT vehicles are much more diverse, however, for two reasons. First, articulated vehicles require different trucks under vehicle bodies than those under body joints because of different weight distributions and limited space in those trucks. Second, low-floor vehicles have even more constraints in space for motor placements, and

some of their wheels have small diameters and single suspensions—i.e., no axles.

Among numerous LRT vehicle designs, four most common truck types with wheel-axle-motor assemblies are shown in Figure 6.5 a to h and described here.

- a. Monomotor trucks, where one motor powers both axles in the truck. This design reduces spinning (which can occur only when all four wheels lose traction), but it requires very precise maintenance of wheel diameters as well as rails and track alignment. The use of monomotor trucks has decreased in recent years.
- b–c. Most common designs for rail vehicles: two motors, perpendicular to or parallel with axles, with corresponding sets of gear transmissions.
- d–e. On 100% low-floor cars, there is no space for motors under the floor, nor can wheels have axles, as mentioned above. Motors are then placed perpendicular to the axle lines of wheels, each one powering one wheel or two wheels behind each other. Wheels are individually suspended, there are no full axles, and all motors are placed so that a low-floor aisle can go longitudinally through the center, between its wheels.
- f–h. Alternate designs for 100% low-floor cars with one motor for each individually suspended wheel. The motors in the three cases are, respectively, parallel with wheel axles, hub motors directly on wheel axles, and hub motors with planetary gears for reduction of rpms and water cooling.

Two examples of different motor locations in trucks are shown in Photos 6.9a and b.

In recent years considerable progress has been made in the design of compact motors, so that the maximum power of LRT motors with this design has been increased from 100 to 235 kW. Motors powering single axles usually have an hourly rating of 40 to 70 kW. More details about electric propulsion, types of motors, and methods of their control are given in Section 3.4.

6.2.2.2 Braking Systems. Rail transit cars have two, three, or four different braking systems. One or two are used in regular operation, while another one

or two, independent of these, are applied in emergencies or for holding cars. The most common operating brake is the *dynamic (motor) brake*, described in Section 3.4.2.2. It is very powerful, particularly at high speed, has a rapid response, and requires little maintenance, since it involves no mechanical friction.

Pneumatic (air) brakes consist of a compressor, air reservoir, and cylinder with a piston that is mechanically connected with brake shoes on wheels or discs. Changes in air pressure in the cylinder (decrease on some and increase on other systems) press the shoes against the rotating surface, thus braking the wheels by friction. Pneumatic brakes are often used in combination with dynamic: they take over at low speed when dynamic braking begins to phase out and bring the car to a stop. Unlike dynamic braking, pneumatic brakes can cause full locking of wheels, resulting in reduced adhesion. For this reason as well as because of more complicated maintenance, pneumatic brakes are seldom used on LRT vehicles. RRT equipment often has pneumatic brakes as auxiliary to dynamic at low speeds, while on many RGR MU cars and on all locomotive-towed trains, pneumatic brakes serve as the basic operational braking system.

Most equipments that have air brakes use them for emergency braking because of their high reliability. The driver's control handle has a special position for emergency braking. When applied, it activates the maximum force of pneumatic (or other types) of brakes until the vehicle is stopped. Only then can the brake be released again. On signal-controlled systems, each application of emergency brakes is recorded and the driver is required to explain the reason for its use.

Other types of brakes, used in combination with dynamic or as emergency brakes, include the *solenoid brake*, which is fed by the current generated by dynamic braking. Used for regular braking of nonmotored axles, the solenoid brake acts via a disc attached to the axle. *Drum brakes* on driveshafts or *disk brakes* on axles, operated mechanically by springs, are used for emergencies and for holding. Their basic position is with active brakes except when air pressure is applied to the cylinders in order to overcome the pressure from the springs (brakes off). If a failure in the air-pressure system develops, such as leakage, the springs automatically put pressure to the braking pads pressing

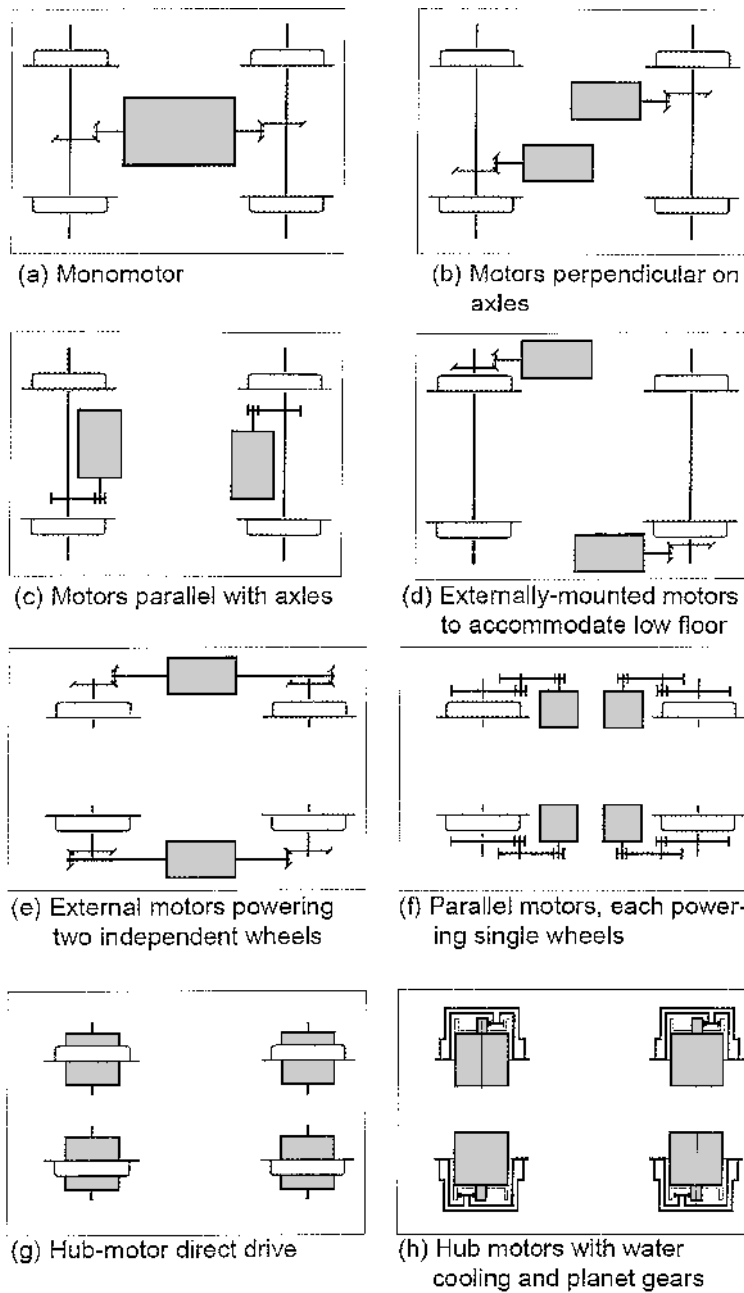
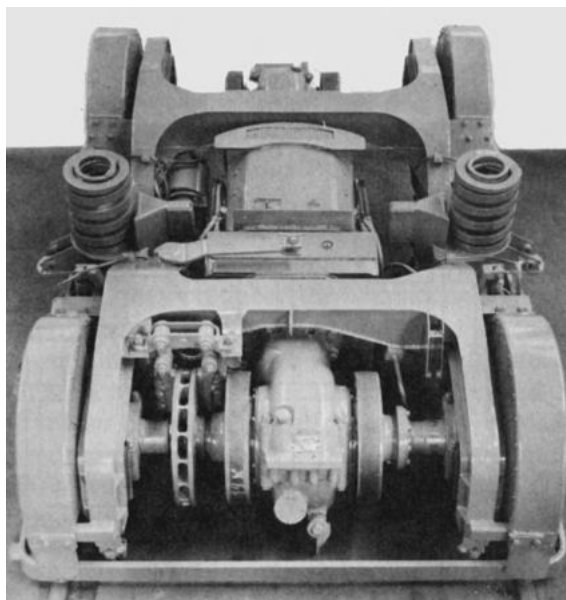
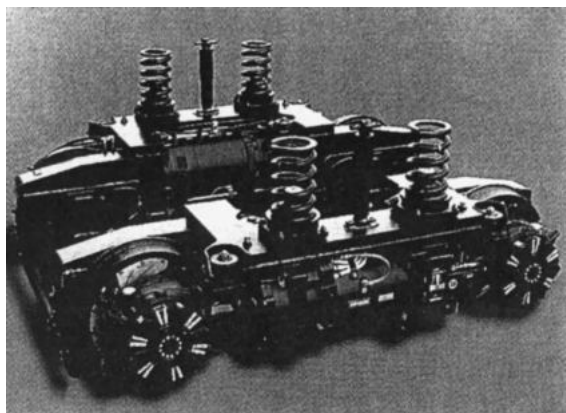


Figure 6.5 Different types of wheel and motor configurations in LRT car trucks (Courtesy Dr. Adolf Müller-Hellmann, VDV)



(a)



(b)

Photo 6.9 Examples of light rail truck configurations: a. conventional with monomotor drive above (Courtesy of Siemens DÜWAG, Düsseldorf) and b. unconventional with external, longitudinal drive (Courtesy of VDV)

the discs. These brakes are used for LRT as well as for RRT and RGR rolling stock. Although the latter still widely use pneumatic brakes, the trend is toward less use of wheel brakes.

SCR and LRT cars are required to have the highest ability for rapid braking because their track area is also used by other vehicles and pedestrians. They are therefore also equipped with *magnetic track brakes* (in some countries these are required by law). Track brakes consist of steel bars with electric coils suspended between the wheels in each truck at a distance of 8 mm above the rail. Under normal conditions, the magnets are inactive. When the brake is activated, the coils are energized and the brakes are dropped and attracted to the rails by a magnetic force of between 2 and 4 tons, depending on brake size. Track brakes are thus very powerful and effective for emergency braking or holding. They are not suited for regular braking because they cannot be applied gradually and they cause more wear of rails than brakes acting via wheels. A magnetic track brake is shown in Photo 6.10.

The controls of most rail transit cars have a “dead man” safety feature. One or two of the driver’s control handles or pedals must always be held in a depressed condition during car movement. If this device is released, the motors are automatically switched off and the brakes applied. Thus, if the driver’s attention or health should fail, or in any other emergency, the vehicle (train) is brought automatically to a stop. Many RGR systems have a similar “alerter” button that requires periodic contact/response from the driver.

6.2.2.3 Other Equipment. Electrical controls for motors are located under the vehicle body and in some cases in a compartment within the vehicle body, where it has good accessibility. Other mechanical and electrical equipment usually located under the car floor includes a motor-generator group and a battery. The motor, running on the line voltage (600 to 800 V), propels the generator, which generates low-voltage (usually 24 to 40 V) power stored in a battery. Much of the auxiliary electrical equipment—such as servomotors, emergency lights, and so on—is operated from the battery. Motor control equipment, compressor, reservoir, and cylinders for air brakes are other components occupying space under the vehicle floor. To reduce the cost and space required for this equipment, RRT stock often utilizes married-pair units, in which

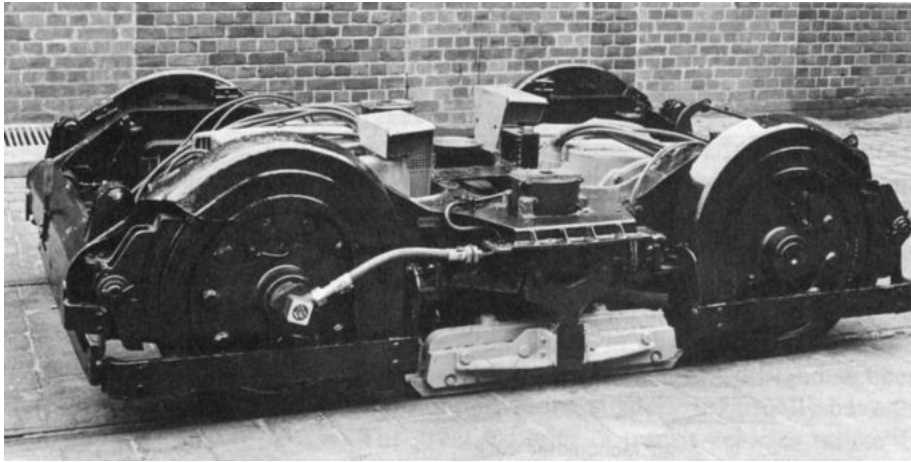


Photo 6.10 Rail car truck; magnetic track brake is suspended between wheels

a single set of equipment is shared by two cars. An example of the distribution of equipment units between A and B cars with chopper control is shown in Figure 6.6.

Couplers on rail cars contain many contact buttons for transfer of commands and communications between cars: motor, brake, and door controls; public address system; and so on. Both coupling and uncoupling are automatic and can be performed by the driver alone: he or she couples cars by bringing one car to another at a low speed and uncouples them by a push-

button mechanism, which may be applied even during train movement at low speed.

Power collection from an overhead wire is performed by a pantograph (diamond or half-diamond) with one or two contact bars, which presses against the wire. Trolley poles, used previously on streetcars, have been replaced on LRT and modern tram systems by pantographs, since the latter cannot jump off the wire, cause less arcing and electrical interference, and need not be changed when reversing the direction of vehicle travel. The conversion from trolley poles to panto-

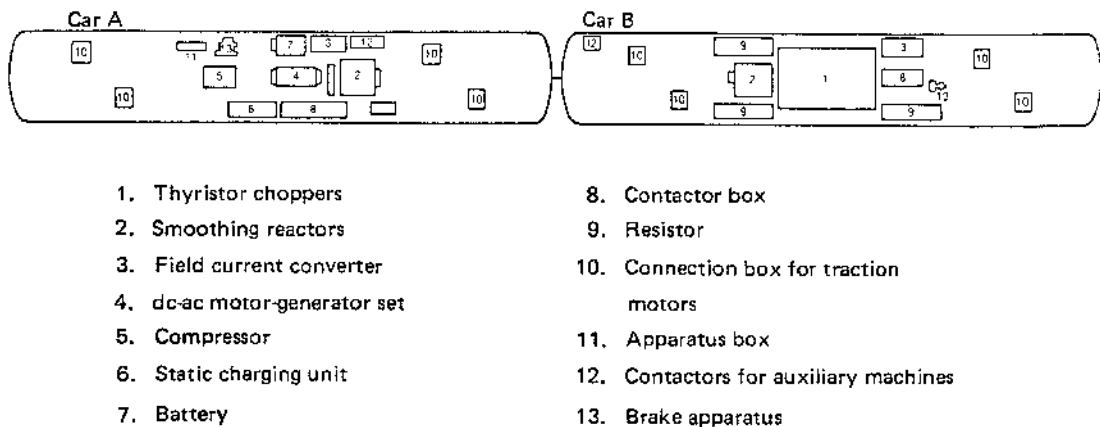


Figure 6.6 An example of equipment distribution on a married pair (Stockholm RRT vehicles)

graphs requires certain modifications of overhead wires. Contemporary wire suspension for pantographs has a zigzag alignment (about 20 cm to either side from track centerline), which ensures even wear of the pantograph bar and prevents the formation of a groove in it. Tension in the wire, when regulated by weights suspended on supporting poles at certain distances along the line, is constant, preventing its sagging with warm temperatures. Switches on wires are not needed, since pantographs slide from one wire to another.

RRT vehicles on lines with a third-rail power supply have a pick-up shoe for power collection between the axles on both sides of each truck. The shoes are sprung to exert the pressure against the third rail necessary for good contact from below, on top or laterally. A third-rail underriding power pick-up shoe is shown in Photo 6.11.

6.2.3 Vehicle Body

Several major factors affect the design of the vehicle body:

- *System operations*, including required line capacities and headways at different times, the driver's position and duties, operating costs, and so on.
- *Passenger operations*, such as easy stepping into and out of the vehicle, prevention of congestion around doors inside the vehicle, number of doors, and comfortable seating.
- *Aesthetic considerations* require that the vehicle have a pleasing exterior and interior so that its appearance gives it a popular, positive image with the population on one hand and creates a positive psychological attitude in passengers riding the system on the other.
- *Maintenance costs*—which are heavily influenced by such factors as the durability of materials used, easy replacement of parts, surfaces that are vandalproof and easy to clean, a body form that permits easy automatic washing, the areas of painted surfaces, and so on.
- *Investment costs*, which depend on vehicle type (single body, articulated, married pair, etc.), impact on fixed facilities design, complexity, dura-

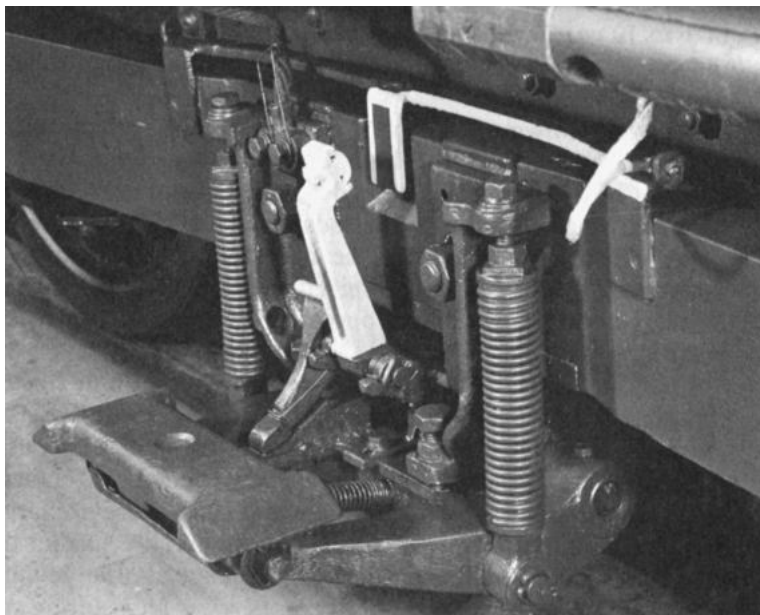


Photo 6.11 RRT truck showing power pick-up shoe in center

bility and number of components, materials used, types of heating/ventilation, and so on.

As is the case in many design processes, a compromise between these groups of factors must usually be found. The relative weight given to each varies from case to case. Operational characteristics are particularly important on large systems with high passenger volumes, where inefficiencies are costly and high speed and capacity of the system are critical for system performance. Aesthetic aspects always represent an important component of the transit system's image in the city; they also have an impact on the modal choice of some riders, thus influencing the total number of passengers using the system. It is always desirable to minimize investment and maintenance costs, but where there is a trade-off between the two, the choice must take into account the total lifetime costs of equipment, trends in labor costs for maintenance, as well as availability of the investment and operating funds. Because of the growing requirements for high-quality service as well as increasing labor costs, the trend has been toward viewing operating costs as increasingly important relative to the purchase cost of vehicles.

6.2.3.1 Body Structure and Size. Rail vehicles have an extremely wide range of sizes: different types of bodies, dimensions, and seat/standing arrangements permit design of single-body vehicles for RRT and RGR systems with lengths from 14 to 26 m, and train consists of 1 to 10 cars, with a maximum TU length of over 200 m. SCR and LRT articulated vehicles are 18 to 54 m long and 2.20 to 2.80 m wide. Their one-to four-car TUs on some new North American LRT systems, with categories A and B ROW and special signal controls at intersections, are as long as 72 to 96 m (Calgary, San Diego, Sacramento, Denver).

As was shown in Chapter 2, the optimal vehicle size increases with passenger volume on the line. Consequently, on a typical transit system, TUs of different sizes should be used at different times of the day (large for peak, small for off-peak periods). Since operation of two different vehicle types is usually impractical, the operator must choose the vehicle size by comparing the higher operating efficiency and lower cost of large

vehicles or TUs during peaks with the lower operating cost of shorter vehicles or TUs during off-peak periods and weekends.

Many rail transit systems can operate different unit sizes, each during the periods for which it is optimal, by changing train consists. Rapid transit in Cleveland and PATCO in Philadelphia, for example, operate six-car trains at peaks and one-car trains at night. When this cannot be done, peak conditions tend to dictate the choice of vehicle size, since the additional cost of operation and maintenance of large instead of small vehicles in off-peak periods is usually considerably smaller than the additional cost of providing peak capacity by small instead of large vehicles (labor cost, by far the most important cost item, is very high during peaks). Moreover, some overdesign of capacity during off-peak periods is desirable because it results in greater comfort and competitiveness with auto travel; that are more important in off-peak than peak periods. Consequently, in most cases, transit systems use the largest vehicles that can physically operate on their networks.

The elements physically limiting the maximum vehicle size are usually the clearances in curves with minimum radii. The critical body points in negotiating curves are shown in Figure 6.7. For given vehicle dimensions l_i , l_o , and W and track centerline radius R , the positions of these points are expressed by the following equations, derived as shown in the figure (all dimensions are distances in units of meters or feet):

$$R' = \sqrt{R^2 - \left(\frac{l_i}{2}\right)^2}. \quad (6.1)$$

The inner and outer body radii are, respectively,

$$R_b^i = R' - \frac{W}{2} \quad (6.2)$$

and

$$R_b^o = \sqrt{\left(R' + \frac{W}{2}\right)^2 + \left(\frac{l_i}{2} + l_o\right)^2}. \quad (6.3)$$

The widening of the free profile on the inner and outer sides are, respectively,

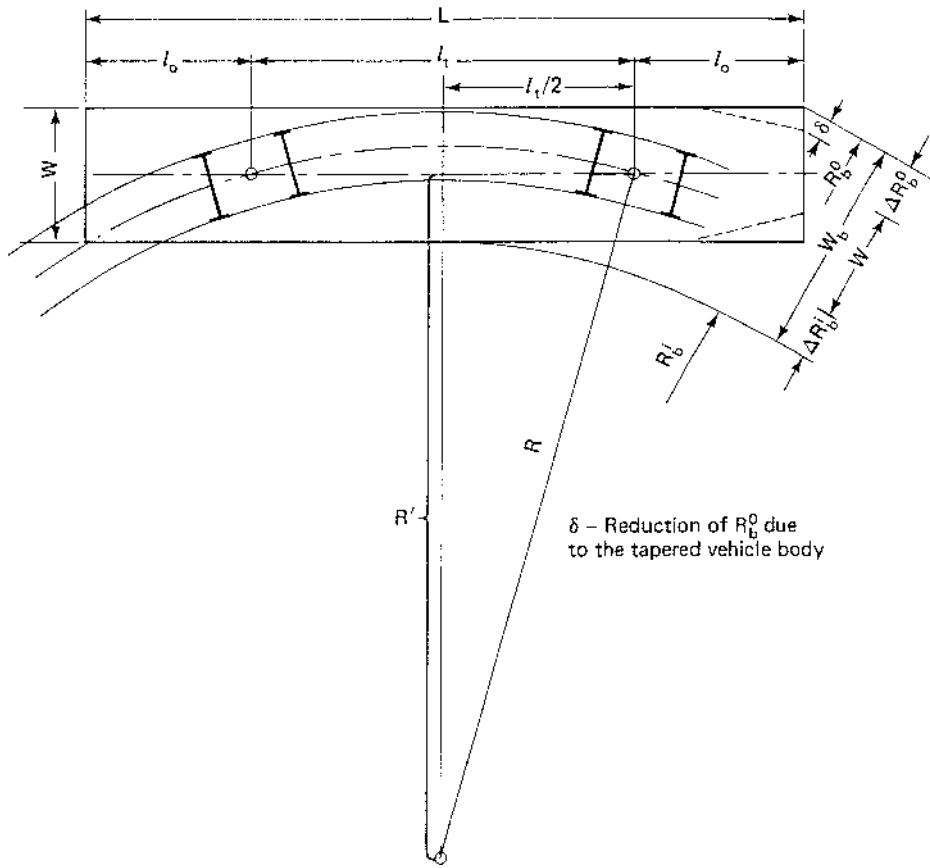


Figure 6.7 Turning geometry of a four-axle rail vehicle

$$\Delta R_b^i = R - R' \quad (6.4)$$

and

$$\Delta R_b^o = \sqrt{\left(R' + \frac{W}{2}\right)^2 + \left(\frac{l_t}{2} + l_o\right)^2} - \left(R + \frac{W}{2}\right). \quad (6.5)$$

The total width of the free profile is

$$\begin{aligned} W_b &= W + \Delta R_b^i + \Delta R_b^o \\ &= \sqrt{\left(R' + \frac{W}{2}\right)^2 + \left(\frac{l_t}{2} + l_o\right)^2} - R' + \frac{W}{2}. \end{aligned} \quad (6.6)$$

As Eqs. (6.4) and (6.1) show, profile widening on the inside of the curve depends on the distance between truck swivels, l_t ; the widening on the outside [Eqs. (6.5) and (6.1)] depends mostly on the overhang length, l_o .

The preceding equations are derived for conventional rail transit vehicles with single bodies and two trucks/bogies, as shown in Figure 6.3b. Their outside critical points are the outer body corners, while the inside critical point is the center point between the two truck swivel points. The same equations can be used for computations of turning geometry elements of articulated vehicles (Figure 6.3c), because the outside critical points of these vehicles are also the outside corners, while the inner critical points are the two center points between truck swivels. Thus, geometrically

a three-truck articulated car is the same as if two four-axle cars had one of their overhangs “cut off” and then the remaining bodies were connected by a body joint above the center truck.

Articulated cars became the dominant vehicle type on LRT/SCR systems since their introduction in Germany in the late 1950s. In many cities articulated cars are operated as one- to four-car TUs: Frankfurt, San Diego, and Denver three, Sacramento four cars. They became virtually the exclusive vehicle type on all new LRT systems around the world since the 1970s. The reasons for this transition to articulated cars are summarized in the box below.

LRT/SCR vehicles are designed to negotiate sharp curves (minimum radii are 15 to 25 m). Therefore their dimension l_t is only 6 to 7 m, exceptionally 10 m. Their overhangs l_o are 2 to 4 m long, but their body ends are tapered to reduce ΔR_b^o , as shown in Figure 6.7. Single-body four-axle LRT/SCR vehicles have lengths of 13 to 14 m, exceptionally 16 m. Single-articulated six-axle vehicles, which have been introduced for nearly all new and upgraded LRT systems in North America, are 18 to 24 m, exceptionally up to 27 m long, and double-articulated eight-axle LRT vehicles, used in many European cities, have lengths of 23 to 29 m, exceptionally up to 32 m long.

The geometry of most low-floor LRT vehicles, described next, which have body sections above center trucks and body joints between the trucks (Figure 6.8), is more complicated for exact computations. However, most of the low-floor cars are designed with more body joints, allowing them to “bend” even better and have a narrower profile in curves than conventional six- and eight-axle articulated cars.

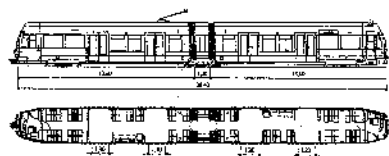
A major innovation in LRT vehicle design, initiated by Siemens-Duewag with its vehicle for Geneva in 1985, led to a revolution in the design of LRT/SCR vehicles; it also spread to some RGR systems that have low platforms. The innovation was the low-floor vehicle, with the floor only 0.30 to 0.35 m above TOR.

The reasons for the introduction of low-floor vehicles were mainly to provide faster and easier boarding/alighting without steps for all passengers as well as accessibility for the disabled in wheelchairs, persons handling strollers, bicycles, luggage, etc. The concept of low-floor vehicles was received very well and led to a great number of new design features of LRT vehicles, particularly the following:

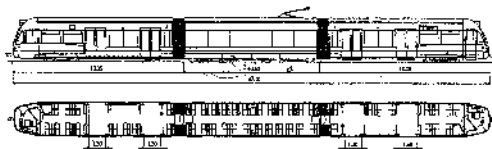
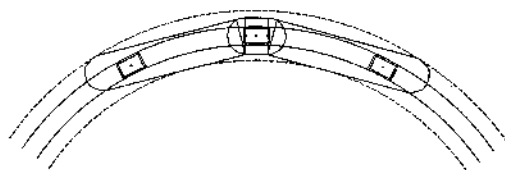
- Steerable axles in two-axle trucks
- Single-axle trucks
- Different motor locations, including one longitudinally oriented motor powering two single wheels behind each other (see Figure 6.5)
- Single steered wheels, unpowered or powered by individual motors
- Placement of mechanical and electrical equipment on vehicle roof rather than under the floor
- Short body sections on a single truck articulated to longer body sections on each side (thus, former six-axle single-articulated vehicles were replaced by somewhat longer six-axle double-articulated vehicles)
- Introduction of five- and seven-section articulated vehicles with overall lengths of 35 to 45 m (the longest LRT vehicle, introduced by Budapest, has reached a length of 54 m)

Articulated vehicles compared with two-truck four-axle vehicles coupled in two- to three-car TUs have:

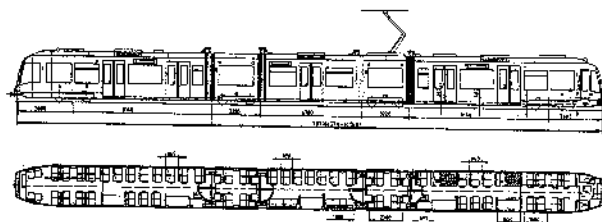
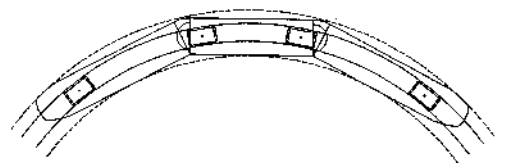
- + Better distribution of passengers throughout the single vehicle than between separate ones
- + Presence of the driver in the vehicle
- + Somewhat better riding comfort (middle sections are superior to overhangs)
- + Better utilization of station and street length (no lost coupler distance)
- Less possibility of changing TU size by coupling/uncoupling vehicles and thus reducing operating costs during off-peak periods



(a) 6-axle 70% low floor 28.40 m long car for Cologne, Croydon, Stockholm and Istanbul



(b) 8-axle 37.10 m long car for Saarbrücken



(c) 8-axle 5-body 38.70 m long car for Karlsruhe

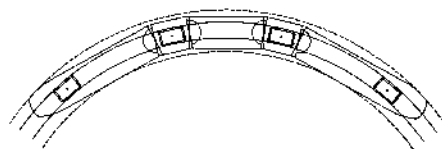


Figure 6.8 Selected models of contemporary LRT low-floor vehicles (Source: Girnau et al., 2000)

Functionally, low-floor vehicles are classified into three general categories by the proportion of the floor that is low:

1. Cars with 35% low floor are vehicles with a low-floor section between two trucks only. This design requires redesign of the body section with a low-floor section and steps to the standard-floor-height aisles on both outer body sections. The advantage of this vehicle type is that its trucks, motors, and other equipment remain standard. The disadvantage is that the low-floor section is short, not allowing a sufficient number or size of doors and seats or spaces for wheelchairs.
2. Cars with 70% low floors are typically vehicles with standard floor heights on both car ends and steps down to the central low-floor section,

which extends over the center truck. To accommodate passage of the low-floor section, the center truck is not powered and usually has single-suspended and sometimes slightly smaller wheels.

3. The 100% low-floor car has the entire floor at the low level, with single-suspended wheels (no axles) powered by single motors or one motor powering two wheels behind each other. Boxes covering wheels protrude into vehicle body, usually under several seats. This vehicle type has the entire floor at the same level and no steps in the aisle. However, 100% low-floor vehicles have by far the most complicated design because they have single suspended and steered wheels without axles, specially designed and connected motors, and all equipment on the roof.

All these nonconventional elements, particularly single-suspended wheels, specially designed motors and suspension systems, small-diameter wheels, etc., have been introduced on many different vehicle models and proven feasible in operations in many cities. Several of these features, however, are more complicated and sensitive in operations. They require precise track maintenance and in some cases offer somewhat less stable ride and cause greater rail wear than conventional trucks. This is particularly the case with 100% low-floor vehicles whose single-suspended wheels sometimes cause higher wear of rails and are not used on vehicles exceeding speeds of about 80 km/h. Moreover, the special and more complicated designs of these elements increase both the purchase price and maintenance cost of low-floor cars. On the other hand, the benefits of low-floor vehicles include not only easier boarding but also simpler stops and the ability to place LRT stations in pedestrian areas and without high, long, and often visually and physically disruptive platforms.

The 35% low-floor rail cars are usually introduced on existing LRT systems, which are retrofitted to provide full accessibility, but seldom on new systems. The 100% low-floor cars gained popularity as vehicles with level boarding (without steps) and a flat floor through the entire vehicle, so that there was pressure to order this model in many cities. Strasbourg, Berlin, Vienna, and other cities introduced considerable numbers of these models. However, the higher costs and various operational experiences with these rather complicated vehicles are still being evaluated and debated in many cities.

The 70% low-floor cars have proven to be well accepted in a great number of cities because they offer passengers the choice of sitting in the low-floor section or walking up to the high-floor sections. It has been shown that the majority of passengers prefer sitting at a higher level, because they do not like to sit at nearly ground level and look up at passing pedestrians on the street. All doors are at low level, meeting the needs of persons requiring full accessibility. Mechanically, the two end trucks are standard; only the middle one is specially designed to accommodate a low aisle by having single wheels without axles, or a slightly raised

floor in the center of the vehicle allows accommodation of axles. Thus, all the advantages of low-floor design are achieved, but at a minimum deviation from standard mechanical elements. The comparison of the two most common low-floor car designs is summarized in the box on page 328.

In summary, the 100% low-floor car has the advantage of a flat floor without steps, but the 70% low-floor gives a choice in seating positions, has better performance, and involves lower purchasing and operating costs. There is no difference in boarding because all doors are in the low-floor sections areas.

Another recent trend in LRT vehicle development has been modular design: vehicle bodies and major aggregates are designed so that they can be detached or connected. Thus, some manufacturers offers a "family of models," which consists of different numbers of body components and trucks, as shown in Figure 6.9, from a four-axle vehicle with three bodies to an eight-axle vehicle with seven body sections.

Modular construction is often applied to various other auxiliary equipment, motors, trucks and body parts. This allows exchange of these elements when they need maintenance or repair, so that the time a vehicle is out of service is minimized. Increased vehicle utilization can bring significant operating efficiencies and a reduced requirement for fleet size.

The requirements for higher TU capacity and passenger comfort have resulted in a general trend toward using larger vehicles and operating longer TUs on many rail modes. On LRT systems, many agencies using six-axle single-articulated cars operate TUs consisting of two to four articulated cars during peak periods. The recently purchased low-floor cars described above have lengths of 27 to 42 m, whereas the lengths of earlier articulated cars seldom reached 30 m.

Recently built RRT systems have vehicles 18 to 23 m long and 2.80 to 3.10 m wide (Figure 6.10). Rubber-tired RRT vehicles usually have smaller dimensions, while extensive metros with a small portion of lines in tunnels and extensive lines in suburbs, such as BART and Atlanta, have wider cars, approaching those of RGR systems.

Compared to 100% low-floor rail vehicle cars, 70% low-floor cars have the following advantages (+) and disadvantages (–):

- + Passengers can choose seating between low- and high-level sections; many prefer the latter.
- + With less specialized design, the 70% low-floor car has lower purchase price and involves lower operating costs.
- + Having two conventional and one slightly modified truck, it has no speed restrictions; the 100% low-floor cars are limited to 70 to 80 km/h.
- + With conventional trucks, it provides better riding comfort and also causes less vibration and rail wear than the 100% low-floor car with single-wheel suspensions.
- + It has fewer intrusions in the passenger compartment by boxes accommodating steered single wheels.
- The 70% low-floor car has two sets of steps in its aisle, while the 100% low-floor car has a flat floor throughout.
- The 100% low-floor car has a greater choice of door locations.

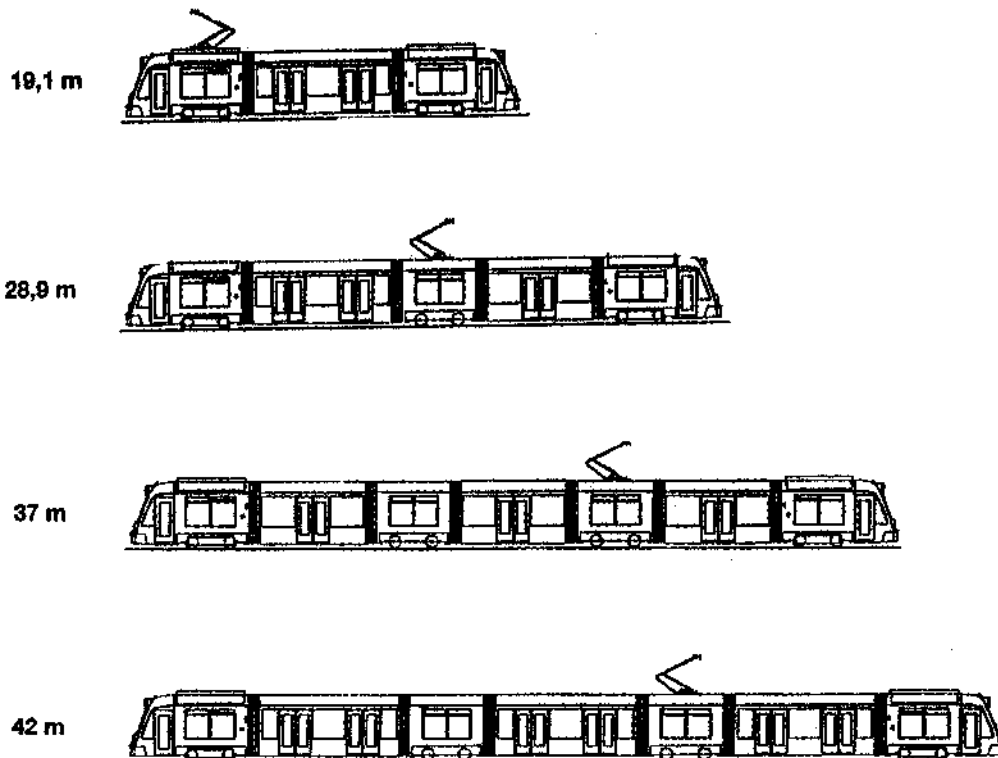
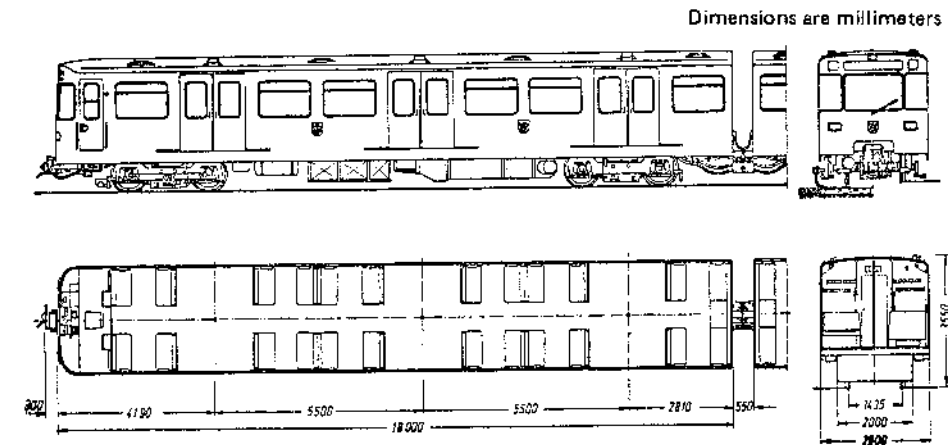
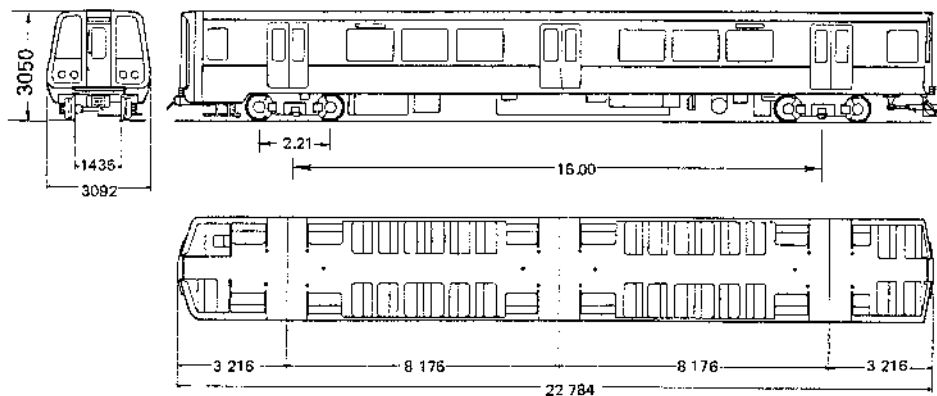


Figure 6.9 Modular design of three- to seven-section light rail vehicles (Source: Girnau et al., 2000)



a. Munich U-Bahn



b. Washington Metro

Figure 6.10 Rapid transit cars

The vast majority of RRT systems operate conventional four-axle two-truck vehicles coupled in different operating units. However, an increasing number of RRT systems have been introducing four-axle cars with articulated bodies in four-, five-, and even eight-car consists. Body articulations are designed so that they allow accommodation of horizontal and vertical misalignment of the two connected bodies in curves. To

minimize these, track curve radii cannot be small, while vehicle overhangs must be rather short. Tokyo uses five-car units, coupling them in ten-car consists. Hong Kong MTR, opened in 1979, was designed to operate only trains with eight cars with continuous interiors. More recently, Singapore, Rome, and other cities began to use the “continuous body” trains. Their advantages are significant: full utilization of train

length for passenger accommodation, elimination of doors between cars and safety risks for passengers walking through them, easy distribution of passengers among the cars along the train, and increased security. However, jointed bodies also have several important disadvantages. First, adjusting train lengths to passenger volumes is not possible; this prevents reduction of car-kilometers operated during off-peak periods, particularly over weekends, which can bring considerable reductions in operating costs. Second, a breakdown of one car eliminates from service the entire set of jointed cars. And third, maintenance of a set of jointed cars in the shops is more complicated than work on shorter units, such as single units or married pairs.

RGR vehicles (Figure 6.11) can have the largest dimensions of all modes, since they are usually determined by the standard railroad vehicle clearances. Maximum vehicle lengths of 26 m (85 ft) and widths of 3.20 m are found in many cities. Bilevel vehicles have a height of about 5.00 m. Some bilevel cars have double decks over their entire areas; others (see Photo 6.12) have two levels in the middle and single levels toward their ends.

Since the 1990s, there has been a great increase in the introduction of bilevel rolling stock on existing systems (Berlin, Boston, Frankfurt, New York–Long Island Rail Road, Paris), as well as on many new RGR systems (Tri-Rail in Florida, Los Angeles Metrolink, Zürich). Increasing ridership and the trend to provide seats for most passengers on increasingly long RGR lines have necessitated the use of two decks to provide more seats without excessive train and station lengths.

6.2.3.2 Vehicle Exterior. The design of vehicle exteriors is affected by the operational factors relating to the efficiency of boarding and alighting and to safety in normal operations and emergencies. Simple maintenance and reliability of doors functioning under adverse weather conditions must also be considered. Further, the aesthetics of vehicles is an important although sometimes neglected factor. Finally, the purchase price and maintenance cost of vehicles can be affected by their exterior design.

Vehicle front-side design is particularly important. The distinctions of LRT cars that affect their front designs are that they often have tapered bodies and that

the driver's visibility must be better than for RRT cars, which have controlled ROW, so that the driver's attention is focused primarily on signals. LRT vehicles therefore usually have large windshields to provide a wide visibility angle, tilted to reduce sun glare. The many different front designs of LRT vehicles add to the "personality" and identity of these vehicles. In many cities, LRT vehicles are used as a basic symbol of the city.

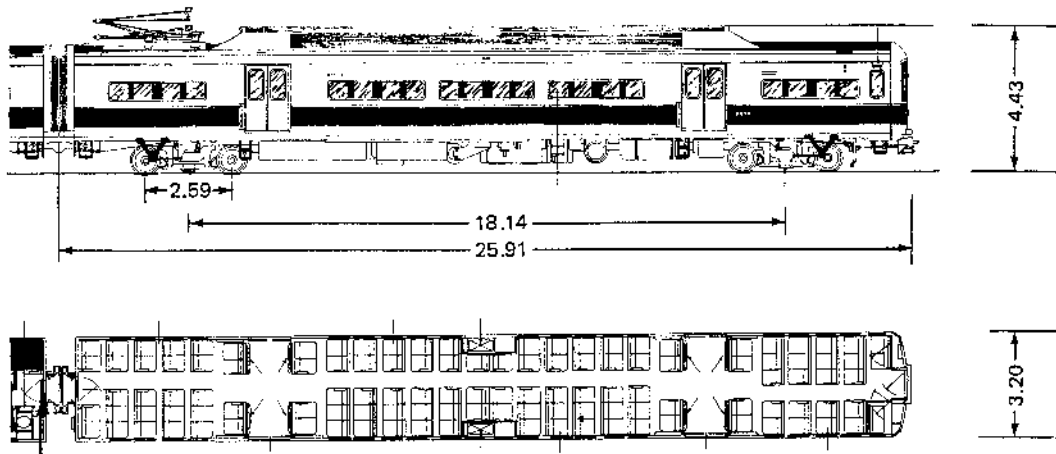
Front sides of RRT and RGR cars often present a special design problem, since they must satisfy several conflicting requirements. Most rail systems have the operational requirement that there be a passage from one car to another. All front sides—which are sometimes leading ends of a train, such as both ends of SU and outside ends of MP units—should be streamlined and appear aesthetically pleasing. In addition, there is the necessity of providing the driver's controls or cabin and, in some cases, an emergency exit through the front.

To provide passage between cars or an emergency exit to the center of the track, the fronts generally use the center one-third of the car width for that passage and "squeeze" the driver's cabin into the vehicle corner to the right of the door. Very often, particularly in North American cities no consideration has been given to the aesthetic requirement, the result being that fronts of many RRT and RGR cars do not have any aesthetic form but look like part of a train that has been disconnected in the middle: there is no streamlining, the doors are not flush with the front wall, and the metal protecting gates and chains are aesthetically unattractive.

This type of design is obsolete and cannot satisfy requirements for modern rail transit rolling stock. The designer of a vehicle should consider several questions and requirements. First, should the front be streamlined to reduce air resistance? Second, are the aesthetics of vehicle front appropriate? Third, what kind of couplers and passage between vehicles is required for passengers? Finally, is an emergency exit through the front needed? These questions are discussed here in sequence.

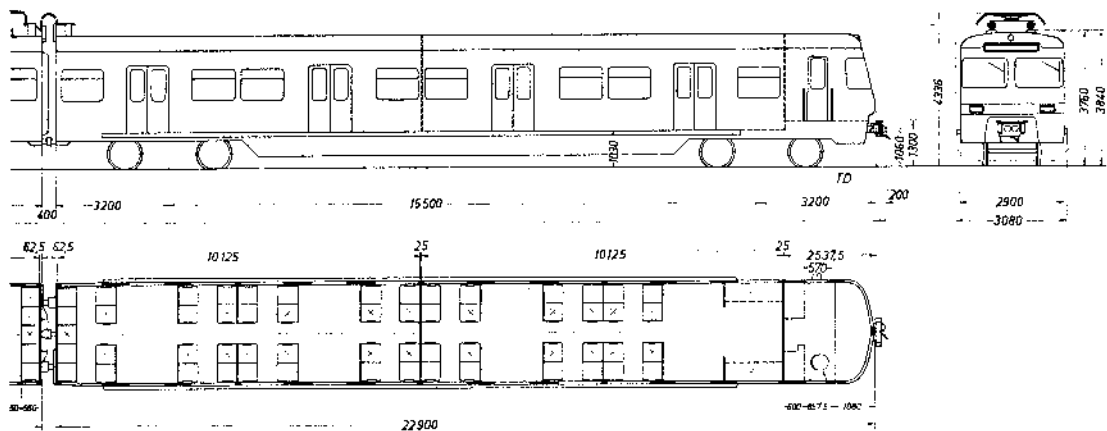
Streamlining has little significance for low-speed vehicles such as street transit; however, many RRT and RGR systems achieve speeds of 70 to 100 km/h and

Dimensions are meters



a. Layout for maximum seating ("Cosmopolitan" for New Haven division in New York); one car of a married pair unit shown (Courtesy of General Electric Co.)

Dimensions are millimeters



b. Lower density seating with standing areas for short trips and peak hours (ET 420 operating in Munich, Frankfurt, and Ruhr cities); one car of a 3-car unit is shown

Figure 6.11 Regional rail cars

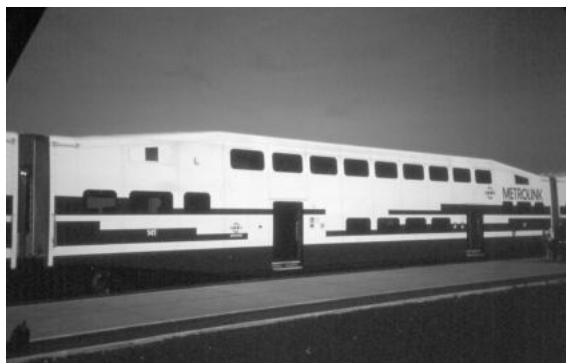


Photo 6.12 Bombardier bilevel car in Los Angeles—design now standard for many U.S. and Canadian RGR systems

higher, at which speeds streamlining can reduce air resistance considerably. The aesthetic appeal of rail transit vehicles is an important component of their system image and ability to attract passengers. The aesthetics of the front is therefore an important requirement for all vehicles that are sometimes train ends. Further, passage between vehicles is not absolutely necessary if all tunnels have catwalk paths for evacuation in emergencies and there is no need for supervisory personnel to move between cars. Some RRT systems—such as those of Hamburg, Munich, and Rotterdam—do not have passages between cars and have good-looking fronts. However, the cars on the PATCO Line in Philadelphia have front doors, yet they are flush and allow a streamlined car “face,” as Photos 6.13 and 6.14 show. The London Tube vehicles have emergency passage through the driver’s cabin, because tube tunnels in that city have no emergency



Photo 6.13 Front side designs on PATCO RRT and on NJT RGR cars (Courtesy of J. W. Vigrass)



Photo 6.14 PATCO line in Philadelphia, a system “between” RRT and RGR (Courtesy of Bob Vogel)

walkways. Hong Kong and many Tokyo lines also have emergency exit through the cabin and front, over a door that can be lowered and provides steps, as shown in Photo 6.15. Thus provision of passage as well as emergency exit can be reconciled with streamlining and the aesthetics of the front.

Vehicle sides are affected considerably by the number of doors. Most RRT cars with lengths below 15 m have only two doors per side; those between 15 and 18 m have three doors, and those over 18 m usually have four doors. However, variations exist, depending on passenger volumes. The more doors the vehicle has, the faster its boarding/alighting process at stations but the smaller its seating capacity. Systems that have extremely high passenger volumes, intensive passenger exchanges at stations, and relatively short average trip lengths should have the highest door-to-capacity ratios. Examples of this are New York City, Paris, and most Russian and Japanese cities. Rolling stock for long lines has the smallest number of doors to provide maximum seating comfort. Some of the RRT and RGR lines serving distant suburbs have only two doors per side, although their length exceeds 20 m (BART, PATCO Line, many RGR systems). This design provides for the maximum possible seating capacity but requires long boarding/alighting times, so that it is not suited to heavy passenger loads or lines with many stations. The impact of longer station standing times on operating speed and the resulting reduction in vehicle productivity are sometimes overlooked, although they may outweigh the gains from the higher seating capacity of this design.



Photo 6.15 Tokyo RRT car with an emergency exit through the front (Courtesy of Teito Rapid Transit Authority)

Optimal locations of doors along the sides of rail cars are usually based on the objective of minimizing the distance from the doors to any point within the vehicle. This objective is satisfied when k doors along the l_c length of the passenger section of the car (car length minus driver's cabin length) are located l_c/k distance from each other and $l_c/2k$ from the ends of the passenger section. This rule is followed on most RRT systems.

In addition to providing a sufficient number of doors, standing times at stations are kept short if sufficient areas in the car around doors are provided to permit passengers to prepare for alighting and to accept the boarded passengers prior to their distribution to seats. It is advisable for metro lines serving many short trips to provide a standing space for one person between the door and the seat adjacent to it, since passengers making such trips tend to stand immediately behind the doors in order to alight easily. If this space is not provided, they still remain at the doors and impede passenger flow.

LRT vehicles usually have one door in the front for fare payment to the driver. The locations of other doors are constrained by the locations of trucks and body joints. Because of relatively heavy passenger exchange at stations, LRT vehicles usually have high door-to-capacity ratios. When this ratio is very high, as in 25- to 54-m-long vehicles with five to six doors and up to ten door channels per side, they have a low seating capacity.

LRT vehicles with floor heights between 0.85 and 1.00 m usually have two intermediate steps. Several models feature movable steps for operation with both high- and low-level platforms. Activated by pushbutton control of the driver, the two steps can be raised or lowered in several seconds. Double-channel doors often have a short railing to define the two channels. This is particularly useful for the door at the front, since it separates the passengers who have to pay a fare from those with passes.

Most rail car doors are 1.10 to 1.50 m wide, providing double-channel passenger flow. Three types of doors are common: folding doors, used for LRT and exceptionally for RRT systems (Chicago); sliding doors, which have the fastest operation and are well

suited to crowded conditions, used on RRT and RGR cars; and "plug" doors, flush with the outside body surface, which pop out and slide along the outside wall surface. The plug doors, used on some models of RRT and LRT cars, have the advantage that they do not require internal space or thick car walls. However, they are mechanically the most complicated type, sometimes resulting in low reliability of operation.

The trend has been toward providing larger car windows to allow a "panoramic" view for the passengers. Vandalism incidents on some systems have required the use of shatterproof materials instead of glass windows or a replicable layer of plastic film protecting the glass from scratching. With respect to aesthetics, windows and car doors of uniform size along the car side usually make for a much better appearance than variable sizes and types of doors and windows.

To reduce the cost of painting their vehicles, a number of transit agencies use stainless steel or aluminum plates for the outside walls of RRT and RGR car bodies. This has proved to reduce maintenance, but such cars tend to look less attractive than painted ones. The agencies with good public relations and marketing therefore tend to use different color schemes and designs for LRT vehicles (as well as buses), which make them conspicuous on streets. Most recent RRT and RGR vehicles are also partially or fully painted. In many cities that have separate rolling stock for each line (Boston, Buenos Aires, Tokyo), each line has a different color scheme, contributing significantly to passenger orientation. On the other hand, use of one basic color for all transit vehicles in a city also has advantages, since it gives the transit system a distinct image: Munich is well known by its blue, Stuttgart and Copenhagen by their yellow transit vehicles.

6.2.3.3 Vehicle Interior. Once vehicle length and width are determined, the designer must decide on the type and size of the driver's seat or cabin. On some LRT vehicles, the driver's seat is designed so that he or she can supervise fare payment or sell tickets to boarding passengers. The driver is therefore only partially separated by a glass wall or low fence from the passenger section. However, RRT, RGR, and some

LRT cars have an enclosed cabin for the driver. Requirements for design of the cabin are as follows:

- It should take little space, since that space is not used for passengers.
- It is desirable to provide a forward view for passengers from their section.
- Various geometric and mechanical requirements, such as provision of head doors (when required) and the aesthetics of the vehicle, must be considered.
- Adequate space for panels and controls and generally good working conditions for the driver must be provided.
- For a system in which the driver supervises the doors, he must have access to the side or sides on which station platforms are located or a video screen for supervision.

Cabin designs vary greatly among systems. One extreme with respect to its size is the design typical for U.S. systems: the cabin is in the right corner, occupying approximately one-third of the car width. This design minimizes loss of space for passengers and provides some forward view for them, but it also minimizes the driver's working area. The other extreme is found on many European systems, as in Amsterdam, Hamburg, and Vienna: the cabin takes the entire width of the car, blocking off the passengers' front view. Since the cabin's depth is approximately 1.2 to 1.3 m, the area taken by these cabins represents some 7% to 10% of the total vehicle area. Considering the fact that optimal utilization of car space is always carefully planned to the extent that every centimeter of car width is analyzed, allocation of so much space to the driver can be considered wasteful. However, on some systems, a full-width cabin is necessary, since the driver has to supervise both center and side platforms at different stations. A good solution to this problem has been that used in Washington and Berlin: the cabin takes the full car width only when the driver uses it. At other times, its wall folds and makes available to passengers the entire area except a cubicle with the driver's controls.

An interesting concept of driver's cabin design was introduced on the PATCO Line in Philadelphia in 1969: instead of a fully enclosed cabin, the driver has a seat with a low fence around it. He or she is not confined to a small space, yet the floor area occupied is minimal, so that the aisle and seats continue to the front wall. Passengers have an extremely attractive view in the direction of train travel. The driver's exposure to passengers does not create any safety problems: on the contrary, his presence in the passenger area, as in LRT vehicles, is welcomed by passengers. This design has unfortunately not been copied elsewhere.

Design of the passenger area varies considerably with the type of service the vehicle is intended to provide. The basic decision is selection of the ratio of seated to standing passengers. The dimensions that the designer must have are as follows:

Each seat takes between 0.35 and 0.55 m², depending on its shape and the comfort provided. Single seats require a somewhat larger space per person than do double seats.

Area per standee used by different transit agencies and vehicle manufacturers for vehicle capacity computations varies between 0.17 and 0.25 m²/space (6 to 4 prs/m²). An area of 0.20 m²/prs (approximately equal to the 2.2 ft² used by many U.S. transit agencies) is actually the minimum average area that can be achieved under most conditions (it is reached in peak hours on many heavily used rail systems). That value is therefore used in this book. Smaller values (0.17 m²/sp) can be used for the more conservative computations of vehicle structural strength (typically for buses), but they yield unrealistically high capacities. A value of 0.25 m²/sp assumes somewhat better conditions than the maximum crowding or "crush load": movement of persons through the crowd is possible although still rather difficult. For transit systems with high comfort standards, an even larger area per standee can be assumed for scheduling purposes, but the maximum potential capacity remains the one based on approximately 0.20 to 0.25 m² per standing space.

Since seated passengers take two to three times more space than standing passengers, the trade-off in deciding on seating arrangements in a vehicle is be-

tween passenger comfort and maximum vehicle capacity. The trend has been toward increasing seat/standee ratios because of the need to increase the attractiveness of transit service.

Maximum comfort is achieved by allocating most of the vehicle area to transverse seats. Cars with body widths up to 2.40 m can have only 2 + 1 rows of seats. Car widths of 2.50 to 2.60 m allow 2 + 2 seating arrangement, but with a narrow aisle that is not satisfactory when standees are carried. For adequate circulation with 2 + 2 seating, a width of 2.65 to 2.90 m is required. RGR and some RRT systems with car widths over 3.10 m (Toronto, Oslo) have 3 + 2 seating. In all cases desirable aisle widths are 0.60 to 0.80 m, to allow comfortable circulation through the vehicle when there are some standees.

In conclusion, the design of the vehicle interior is a compromise among the requirements for capacity, comfort (seating), and easy circulation (aisle and door areas). The relative importance of these requirements depends mostly on trip duration, peaking of passenger volume, and intensity of passenger exchange at individual stations. The longer the trips (primarily in terms of time), the higher the degree of comfort required; the sharper the peaks, the more important the capacity; and, the more frequent the exchange of passengers (short trip lengths), the larger the circulation areas needed.

Only longitudinal seating is provided on systems that have maximum capacity as the dominant requirement, such as those in New York, Moscow, Seoul, and Japanese cities. The other extreme—maximum transverse seating and bilevel cars—is typical for RGR systems, such as those in New York and New Jersey (NJT and LIRR), San Francisco (Caltrain), Chicago (Metra), Paris (RER), and Sydney. A great majority of LRT and RRT as well as many RGR systems use intermediate solutions: a combination of transverse and longitudinal seats with adequate aisle widths and door areas.

The quality of seats depends again on the type of service offered and conditions on the line. For extreme crowding, short average passenger trips, or frequent vandalism, plastic molded seats are the best solution. Longer average trips with lower passenger turnover and crowding justify the provision of upholstered seats. The dimensions and form of seats may influence pas-

senger comfort as much as the softness of their surfaces.

6.2.4 Review of Characteristics of Different Rail Vehicle Models

A review of the basic technical data of rail vehicle models, classified by modes, is presented in Table 6.2. The ranges shown include most currently used models except for very specialized designs. The “typical” values are those most commonly found, but their collection does not necessarily represent an optimal vehicle design for any given application. Detailed data on selected vehicle models of LRT (most diversified), RRT, and RGR modes are given in Tables 6.3, 6.4, and 6.5, respectively. This information for the listed models and many others was obtained from vehicle manufacturers’ technical specification sheets and from various technical journals, and it was used for the analyses of vehicle characteristics in the following section.

6.2.4.1 Dimensions, Weights, and Power. To obtain an easy overview of vehicle characteristics, the data for approximately 90 vehicle models were plotted on five diagrams, with different code designations for LRT (including SCR), RRT, and RGR modes. The diagrams can also be used by transit planners to develop new vehicle models or compare proposed models with existing rolling stock from different cities.

To resolve the problem of different definitions and incomplete information, several approximations were made.

- Body length was assumed to be 1.00 m shorter than length over couplers, because each coupler extends about 0.35 to 0.65 m over the body.
- Floor area was computed as body length $\times$ body width. Net available area is actually about 5% to 15% smaller due to driver’s cabin, steps, wall thickness, etc.
- All data are for one car: for LRT, for articulated car, for RRT and RGR single cars, half of MP units, or one-third of a three-car unit.
- An area per standee of 0.20 m² was used, and average passenger weight in assumed to be 70 kg.

Table 6.2 Technical data for rail transit vehicles by mode

Vehicle Category		SCR/Tram, 4-axle			LRT, 6-axle, 70% LF			LRT, >6 axle, 5-7 sec.			Rapid Transit			Regional Rail		
Item	Unit	Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.
Length over couplers	m	13.6	14.1	20.0	19.1	25.0	30.0	23.5	30.0	54.0	14.6	18.0	22.9	17.5	25.9	25.9
Distance between truck centers	m	6.0	6.4	11.8	6.0	9.0	10.0	6.0	6.5	7.1	8.2	12.0	16.5	10.0	16.5	18.2
Body width	m	2.20	2.40	2.70	2.20	2.65	3.00	2.20	2.40	2.65	2.50	2.90	3.20	3.05	3.15	3.20
No. of powered axles	—	4	4	4	2	4	6	4	4	8	2	4	4	2	4	4
No. of doors on one side	—	2	3	4	2	4	4	4	4	5	2	3	5	1	3	4
Number of seats	—	20	35	60	30	45	90	44	64	90	35	60	83	70	100	175
Total capacity	—	100	110	170	117	160	210	160	185	240	137	170	300	140	160	250
Total power	kW	160	160	360	200	300	470	200	300	430	270	400	470	300	450	530
Tare weight	tons	15.2	17.0	28.8	19.8	24.0	39.0	25.4	33.0	38.8	19.0	25.0	38.0	28.0	34.0	59.0
Max. acceleration rates	m/s ²	1.0	1.2	1.9	1.0	1.0	1.7	0.9	1.0	1.3	1.0	1.1	1.4	0.8	1.0	1.3
Emergency deceleration rate	m/s ²	2.0	3.0	3.7	2.0	3.0	3.0	2.0	3.0	3.0	1.1	1.3	2.1	1.0	1.2	1.4
Max. speed	km/h	60	70	125	65	80	100	65	80	80	70	85	130	100	120	160

Table 6.3 Technical data of selected LRT vehicle models

<i>Rail Vehicle ID (in fol. diagrams)</i>	—	3	4	5	6	11	13	24
1. City, country	—	Calgary, Canada	Charlotte, USA	Cologne, Germany	Cologne, Ger- many	Düsseldorf, Germany	Frankfurt, Germany	Los Angeles, USA
2. Manufacturer	—	Siemens	Siemens	Bombardier	Bombardier	Siemens	Duewag	Siemens
3. Model	—	SD160	S70	City-tram K5000	City-tram K4500	R100 Combino	LF Tram	P2000
4. Years of production	—	2000	2004	2002–03	2004–06	1998	1997	2002
5. Body sections	—	—	—	—	—	—	—	—
6. Number of axles: total/ powered	—/—	6/4	6/4	6/4	6/4	8/6	6/4	6/4
7. Body length	m	24.60	27.50	28.00	27.40	29.00	26.60	26.30
9. Truck wheel base/min. turning radius	m/m	1.8/25	1.9/25	1.8/25(23)	1.8/25(23)	1.8/15	n.a./18	2.1/25
10. Car width/height	m/m	2.65/3.84	2.65/3.68	2.65/3.65	2.65/3.57	2.4/3.54	2.35/3.30	2.65/3.76
11. Floor level	m	0.985	0.856	0.980	0.400/0.580	0.300/0.360	0.300/0.350	0.975
12. Number of doors per side	—	4	4	4	4	5	4	4
13. Capacity: seats/total	—/—	64/184	58/180	62/186	70/208	0/170	59/170	76/176
14. Power	kW	580	520	480	480	400	440	552
15. Gauge	m	1.435	1.435	1.435	1.435	1.435	1.435	1.435
16. Weight: tare/gross	ton	45/57.9	44/56.6	36.5/49.5	36.3/50.9	49/74	30/41.9	44.5/56.8
17. Max. acceleration rate	m/s ²	1.34	1.34	1.2	1.2	1.2	1.3	1.35
18. Deceleration rates: normal/emergency	m/s ²	1.25/1.56	1.34/2.33	1.3/2.73	1.3/2.8	1.5/2.7	1.5/2.73	1.55/2.32
19. Maximum speed	km/h	80	115	80	80	65	70	113

Table 6.3 (continued)

Rail Vehicle ID (in fol. diagrams)	—	25	31	36	18	38	40
1. City, country	—	Milano, Italy	Saarbrücken, Germany	San Francisco, USA	JFK Airport, USA	St. Louis, USA	Trenton-Camden, USA
2. Manufacturer	—	Breda	Bombardier	Breda	Bombardier	Siemens	Stadler
3. Model	—	Cirio	Tram-Train	LRV2	ART MKII-AirTrain	SD460	RiverLine-DMU
4. Year of production	—	2002	1997	1996	2002	2002	2002
5. Body sections	—	—	—	—	—	—	—
6. Number of axles: total/ powered	—/—	8/4	8/8	6/4	4/0 (LIM)	6/4	6/4
7. Body length	m	34.35	37.10	22.90	16.60	26.10	30.20
9. Truck wheel base/min. turning radius	m/m	1.70/n.a.	n.a./25(23)	1.90/13.70	1.90/n.a.	2.11/n.a.	2.00/40
10. Car width/height	m/m	2.40/3.40	2.65/3.80	2.74/3.50	3.20/3.81	2.65/3.81	3.00/3.91
11. Floor level	m	0.350	0.600	0.864	1.118	1.006	0.584/0.999
12. Number of doors per side	—	3	4	4	2	4	2
13. Capacity: seats/total	—/—	71/259	96/243	60/192	26/159	72/178	90/184
14. Power	kW	424	960	524	LIM	560	550 Diesel
15. Gauge	m	1.445	1.435	1.425	1.435	1.435	1.435
16. Weight: tare/gross	ton	n.a.	55.4/72.4	35.4/48.8	24.0/35.1	42.0/54.5	55.0/67.9
17. Max. acceleration rate	m/s ²	n.a.	1.1	1.34	1.34	1.35	0.90
18. Deceleration rates: normal/emergency	m/s ²	n.a.	1.6/1.8	1.56/2.68	1.00/1.43	1.35/2.55	1.00/2.00
19. Maximum speed	km/h	70	100	84	109	105	112

Table 6.4 Technical data of selected RRT vehicle models

Rail Vehicle ID	—	77	78	80	82	84	85	88	90
1. City, country	—	Ankara, Turkey	Bilbao, Spain	Madrid, Spain	Mexico City, Mexico	NY City, USA	Philadelphia, USA	San Juan, Puerto Rico	Washington D.C., USA
2. Manufacturer	—	Bombardier	CAF	Breda	Bombardier	Kawasaki	ABB	Siemens	CAF
3. Model	—	ATO H6 Train	Electric Units	Series 7000	FM-95A	R143	M-4	Tren Urbano	Metro
4. Years of production	—	1995	2000	2001	1999	2004	1997	2004	1998
6. Number of axes: total/ powered	—/—	4/n.a.	4/n.a.	n.a.	4/4	4/4	4/2-4	4/4	4/4
7. Body length	m	21.90	17.80	16.95	15.50	17.35	15.80	22.00	22.86
8. Distance between truck centers	m	16.46	12.50	n.a.	11.00	13.59	11.48	15.90	15.85
9. Truck wheel base	m	2.08	2.20	2.20	1.36	2.08	2.03	2.40	1.90
10. Car width/height	m/m	3.10/3.65	2.80/3.85	2.81/3.65	2.50/3.60	3.00/3.67	2.78/3.96	3.20/3.81	3.10/3.60
11. Number of doors per side	—	n.a.	3	n.a.	4	4	3	3	3
12. Capacity: seats/total	—/—	61/217	36/130	30/160	36/126	42/144	49/111	72/183	66/110
13. Power	kW	n.a.	720	792	n.a.	n.a.	624	500	
14. Wheel diameter/gauge	m	0.711/1.435	0.840/1.000	n.a.	0.860/1.435	n.a./1.435	0.760/1.581	0.710/1.435	n.a./1.435
15. Weight: tear/gross	ton	31.8/47.0	36.5/45.6	n.a.	24.1/32.9	38.0/48.1	28.7/36.5	n.a.	n.a.
16. Acceleration rate	m/s ²	0.9	1.15	n.a.	1.0	1.1	1.2	1.25	1.25
17. Deceleration rates: normal/emergency	m/s ²	1.25/1.35	1.0/1.2	n.a.	1.0/1.27	n.a.	n.a./2.68	1.35/1.55	1.3/1.43
18. Maximum speed	km/h	86	80	120	100	88	105	100	120

Table 6.5 Technical data of selected RGR vehicle models

Rail Vehicle ID	—	48	57	60	64	66	68
1. City, country	—	Berlin, Germany	Hong Kong, China	Miami, USA	Norwegian State RW	NY city, USA	San Francisco, USA
2. Manufacturer	—	Bombardier	CAF	Colorado RC	Bombardier	Bombardier	MKC
3. Model	—	Talent MU's RegioBahn	Airport Express	Bi-level Commuter DMU	Talent Class 93	M-7 EMU	California Car
4. Years of production	—	1999	1996	2005	2002	1999	1996
6. Number of axes: total/ powered	—/—	6/n.a.	4/4	4/n.a.	6/n.a.	4/n.a.	4/0
7. Body length	m	16.30	23.00	26.20	18.10	24.90	24.90
8. Distance between truck centers	m	n.a.	15.60	18.13	n.a.	18.14	18.80
9. Truck wheel base	m/m	n.a.	2.50	2.59	n.a.	2.59	2.59
10. Car width/height	m/m	2.93/4.02	3.10/3.70	3.00/5.90	2.93/n.a.	3.20/3.95	3.10/4.90
11. Number of doors per side	—	1	2	1	n.a.	2	2
12. Capacity: seats/total	—/—	49/99	64/114	180/296	41/171	106/224	146/163
13. Power	kW	315	795	895	n.a.	200	0
14. Wheel diameter / gauge	m	n.a.	(0.860/0.785)/1.435	0.914/1.435	n.a.	0.914/1.435	0.914/1.435
15. Weight: tear /gross	ton	27.5/34.4	40.5/48.57	7.6/98.3	28.1/40.1	57.5/73.2	59.0/70.4
16. Acceleration rate	m/s ²	1.1	n.a.	1.3	n.a.	0.9	n.a.
17. Deceleration rates: normal/emergency	m/s ²	1.0/n.a.	1.0/1.3	0.67/0.8	n.a.	1.3/1.4	n.a.
18. Maximum speed	km/h	100	135	161	n.a.	160	201

This standard of 5 prs/m² is too low for many cities in industrialized countries (shown capacities are 25% greater than for the 4 prs/m² standard), but they are realistic or even high for rail systems with heavy passenger loads, as in very large cities (Tokyo, New York, Moscow) and in developing countries.

The numbers in Figures 6.12 to 6.16 are designations of models in the tables and in the listing of models.

The diagram in Figure 6.12 is a plot of vehicle lengths, widths, and gross floor area. It shows that RRT cars have lengths in the range from 15 to 23 m, widths from 2.50 to 3.20 m, and floor areas between 39 and 71 m². RGR cars have somewhat greater lengths and widths, reaching floor areas as large as 85 m² (the additional floor area on the second deck of bilevel cars is not included in the diagram). LRT cars, however, are

spread much more on the diagram. Their widths are mostly limited to 2.65 m, but their lengths cover the range from 18 m (four-axle streetcars, typically 14 m long, are not shown) to over 40 m, with a trend toward even longer cars. This length is obtained by articulated vehicle designs. With such lengths, some LRT car floor areas go over 100 m², exceeding even the RGR vehicles.

Figure 6.13 shows gross floor areas and tare weights of vehicles, important indicators of their energy consumption. The diagram shows that the three modes overlap in their weight/floor area ratios, most models congregating in the range of 400 to 800 kg/m². Yet it is noticeable that RGR cars are in a higher area of this range than LRT cars.

Distinct differences among the three modes are clearly shown in Figure 6.14. RRT and RGR show axle loadings increasing proportionally with the gross floor

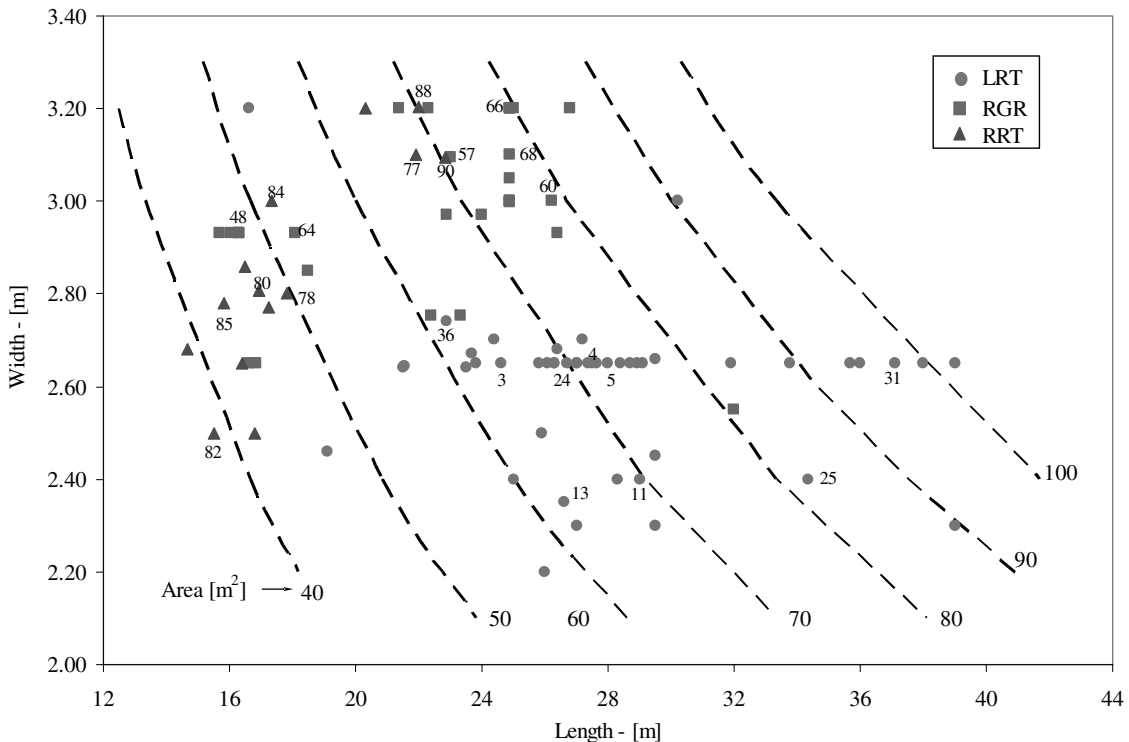


Figure 6.12 Length, width, and gross floor area of rail transit vehicles



Photo 6.16 Articulated LRT cars in Rotterdam provide high capacity for seating and standing (Courtesy of R. Meinen)

areas, while the LRT cars remain in the range of 5 to 11 t/m² regardless of their floor areas. This is due to the fact that LRT cars have articulated bodies, so that their number of axles increases with body length, resulting in rather constant axle loadings. This vehicle feature is the reason that LRT requires “lighter” track structures and penetrates urban areas more easily than RRT and RGR modes, with considerably greater axle loadings and supporting structures.

The last two diagrams, in Figures 6.15 and 6.16, show the relationships of motor power to vehicle tare weight, the main factor of vehicle performance, and power to vehicle capacity, i.e., spaces per vehicle. The two diagrams do not show any clear modal distinctions

in power to weight ratios, but they indicate a greater motor power per unit of capacity on the RRT and RGR than on the LRT mode.

6.2.4.2 Trends in Vehicle Design. As described in the preceding sections, rail transit vehicles have had many innovations in the design of their bodies, floor levels, trucks, axles, and motors, resulting in the continuously increasing diversity, sophistication, and operational efficiency of their rolling stock. These innovations and trends in vehicle dimensions, weights, and powering can be seen through a comparison of the diagrams in Figs. 6.12 through 6.16 with the corresponding set of charts published in the first edition of this book (Vuchic 1981). Such a comparison of rail vehicle characteristics during a period of approximately 25 years leads to the following conclusions.

- In 1981 SCR/LRT vehicle widths (Figure 6.12) were predominantly in the range of 2.20 to 2.40 m; in 2006, the majority of vehicles are 2.65 m wide. This change is largely due to the opening of numerous new LRT systems, notably about 20 in North America, which have adopted the 2.65 m dimension for increased capacity and ability to provide 2 + 2 seating (Photo 6.17).
- RRT vehicle floor areas remain concentrated in the range of 50 to 70 m², with some trend toward its higher end. This dimension is influenced by the fact that metro systems using tunnel alignments are constrained by the tendency to keep the vehicle profile limited so as to keep tunneling costs low.
- RGRs are shown concentrated in the upper limit of rail vehicle length, in the range of about 24 to 26 m. Actually, many RGR vehicles have considerably greater floor area than shown, because the second-level floors of bilevel cars are not included in the diagram.
- With respect to unit weight (kg/m²), in 1981 the majority of vehicles were in the range of 400 to 650 kg/m², while in 2006 the greatest concentration is in the range of 500 to 800 kg/m² (Figure 6.13). Despite the importance of weight reduction for better performance and energy efficiency, this

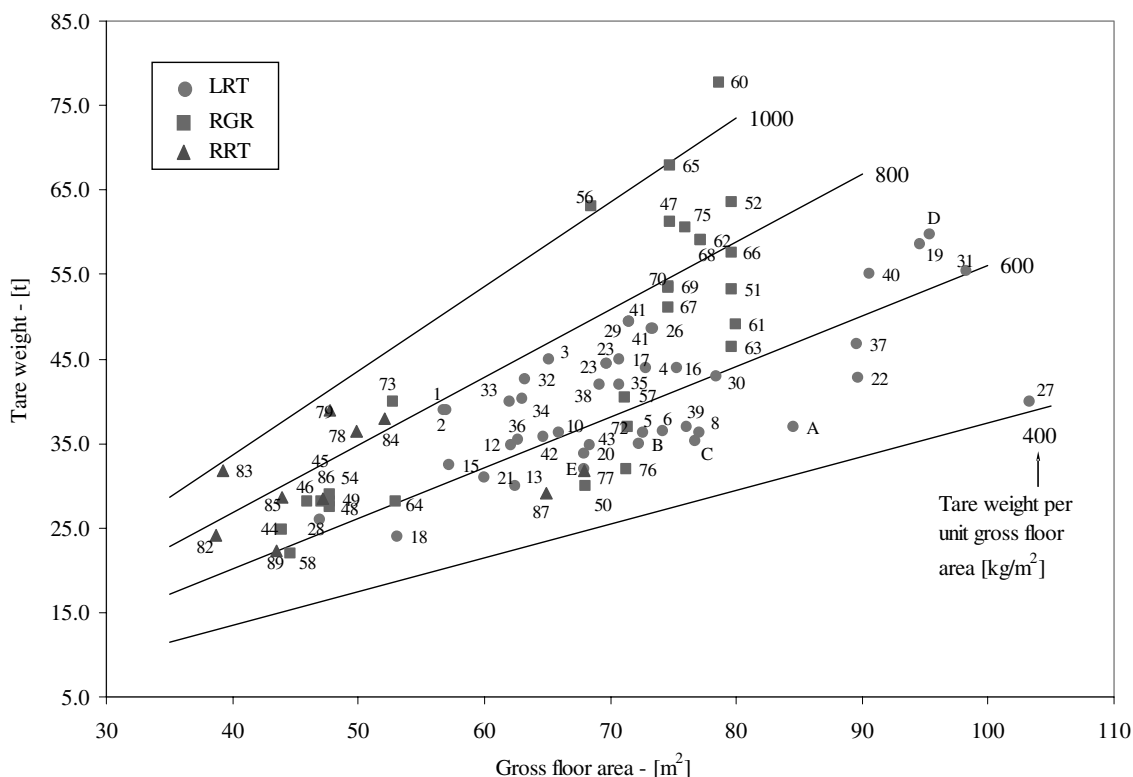


Figure 6.13 Tare weight versus gross floor area of rail transit vehicles

trend shows that additional equipment, such as air conditioning and in some cases safety requirements, have actually caused this undesirable trend.

- Gross axle loadings (Figure 6.14) show a considerable increase for LRT models. In 1981 they were in the range of 5 to 7 tons. In 2006 they have spread upward, showing values from 5 to 11 tons. This reflects the broadening use of LRT from urban lines to larger, higher-speed rolling stock for many new long LRT lines.
- A similar trend toward larger and higher-performance vehicles is seen in the diagram of motor power versus vehicle tare weight in Figure 6.15. In 1981, most models were concentrated between 8 and 15 kW/ton; in 2006, most models are in the range between 11 and 16 kW/ton, with-

out distinct differences among modes. However, the diagram of power versus vehicle capacity in Figure 6.16 (not shown in 1981) indicates distinctly lower powering per offered space for LRT than for RRT and RGR models.

6.2.5 Basic Operating Units and Train Consists

Selection of the basic unit for a transit system is an important step in planning rolling stock, since it affects system performance and operational efficiency. Selection of the basic vehicle type for LRT systems was discussed in Section 6.2.3.1. This section refers primarily to the basic units and composition of RRT and RGR trains.

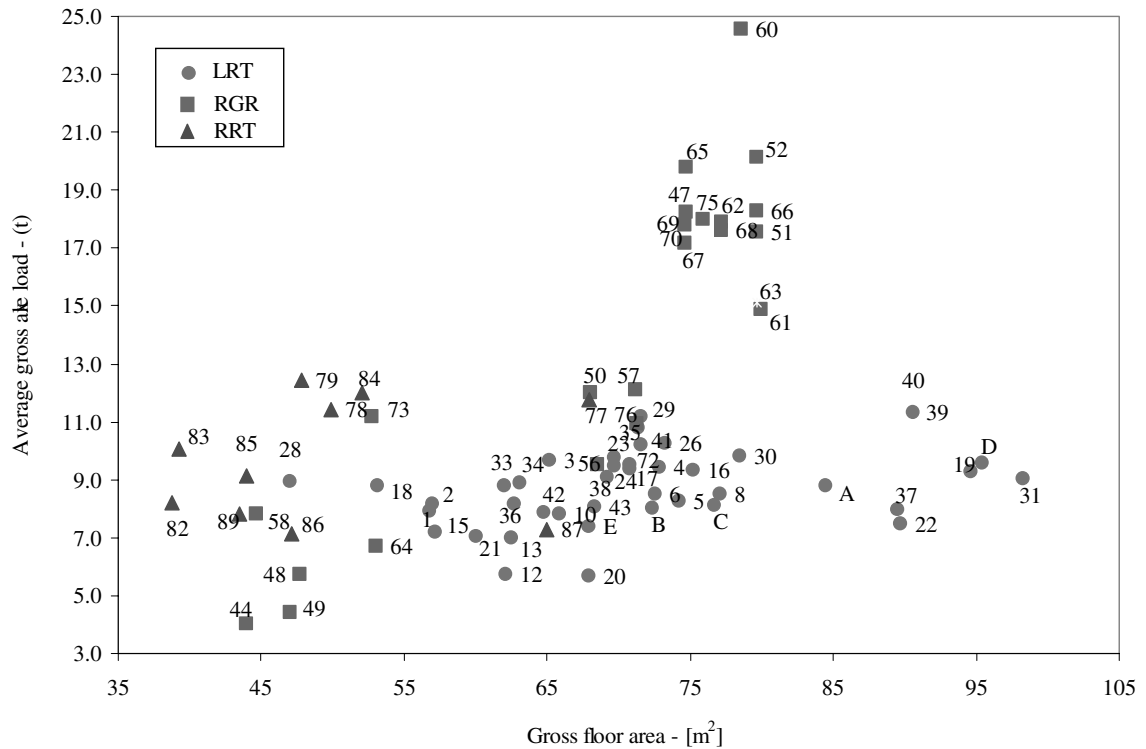


Figure 6.14 Average gross axle loading versus gross floor area for rail vehicles

6.2.5.1 Factors Determining the Optimal Basic Unit. The following main factors must be analyzed in selecting the basic train unit. Most of these factors affect both investment and operating costs of the rolling stock.

Different Train Sizes. It is always desirable to have the option of adjusting the number of cars per train to the demand. The more precise this adjustment is, the better the utilization of vehicle capacity that can be achieved at any given time of day. Thus the operating cost of the system can be minimized.

Minimum Train Size. Some metro systems have long periods, particularly over weekends and during evening/night hours, when passenger demand is low, but it is important to maintain policy headways not longer than 6 to 10 min for attractive service and easy

transfer among lines. In such cases, it is desirable to operate very short trains so that the operating costs, particularly energy consumption, are minimized.

Utilization of Mechanical and Electrical Equipment in Vehicles. While a car that operates by itself must contain all auxiliary mechanical and electrical equipment, when two or three cars are semipermanently coupled, they can share a number of joint aggregates, thus reducing the investment and maintenance costs of the equipment.

Number of Driver Control Sets per Car. Since driver controls contain equipment that is rather expensive (particularly on some recent car models with high degrees of automation), it is desirable to minimize the number of driver control sets per train. Because of the

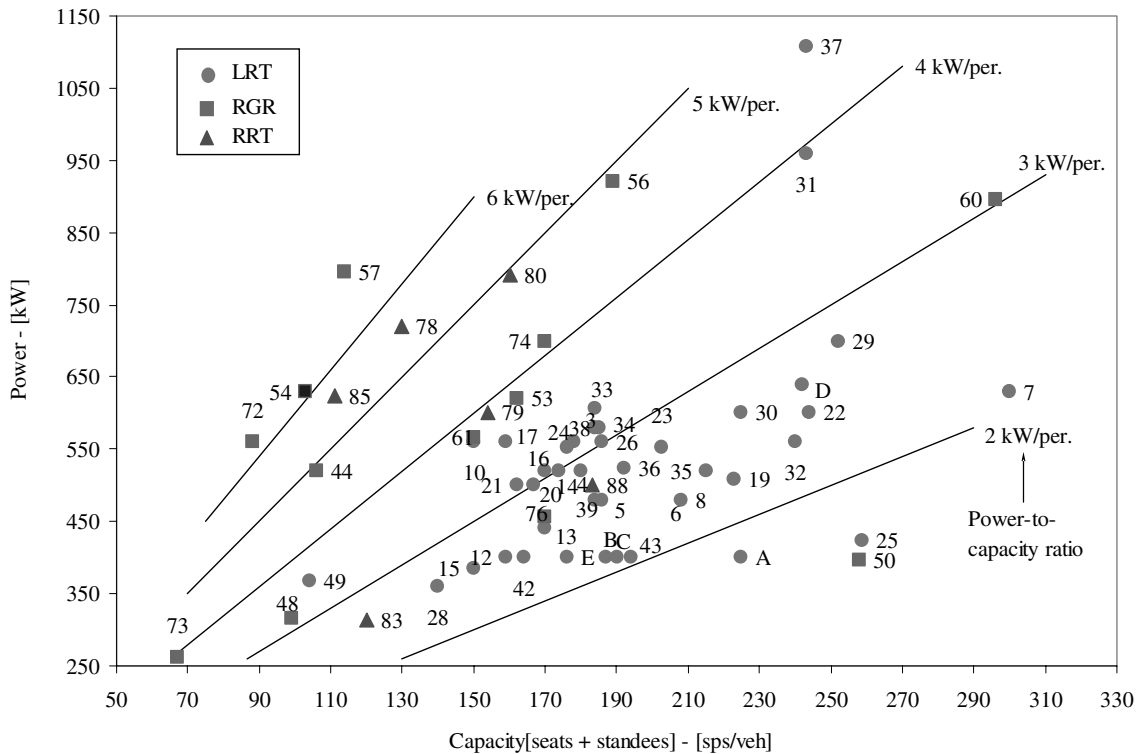


Figure 6.16 Capacity versus power of rail transit vehicles

car-kilometers for any given passenger demand. These cars are therefore particularly useful for systems that have very low passenger volumes in off-peak periods, including night hours.

On the negative side, SU cars have high purchase and operating costs per unit capacity because each car must have two driver cabins and control sets, and all auxiliary equipment, which reduces passenger capacity and increases vehicle complexity.

Married Pairs (MP). The most common basic unit for RRT rolling stock consists of two semipermanently coupled cars (A and B) that are operational only when they are coupled together but can be uncoupled for maintenance purposes. The main advantage of this arrangement is that some of the equipment—such as the motor-generator, battery, and air compressor—is contained in only one of the two cars and not duplicated in the other, thus achieving lower cost of purchasing

and operation of vehicle, lower weight, and better accessibility for maintenance. In addition, only the outer ends of the two cars have driver control sets, thus providing only one set per car. The pairs can be easily coupled or uncoupled into train lengths of any even number of cars.

The inability of fleets with married pairs to operate single cars is a disadvantage on some systems. Moreover, such fleets do not allow formation of three- or five-car trains either, which results in a somewhat lower ability to fit offered capacity to passenger demand and a lower vehicle utilization ratio in comparison with SU cars. Also, each failure usually eliminates two cars from service.

Three-Car Units. Like the married pairs, three-car units (Photo 6.18) are designed as semipermanently coupled units with joint auxiliary equipment and two



Photo 6.17 Two six-axle LRT train in San Diego (Siemens S70 model)

driver control sets for three cars. The center car, designated as C type, is usually but not always powered.

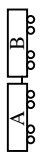
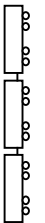
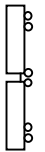
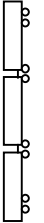
The advantages and disadvantages of a three-car unit (A-C-A or A-C-B) in comparison with a two-car unit are similar to those between married pairs and SU cars. The three-car unit has an even better utilization of mechanical equipment, a lower weight-to-capacity ratio, and an average of only two-thirds of a driver control set per car, resulting in lower purchase and operating costs. On the negative side, the smallest unit that can be operated with this type of equipment consists of three cars, and train lengths can only be three, six, and nine. Repair of any one car eliminates three cars from service. Finally, handling of three-car units in the maintenance shops is somewhat more complicated than for smaller units.

Articulated Units. As mentioned in the preceding section, an increasing number of metro systems are introducing sets of three to eight cars with fully articulated

bodies, providing a continuous interior. This has considerable advantages in passenger boarding and distribution at the cost of inability to change transit consists. Hong Kong MTR has eight-car train units (Photo 6.19), while several Japanese cities have five-car units, allowing operation of five- and ten-car trains. These units are therefore very useful under two conditions: when passenger volumes are substantial at most daily hours and when rolling stock is very reliable, because when a single car fails, the entire train has to be withdrawn.

6.2.5.3 Fleet Compositions. It is obvious that each type of basic vehicle unit has some advantages and some disadvantages in comparison with other units. Depending on the specific local conditions in any city, one unit type is preferable to others. Some cities have, based on the analyses of all these facts, selected one type of unit and used it for all their lines. For example,

Table 6.6 Characteristics of different basic rapid transit train units

Designation	Characteristics		Cars/ Unit	Cars/ Train	Min. Train Length	Trucks/ Unit	Car Length/ Truck	Car Length/ Control Set	Ease of Maintenance	Fleet Utilization	Cities Where Used
	Sketch										
SU ^a			1	Any	$l_t + 2l_o$	2	$\frac{l_t}{2} + l_o$	$\frac{l_t}{2} + l_o$	Good	Good	Boston Cleveland PATCO
MP ^b			2	k-2	$2(l_t + 2l_o)$	4	$\frac{l_t}{2} + l_o$	$l_t + 2l_o$	Good	Average	Cleveland London Munich
3-car ^c			3	k-3	$3(l_t + 2l_o)$	6	$\frac{l_t}{2} + l_o$	$\frac{3}{2}l_t + 3l_o$	Average	Average	London Montreal Mexico City
MP- articulated			2	k-2	$2(l_t + l_o)$	3	$\frac{2}{2}(l_t + l_o)$	$l_t + l_o$	Average	Average	Rotterdam
3-car articulated			3	k-3	$3l_t + 2l_o$	4	$\frac{3}{4}l_t + \frac{l_o}{2}$	$\frac{3}{2}l_t + l_o$	Poor	Average	Paris
Double MP ^d			4	k-4	$4(l_t + 2l_o)$	8	$\frac{l_t}{2} + l_o$	$2(l_t + 2l_o)$	Average	Poor	New York
End and Middle ^e			2	≥ 2	$2(l_t + 2l_o)$	4	$\frac{l_t}{2} + l_o$	$\geq l_t + 2l_o$	Good	Poor	San Francisco

^aSingle unit: optimum fleet utilization; maximum investment and operating cost.

^bMarried pair: the most common type.

^cCar C may be a trailer.

^dFor very high volume lines only.

^eMaximum saving on control equipment but complicated maneuvering, inflexible operation, and uneven utilization of A and C cars.



Photo 6.18 Three-car unit bilevel train on Munich S-Bahn (Courtesy of Tobias Köhler)



Photo 6.20 RRT in Madrid (Courtesy of Carlos Pérez Arnau)



Photo 6.19 Continuous interior through RRT cars in Hong Kong

Amsterdam, Berlin, Chicago, Munich, and Nürnberg have married pairs only; Mexico City and Montreal have three-car units, while New York City has many different train units. A Metro train in Madrid is shown in Photo 6.20.

Other cities find that, because of different conditions on individual lines or other varying operational requirements, they need more than one type of operating unit. Thus combinations of several types within the same system are not uncommon. PATCO in Philadelphia as well as RT systems in Cleveland and Boston have both SU cars and married pairs. This allows them the economy of married pairs with minimum ve-

hicle mileage in off-peak periods running through deployment of SU cars. Paris has two- and three-car units, as well as three-car articulated sets on one of its lines. London finds that with married pairs and three-car units, it can best satisfy varying demands, since train consists can be of any length from two cars up to the maximum of eight. Finally, some cities have such specific conditions that they develop unique designs which are not suitable to any other city.

6.3 RAIL TRANSIT WAYS: GEOMETRY AND FACILITIES

Rights-of-way and transit way facilities—which together with stations and maintenance facilities comprise the rail system infrastructure—represent components of rail transit systems that require the highest investment and give these modes most of their distinctive features. For a description of ways, also referred to as “permanent ways” or “travel ways,” several basic concepts are defined.

Geometric elements of ways encompass three aspects: horizontal alignment (track layout), vertical alignment (track profile), and clearance (free cross-sectional area for vehicle passage).

Right-of-way (ROW) or travelway is the strip of land on which TUs travel. In the case of rail transit, it is the land on which tracks are laid out. Where inde-

pendent from streets, ROW designates the track area owned by the transit agency. Different positions of the tracks with respect to location, elevation, exclusive control or joint use by different modes, and other physical and legal characteristics are generally referred to as ROW categories, as defined in Section 2.1.2.1.

Roadbed is the earth base on which the track superstructure rests. It may have many forms, from graded and compacted ground surfaces or embankments to major structures such as large cuts and fills.

Way structures include all structures on the rail ROW that carry the superstructure. The most common types are bridges, viaducts, aerial structures, and tunnels.

The superstructure represents all the fixed physical components that directly support and guide the rail vehicles. The major ones are ballast and ties (if used), rails, and track switches.

A *guideway*, a term sometimes incorrectly used to designate way structures such as a roadway, represents the part of the transportation way that physically guides vehicles. Thus driver-steered vehicles, such as buses, do not have guideways. In the case of rail modes, the guideway is the track.

Wayside equipment includes such components as signals, communication cables, and storage facilities located along the tracks for the operation, control, and maintenance of the line.

Electrification equipment refers to all components required for bringing power from power plants to vehicles running on the tracks. It includes substations, third rail or catenary with supporting masts, and grounding for return current conduits.

6.3.1 Geometric Elements

The selection of geometric elements for any transit mode should be determined from the requirements of local physical and environmental conditions, system performance, and its investment and operating costs. Easy fitting to the existing street networks and other convenient ROW facilities usually reduces investment costs but may not provide high system performance (speed, capacity, comfort). Independent alignment, on

the other hand, requires higher investment but provides high performance and lower operating costs. Geometric standards of the alignment should be based on the trade-offs between these factors.

The most important limiting geometric elements are the minimum curve radius for horizontal alignment and the maximum gradient for vertical alignment. These two elements are subject to several different constraints.

Technological capability represents the absolute constraint on the geometric elements. It determines the extreme values that vehicles of specific technology can negotiate safely at a specified speed. Use of the ultimate physical capabilities may, however, require impractical design specifications (e.g., excessive power/weight ratio).

Economic/operational factors determine the extreme values that are practically acceptable. These considerations usually dictate the use of less than the extreme geometric standards the specific technology is physically capable of negotiating.

Performance requirements are always the most restrictive of the three constraints. In most RRT systems, particularly newer ones, the minimum geometric standards are determined by the desired minimum speed that should be possible on the entire network. This standard is usually well above the physical limits of rail technology and the economics of its operation. LRT systems are also influenced by performance requirements, but they must be capable of negotiating much more restrictive alignments than metro and RGR modes.

6.3.1.1 Curvature and Gradient. Most RRT systems have minimum curve radii between 100 and 200 m, while several older systems have values between 75 and 100 m. The only systems utilizing even shorter radii are those in several U.S. cities: New York, 52 m; Philadelphia, 43 m; and Chicago, 27 m. Newer systems have generally adopted greater minimum radii: except for Mexico City (105 m), no system has used radii below 120 m. Standards for new RRT lines adopted in several cities and countries are even higher, as Table 6.7 shows. Although these values provide for very high performance, they make RRT alignments in inner ur-

Table 6.7 Geometric design standards for several recently built rapid transit systems

Item	Symbol	Unit	London	Regular/Exceptional Values				Los Angeles LRT (for Comparison)
				German Recommended Standards	BART San Francisco	São Paulo	Los Angeles	
1. Design speed	V	km/h	70/55	80/70	130	100	120	89
2. Minimum curve radius	$R_{\min}$	m	400/240	300/180	152	300/150	427/230	92/31
3. Maximum superelevation	$e_{\max}$	mm	153	150	210	170	102	102
4. Distance between track centers	—	m	3.40	3.90	4.27	4.35	4.27	4.75/3.50
5. Gradient	i	%	1.00/1.67	2.50/5.00	3.00/4.00	4.00	3.00/4.00	4.00/6.00
Open line Stations	i	%	1.00	0.25	1.00	n.a.	1.00	1.00
6. Safety walkway: width $\times$ height	—	m	n.a.	0.70×2.00	0.76×1.98	0.60×2.00	0.76×1.0	0.76
7. Tunnel width and height	—	m	7.34×3.85	7.30×4.30	8.24×4.12	10.00×4.05	5.44 dia^a	5.8 dia
8. Platform height	—	m	0.52	0.88	0.99	0.85	1.137	0.84
9. Platform length	—	m	137	125	214	136	137	82
10. Gauge	—	m	1,435	1,435	1,676	1,600	1,435	1,435

^a Diameter of circular tunnel

n.a. = not available

ban areas difficult to design and may result in excessive construction costs.

RGR systems generally have very mild (large radius) curves, far above the physical capabilities of the rolling stock. Only sections in central urban areas or under topographic constraints have minimum radii as short as 150 m.

LRT, on the other hand, is required to have the capability of operating in geometrically constrained conditions. In addition, this mode is less sensitive to sharp curves than RRT because its short trains pass through a restrictive curve in a shorter period of time than a six- to ten-car RRT train. Consequently, LRT vehicles are capable of negotiating curves with 15- to 25-m radii. On most lines, the minimum radii of 25 to 50 m are common. The exceptions are “premetro” LRT systems designed with RRT elements, which allowed later conversion to RRT (Brussels, Frankfurt). Because of the requirement for negotiating sharp curves, LRT vehicles have a relatively short distance between truck centers (6 to 7 m, exceptionally 10 m).

Rail technology is physically capable of negotiating gradients in excess of 10% (Pittsburgh had a streetcar line with 15% grade), but these require extreme care and are highly undesirable for regular operation. Most LRT systems do not exceed 6% to 9%. Vehicles capable of negotiating gradients greater than 6% must have higher power-to-weight ratios than those operating on less severe alignments.

Because of their greater weight and the higher degree of safety they require, RRT systems are more sensitive to gradients than LRT. Maximum gradients for

RRT systems are usually selected on the basis of performance requirements that are more restrictive than the safety-dictated ones: most RRT systems have maximum gradients of only 3.0% to 4.0%. The steepest gradient on an RRT system is 6.25% (Brussels), which approaches the practical physical limit of this mode: while regular operation creates no problems at all, pushing a stalled train becomes critical on this gradient. The maximum used on a rubber-tired rapid transit (RTRT) system (see Section 6.4) is 7.0% (Mexico City). Although the tendency is to use higher geometric standards for new systems, the effect of steeper gradients on system operations is now smaller than it used to be because of the higher performance of modern vehicles. Many experts believe that there is no reason why, where necessary, RRT systems could not operate on gradients of up to 6.0%. This would make application of RRT possible in many areas where it is now considered infeasible. Similarly, RTRT could probably negotiate, if necessary, 8.0% gradients in tunnels (this ability does not exist where the track is open to the weather).

RGR has the highest standards, seldom reaching and never exceeding a gradient of 4.0%.

Table 6.8 presents approximate extreme values of the curve radius and gradient for LRT and RRT modes. Gradients with the superscript “a” are those that have not been used because system performance requirements govern.

It is important to bear in mind the differences among the three types of vehicle performance capabilities and requirements—technological, economic,

Table 6.8 Extreme values of curve radii and gradients for rail transit

<i>Item</i>	<i>Physically Possible</i>	<i>Used in Operation</i>	<i>Recommended Extremes for New Lines</i>
Minimum curve radius (m)			
Light rail transit	13	20–25	25–50
Rapid transit	25	(27)–75	125
Maximum gradient (%)			
Light rail transit	15	15	8–10
Rapid transit: rail	6–8 ^a	5.0–6.2	6.0–6.5 ^a
Rapid transit: rubber-tired, in tunnel	7–9 ^a	6.3–7.0	7.0–7.5 ^a

^a Specific values depend on ROW type, climate, vehicle performance, and other factors.

and performance—on geometric elements. Major errors occur when the geometric standards of one mode based on performance requirements are compared with the standards of another mode based on technological capabilities. A common case of this error is in comparing the existing rail systems with some proposed AGT or monorail modes (see Chapter 7).

6.3.1.2 Cross-Sectional Profile. The cross-sectional profile of the space that must be free for safe passage of vehicles is mostly determined by vehicle width, height, and method of power collection. The necessary widening in curves depends on vehicle dimension and design, as discussed in Section 6.2.3.1

The vehicle clearance dimensions must be somewhat greater than vehicle dimensions to accommodate vehicle sway, variations in suspension, dynamic motions of the pantograph, and so on. The difference between body shape and the clearance is usually about 20 cm on each side. Thus clearance width is about 40 cm greater than vehicle width. For safety, an additional distance must be provided between the allowed clearance and fixed wayside objects or trains on the adjacent tracks. This distance is between 10 and 30 cm.

Vertical clearance depends primarily on the method of power collection. A third rail, while requiring some extra width at the wheel level, permits only a small distance (10 to 25 cm) between vehicle roof and tunnel ceiling. Overhead power collection, of course, requires additional height clearance, but the difference is much smaller than the normal pantograph height: a pantograph in its suppressed position requires only about 40 cm of additional clearance.

Selection of clearances is particularly important for systems that operate in tunnels, since the cost of tunnel construction in some cases (boring method) is directly proportional to its cross section. The best known small cross-section tunnel is found in London. Its “Tube” lines have an internal diameter of only 12 ft (3.66 m). The track superstructure fits in it, and vehicles are so designed that their roofs closely follow the tunnel curvature. The shape is such that the doors make a sizable protrusion into the roof. Most other systems utilize considerably larger cross sections: the Toronto RRT

has an internal tube diameter of 4.88 m, San Francisco BART 5.02 m, and Munich 5.74 m. Rectangular tunnels usually accommodate both tracks. A 45- to 90-cm-wide path for maintenance and emergency escape is provided in both types of tunnels except the minimum-section tubes.

In addition to circular and rectangular, there are many other types of tunnel cross sections. Actually, each RRT system has tunnels with a specific form dimensions. Generally, larger cross sections involve higher construction costs, but they allow easier maintenance and lower energy consumption because of less air resistance.

Small and large tunnel cross sections, both rectangular and tube, are shown in Figure 6.17. Most RRT systems have tunnels with cross-sectional area between these two. The difference between cross sections for third-rail and overhead power supply is illustrated in Figure 6.18. Tunnel cross sections for high-performance LRT and RGR systems are shown in Figure 6.19.

6.3.2 Track Superstructure

Major technological progress has been made in rail technology in recent decades. While old rail transit was often associated with noise and vibrations, modern rail systems provide by far the greatest comfort of all currently operational transportation technologies. Much of that progress has been in the components of track superstructure.

6.3.2.1 Ballast, Ties, and Rails. The standard crushed-stone ballast, which holds ties and transfers their load to a wider roadbed area, remains the most common track support on earth roadbeds for at-grade or embankment alignments. It is simple to construct and allows easy adjustment of deviations in vertical and horizontal track alignments.

Ties, spaced at distances of 60 to 70 cm support the rails and hold them in position, securing precise gauge width. There are three types of ties: wooden, prestressed concrete, and steel. Wooden ties are still

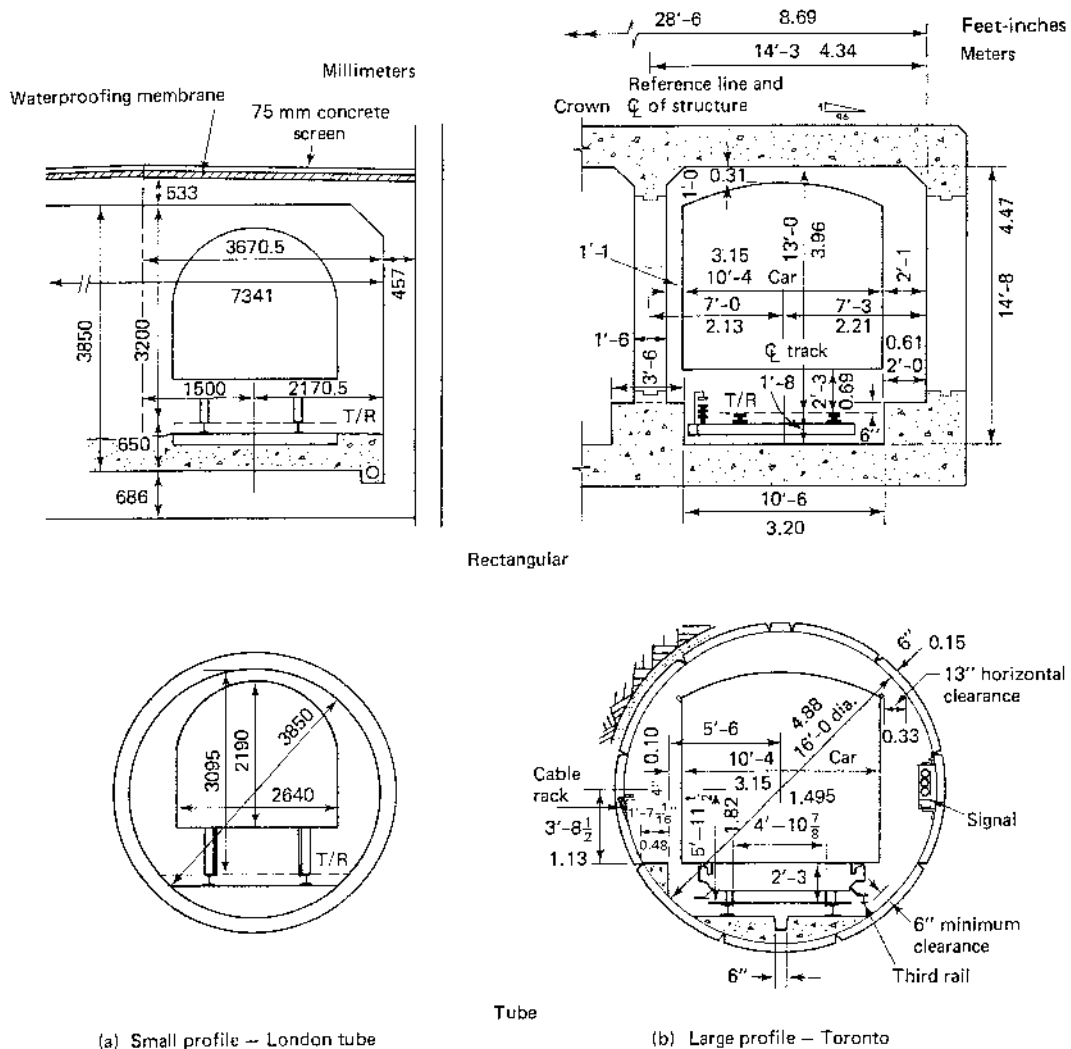
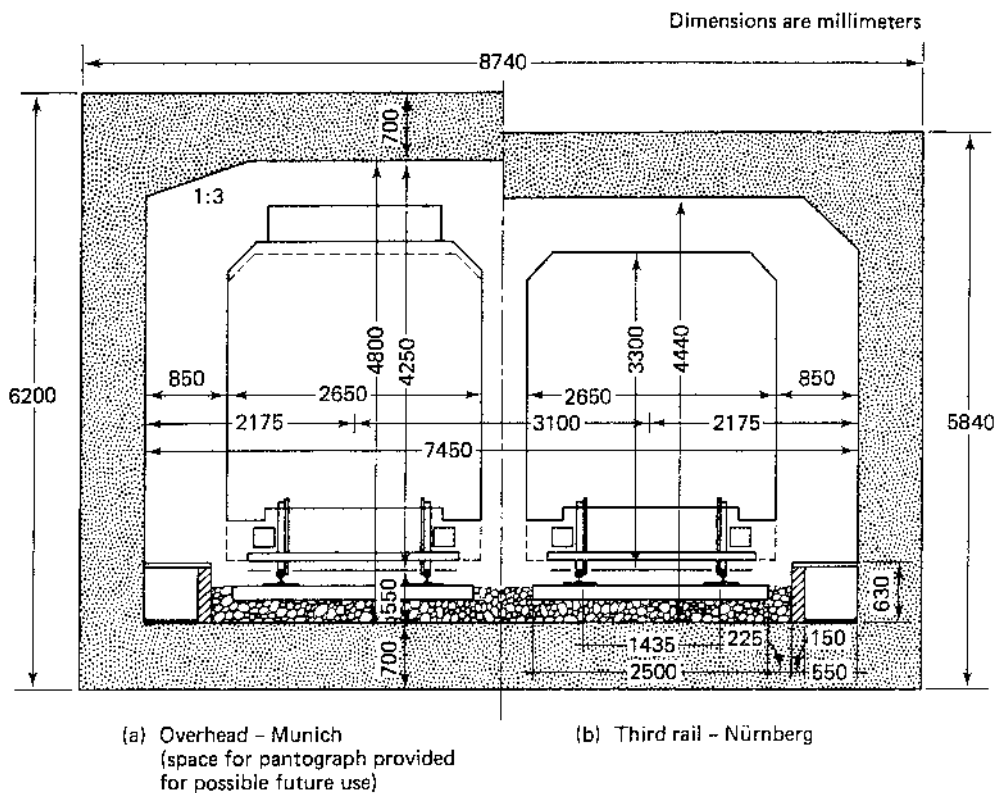


Figure 6.17 Cross sections of rapid transit tunnel

the most commonly used type. They are relatively light and easy to install and replace. They are held in position by friction against the ballast. Concrete ties are heavier and their handling during construction is more difficult, but they provide greater track stability and are more durable. Steel ties are the least commonly used. Like concrete ties, they are less convenient for adjust-

ment of position and maintenance of fasteners and may produce more noise than wooden ties. The relative costs of the three types vary considerably with local conditions (primarily the cost of wood).

For track alignments on structures, such as aerials and tunnels, increasing use is being made of tracks without ballast. Ties or special elastomeric pads that



Note: This was initial design. Later 2.90 m-wide cars and correspondingly wider tunnels were adopted.

Figure 6.18 Cross sections of rapid transit tunnel for overhead and for third rail power supply

dampen noise and vibration are imbedded in the concrete floor. Rails are attached to them by spring-loaded fasteners. Such track with direct fixation to the concrete base and no ballast, shown in Figure 6.20, has several advantages. The weight of the superstructure is greatly reduced, allowing use of longer spans and lighter aerial structures (Photo 6.21). Superstructure height is reduced by 20 to 35 cm, a very significant factor for tunnels.

Although most tracks with this construction have been built rather recently, their performance has proved very satisfactory. They require somewhat higher construction cost and precise work, but they need virtually

no maintenance for many years. Even if the track base has a sizable settlement (up to several centimeters), track position can be corrected by inserting supporting plates. According to noise measurements performed in Cologne, track without ballast and ties produces slightly more (about 3 dB) direct (airborne) noise than ballasted track, but its groundborne noise is somewhat lower.

LRT tracks in roadway pavement are usually laid on a concrete base with an intermediate layer of asphalt for flexible connection, which dampens sound and vibration. Several typical flexible track constructions in pavement are shown in Figure 6.21. Tracks

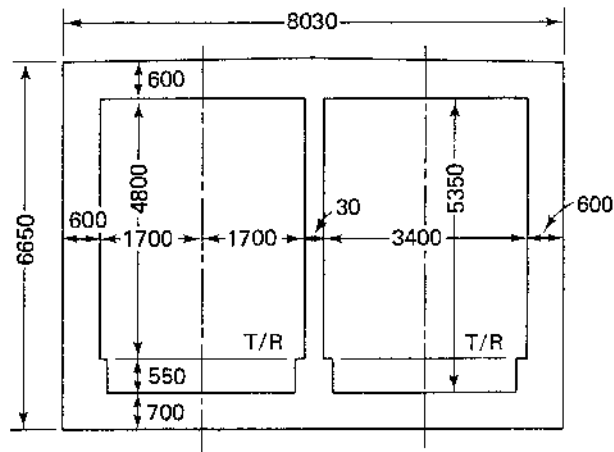
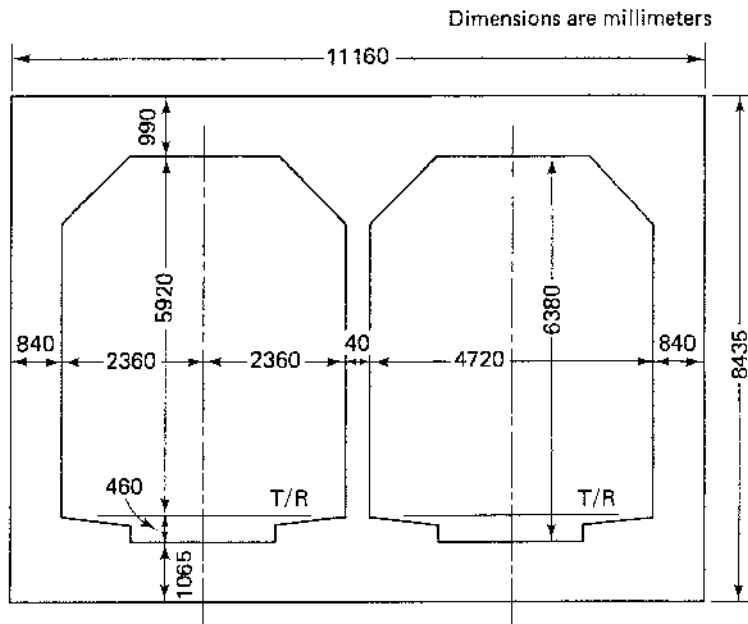
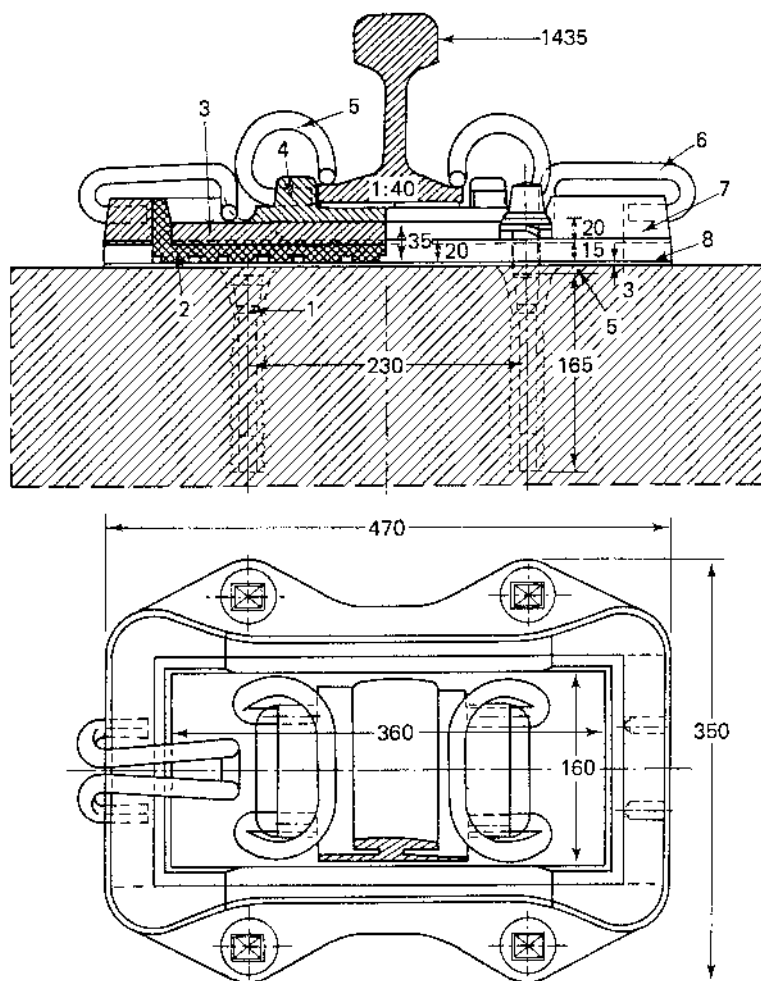


Figure 6.19 Tunnel cross sections for regional rail and light rail



1. Plastic screw socket	4. Ribbed plate (pad)
2. Rubber pad	5, 6. Holding springs
3. Base pad	7, 8. Base pads

Figure 6.20 Rail fastener for tieless track (Courtesy of Kölner Verkehrsbetriebe, Cologne, Germany)

rigidly embedded in the pavement are also used in some cities (e.g., Zürich). They are somewhat simpler to construct, but they produce more noise and vibration. Both types of construction provide tracks that give a stable ride, cause minimum interference for

rubber-tired vehicles, and have high durability (15 to 25 years without any major maintenance).

In recent years the technology of track construction in grassed areas has been perfected. Many cities, particularly in Germany and France, have built SCR and



Photo 6.21 Direct-fixation track with rails fastened to the concrete base on Los Angeles LRT Pasadena ("Gold") Line (Courtesy of James Aslaksen)

LRT tracks in grass-covered street medians and other types of ROW with only four rails standing above ground. This type of tracks is very environmentally attractive due to superb aesthetics, low noise, and prevention of intrusion by nonrail vehicles.

The standard railroad gauge of 1.435 m (4 ft 8 1/2 in.) is the most common one for rail transit also. "Meter gauge" (1.00 m), found on a number of European LRT systems (e.g., Belgrade, Essen, Gent, Mannheim, Zagreb, and all Swiss cities), is adequate for streetcar lines on urban streets, but in most cases these systems use vehicles with a width of only 2.20 to 2.30 m. Although there are systems on which much

wider and longer cars are used (several lines of the Tokyo Subway operate 20.00-m-long and 2.80-m-wide cars on track gauge of 1.067 m), all new LRT systems are designed with standard gauge as more appropriate for longer lines and greater speeds. Several cities have changed meters into standard gauge when they upgraded streetcars into LRT systems (Stuttgart, Essen, planned for Belgrade). Several U.S. cities have wider-than-standard gauge for LRT and RRT (Philadelphia, 1.581 m; San Francisco BART, 1.676 m). In most cases use of nonstandard gauges is a great obstacle in efforts to integrate different rail systems. In Russia, standard gauge for both railways and transit is 1.524 m.

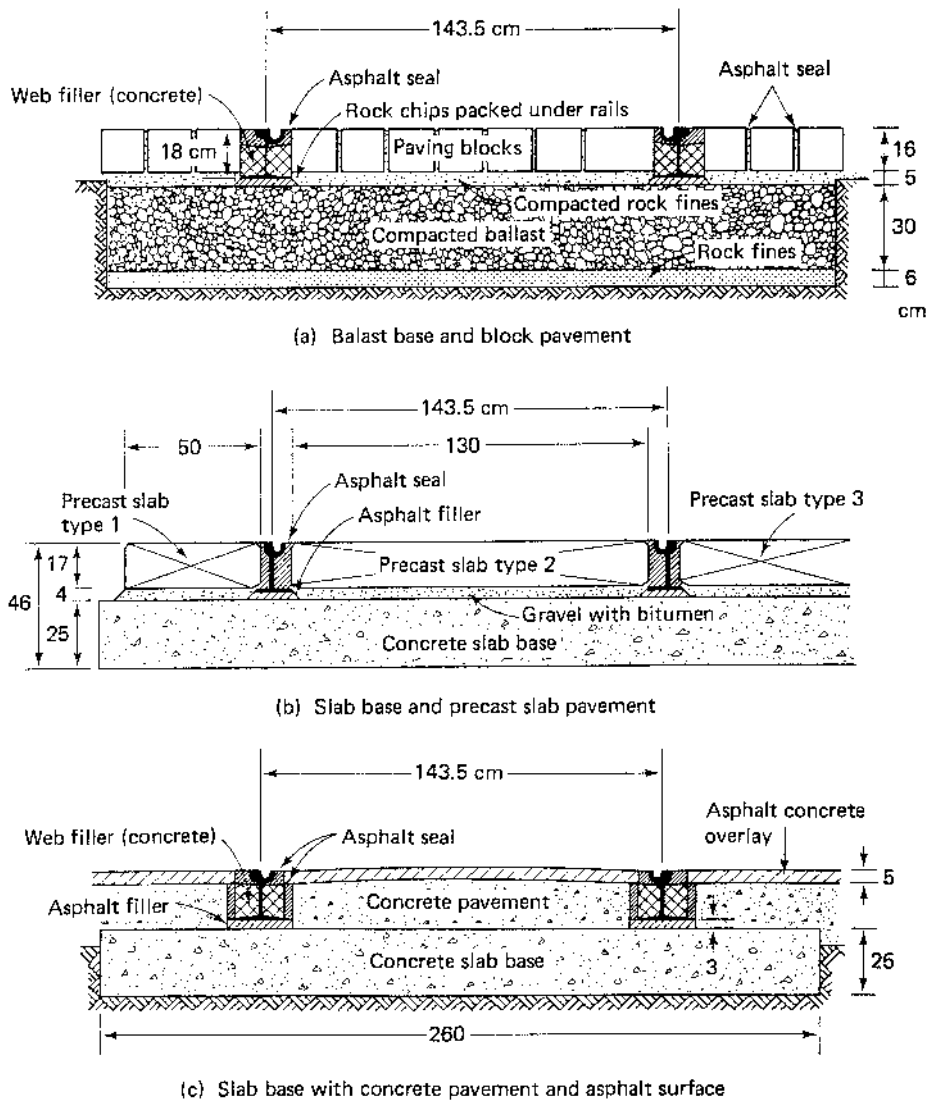
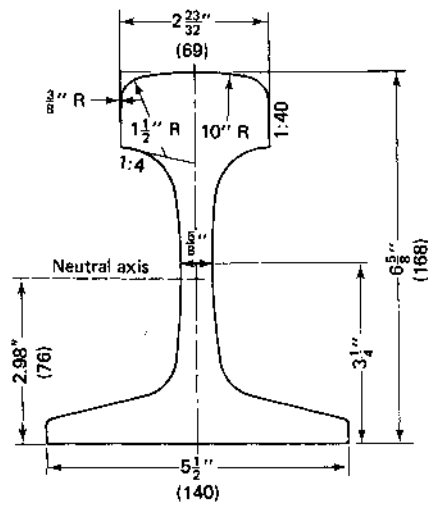


Figure 6.21 Different types of flexible track construction in pavement (Fox 1978)

The rails used for RRT and RGR transit usually have the same profile as lighter types of railroad rails. In the United States, a common profile of "T" rail is 80 to 115 (exceptionally 132) lb/yd (65 kg/m), in Germany 41 to 49 kg/m. Grooved girder rails, used for

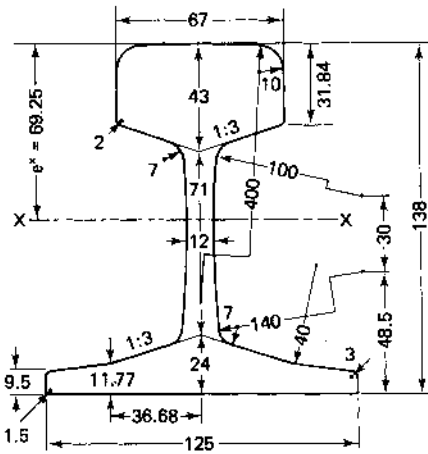
tracks in street pavements, are usually somewhat heavier. In Germany a profile of 59 kg/m is common. Typical rail profiles are shown in Figure 6.22.

Rails embedded in pavement have always been continuously welded, since they have good dissipation of

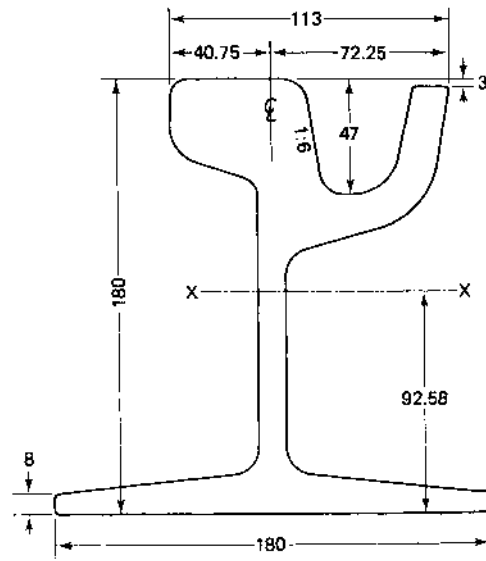


(a) Common RRT rail - USA
[in inches (mm)]

	Rail profile		
	(a)	(b)	(c)
Bending moment of inertia I [cm ⁴]	2732.2 (65.5 in ⁴)	1385.0	3257.0
Section modulus S [cm ³]	294.8 (18.0 in ³)	200.0	373.0
Weight per length g [kg/m]	57.07 (114.7 lb/yd)	41.4	58.96



(b) T-rail for LRT - W. Germany
(in mm)



(c) Grooved rail for LAT - W. Germany
(in mm)

Figure 6.22 Typical rail profiles

excessive heat. Free-standing rails, however, had to have expansion joints until the technique of anchoring the rails strongly to their supports was developed. This technique prevents the building of a longitudinal ex-

pansion force in the rails, thus making joints unnecessary. Introduced in wider use during the 1950s, welded rails are now standard for all modern transit (as well as railroad) systems.

6.3.2.2 Track Switches. The basic components of a single switch (also called a “turnout”) are shown in Figure 6.23 and Photo 6.22. Different types of switches are defined by the angles of the diverging tracks. The common switch designation in the United States is by the frog number (N), which represents the ratio (see Figure 6.23a):

$$N = \frac{k}{w} = \frac{1}{2 \tan \frac{\alpha}{2}} \approx \cot \alpha \quad (6.7)$$

The common practice in Europe is to define switches by $\tan \alpha$, or sometimes by $2 \sin (\alpha/2)$. Thus a switch No. 10 in the United States would be designated a 1:10 switch in Europe.

For SCR trackage in limited space, switches with sharp angles (Nos. 4 to 7) are used. LRT and RRT commonly use No. 9 switches; for high-speed operation, switches Nos. 12 to 18 are recommended.

The switch radius is a function of the frog number, N . Therefore, N (and thus curve radius) must be selected to suit the speed requirement for the “turning out” direction. For very slow operation, LRT systems use radii of 25, 50, and 100 m. For a speed of 40 and 50 km/h, radii of 190 and 300 m, respectively, are required. There is no speed reduction for travel in the straight direction.

The two rail points are the only movable parts of a conventional switch. While switch-point positioning can be done manually, on transit systems it is usually performed by an electric motor through remote electrical control by the vehicle driver (LRT), by a central control train dispatcher, or automatically by signals from the vehicle, which are preprogrammed for a complete train run along a route. The position of a switch can be changed in 0.6 s. The points are locked in one of the two positions whenever the presence of a vehicle is detected in the immediate vicinity. On signalized lines, green signals can be given only when the switches on respective track sections are locked in the proper position.

A “slip switch” and a “double slip switch,” shown in Fig. 6.23b and c, provide for, respectively, single or

double connections between two tracks intersecting each other at a small angle. These switches are often used to save space in stations, yards, and storage areas.

A switch can be built with a movable frog (Fig. 6.23d). This eliminates rail discontinuities at that point. Initially invented for very high speed railroads, this switch has been found useful for mixed operation of rolling stock with different wheel-rim profiles, such as LRT and regular railroads, because it eliminates the need for guardrails.

Track layouts in rail yards usually have many types of track switches and crossings, as illustrated in Photo 6.23.

6.3.2.3 Track Plan. To achieve operational flexibility and high reliability of service, rail transit lines should always be designed with an adequate number of sidings, turnback tracks, and crossovers for special movements. Many SCR systems operated by unidirectional vehicles sometimes have an intermediate loop to allow cutbacks of runs. Properly designed RRT lines have track connections between every three to four stations. These track designs, illustrated for typical LRT and RRT lines in Figure 6.24, and Photos 6.24 and 6.25 allow easier scheduling, reduced vehicle-km in operation through storage of equipment between peaks at convenient locations, and fast recovery from any disturbance by removing disabled vehicles, single-tracking operations, and so on.

6.3.3 Rights-of-Way

The *physical characteristics* of transit rights-of-way are mostly determined by their vertical positions and separation from other traffic. They can be classified into four general categories.

- *Elevated or aerial* utilizes embankments, viaducts (aerials), and bridges. It almost always has fully controlled operation (category A) for that portion of track.
- *At-grade* refers to ground-level operation of a transit line, which may have shared, semiexclusive, or fully exclusive treatment (C, B, or A, re-

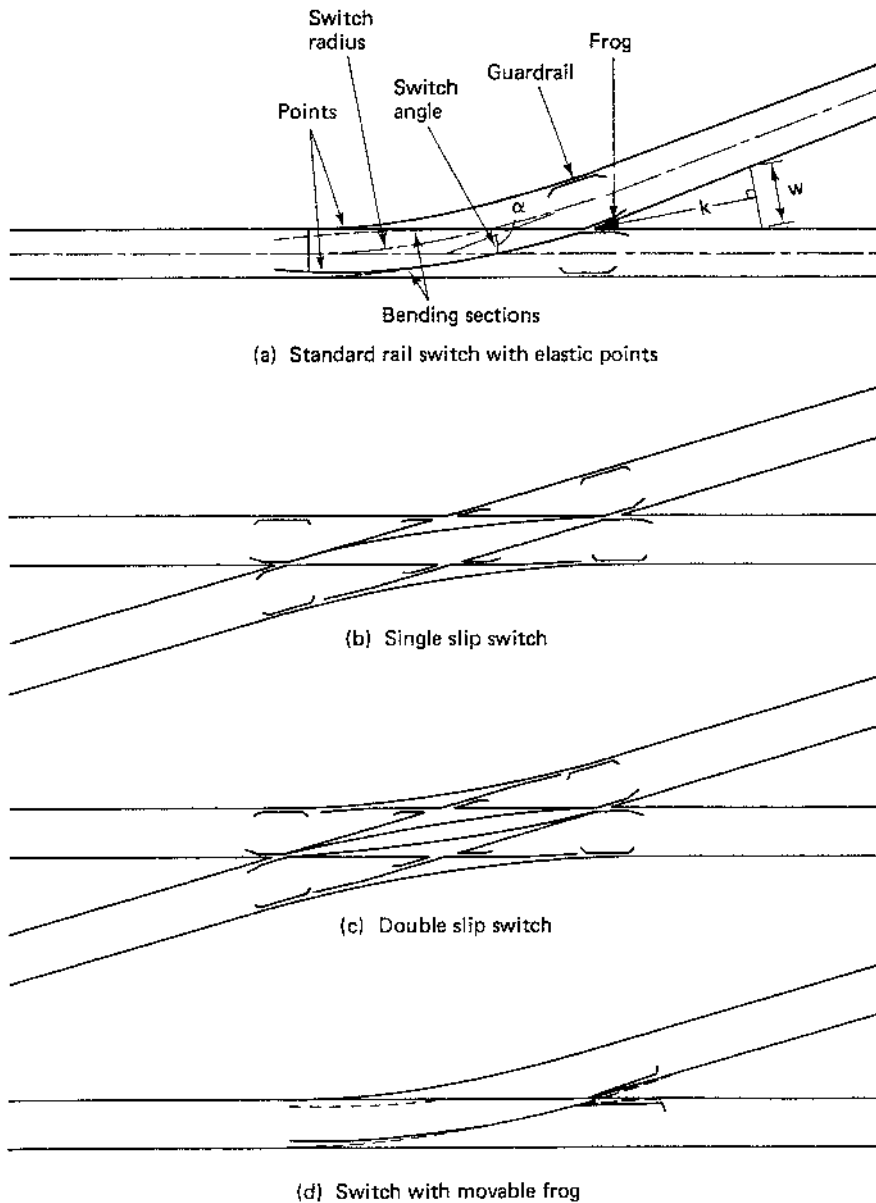


Figure 6.23 Different types of rail switches

spectively). In the exclusive case, curbs, barriers, turn prohibitions, special signals, and grade separation at important intersections may be incorporated.

- *Depressed ROW* refers to tracks placed below ground level but with an open-cut design. It is often used on sections for which visual or audio intrusion is to be minimized and for sections of



Photo 6.22 Modern rail switch with elastic points (Courtesy of James Aslaksen)

at-grade systems where there are several closely spaced intersections that require separation for high-speed, safe transit operation.

- *Tunnels* represent enclosed below-ground, fully controlled facilities specially constructed for transit.

Other important features of transit ROW include category B: *treatment of transit vehicles at crossings* (no priority or different degrees of it) and *locational characteristics* (e.g., park land, residential areas, pedestrian malls, transportation corridors, etc.).

Separation of transit from other traffic has the greatest influence on the operating and physical characteristics of the transit modes. ROW are therefore described here in the ascending order of their separation, which generally represents an ascending level of investment but also an increasing LOS, service quality (SQ), and passenger attraction.

6.3.3.1 Shared Rights-of-Way (Category C). Construction of tracks in street pavements is more costly than on independent ROW, but it does not involve the acquisition of land.

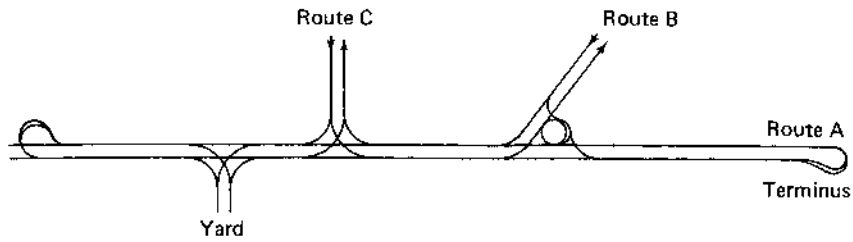
Position of tracks in streets is generally less desirable than on an independent ROW, but the quality of operation it offers can vary greatly as a function of the applied regulatory measures. Without such measures,



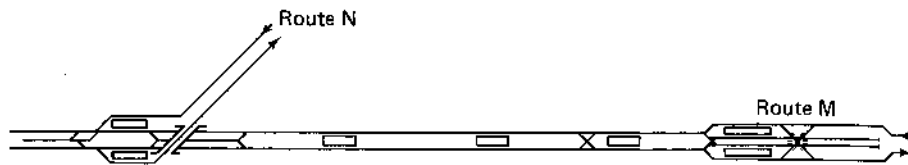
Photo 6.23 Track layout in a rapid transit yard with many types of track switches and crossings on Berlin U-Bahn

SCR operation causes friction with other traffic, and it is often less satisfactory than the operation of buses, which can maneuver better. Many innovative traffic engineering measures, extensively used in European cities with LRT systems, have shown that the friction between rail vehicles and other traffic can be greatly reduced, so that LRT street running is in many cases quite efficient and safe (Amsterdam, Zürich). The most common regulatory measures are the following:

Elimination of left turns at minor intersections and their control by special signal phases at major intersections, where turning lanes can be separated from the tracks.



(a) Unidirectional vehicles (some SCR and LRT): several loops or "Y's" on each line for turning vehicles back when required



(b) Bidirectional vehicles (RRT, RGR, some LRT): frequent crossovers and storage tracks

Figure 6.24 Track layout for flexible operations



Photo 6.24 Entrance to the Chicago "Loop." Substandard at-grade crossing but handles record train frequencies (Courtesy of CTA)



Photo 6.25 Track layout in a multitrack station of the London Tube allows many train routings (Courtesy of Stephen Knight)

Prohibition of cross traffic at nonsignalized intersections: only right turns into and out of cross streets are permitted. This measure is usually desirable for other modes besides rail traffic on arterials also.

Introduction of “signal islands” at transit stops. As Figure 6.25a shows, a signal island consists of a signal and a stop line prior to a near-side transit stop. The signal applies to auto traffic only. It is always green except when a rail vehicle approaches the stop and activates it via an overhead wire. The red signal prevents automobiles from entering the passenger boarding/alighting zone.

Curbed pedestrian islands should be provided for stops whenever sufficient width exists. At dangerous locations, a physical barrier in the direction of oncoming traffic should be provided. At stops with high passenger volumes, a signal island should also be used for safe pedestrian crossing between the island and the sidewalk (Figure 6.25b).

Actuation of signals at intersections by rail vehicles, combined with signal islands, allows rail vehicles to get ahead of other traffic in crossing the intersection.

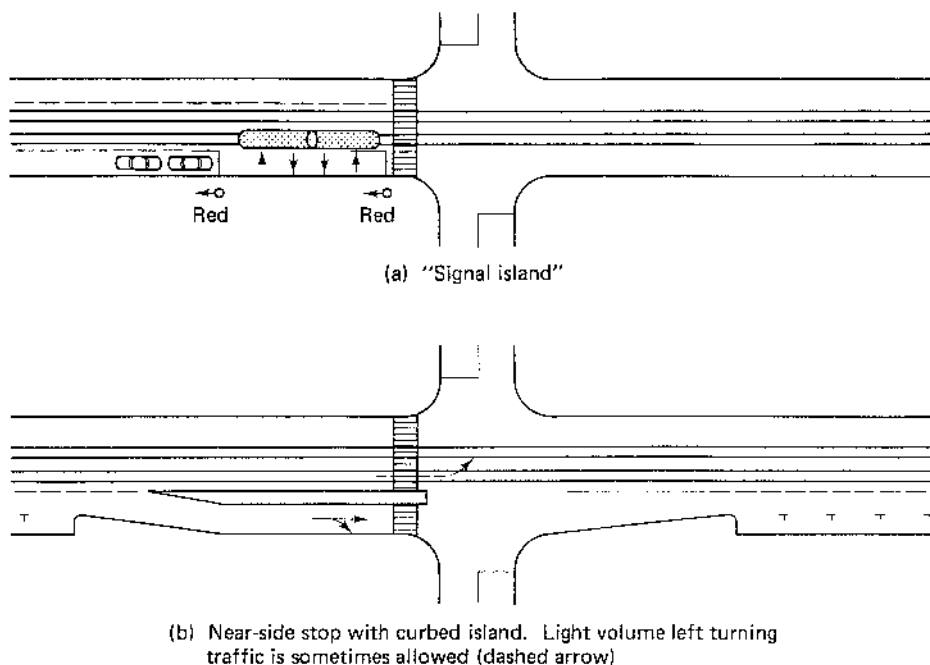


Figure 6.25 LRT/streetcar stops with “signal island” and curbed island

Special signal phases for turning rail vehicles allow them movement without undue delays.

Elimination of parking through prohibition or creation of parking bays by street reconstruction reduces impedance to traffic flow or may allow introduction of a reserved track area. In many cases elimination of parking can make creation of ROW B for LRT tracks feasible.

Reserved transit lanes can be delineated by a single solid line, diagonal striping of the track area, or by metal or plastic studs in the pavement, similar to those used on California freeways for lane lines.

Asymmetric track positions and contraflow operation using markings or curbs for separation from other traffic are usually very effective on one-way streets. Two typical cases in Figure 6.26 show that adjacent track and auto lanes need not be separated when they are in the same direction, but a curb is required when they are opposite, particularly with “left-hand driving.”

Joint use of reserved lanes by LRT and buses has been introduced on special sections, such as bridges (Gothenburg), tunnels (Pittsburgh), and transit stop areas (Bremen, The Hague). This mixed operation requires greater than minimum distance between tracks because of the lower driving precision of the buses.

LRT lines in pedestrian malls are successfully operated in dozens of cities in Europe (Grenoble, Karlsruhe, Mannheim, Oslo, Zürich) as well as in other countries (Calgary, Melbourne, Portland, Sacramento). LRT vehicles travel at moderate speeds and provide immediate service to high-attraction pedestrian areas. Experience has shown that the safety of this operation is good. Fixed paths, quietness, and lack of exhaust from the rail vehicles make them more compatible with pedestrian areas than buses (Photo 6.26).

All these and many other traffic engineering solutions for improved street operations of rail vehicles have been introduced in many European cities since the mid-1960s, with very significant results. Some of the best examples of traffic improvement through these measures are found in most Austrian, Dutch, German, French, Swiss, and other cities.

6.3.3.2 Separate Rights-of-Way (Category B). This category includes ROW physically protected by curbs or barriers that prevent other vehicles from en-

tering the ROW under normal conditions. Entrance of special vehicles (emergency) is sometimes permitted, and pedestrian crossings are usually possible. Intersections are in most cases at grade. Physical separation instead of only by lane lines is a major step in improvement from in-street rail operations, and several technical solutions for it exist.

Curbs and small elevation in existing pavement represent an effective, low-cost measure that can be quickly implemented. This creates the required separation, although only a minimal one, with a temporary appearance (Figure 6.27a).

Curbs with raised track area (Figure 6.27b), usually with a gravel or grass surface, is by far the most common design of separated tracks in streets. It gives a distinct identity to the transit ROW, discourages uncontrolled crossings by pedestrians, and allows simple, easy-to-maintain track construction. Grass-covered medians with only four tracks visible give a particularly attractive, environmentally friendly appearance.

The curbed ROW is usually placed in the center of the street, as shown in Figure 6.27a,b. Symmetric locations on each side between roadway and sidewalks, as well as asymmetric location of both tracks on one side of the roadway are also possible (Figure 6.27c,d). The central location generally permits higher speeds because it is farther from slow traffic lanes and pedestrian sidewalks, and it allows better a geometry of turning movements at intersections (lateral positions require a special signal phase for left turning track to cross both directions of traffic simultaneously). A major advantage of lateral positions is that they do not require two separate directional roadways. Recommended and minimum dimensions for the three designs are given in Figure 6.27. Figure 6.28 shows the detailed minimum median dimensions within medians. It is obvious that designs in Figure 6.27 (c) and (d) can be used in considerably narrower streets than (b). However, because of its superior operational characteristics, a central location (b) is always preferable when the required street width is available.

Wherever the width of the curbed ROW allows, additional separation should be provided. A chain or fence between the tracks in the central median can be used to prevent pedestrians from crossing the tracks at midblock locations. Bushes, shrubbery, and even flow-

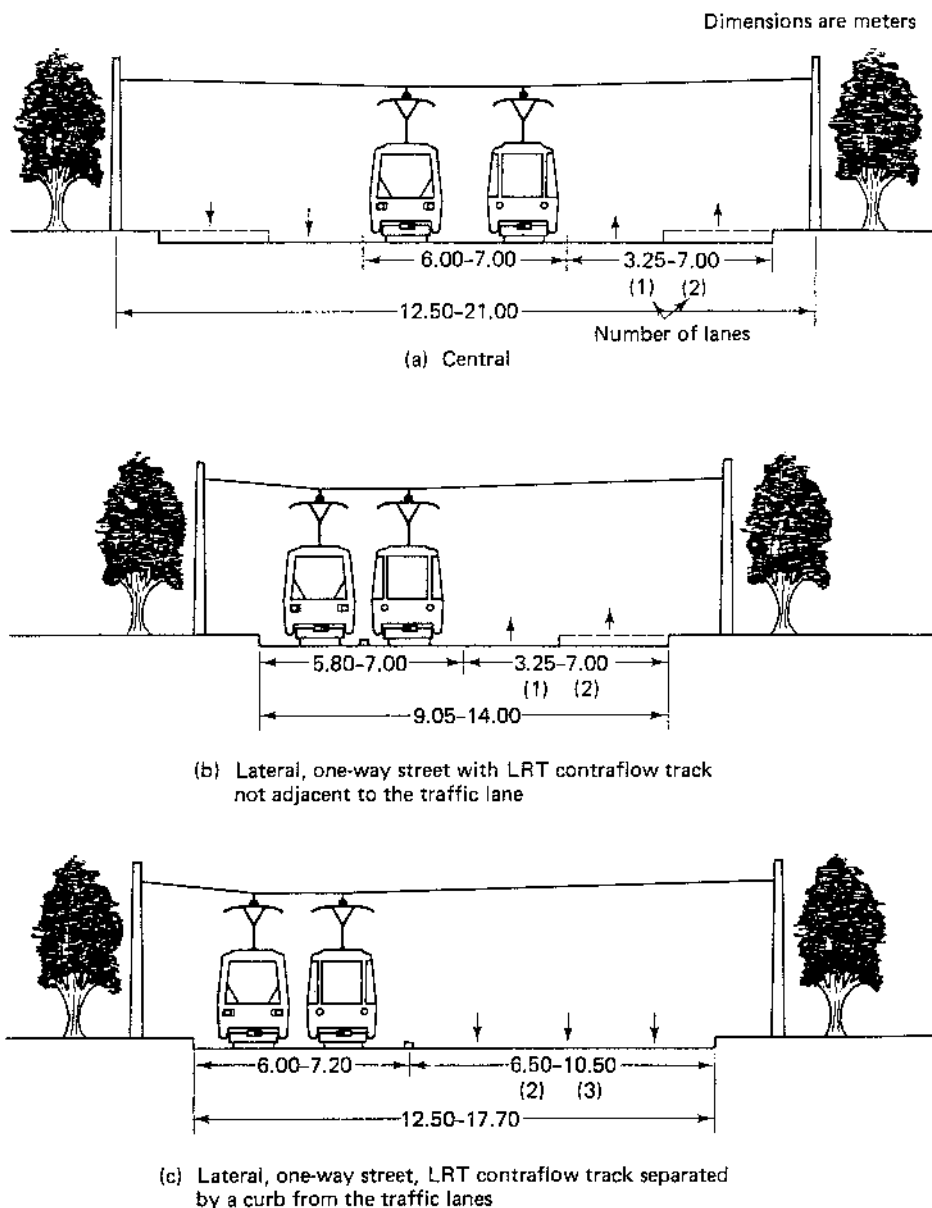


Figure 6.26 Different LRT track positions in street

ers are often planted between the tracks and the roadways or between tracks located in a lateral position and the sidewalks. These plantings require some width (minimum about 1 m) and involve maintenance, but

they improve safety and greatly enhance the aesthetic appearance of the entire street.

Tracks through green strips or parks are found in many cities. They require low investment and main-



Photo 6.26 Light rail operates in pedestrian malls in many cities (Kassel)

tenance costs and offer riders a very pleasant travel environment, as Photo 6.27 illustrates (see also Section 6.3.2.1).

The highest degree of separation at grade is achieved by *concrete barriers* placed between the tracks and roadways. However, this design is seldom used because the barriers are aesthetically much less satisfactory than plantings. In some cases, the possibility of crossing the ROW for special purposes (maintenance, emergency, etc.), which plantings allow, is considered desirable.

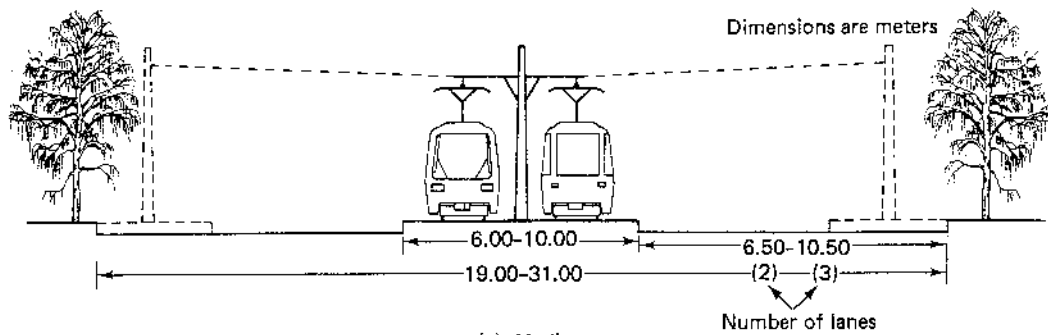
Naturally, all these physical separators are discontinued at intersections. Carefully designed pedestrian crossings, sometimes controlled by actuated signals, can be provided at midblock locations.

Curbed ROW in the median must accommodate areas for passenger stops and stations. When a wide ROW is available, this is achieved by discontinuing plantings at stop locations. With minimum-width medians, widenings must be provided. An economical and

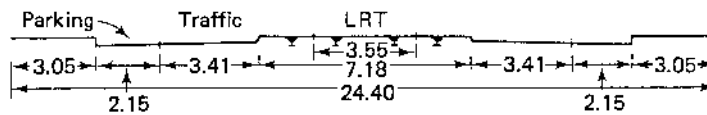
operationally adequate design for intermediate ROW widths involves the introduction of a mild S curve in the track alignment, which allows use of the same width for stops in both directions. Several common intersection designs with LRT medians without and with left turns are shown in Figures 6.29 and 6.30, respectively. For evaluation of reserved ROW for LRT, see the box on page 375.

The fact that the curbed track area cannot be shared by turning automobile traffic is actually a major advantage. Where it is absolutely necessary, left turns can be accommodated by lowering and paving a short section of the track at the intersection approach.

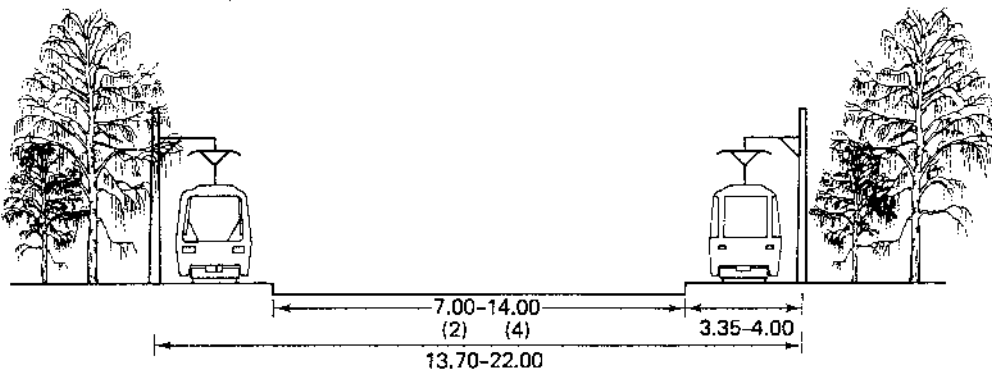
6.3.3.3 Treatment of Rail Transit at Intersections and Crossings. Priority treatment of rail vehicles at intersections is important because they are locations of the most frequent delays. Track separation on reserved lanes or curbed ROW makes priority treatments easier. The major methods for priority, in sequence of increasing benefits to rail transit, are:



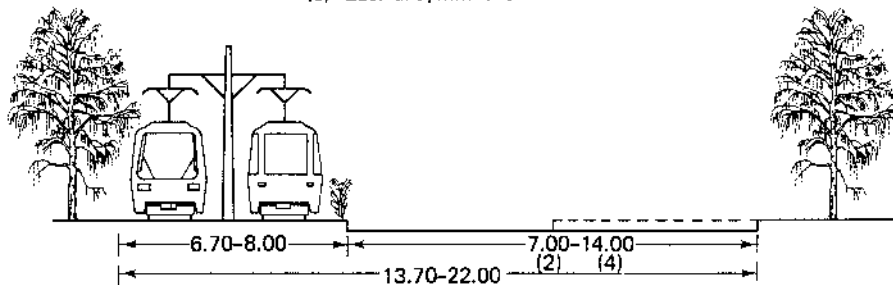
(a) Median



(b) Median on a reconstructed street, restricted width (San Francisco).



(c) Lateral symmetric



(d) Lateral asymmetric

Figure 6.27 Curbed LRT rights-of-way

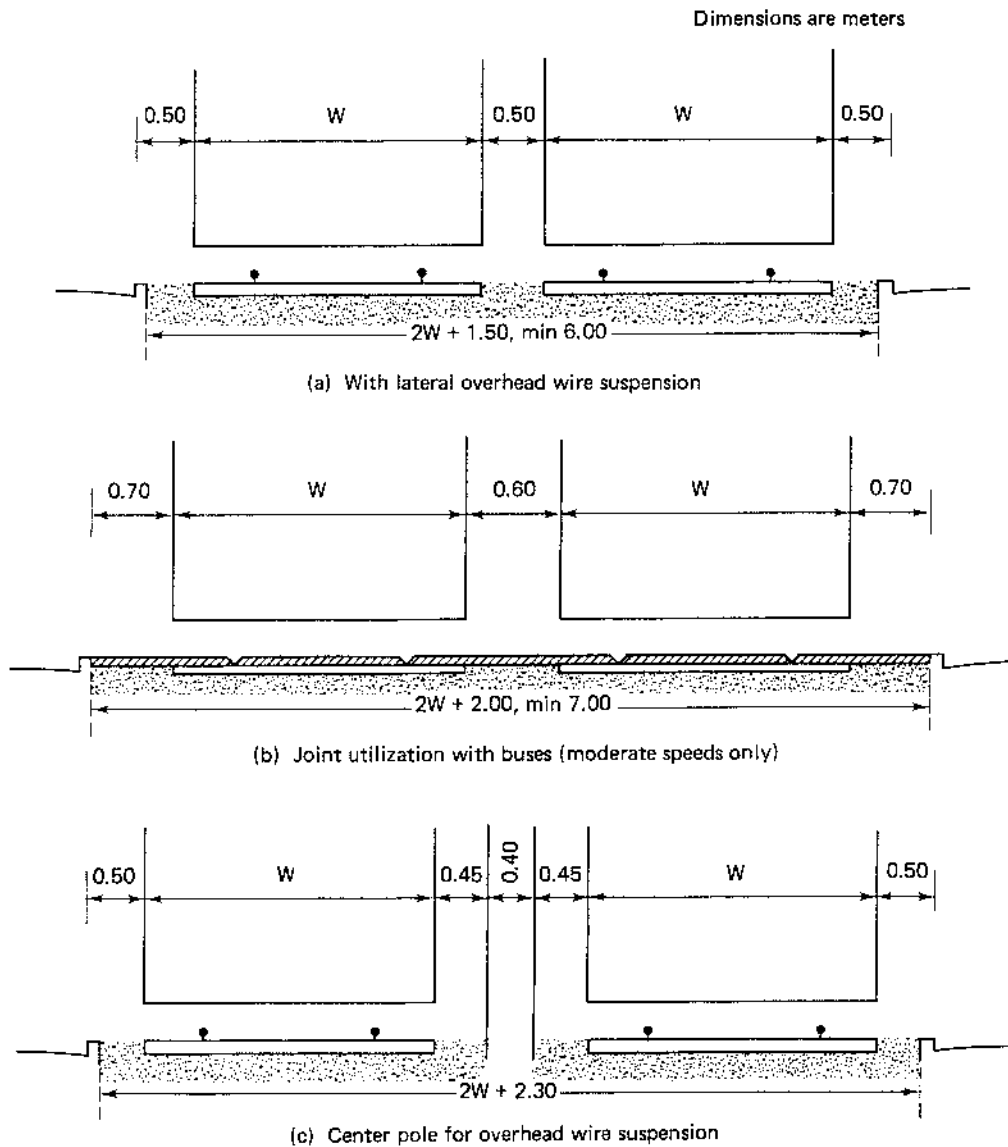


Figure 6.28 Minimum widths of curbed medians with LRT tracks

- Elimination of left turns for auto traffic
- “LRT gate” regulation, similar to a bus gate (see Section 5.3.3.3)
- Special signal phases for rail vehicles in fixed-time cycle
- Signal actuation by rail vehicles

- Actuated flashing signals and barriers (signal pre-emption)
- Grade separation of the track.

The first method was discussed in the preceding section. Special signal phases are useful to give faster and safer passage of rail vehicles, particularly for turn-



Photo 6.27 Light rail ROW through a park in Antwerp (Courtesy of John W. Lozier, Ph.D.)

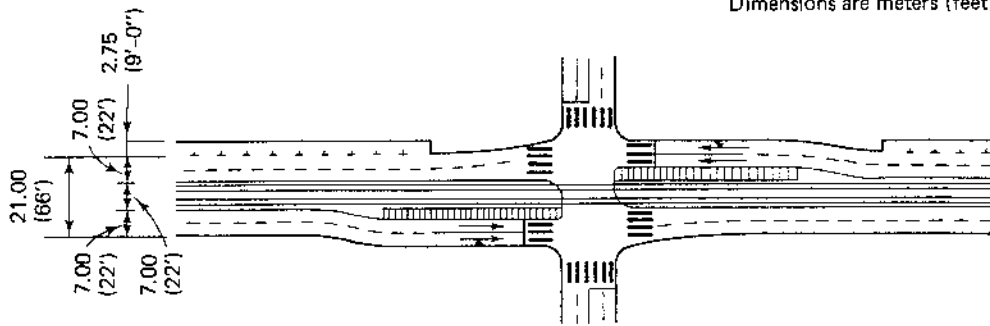
ing. Signal actuation can have several forms. The first is when actuation gives rail vehicles an advanced or a lagging green (Figure 6.31), decreasing the probability that the vehicle will encounter a red phase. Full signal override by rail vehicles always provides a free signal and gives the high-capacity rail vehicles passage without delay at the expense of cross-street traffic. Rail vehicle travel can be partially or fully synchronized with signal progression along the same street by careful timing and selection of LRT stop locations before and after intersections.

In many cities different types of SCR/LRT priorities are used, singly or in combination. “Fitting” of LRT vehicle travel in signal progression by strategic locations of LRT stops in relation to signalized intersections is used on Eschersheimer Strasse in Frankfurt; signal override by LRT with barrier protection has

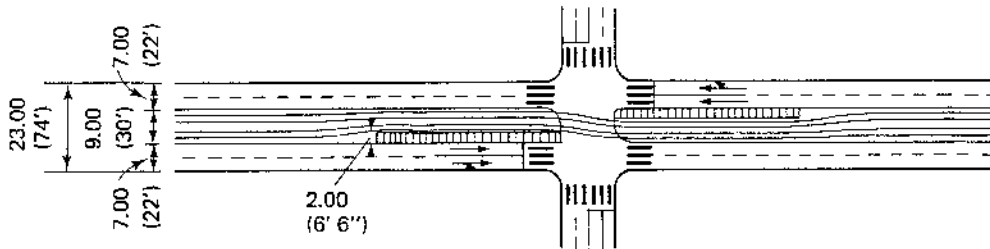
been successfully applied on the LRT lines in Edmonton, Denver, RiverLine between Trenton and Camden in New Jersey, and a number of other cities.

Grade crossings of tracks by streets or pedestrian paths are regulated in a number of ways, depending on the type of rail line and the character of crossing traffic. Small, lightly traveled streets crossing SCR and LRT lines with speeds not exceeding 70 km/h where visibility is adequate can be controlled by stop signs or by flashing red lights actuated by rail vehicles. For LRT lines with higher speeds and all crossings of RGR tracks, flashing lights and barriers must be provided. With automatic protection of this type and careful design for control of pedestrians, safety can be very good, so that the crossings need not involve any speed reduction by rail vehicles. For example, most private railway lines that provide regional service to Japanese

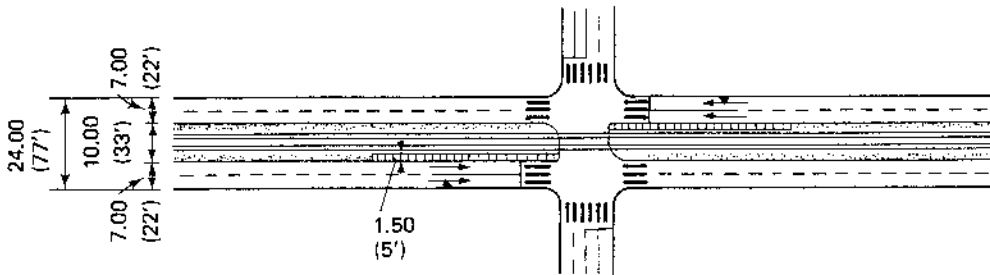
Dimensions are meters (feet)



(a) Minimum width median, stop area obtained from parking lane and street widening, respectively



(b) Median width greater than minimum allows space for staggered stops by introduction of a mild "S" curve in the tracks



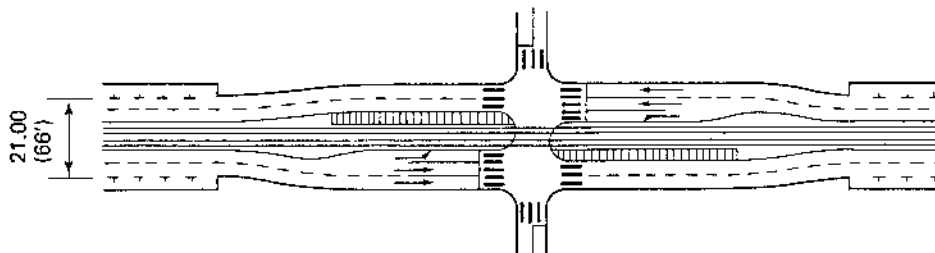
(c) Median width greater than in (b) allows space for stops and a strip of greenery



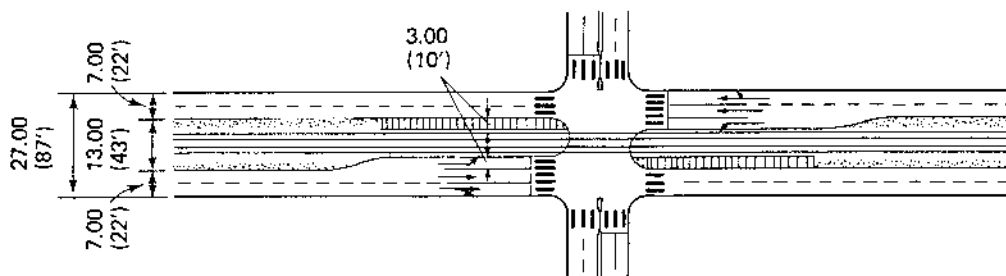
(d) Signal phasing (all three designs)

Figure 6.29 Design of intersection with LRT median, no left turns allowed

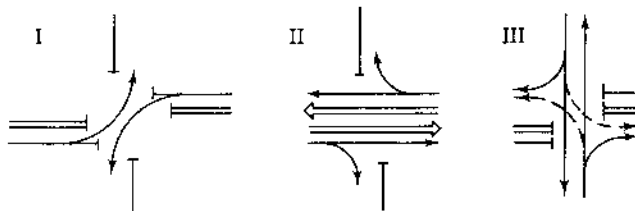
Dimensions are meters (feet)



(a) The same cross section as in Fig. 5-29a, but use of far-side stops allows provision of left turn lanes. Parking lanes on both sides



(b) Wide median with a green strip accommodates both stops (far-side) and left turn lanes



(c) Signal phasing (both designs)

Figure 6.30 Design of intersection with LRT median, left turns accommodated

cities (Tokyo, Kobe, Kyoto, Osaka, and others) have numerous automatically protected street crossings over which trains run at up to 110 km/h with a good safety record. In the United States, a number of states (e.g., California, Texas) require LRT trains to initiate a loud horn signal approaching all gated crossings. The noise resulting from this excessive requirement is a major source of environmental intrusion into the community.

Grade separation is the best solution wherever space conditions allow and capital can be found, because it provides absolute safety and eliminates interference by other traffic. Grade separation of LRT at intersections is provided for in one of three ways: underpass, overpass, or viaduct. The underpass is most common, since the downgrade-upgrade sequence is efficient for maintenance of speed; additionally, under-

In review, *physically protected ROW*, compared with *reserved (designated) lanes* for LRT, has:

- + Considerably higher LOS, particularly speed and reliability
- + Reduced operating cost because of higher speed and productivity
- + No need for enforcement
- + Much better visual identification
- + Greater passenger attraction
- + Better aesthetics and lower noise when plantings are used
- Somewhat greater width requirement
- In some cases, higher investment cost
- If plantings are used, the need for additional maintenance

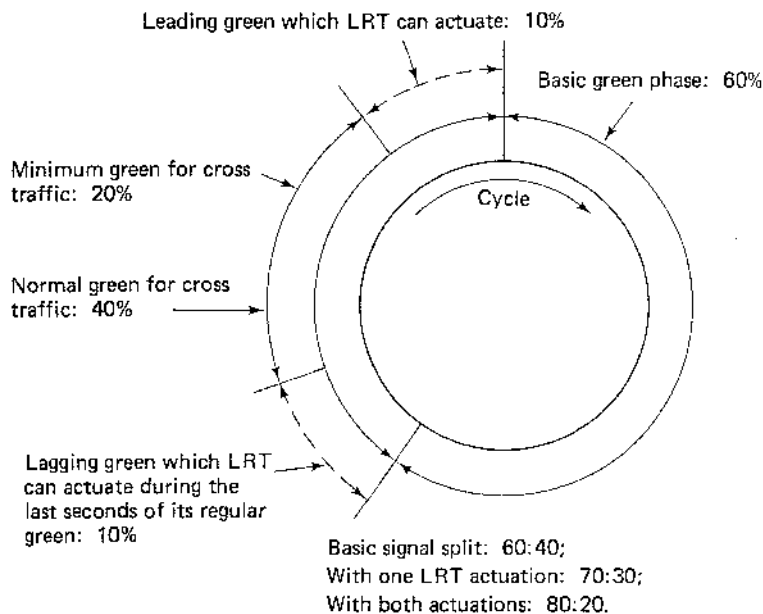


Figure 6.31 Signal cycle with possible LRT actuation

passes are visually unobtrusive. Since LRT vehicles can easily negotiate 5% to 6% gradients, underpasses do not require excessive length. Lower gradients may be used if later conversion to RRT is considered.

Where geometric conditions and other factors are conducive, overpasses and viaducts can be effectively deployed at major intersections or longer line sections (Cologne, Denver, Rotterdam, and Sacramento). LRT

overpasses and viaducts are generally far less objectionable than elevated highways, since they produce much less noise, take several times less space, and have a lighter appearance. Again, RRT design standards should be used if later conversion to that mode is possible.

Because of the high geometric standards of RGR, its grade separations can be achieved only by raising



Photo 6.28 BART train on aerial structure

or lowering cross streets or by placing its ROW on a long viaduct or in a cut.

The next step of priority is to provide LRT with an *independent ROW* aligned and designed to suit the specific needs of the transit service. Such ROW for LRT lines may parallel existing arterial streets and may be placed in parks or on unused or used railroad ROW. This type of alignment may be used for short segments or for entire routes.

6.3.3.4 Elevated/Aerial Rights-of-Way (Category A). Many rail transit systems utilize elevated structures, since—with the exception of considerably more expensive tunnels—they sometimes represent the only possibility for grade-separated ROW in built-up urban areas.

Typical steel RRT and RGR elevated structures, which still exist in many cities, have serious deficiencies with respect to their environmental aspects. The complicated, heavy structure is aesthetically objectionable, it transmits and radiates noise, and its two rows

of supporting columns impede traffic if the structure is within a street roadway. In some cases (e.g., New York, Philadelphia, Chicago) these structures have had, in the long run, negative impacts on their surrounding areas.

Stone viaducts, built as early as the 1890s for RRT and RGR lines (Berlin, New York), have fewer negative impacts, but their massive structures are expensive to construct.

The advent of prestressed concrete led to a radical change in the characteristics of elevated transit structures. Instead of the heavy steel designs, modern “aerial” structures have a sleek, aesthetically pleasing appearance, as Photo 6.28 clearly illustrates. Typical structures consist of a single column supporting concrete roadbeds for two tracks. The column diameter may be only 1.00 to 1.50 m; the span between columns is usually 20 to 30 m. The total width of the structure for two tracks and a “catwalk” for maintenance and emergencies is usually about 7.75 m for RRT and approximately 0.50 m narrower for LRT systems (Figure 6.32).

Dimensions are meters

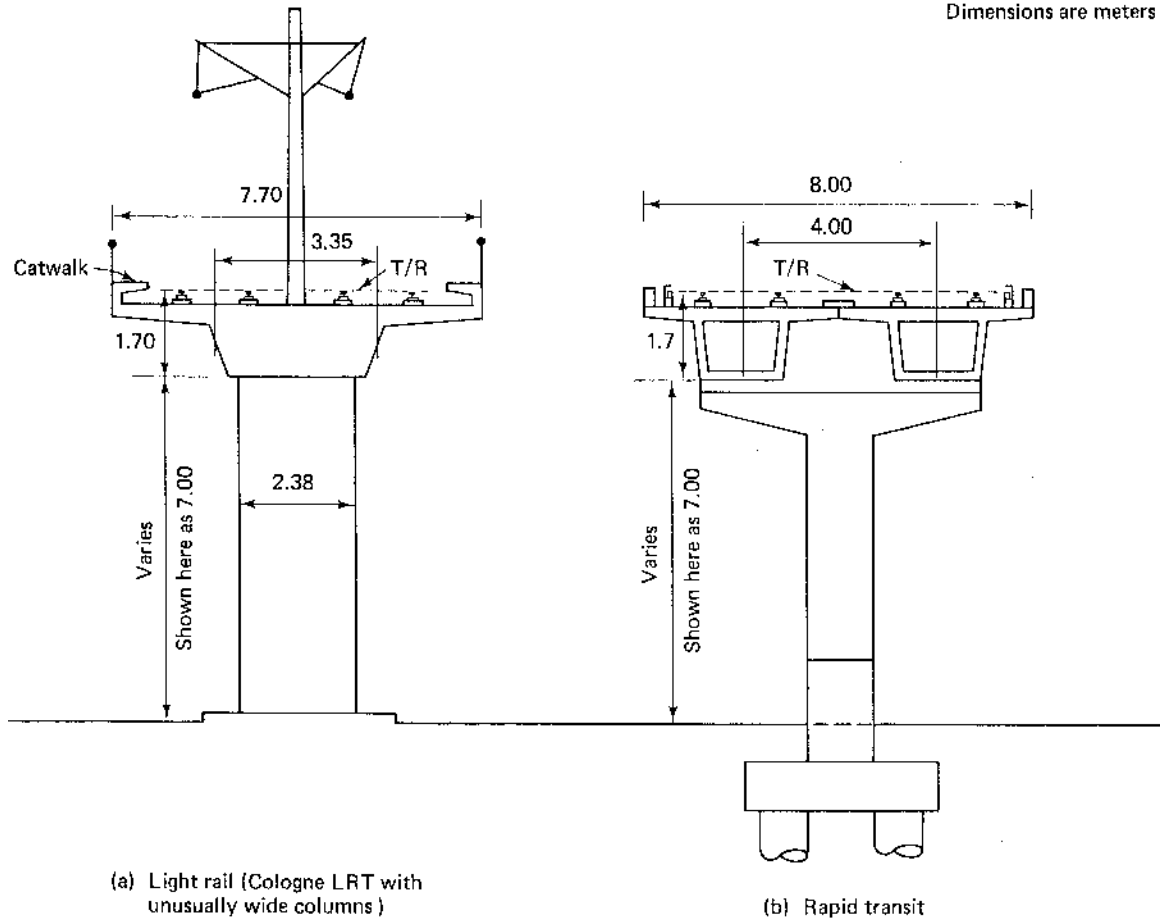


Figure 6.32 Cross sections of aerial LRT and RRT structures

The opposition to construction of aerial rail transit structures sometimes encountered in neighborhoods or entire cities is based primarily on experience with the old-type elevated steel structures. Such objections are less applicable to the modern aerial structures. Once the public becomes fully aware of the drastic differences between the two, opposition tends to subside. The use of aerial transit structures depends, however, on the densities and types of land uses of surrounding areas.

Primary alignments for aerial or independent at-grade transit ROW are wide avenues and boulevards, railroad rights-of-way, and freeway medians where

there are overpasses for access to stations. Independent alignments through open spaces, along rivers, and so on, can also be used. Even the most modern aerial structures are objectionable in streets with limited free space and tall buildings because of the columns, visual intrusion of the structure, some noise production, and the difficulties in fitting aerial stations.

Consequently, present trends in the use of aerial structures vary with their locations. Old elevated structures in built-up areas, such as the Chicago Loop, are in some cases being replaced by tunnels. In outlying areas, the old structures are being replaced by new concrete ones. The major difficulties in this replacement

are the cost and complexity of maintaining service during the reconstruction. For new RRT and LRT and some RGR lines, aerial structures are used extensively in outlying areas as well as on convenient alignments within built-up areas.

Embankments are frequently used for RRT and RGR lines in outlying areas. They require lower investment than aerial structures but take a wider ROW and, most importantly, represent a strong physical barrier between the areas on the two sides. The only connection is through underpasses.

6.3.3.5 Tunnels (Category A). Rail transit systems use tunnels extensively, particularly in central urban areas. They are most often used for RRT, but also for sections of RGR and LRT networks.

Tunnels represent the ultimate solution in ROW control: transit operation in them is physically protected from all interferences, including weather. Reliability and safety of operation are therefore extremely high and maintenance of tracks and facilities is low.

Building of transit tunnels involves higher cost than any other ROW type. Also, it often causes considerable street disruption during several months or even the 1 to 2 years needed for construction. The disturbance is, however, often caused not only by the tunnel construction but also by major redesign of the street and adjacent areas, which are side benefits of metro construction. For example, Market Street in San Francisco was reconstructed, upgraded, and made much more livable at the time of BART/Muni tunnel construction around 1970. Similar rebuilding of avenues or large plazas was done with the construction of the metro system tunnels in Mexico, Montreal, and Washington, LRT tunnels in Hannover, and dozens of other cities. However, once it is finished, the transit tunnel is the most permanent ROW and usually has no negative environmental impact on the surroundings (sometimes close buildings experience vibrations).

Tunnels can be of two different types, according to their alignment, elevation, and construction method. *Shallow tunnels* (with floors usually less than 20 m below street surface) are built from the surface; they follow street alignments or other open areas. *Deep tunnels* are constructed by boring techniques at greater

depths (sometimes as deep as 60 m) and can have alignments independent of the street network. The construction techniques for the two are very different.

The *cut-and-cover* construction method encompasses a series of steps; the major ones, illustrated in Figure 6.33(a), are as follows. Preparatory work consists of removing utilities from the areas to be excavated for tunnel construction. Usually, the utilities (water, sewer, electric, gas, telephone, fiberoptic cables, and others) are relocated under the sidewalks. In some cases, they are suspended during the construction and then permanently left in the same locations. Construction starts with the driving of soldier piles, which form the supporting walls for the large trench. Excavation of earth between the walls by excavators then starts, and as it proceeds, cross beams are added both to hold the supporting walls and, in some cases, to carry a temporary roadway, pedestrian bridges, suspended utilities, and so on, as Photo 6.29 shows. In some terrains, water must be continuously pumped out as the excavation proceeds, until the depth required for the bottom of the future tunnel is reached; then a concrete tunnel is built. It is usually rectangular and contains both tracks.

The tunnel must have complete water insulation, which can be achieved by several different methods, depending on the type of construction and local conditions. Precise work is required, but it is possible to achieve permanent insulation of tunnels even where they are well below the underground water level. Careful insulation is extremely important, because the repair of leaks is very difficult.

When the tunnel structure is finished, it is covered by earth and the street pavement is reconstructed.

Cover-and-cut or “*Milan*” (Figure 6.33b) is another method of tunnel construction. First developed in the city of Milan, Italy, it is considerably different from the cut-and-cover method. Following the relocation of utilities, deep, narrow trenches are excavated along both future tunnel walls. The trenches are filled with a bentonite slurry, which supports their sides until the excavation is completed. Reinforcing steel is then placed in the trenches, and the slurry is displaced by poured concrete, forming reinforced tunnel walls.

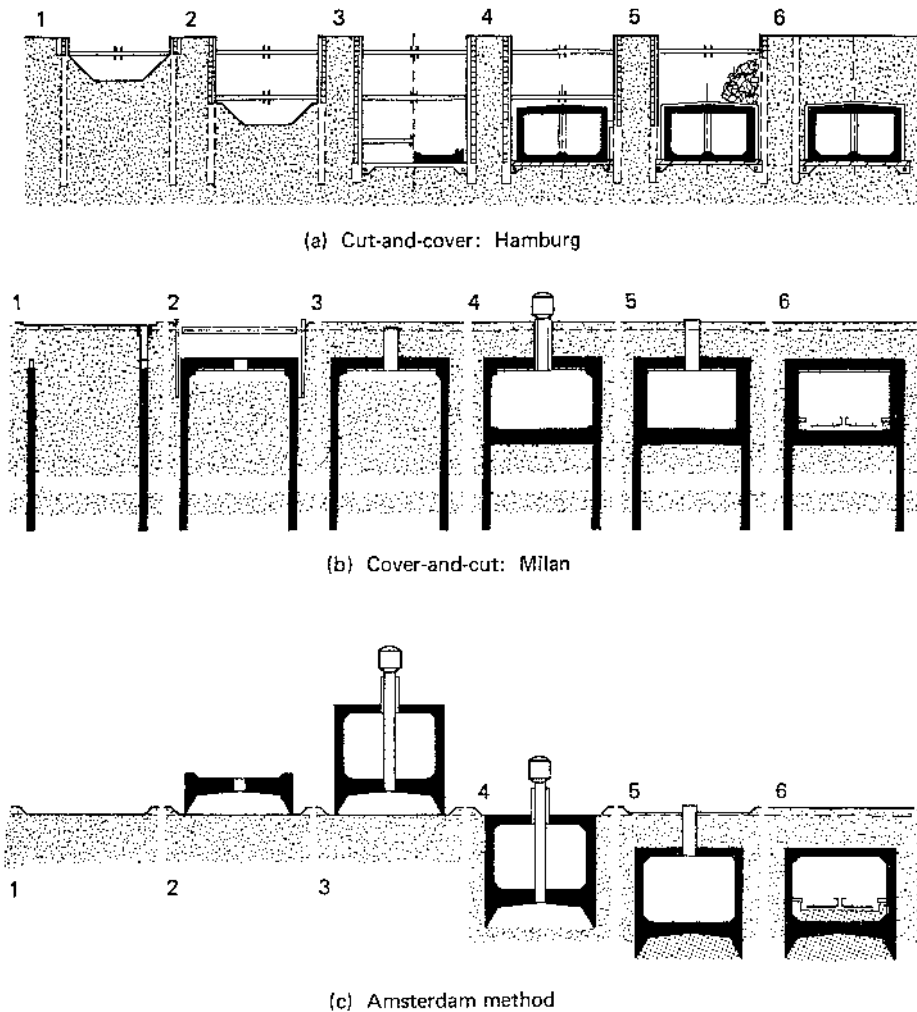


Figure 6.33 Different methods of shallow tunnel construction

Only now is street traffic diverted from the street, and the area between the two tunnel walls is excavated to the level of the future tunnel roof. The roof is then constructed, the trench is filled, and the street reconstructed and opened to traffic. The final step is then excavation of the tunnel inside the roof and finished walls, followed by construction of the tunnel floor.

The Milan construction method has advantages over the cut-and-cover method in that street disruption is much shorter and sheet piling is not necessary. Al-

though the construction works may be more complex and several cities found them more expensive than the cut-and-cover method, the Milan method is advantageous where minimum interruption of street traffic is very important.

The *tunneling* method consists of digging shafts in the ground at several locations along the subway alignment and boring tunnels by techniques similar to those of railroad tunnel construction. Various methods of tunneling exist, most of them utilizing tunnel-boring

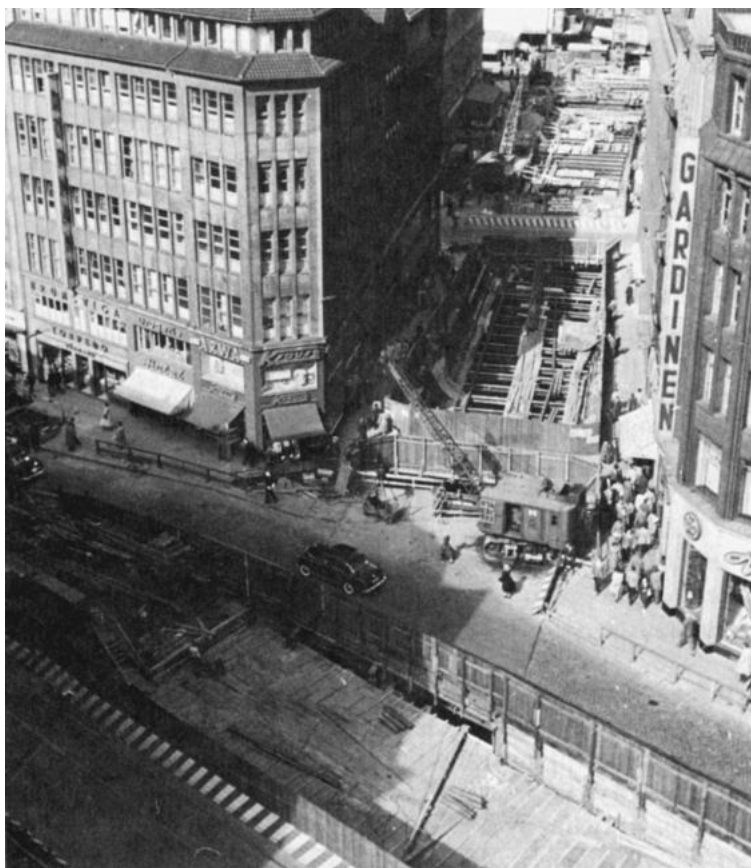


Photo 6.29 Cut-and-cover RRT tunnel construction (Courtesy of Hamburger Hochbahn AG)

machines (TBMs), which have shields with blades similar to those of meat-grinding machines for excavating the ground. The excavated material is loaded on open narrow-gauge rail cars and carried to the shafts, where it is lifted to the surface. The shield is pushed by jacks and, as it moves ahead, a steel lining is built to support the earth surfaces. Once the lining is in place, a concrete shell is built, forming the tunnel.

The type of tunneling shield depends on the construction conditions. Dry, stable ground allows the use of rotary-head machines. Closed-face machines must be used where the soil is unstable and caving-in is possible. For excavation below the groundwater level, special construction methods with high air pressure must be used. Figure 6.34 illustrates a construction

method used under normal conditions; a finished tunnel is shown in Photo 6.30.

The choice of shallow or deep tunnels and their respective construction methods should be made on the basis of their comparison for local conditions in the city or along the individual line. There are considerable differences between these two tunnel types, not only in construction but also in vehicle sizes and, particularly, in metro line alignments, station locations, and the relationship between the system and the city in general. Deep tunnels make the metro network less accessible because of the greater differences in elevation that passengers have to negotiate. This makes metros with deep tunnels, such as those of Moscow Metro and London Tubes, much less convenient to use for short-

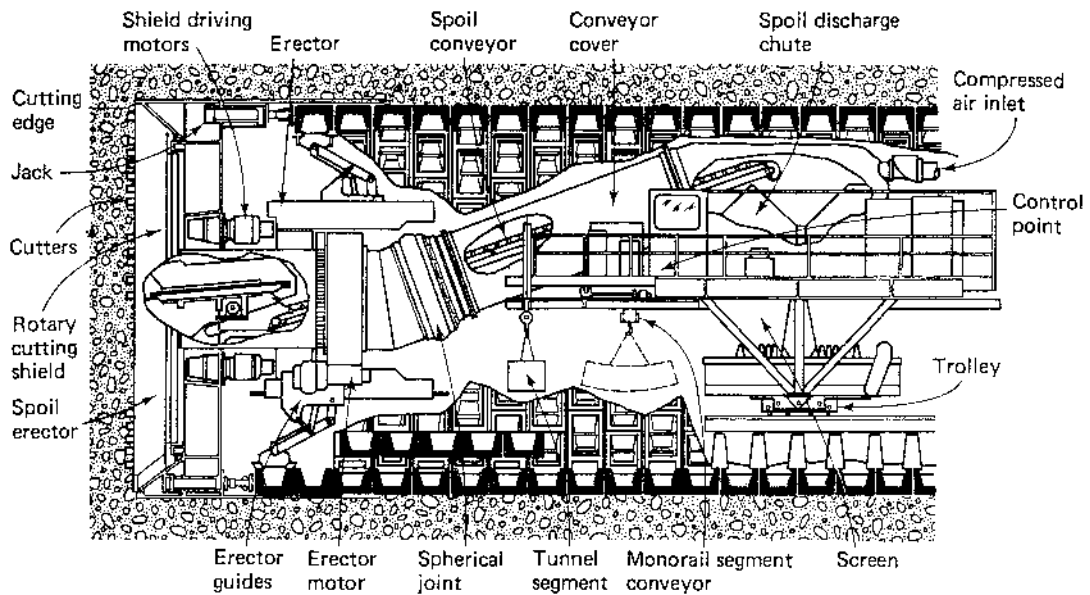


Figure 6.34 Tunnel construction by tunnel-boring machine (TBM) (*The Railway Gazette*, 1966)



Photo 6.30 Bored tunnel in Prague with Soviet-designed standard RRT vehicle (Courtesy of Praha Metro; photo by Antonin Plevka)

to medium-length trips than the Paris Metro and New York Subway, which use mostly shallow tunnels (see the box).

Consequently a majority of RRT system alignments follow major streets and utilize shallow tunnels. Tunneling is applied for individual sections where deep

Shallow tunnels, compared with *deep tunnels*, have the following advantages (+) and disadvantages (-):

- + More convenient for passengers because of the smaller vertical distance from the street level.
- + Station mezzanine areas immediately below the surface can be used for basement entrances to buildings, as locations of stores, and for underground pedestrian crossings of major streets.
- + Construction cost is lower wherever the cut-and-cover method can be used. Station construction costs are particularly significant here.
- + Larger vehicles can be used because cut-and-cover construction costs are less sensitive to the dimensions of the tunnel cross section than are tunneling costs.
- ± Cut-and-cover cannot be used where the alignment goes under bodies of water, hills, buildings, and other objects. However, tunneling cannot be performed on shallow alignments.
- Construction from the surface causes much more interruption of street activities, traffic flows, and so on.

tunnels have to be used. However, some cities have found that deep tunnels are better for their conditions because of the ability to use alignments independent of street networks. London is a particularly interesting case. It has three lines with shallow tunnels (called the “Underground”) constructed by the cut-and-cover method and served by large-profile rolling stock. The more recently built lines are in deep tunnels (“Tubes”) with much smaller rolling stock, since the internal tunnel diameter is only 3.66 m (12 ft), with slight variations among lines. It is interesting that this profile has also been used for the most recently built lines (Victoria, Jubilee), although the small cars are increasingly limiting because the trend is to provide more spacious metro cars for more seats and greater comfort for standees. Yet the prevailing factor has been that because of the city’s irregular street network, independent underground alignments have significant advantages. Special ground conditions—clay—make tunneling easier and cheaper than cut-and-cover.

Other tunnel construction methods are used for special alignments and local conditions. Particularly interesting solutions are those used in San Francisco and Amsterdam.

While most subaqueous rail transit tunnels are built by the tunneling method, BART’s 5.8-km-long tube under the San Francisco Bay was constructed from the surface. A trench, at some points as much as 30 m

deep, was excavated in the bottom of the bay from barges. The trench was then covered with a layer of gravel and carefully graded. Prefabricated tunnel sections containing both tubes were built on the shore. Their length varied between 83 and 112 m, width was 14.5 m, and height was 7.3 m. A special twin-hulled barge connected by two bridges towed each tunnel section to the appropriate location and lowered it into the trench with guidance by a diver (Photo 6.31).

After precise positioning, the sections were connected by special couplers and opened up, forming a pair of continuous tunnels. A similar construction method was used for RRT line passage under the river Maas in Rotterdam and for the two-level four-track tunnel for the New York City subway and Long Island Rail Road lines at 63rd Street between Manhattan and Queens.

Underground construction conditions in Amsterdam are extremely difficult because the ground is mostly sand, with a very high water level. A special method utilizing caissons was therefore developed (Figure 6.33c). First, a rectangular concrete tunnel section was constructed on the surface. Then, by a special technique, sand was excavated under that section, which was gradually lowered until it reached the desired level. It was then connected with the preceding tunnel section, forming a continuous tunnel structure.

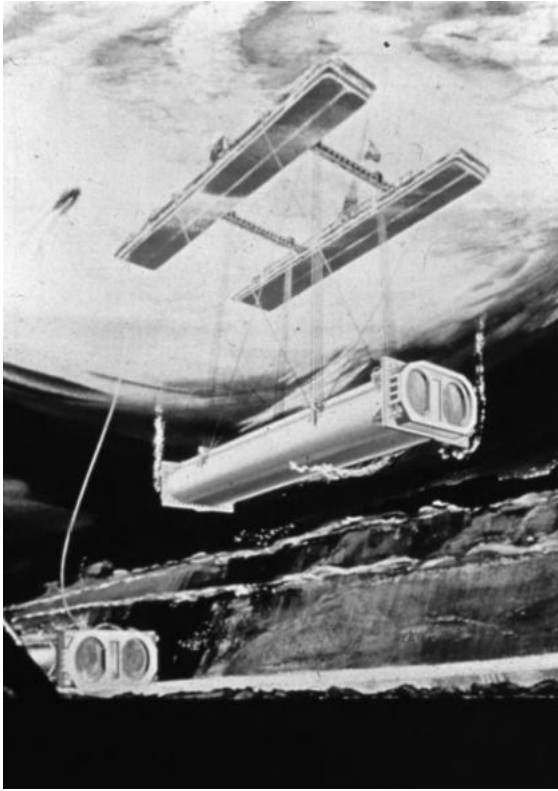


Photo 6.31 Illustration of BART Trans-Bay Tubes construction technique

All tunnels must have provisions for protected stand-by of maintenance crews and for evacuation of passengers from disabled trains. Also, fire prevention devices must be strategically located and clearly marked; nonflammable surfaces and objects must be used; emergency escape paths and exits, ventilations of smoke and other fire protection measures are also standard requirements for transit tunnel design.

6.3.3.6 Other Types of Exclusive Rights-of-Way. Several other ROW types can be used in special cases.

Open cuts—with either natural slopes of ground or vertical retaining walls—are cheaper to construct than tunnels. However, they represent a barrier requiring bridges to connect the areas they cross. With respect to visual and sound aspects, cuts are also inferior to tunnels but usually superior to embankments.

Freeway medians can be a very convenient location for rail transit ROW if adequate space is provided during the freeway design, particularly for stations. Tracks are usually at grade with the roadways. If the freeway has no overpasses, aerial structures can also be used, requiring less ROW width but higher investment cost.

The most important advantage of rail transit alignments in freeway medians is that ROW acquisition is cheap because it is only a fraction of the acquired wide freeway ROW. Its very serious limitation is that freeway alignments seldom coincide with optimal alignments for transit lines, since freeways avoid major activity centers and the residential areas that transit should serve. Moreover, transit stations in freeway medians usually require long pedestrian access through car-oriented areas surrounding the freeway.

At-grade ROW is always the least expensive type to construct. It has extensive applications only on existing railroad rights-of-way that have widely spaced street crossings or grade separation or for rail lines planned simultaneously with street networks for newly developed areas. New alignments for exclusive rights-of-way (category A) in built-up areas usually cannot be placed at grade because frequent street crossings would require numerous under- or overpasses. In such cases, aerial structures or tunnels are preferable solutions.

6.4 RUBBER-TIRED RAPID TRANSIT (RTRT)

Several cities utilize rapid transit systems with vehicles that have rubber tires for support and guidance instead of conventional steel wheels on rails. Paris, where this technology was invented with support of a major rubber-tire manufacturer, uses it on several of its Metro lines. Montreal, Mexico, Santiago, Lyon, and Marseille adopted the same technology for their new metro systems. All these systems were planned and built by French designers.

Strictly speaking, this rubber-tired rapid transit (RTRT) mode is only marginally a member of the family of rail transit modes. Each vehicle has 16 rubber tires (8 for support, 8 for guidance) in addition to 8 steel wheels, which are not used in regular running on

sections without switches (Figure 6.35). However, since its basic physical, operational, and service characteristics are very similar to those of RRT, the RTRT mode description and evaluation is included as this separate section in the chapter on rail transit modes.

The first RTRT trains (Photo 6.32) were developed between 1951 and 1956 for the Paris Metro. At that time most of the Metro's rolling stock, several decades old, had poor dynamic and ride characteristics and produced considerable noise. Since the development of conventional rail car and track structure technology had been neglected in France for some time, rubber-tired technology was chosen because it was considered necessary to achieve the following improvements (RATP 1964):

- Increased operating speed through better adhesion for acceleration and deceleration
- Reduced noise
- Lighter, lower-cost cars

The rubber-tired vehicles did achieve significant improvements on the Paris Metro lines in all three factors in comparison with the decades-old rail rolling stock they replaced. In the meantime, however, the development of rail technology resumed, achieving the same goals without some of the disadvantages of rubber-tired stock.

6.4.1 Description of the Technology

Rubber-tired cars have the same basic body/truck configuration as rail cars. Their supporting rubber tires run on special concrete or steel surfaces placed outside the conventional rails. Guidance is provided by a set of smaller horizontal rubber-tired wheels running along vertical surfaces constructed on both sides of the track. Steel wheels and rails are retained for two reasons. First, for switching: since at switches the guiding surfaces above the rails must be discontinued, the steel wheels, which have extra long flanges, guide the vehicle through a standard rail switch. Second, the steel wheels and rails provide support in the event of a tire failure, preventing excessive tilting of the vehicle. Power collection is achieved by means of shoes running along the guiding surface (+) and the rails (-).

Thus, as Figure 6.35 shows, each truck has four large rubber tires for support and four small rubber tires for guidance, in addition to the four steel wheels. The track, shown in Figure 6.36, consists of two horizontal surfaces and two vertical steel surfaces, as well as the rails. Both the vehicles and the track are thus considerably more complicated than conventional rail technology.

A different guidance method, using rubber tires against a center steel guide rail and steel wheels within rubber tires, is used on the rapid transit system in Sapporo (Japan). However, no other metro system uses that technology.

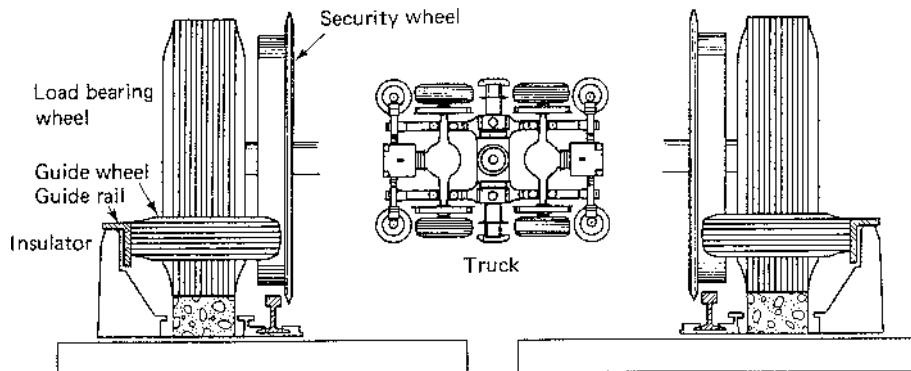


Figure 6.35 Truck and wheels of rubber-tired rapid transit vehicles



Photo 6.32 Rolling stock on a Paris RTRT line (Courtesy of J. W. Vigrass)

6.4.2 Characteristics and Comparison with Rail Technology

RTRT technology has several features that should be carefully evaluated in each case in which this mode is compared with conventional rail technology.

- *Adhesion* between rubber-tired vehicles and a dry guideway is considerably greater than with rail. Ramifications of this feature are as follows:
 - Ability to negotiate steeper grades, which can be useful for cases where severe geometric restrictions exist. However, since steep gradients are operationally undesirable, this asset is used only to a limited extent. Mexico City utilizes a 7% gradient; Montreal, 6.5%; Sapporo only 4.5%, compared with the maximum rail gradients in Brussels, 6.25%; Glasgow, 5.5%; Philadelphia-PATCO, 5.25%; Boston, Oslo, and several other systems, 5%.
- Higher acceleration capability which is also irrelevant under normal conditions, since the maximum allowable acceleration rate is usually determined by passenger comfort and safety or motor power limitations. These limits are easily achievable by rail technology as well. For starting on gradients, the higher adhesion of RTRT can be an advantage.
- Greater sensitivity to wet, snow, and ice conditions (see Section 3.4) represents a significant drawback of rubber-tired technology, particularly in areas with snow and ice. Because of this, the entire metro network in Montreal must be in tunnels, an extremely costly constraint. Sapporo utilizes aerial alignments, but these are

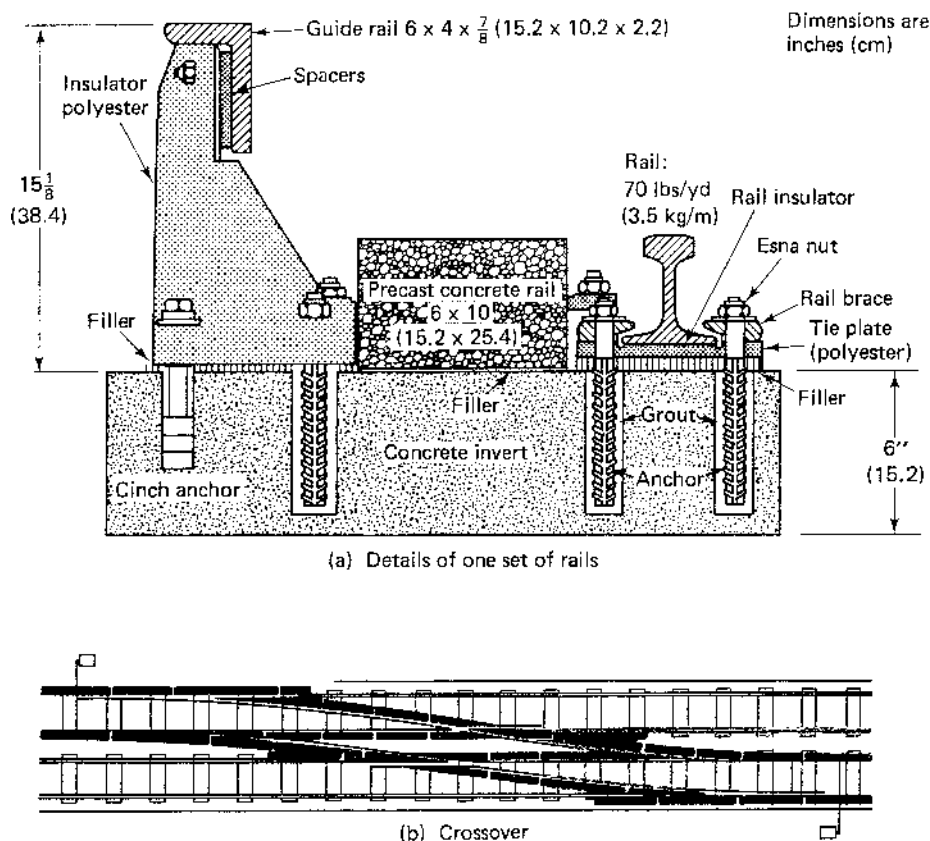


Figure 6.36 Rubber-tired rapid transit track

enclosed in large tubes of questionable aesthetic value. The effect of weather can also be solved by heating the guideways, as has been done on elevated line 6 of the Paris Metro. This, of course, increases system complexity and involves substantial energy consumption.

- Only part of the vehicle weight is needed as adhesion weight for traction. Powered cars can therefore have larger motors and be operated in trains with some trailers, thus lowering the investment and operating costs compared with RRT rolling stock.
- *Noise production*, while much lower than that of old rail equipment, is quite similar to that of modern rail systems. Although the noise produced by

wheels in sharp curves is lower on RTRT than on RRT systems, overall noise production by the two technologies shows overlapping results. Despite the lack of noise of rail vehicles in straight running, they often do produce noise and vibration in curves, and various methods for their reduction are required. RTRT does not have that problem.

- The *weight of RTRT vehicles*, initially expected to be lower, has actually proved to be comparable to that of conventional rail vehicles. The carrying ability of eight rubber tires limits the car size to approximately 50 m² of the gross floor area. Thus the vehicle size is similar to that of the smallest RRT stock, generally designed many decades ago, as in Berlin, Hamburg, Chicago, and Madrid.

The weight economies of large vehicles applied on RRT cars of most contemporary RRT systems, such as Atlanta, Toronto, and San Francisco BART, cannot be used on RTRT stock. Comparative analyses have shown that no general superiority in unit weight (kg/m^2) can be observed for either technology. Actually, the use of aluminum instead of steel in body construction has more influence on weight than does guidance technology.

- *Energy consumption* by RTRT trains is estimated to be considerably greater than by RRT trains. Exact figures are difficult to derive, since modern trains of the two types have never been operated on the same line. Estimates of 25% to 30% difference have been quoted by Danziger (1975) and Guillén (1997), 30% to 35% by other sources. The higher consumption is due to the much higher (about 10 times) rolling resistance of rubber tires than steel wheels, the greater number of contact surfaces, and the greater rotational inertia. This is a serious disadvantage of rubber-tired guided technology.
- *Maintenance cost* of RTRT has been estimated to be about 20% higher than for RRT (Guillén 1997).
- *Heat in tunnels*, produced by rubber-tired trains due to their higher rolling resistance and greater energy consumption, can be a problem. In some cases, powerful ventilation equipment has had to be installed, further increasing complexity and operating costs.
- The *danger of fire* is greater because explosion of a tire can cause arcing with the third rail and ignite fire with the large amount of flammable material (rubber). This has occurred on some RTRT systems.
- *Costs* are difficult to estimate precisely. Although a rather detailed cost analysis for the first RTRT line in Paris (RATP 1964) showed advantages of this technology over the stock it replaced, comparative analyses with modern rail stock are not easy to find. Most independent comparative analyses show, however, that the considerably greater complexity of RTRT technology in both guide-

ways and rolling stock results in higher investment and maintenance costs. Moreover, greater energy consumption causes higher operating costs.

6.4.3 Potential Applications of Rubber-Tired Rapid Transit

Future use of the RTRT mode depends primarily on its technical/economic characteristics relative to those of standard RRT technology.

This comparison shows that RTRT mode has in most applications considerably more significant disadvantages than advantages in comparison with the RRT mode. Consequently, it can be competitive or may represent the optimal technology only in special cases, such as were found in Paris—existing tunnels with frequent sharp curves, no sound-dampening surfaces and gradients that make greater adhesion useful, or on old elevated structures that cannot be insulated from vibrations and whose reconstruction would be costly. Except for rare cases where gradients in excess of 6% must be utilized, RTRT technology has not been competitive with conventional RRT for vast majority of new metro systems.

Individual applications of RTRT and similar modes can be expected to occur again in the future, mostly in cases where other than technical and economic considerations prevail. Convenient financing arrangements and political factors sometimes favor unconventional or proprietary technologies. Or, appeal of a nonstandard technology and a desire to test new vehicle design concepts sometimes influence mode selection, as was the case with two RTRT lines in Sapporo, Japan, where two RTRT systems with different designs from the French one were built. However, in the course of planning of major transit lines in many cities, including Baltimore, Caracas, Pittsburgh, Rome, and San Francisco, two-axle rubber-tired AGT or RTRT were proposed and technically evaluated in comparison with conventional modes. In all these and many other cities RRT and LRT were selected over RTRT. The comparison of the rail and RTRT modes, summarized in the box, explains such selections.

In summary, *RTRT*, compared with *conventional RRT* technology, has:

- + Greater adhesion under normal (dry) conditions, allowing (a) negotiation of steeper grades, and (b) use of trailers.
- + Lower noise production in sharp curves.
- = Comparable maximum acceleration rates.
- Greater vulnerability to wet, snow, and ice conditions, reducing its applications to cities with warm climates or to tunnels only.
- Constraint on vehicle size due to the limited carrying capacity of rubber tires; this makes *RTRT* inferior to *RRT* for large cities.
- Considerably higher energy consumption, mainly due to higher rolling resistance.
- Maximum speed limited to 70 or 80 km/h.
- Higher heat production, requiring the ventilation of tunnels.
- Higher potential fire hazard.
- Higher investment and operating costs because of greater technical complexity and higher energy consumption as a result of the factors listed above.

6.5 STOPS, STATIONS, AND YARDS

Stations and terminals are important components of transit systems, because they represent the facilities where patrons encounter the transit system and experience its image, service, and convenience. Also, stations are contact points of these systems with the surrounding areas and with other modes, such as walking, auto, or other transit services. Terminal design and operations strongly affect passenger convenience, comfort, and safety on one hand and service reliability, operating speed, and line capacity on the other. They also have a strong interaction with their surroundings and environment. Large stations often require considerable investment. Careful design and planning of station operations are therefore very important for optimal use of investment and efficient system operation. This section describes the physical design of rail transit stops and stations.

6.5.1 At-Grade Stops

When *SCR/LRT* tracks are in the roadway, the potential conflict between vehicular traffic and passengers

boarding/alighting at stops must be eliminated through regulation. In many states the law forbids motor vehicles to pass while a streetcar is standing. The adequacy of this safety measure depends principally on its enforcement. The “signal island” concept, described in Section 6.3.3.1, provides a higher degree of safety. An even better solution is provision of a curbed island (Figure 6.25b), since it gives physical protection to waiting passengers, eliminates delays to other traffic during boarding, and facilitates stepping into and out of the vehicles. Consequently, wherever the necessary width can be obtained, curbed islands should be built at stops.

Where *SCR/LRT* tracks are located next to a sidewalk or in a curbed median, protection from vehicular traffic is complete. If a minimum-width median is used, its widening for stops can be provided in several different ways, as shown in Figures 6.29 and 6.30, depending on street layout and traffic conditions.

With the construction of pedestrian areas with transit services in many cities in recent years, numerous *LRT* stops have been placed in the cores of such areas: malls, shopping streets, large pedestrian squares, and so on. In most cases, crossing of the tracks is allowed



Photo 6.33 LRT stations with simple pedestrian crossings

everywhere, since LRT vehicles operate only at moderate speeds. The track area is either flush or slightly depressed and separated by low curbs. In addition to warning pedestrians, the curbs assist vehicle boarding at stops. An effective way of designating stop areas is the use of textured pavement, usually squares of two different colors.

The introduction of low-floor LRT vehicles in many cities has eliminated the need for high platforms on new LRT lines. Low-platform stops with easy access are better integrated with pedestrian environments while also contributing to the livability of central business districts (CBDs) and other major activity centers. Quiet LRT vehicles without any exhaust have become

central elements in the human-oriented urban environment. Pedestrian streets with LRT lines are now symbols of attractive urban areas in many European cities, as described in Section 6.3.3.1.

Pedestrian crossings are usually provided at grade in the areas of LRT stations regardless whether these have low, medium-height, or high platforms (Photos 6.33 and 6.34, respectively).

6.5.2 At-Grade Transfer Stations

Whenever possible, major transfer stations for surface transit should be located in large pedestrian areas, sep-



Photo 6.34 Diesel LRT station with medium-height platform in New Jersey (NJ Transit River Line; courtesy of J. W. Vigrass)

arated from automobile traffic. Short walking between vehicles of different routes should be provided for. The crossing of tracks and roadways is usually unrestricted; only if headways on the lines are short and pedestrian volumes very heavy, over- or underpasses may be needed.

A transfer between LRT and bus lines, typical for an outlying LRT terminal station, is shown in Figure 6.37 and Photo 6.35. Good examples of major multi-track LRT and bus transfer stations are found at the main railroad stations in many European cities, such as Rotterdam, Munich (Figure 6.38), and Leipzig. Similar elaborate track layouts around stations are also found on the central subway section of the Green Line (LRT) network in Boston. Simple and convenient pedestrian crossings and extensive transfers with buses, K+R and P+R facilities have been built on the up-

graded LRT systems in European cities and on new LRT systems in San Diego, Edmonton, Denver, and other cities.

6.5.3 Controlled-Access Stations

All metro, most regional rail, and some light rail systems utilize stations that are grade-separated from other facilities and have full control of passenger access. Typically, fares are collected or checked at the entrances to the boarding areas, so that this process does not delay vehicle boarding. Fare control is also eliminated from the boarding areas on all systems with self-service fare collection. This permits simultaneous loading on all doors along the train. In addition, fully controlled stations usually have platforms and car

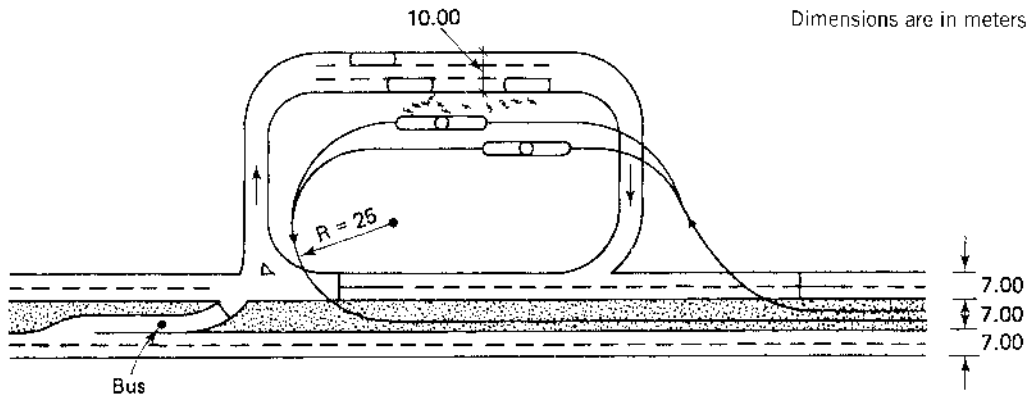


Figure 6.37 Outlying LRT terminal with transfer to bus feeders



Photo 6.35 An LRT/bus transfer station in Hannover

floors at the same level (usually high on RRT and RGR systems, both high or both low on LRT systems), which makes getting into and out of vehicles fast and easy. With long TUs and many doors, it is possible to achieve boarding/alighting rates of 40 to 80 prs/s on RRT systems. On LRT lines served by TUs with three to four six-axle cars and 9 to 16 doors, simultaneous boarding can achieve rates of about 10 to 30 prs/s. These rates are one to two orders of magnitude greater than rates of passenger boarding on surface transit vehicles, which involve fare collection at the entrance, stepping up into the vehicle, and only one or two boarding channels.

Since controlled-access transit stations have a durable impact on both the operation of the transit system

and its interaction with the surrounding environment, their design must be based on a very careful analysis of the requirements of three major affected parties: passengers, operating agency, and the community. These are summarized next.

Passengers utilizing the stations require:

- Minimum time and distance of approach to the platform or between platforms for transferring between lines
- Convenience, including good information about service, orientation, adequate circulation patterns and capacity, easy boarding and alighting, provisions for disabled persons, and other facilities
- Comfort, including aesthetically pleasing design, weather protection, small vertical climbs, and so on
- Safety and security: maximum protection from accidents through safe surfaces as well as good visibility and illumination, which deter vandalism and prevent crime

Operating agency requires the following:

- Minimum operating costs
- Adequate capacity of the transit system and pedestrian areas for peak demand volumes
- Flexibility of operation, including adaptability to different peaking conditions, changes in fare-collection methods, and so on

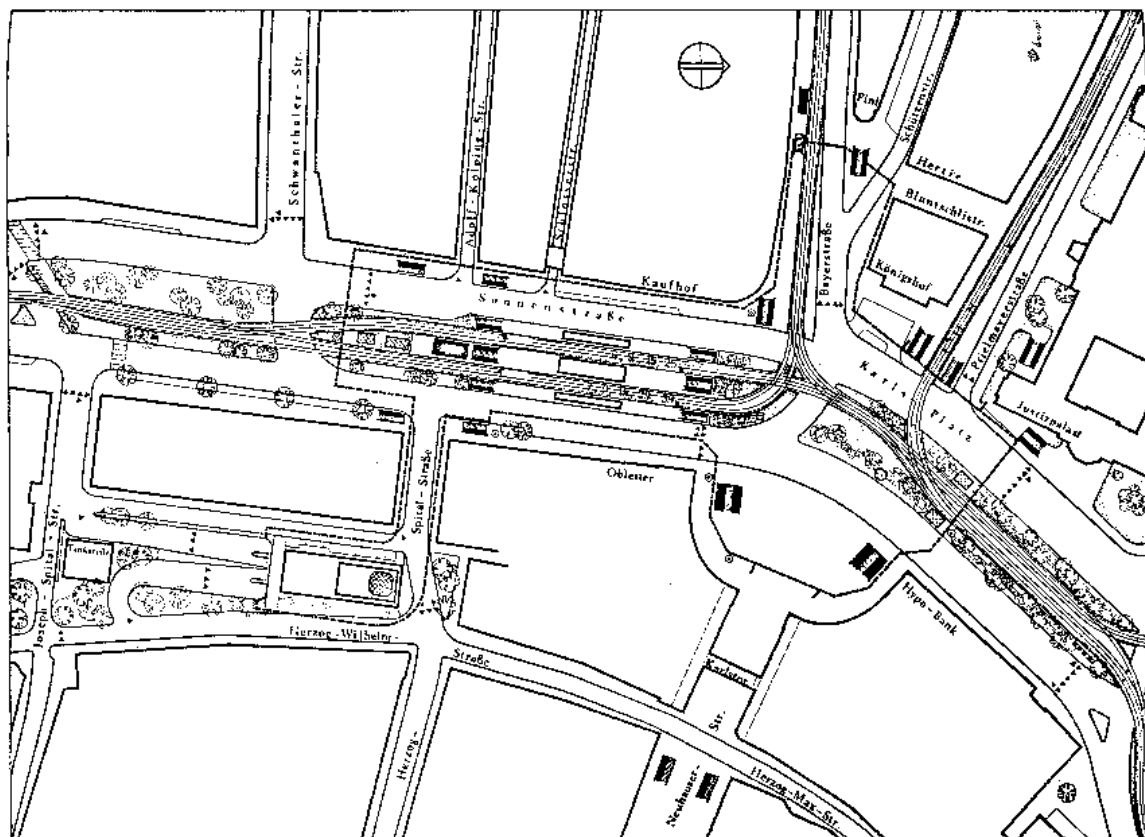


Figure 6.38 Major transfer station of LRT lines (Courtesy of Planungsbüro Obermeyer, Munich)

- Good visibility of platforms, fare collection, and other areas to enable supervision of operations and ensure efficiency, safety, and prevention of vandalism
- Good integration with surrounding areas and utilization of station space for various shops, store accesses, displays, information booths, and so on

The *community* is interested in having a well-utilized and efficiently operated transit system. It is therefore also concerned that the requirements of passengers and the operator be satisfied. The community considers these requirements, together with the investment costs, which are in most cases its obligation. In addition, however, the community is also interested in

both the immediate and long-range effects of the station on its surroundings. The immediate effects include environmental impact, visual aspects, noise, and possible traffic congestion. Long-range effects include the type of development in the vicinity, which may be stimulated or discouraged by the station's presence. Therefore the station design should be aimed at stimulating the desirable and discouraging the undesirable elements in the area.

The interaction between transit and urban development—specifically the positive impact of a permanent transit infrastructure on livability of the central city and suburban major activities centers, transit-oriented design, and similar planning concepts—has been intensified very strongly in recent decades by the

introduction of low-floor LRT vehicles. Lines with such vehicles and low-platform, unobtrusive stops and stations are being introduced into the pedestrian-oriented cores of cities as the main permanent element that encourages economic and social vitality and creates a livable urban environment. Rapid transit stations are also increasingly being planned in central city and suburban activity centers as the key components of coordinated urban plans for intensified commercial, office, and residential developments.

6.5.3.1 Station Platforms. Regular metro stations can have either lateral platforms (Figure 6.39a and Photo 6.36) or a central platform (Figure 6.39b and Photo 6.37). Since cars have doors on both sides, either of the two types can be used at any station along the line. Their comparison is given in the box.

Several metro systems built during the 1950s and 1960s utilized mostly central platforms to reduce or eliminate operating personnel on the platforms. However, with increasing and sometimes total automation,

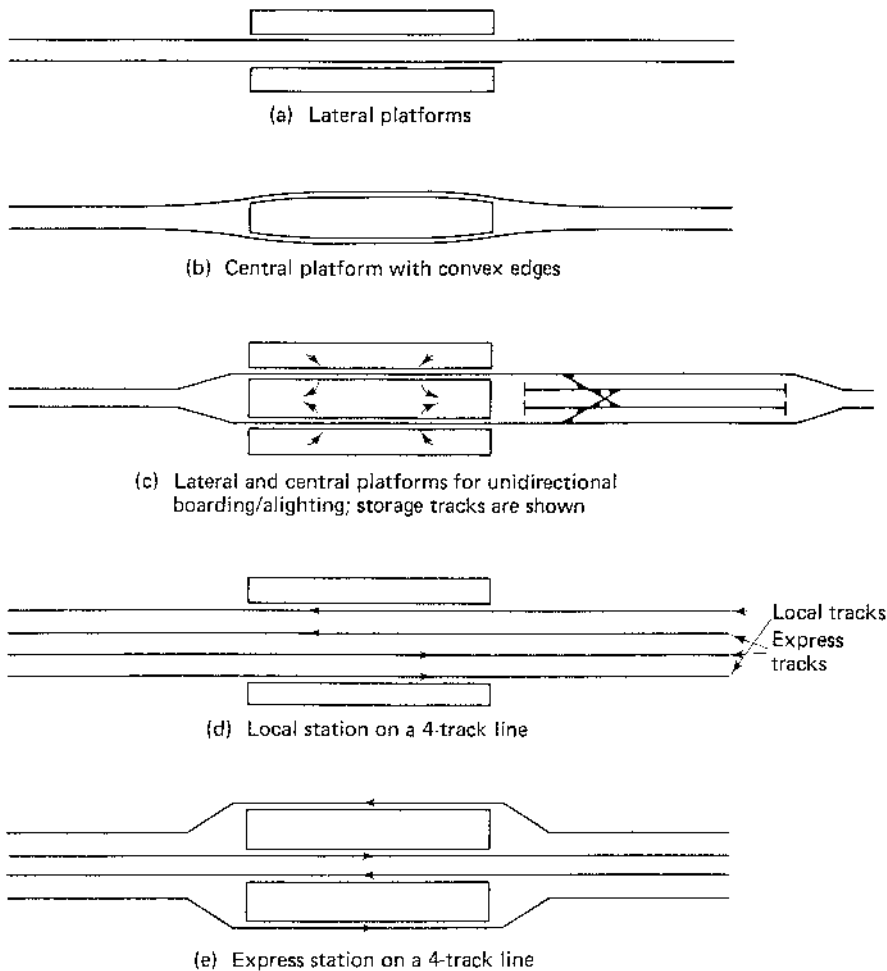


Figure 6.39 Single-line station platform types

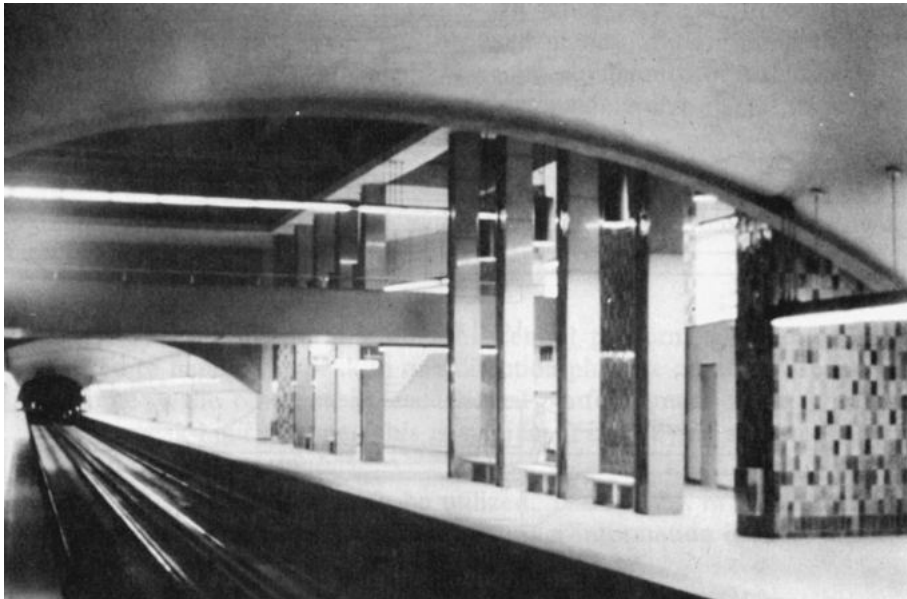


Photo 6.36 Attractive rapid transit stations are part of a healthy urban environment (Montreal Metro)



Photo 6.37 An underground station of the Munich U-Bahn (RRT)

Metro systems stations with *central platforms*, compared with *lateral platforms*, have the following characteristics:

- + Narrower total platform width: the central platform is usually required to handle the peak in one direction plus the contraflow peak volume in the other, while each lateral platform must be designed for its peak-hour volume. This applies more to outlying than to center city stations.
- + A single set of facilities can be utilized. The savings in investment and operating costs of escalators, elevators, lighting, information boards, and so on, can be substantial.
- + Easier supervision by a single person or a single set of TV cameras.
- + Passengers can reverse the direction of travel in case of errors without paying another fare.
- Higher construction costs, since both tracks must have “double S” curves in the alignment, which require widening of the tunnel at station approaches. The curves slightly affect riding comfort, but not train speeds.
- Possibly more passenger confusion about train directions.
- It is impossible to separate directional flows of passengers where this is desirable for operation or fare-collection purposes.

centralized supervision of stations or driver’s monitoring of doors at departures via closed-circuit TV, this difference has in many cases disappeared. The choice between the two platform types thus depends on other factors, such as fare collection, train departure procedure, and entrance locations.

In different stations along a line, entrances and exits from platforms are sometimes located at different points of their length in order to achieve even loading of trains.

Stations with multiple tracks and/or multiple platforms are provided in several different cases. First, when passenger interchange is heavy and the line operates at capacity, three platforms can be provided, so that each track has platforms on both sides. As Figure 6.39c shows, this design permits simultaneous boarding and alighting of passengers on the opposite sides of the trains, considerably reducing their standing times. This type of stations exists, for example, in Barcelona and Boston rapid transit and on the Munich S-Bahn system. The second case is on lines with local and express service. Common designs of local and express stations, found in New York and Philadelphia, are shown in Figure 6.39d and e.

A third type of platform arrangement is used for stations at which routes diverge. When train frequency is high, it is necessary to provide separate tracks for the two converging directions to permit schedule corrections when delays occur. As Figure 6.40a shows, such stations have two platforms and three tracks. The fourth type are four-track two-platform stations for two separate lines. If the lines only “touch” each other at the station, all transferring passengers must use connections above or below the platform level (Figure 6.40c); if the lines cross each other under a flat angle and there are heavy transfers, the tracks should be so arranged that passenger transfers in the predominant direction can be made directly between pairs of trains on each platform (Figure 6.40d).

Platform edges are either straight (Photos 6.38 and 6.39) or slightly convex to allow easy visibility of all doors for safe departure control. Central platforms are often narrowed toward the ends, where passenger concentrations are lower (Figure 6.39b). For determination of platform width, a diagram of expected passenger densities, which are influenced by locations of stairs and stopping locations of trains, is very helpful. Individual passenger flows during each peak hour must be

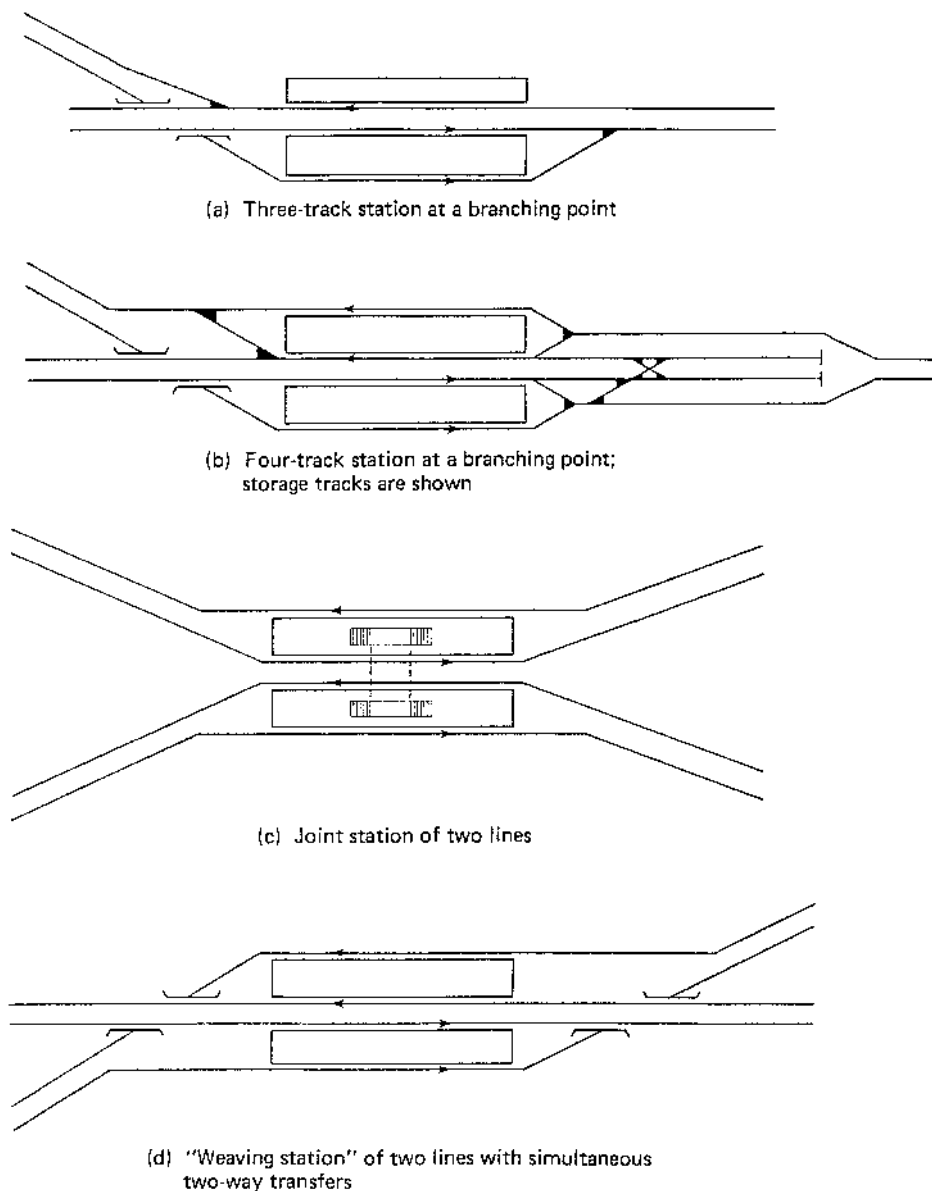


Figure 6.40 Platform arrangements for two-line station

developed and platform dimensions chosen to satisfy each set of conditions. Quite often, emergency evacuation requirements necessitate wider platforms and more stair capacity than are called for by normal passenger loads.

Platform length in rail transit systems is usually determined as the length of the longest train consist plus a distance of 5 to 10 m. Although it involves additional construction cost, this extra distance actually reduces travel time, since it requires a lower precision of brak-



Photo 6.38 Chicago rapid transit: simple but functional stations (Courtesy of Boeing Vertol Company, Philadelphia)



Photo 6.39 An aesthetically pleasing RRT station on the BART system in San Francisco (Courtesy of Eric Haas)

ing by the driver. However, since most new metro systems now have automatic train operation (ATO), which stops trains with a tolerance of ± 0.50 m, platform length need not be greater than train length. LRT stations are sometimes designed for simultaneous stop-

ping of two or three TUs. Even on sections where LRT vehicles are controlled by signals, it is common to provide a permissive signal that allows the following TU to enter a station at a limited speed while the leading TU is still standing. Consequently, typical lengths of

metro platforms are in the range 100 to 180 m (although there are systems considerably outside of this range), while for LRT, typical platform lengths are 30 to 100 m.

Platform heights have a major influence on station construction costs and space requirements as well as on their operations. Traditionally, rail transit vehicles used mainly tramways with steps using low-platform stations, metro having high floors and high platforms, while regional rail had either one—low or high platforms or a combinations of the two along the same line. With the advancement of LRT mode using some elements of metro lines (such as high platforms), diversification of RGR vehicle and station designs, and the recent introduction of low-floor vehicles on LRT and RGR systems, rail transit modes now offer many combinations of vehicle floor heights and station platform heights. Their systematic classification, presented in Table 6.9, shows the following types of rail transit system designs with respect to floor/platform relation-

ships. This discussion proceeds along the three table columns, starting from low platforms.

- Low-level platforms are at 0.20 to 0.35 m, or a curb height, above the top of rail (TOR). When used on traditional SCR, LRT, and some RGR systems with high floors, the vehicles have three or four steps. These platforms require simple, low-cost arrangements but involve slower passenger boarding/alighting. This type of stations will be retained on most systems with high-floor vehicles, but in many cases with the addition of special ramps at stations or lifts on vehicles for disabled passengers.
- The invention of low-floor vehicles has greatly facilitated boarding/alighting of vehicles from low-level platforms. It has also allowed introduction of stations without obtrusive high-level platforms in pedestrian zones. Such arrangements are now used by an increasing number of SCR, LRT,

Table 6.9 Relationships of vehicle floor heights and platform heights on different rail transit modes

Platform Height Vehicle Floor Height			
		Low Platforms	High Platforms
High floor with steps	Trend	Fixed steps: SCR–Toronto St. Petersburg LRT–Milan Denver RGR–Rome Washington–Virginia	Moving steps: LRT–San Francisco Hanover RGR–Philadelphia New Jersey
		Not compatible	Steps not needed
High floor only			Metro–New York Mexico City RGR–New York–LIRR Paris–RER S-Bahn systems LRT–Stuttgart Los Angeles St. Louis
Low floor ^a		SCR–Grenoble Washington, DC LRT–Munich Houston RGR–Los Angeles	Not feasible

^aLow floor at doors; may have high-floor sections.

and some RGR lines as well as the tram-train systems.

- High-level platforms are even with or slightly lower than the car floor (0.85 to 1.00 m above the TOR). These platforms—used on all RRT, most RGR, and some LRT systems—involve considerably higher construction costs and take more space but provide faster, safer, and easier boarding/alighting. Most controlled stations (with access through fare-collection areas only) as well as some open stations have high-level platforms.
- Rail lines with some low- and some high-level platforms are also used on some LRT and RGR systems. Their vehicles have high floors with steps, which can be either raised or covered to provide a high-level floor matching the high platform level.

This review shows that the first combination—low platforms and high floor vehicles with steps—involves negotiating steps. Level boarding is achieved in three vehicle/platform design combinations: low-platform/low-floor, high-platform/high-floor vehicles without steps, and high-platforms/movable steps for both levels. These combinations have thus enabled a much greater share of level boardings since the introduction of low-floor vehicles.

The floor and platform levels have been grouped here into two categories, low and high. Actually, there are considerable variations in these heights in many cities, including different curb heights in station areas and intermediate floor heights on vehicles.

Transit stations with high platforms on RGR lines used also by freight trains must accommodate two different clearances between platform edge and cars: the closer for passenger, farther for freight cars which are wider. This difference between the two clearances can be resolved either by extended floor lips on passenger cars, or by construction of a gauntlet track (two overlapping tracks at a distance equal to the difference between the clearances for the two cars). Then passenger trains use the closer, and freight trains the farther track when going through the station.

6.5.3.2 Station Levels. Controlled-access stations consist of two or three levels, as Figure 6.41 shows. Entrances may have a variety of layouts and designs:

simple stairways from the street, doors and corridors through major buildings, special station buildings from which passengers go to the mezzanine level and many other types.

The intermediate, mezzanine level contains the fare-collection system, which divides it into a “free area”—part of a public street, and a “paid area”—the transit station proper. The third level is that with the platforms and tracks at which boarding of trains takes place. Sometimes geometric conditions and operational factors allow combining the mezzanine level with either the street or the platform level, so that the station has only two levels, but the common design is with the three areas at three different levels for both subway and aerial stations. The mezzanine can be used not only for fare collection but also for various stores, display areas, telephones, as well as a grade-separated pedestrian crossing of the street, and for direct access to the surrounding buildings.

A great variety of designs of station levels is possible, but the most typical can be classified by their three basic characteristics: subway versus aerial stations, two versus three levels, and central versus lateral platforms. The differences between these designs can be seen clearly from their schematic cross sections in Figure 6.41.

6.5.3.3 Transfer Stations. With the exception of the stations at which different lines are brought to parallel platforms at the same level, intersecting rapid transit lines always require additional levels. If both intersecting lines belong to the same system, they can be directly above each other and their geometric position should be such that the walking distance between the trains of the two lines is minimized. This is achieved by locating centers of platforms of the two lines above each other. Other factors may dictate different positions, even such that the ends of platforms overlap, resulting in longer but yet convenient walking over one flight of stairs only. In cases where the two lines belong to different systems and fare control is required, usually an additional level for a pedestrian mezzanine is provided between the lines. Such cases are found in joint stations for RRT and RGR lines in London, Paris, Philadelphia, and many other cities. The same requirement exists in San Francisco, al-

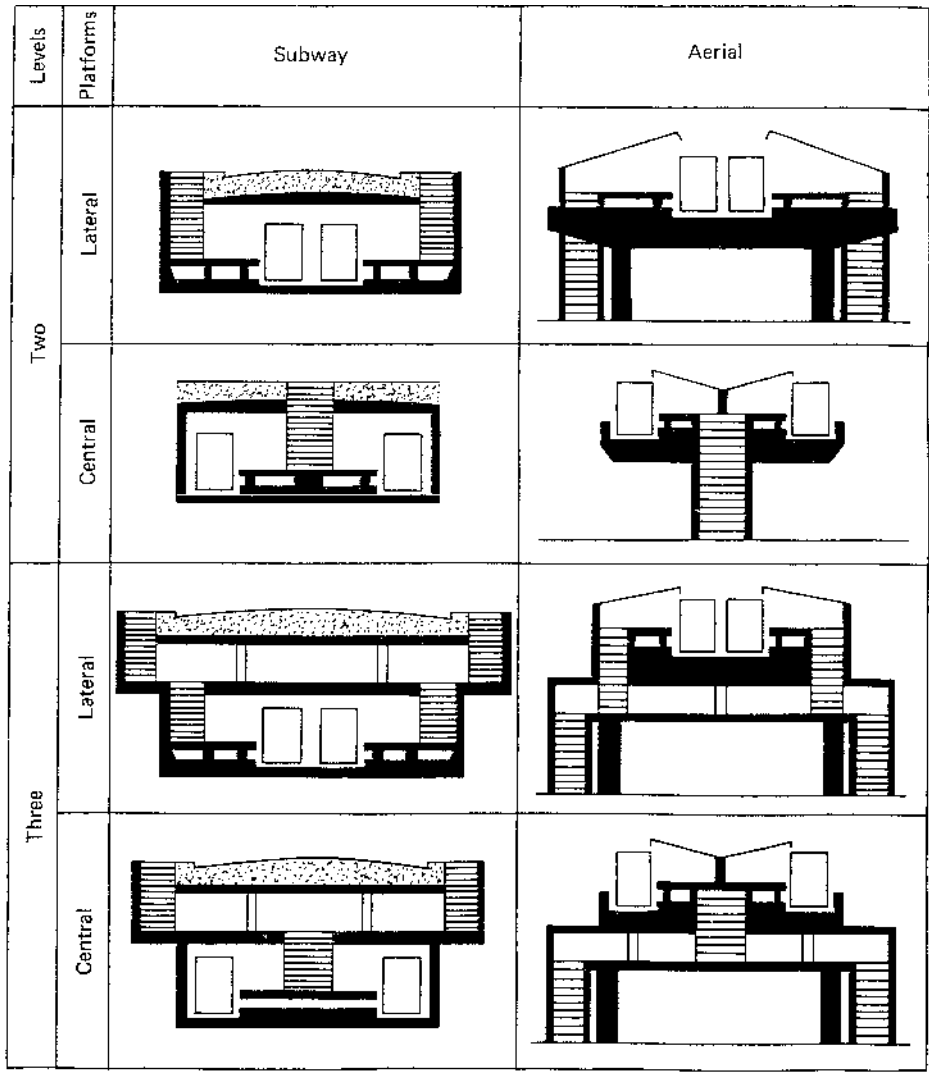


Figure 6.41 Rapid transit station types

though with a different solution: there is only one mezzanine above the Muni's LRT and BART's RRT level but no direct connection between them, so that all transferring must be via the mezzanine.

An example of a very elaborate underground transfer station for four lines is Jungfernstieg in Hamburg, completed in 1975 (Figure 6.42). The Paris Metro also has extremely elaborate stations because of its network

design principle—that passengers are precisely guided by corridors between any two directions. Particularly interesting designs for this operation are the stations Chatelet and Republique. The former has been developed from two Metro stations into a transfer complex between the two major (east-west and north-south) regional (R.E.R.) and four rapid transit (Metro) lines, and it may be the largest underground station in the world.

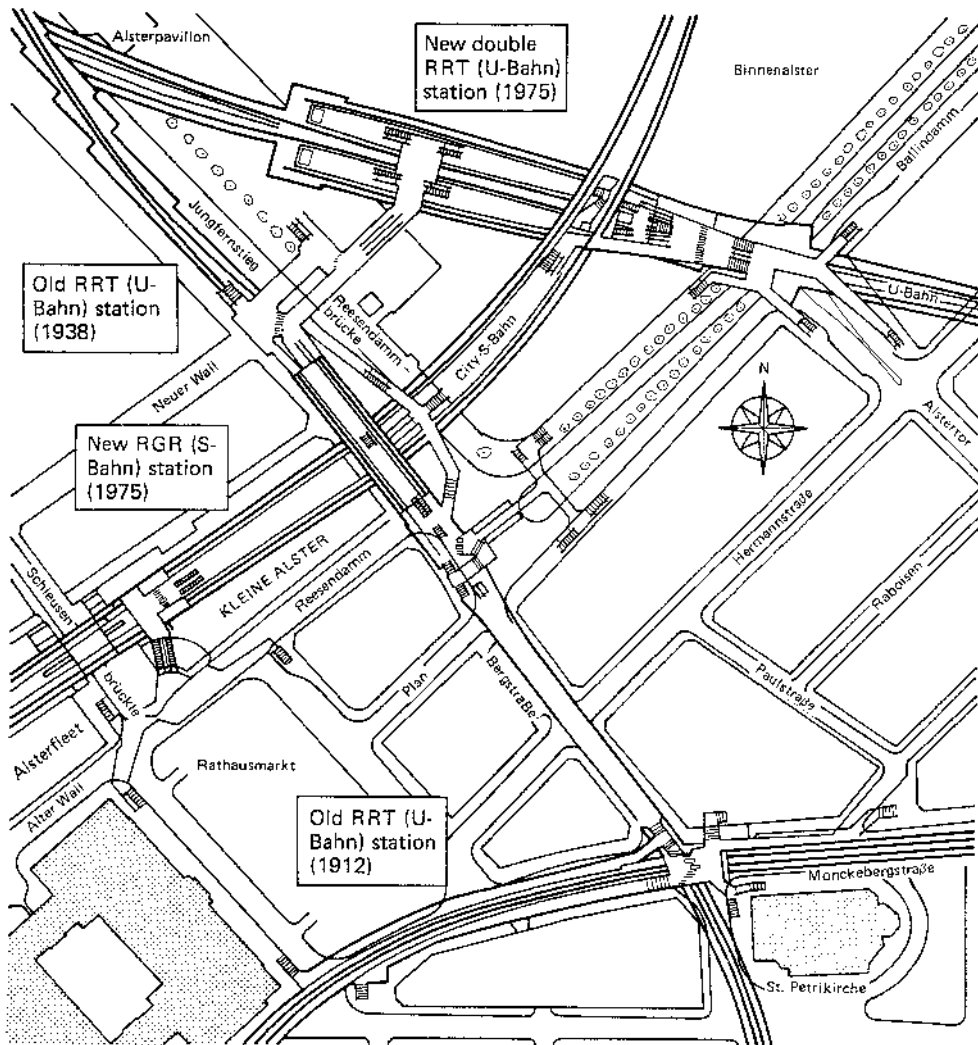


Figure 6.42 Four-line subway transfer station complex

Republique is a common station for five Metro lines. A three-dimensional drawing of the BART–Muni transfer station under Market Street in San Francisco is shown in Photo 6.40, while Photo 6.41 presents a very high-capacity transfer station between the São Paulo Metro and a large number of bus feeders.

As these examples show, the requirement that fare-collection barriers be provided at entrances and between various transit systems greatly complicates the

design of many RRT stations. Additional levels involve substantially higher cost of these already expensive structures; operating costs are also greater; most important, passengers have to negotiate greater distances and more stairways. With self-service fare collection, which allows no-barrier entry, most stations could be substantially simplified and entire levels could be eliminated. Such fare-collection systems have already been in use on all transit modes in a number of cities (Ham-



Photo 6.40 Cutaway of a major underground RRT transfer station (BART RRT/LRT transfer station)



Photo 6.41 Aerial RRT station with direct transfer to bus terminal (São Paulo) (Courtesy of Companhia do Metropolitano de São Paulo)

burg, Munich, Vienna) since the early 1970s and on surface modes in most west European and Russian cities for an even longer time. In North America, self-service fare collection, also known as “proof of payment,” was introduced with the opening of new LRT systems (Edmonton, San Diego), and later also adopted on the Los Angeles Metro and, slowly but steadily, on RGR systems.

So far, station designs in most cities have not been changed to take advantage of these innovations. However, since the trend is clearly toward greater use of self-service fare collection, it is possible that rail transit stations in many cities, presently designed for conventional fare-collection methods, will become obsolete and oversized when self-service methods are adopted in the foreseeable future.

6.5.3.4 Entrances and Integration with Surroundings. The number and locations of station entrances directly influence passenger convenience and transit system integration with adjacent areas and buildings. Since passengers feel that they have reached the transit system when they come to station entrance, station layout should provide stairways at both ends of platform. Such a layout effectively results in an in-

creased area coverage compared with single-entrance layout, as Figure 6.43 shows. The service areas with one and two entrances are respectively:

$$A_1 = r_a^2 \pi \quad \text{and} \quad A_2 \approx r_a^2 \pi + 2 r_a L_s \quad (6.8)$$

where r_a is the radius of the service area and L_s the station length. The difference in areas,

$$\Delta A = A_2 - A_1 \approx 2 r_a L_s \quad \left| \frac{A}{\text{m}^2} \right| \left| \frac{r, L}{\text{m}} \right| \quad (6.9)$$

can be substantial. For example, for $r_a = 400$ m (5-min walk) and $L_s = 200$ m, the additional area is about one-third of the initial served area: $A_1 = 503,000 \text{ m}^2$, $\Delta A = 160,000 \text{ m}^2$.

A common contemporary design of central-city subway stations consists of separate mezzanines under two adjacent intersections and entrances from all directions of major passenger approach flows. Large portions of the mezzanines are outside the fare-collection line, so that they serve as a street underpass, thus decreasing pedestrian volumes crossing streets at grade. It is also common for such mezzanines to incorporate

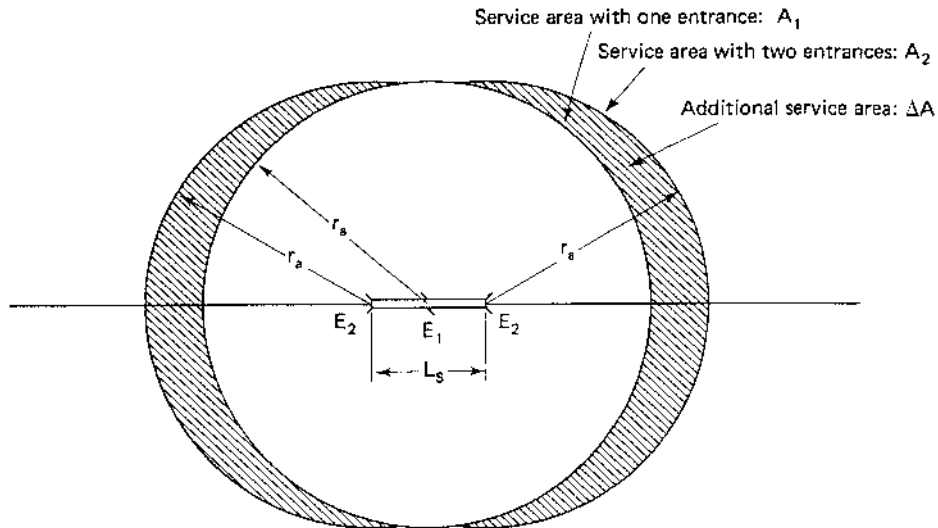


Figure 6.43 Comparison of service areas of stations with one and two entrances

various stores, display windows, and other facilities. Thus mezzanines get multiple use and benefit not only the transit passengers but also other pedestrians and, indirectly, street traffic flow. A typical layout of such a station is shown in Figure 6.44.

Direct connections between the mezzanines and the basements of major stores or other buildings are also common. Well-designed and extensively used large underground plazas and malls—with stores, restaurants, and connections with hotels, office buildings, RRT, and railroad stations—exist in Frankfurt, Hamburg, London, Montreal (Place de la Mairie complex), New York, São Paulo, and many other cities. Subway stations in many Japanese cities have direct connections with major department stores, while most railway stations are surrounded by high-density office and commercial developments.

The use of mechanical facilities to help pedestrian travel in rapid transit stations, primarily escalators, has drastically increased during the extensive rapid transit construction since the mid-1950s. Thus the old systems have few escalators (e.g., Philadelphia's SEPTA and New York average, respectively, 0.13 and 0.20 esca-

lators per station), but new systems make extensive use of them. For example, Toronto, San Francisco's BART, and Washington's Metro average three to seven escalators per station. Many such large rapid transit agencies operate well over a hundred escalators, sometimes 15 to 25 in a single major transfer station (e.g., Jungfernstieg in Hamburg, Figure 6.42).

The main design and operational features of escalators are as follows. The angle of rise is typically between 27 and 35 degrees. The minimum vertical rise justifying the use of escalators is 3.00 to 3.50 m. Common rises are one or two floor levels, but in exceptional cases they may be much greater: a number of stations of the Moscow and Washington Metros and Leicester Square Station of London Transport have escalators with rises exceeding 25 m. The widths of 1-, 1 1/2-, and 2-lane escalators at hip level are approximately 0.80, 1.00, and 1.20 m, respectively. Step widths are some 0.20 m smaller; outside widths, important for construction, 0.40 m greater. Step depth is 0.40 m. Speeds are usually between 0.50 and 0.70 m/s, resulting in capacities of 6000, 7000, and 8000 prs/h for the three widths. Moscow, St. Petersburg, and Stock-

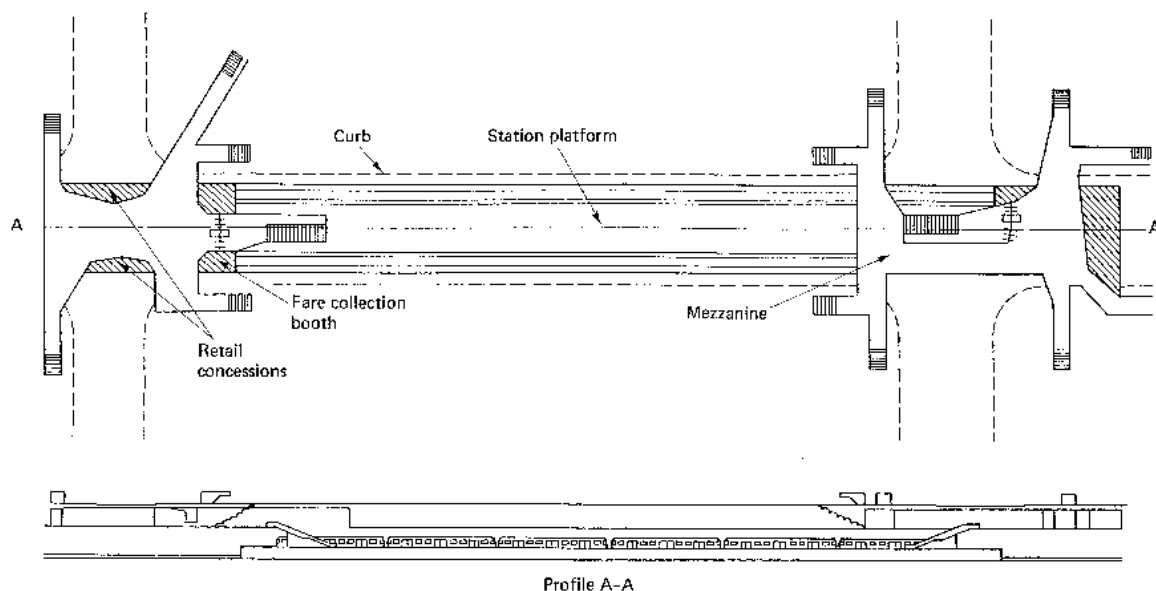


Figure 6.44 Typical metro underground station in central city

holm use speeds of up to 0.75 m/s, while London has operated escalators at 0.90 m/s. High-speed escalators may reach a capacity of 10,000 prs/h.

Several special features of escalators are worth mentioning.

- *Actuated escalators*, which stand when not in use. Actuation, achieved by means of a contact plate or light beam interruption by the approaching passenger, may substantially reduce energy consumption, particularly during off-peak periods.
- *Reversible escalators*, with automatic green and red lights indicating the permitted direction of travel at a given time.
- *Open-air escalators*, operating without weather protection. Purchase and maintenance costs of these are about 10% to 15% higher than those of protected escalators.

Moving sidewalks are used only where large numbers of passengers must walk through long, straight corridors. Since most people stand rather than walk on them, moving sidewalks increase neither average travel speed nor the transporting capacity of the corridor; they serve mainly for greater comfort. Passengers can be urged to “keep walking” while on the moving sidewalk, often with good results.

Elevators are used much less than escalators because of their discontinuous movement and high operating cost (an operator is sometimes required). Generally, they are used in two cases: for access to very deep stations (Hampstead in London, 55-m rise), and for disabled persons. The latter type need not have a large capacity. They have been provided in all stations of recently built RRT systems in U.S. cities. Required by the federal Americans with Disabilities Act (ADA), “full accessibility” has been expanded on transit systems to accommodate not only passengers in wheelchairs, but also those with luggage, strollers, the blind and, under certain conditions, bicycles and the blind. (see Vuchic 2005, Section 6.5).

6.5.3.5 Design for Feeder Lines. Stations with extensive transferring to/from feeder lines should be designed so that passengers have short, convenient paths,

preferably without crossing roadways. Several layout patterns are common (see also Section 5.4.3).

A loop (oval or rectangular) track or roadway with provisions for bypassing allows for many stopping locations around the central island as well as temporary storage for vehicles prior to peak hours. When an integrated fare system is used, access from outside streets may be controlled, so that no fare collection facilities exist between trains and feeder surface lines. A good example of this design is the Billstedt Station in Hamburg (Figure 6.45).

Parallel bays, each for one or two routes, are also used at bus/rail transfer terminals. Buses and trolley-buses enter individual roadways, which usually have a single lane. Each bus platform has a stairway leading to a mezzanine perpendicular to the bays, which leads to the RRT stations platforms. The bays are covered, giving good weather protection. Examples of these designs are found in Toronto and São Paulo (Photo 6.41).

Ostbahnhof in Munich, shown in Figure 6.46, is an interesting combination of loops for buses and LRT (double track) for terminal maneuvers and parallel bays for stops (three for buses, two for LRT) connected to the station by an underground pedestrian passage.

6.5.4 Auto-Transit Interface Stations

To achieve an interface between automobile travel in suburban areas and the transit network, stations must accommodate automobile access in two forms: *kiss-and-ride* ($K+R$) is the widely adopted term for the drop-off and pickup of passengers; *park-and-ride* ($P+R$) is the form where transit passengers park their cars at the station. These access modes usually create high peak-hour volumes, so that station design must make extensive use of traffic engineering techniques. Because of traffic volumes and parking facilities, these stations require very large areas per passenger.

The basic principles governing the design are as follows:

- Priority in convenience of access should be given to modes in this sequence: pedestrians, feeder transit, bicyclists, taxis, $K+R$, $P+R$.

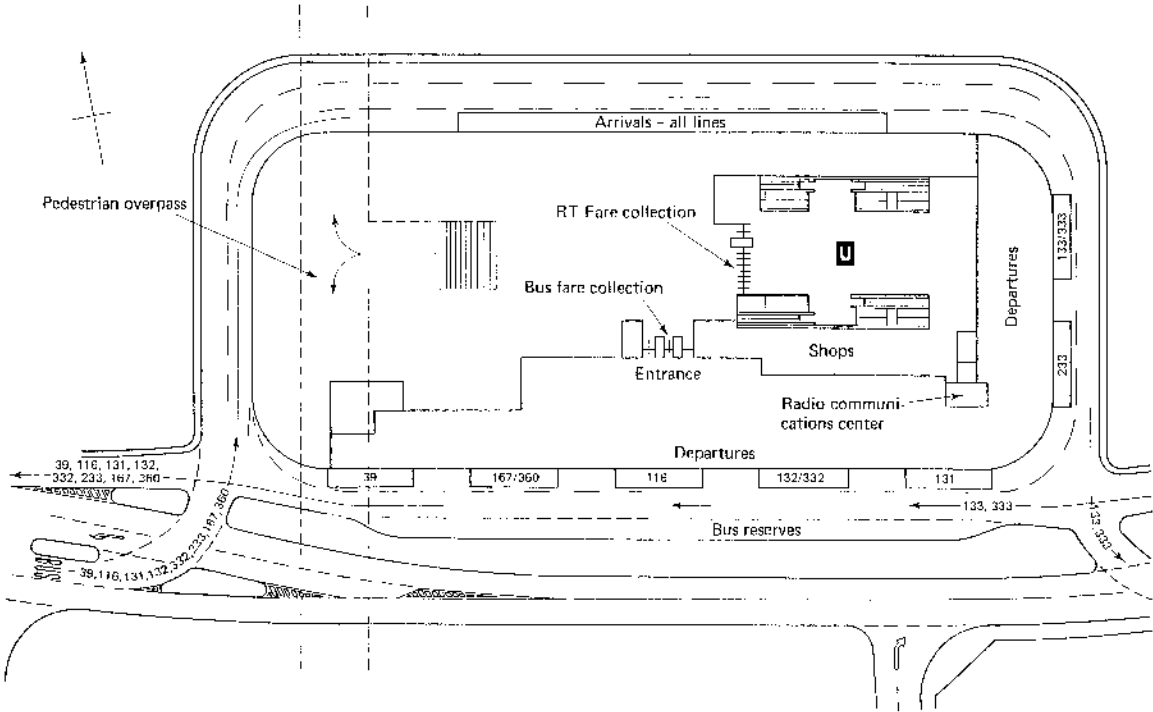


Figure 6.45 Suburban metro station with transfers to bus feeders

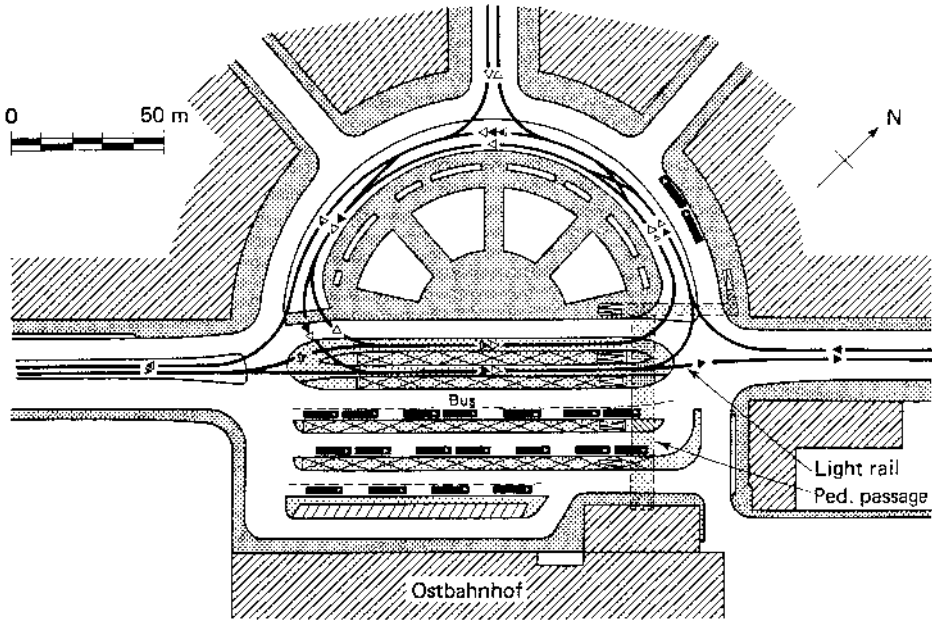


Figure 6.46 Regional rail station with transfers to LRT and bus lines

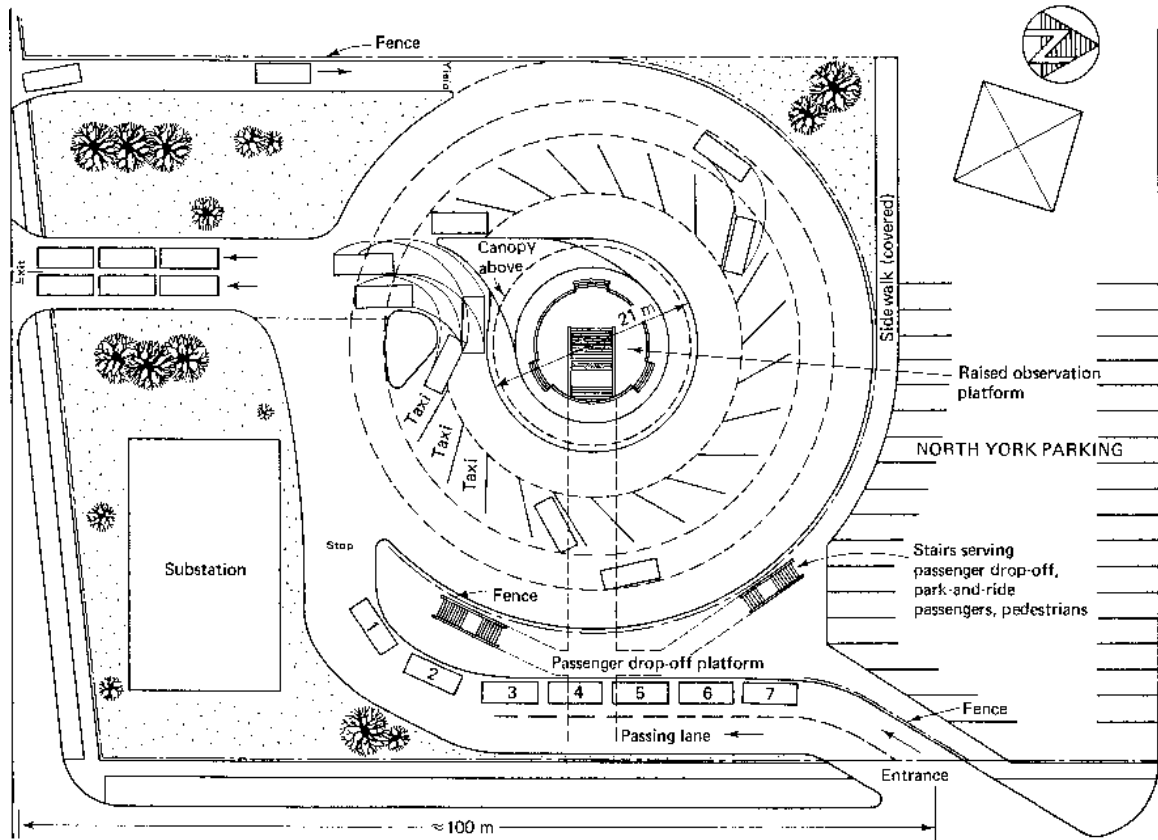


Figure 6.47 Suburban rapid transit station with kiss-and-ride transfer (Courtesy of Toronto Transit Commission)

- Maximum possible separation of all access modes is desirable.
- The pedestrian walk between access modes and the station platform should be safe, convenient, and as short as possible.
- Adequate capacity, easy orientation, and smooth traffic flow should be provided for each mode.

Typically, the station building is located in the middle of the station area. Feeder routes (usually buses) have stops close to station doors along curbs, which may be straight or have a sawtooth pattern. Pedestrian access from all streets and parking areas requires walkways, which should be at least 1.50 m (two pedestrian lanes) wide. Lowered curbs, mild gradients, and con-

venient doors should allow access to stations by the handicapped on wheelchairs. Bicycle racks and, if bicycle volume is heavy (e.g., near schools and college campuses), bicycle lanes should be provided.

The K+R area should be easily reachable from all access streets. It should have a sheltered drop-off area and a parking area for waiting with good visibility of the station exit. A very imaginative design of a K+R facility, including “through” parking stalls and provision for the recirculation of cars, is shown in Figure 6.47.

The remaining station area is used for parking. Its circulation roads should be remote from the station building so as to minimize auto/pedestrian conflicts. Aisles directed toward the building and right-angle

parking are usually best for circulation and space utilization. The dimensions of the stalls should be tighter than those common for public facilities because of sequential arrivals, lower turnover, and regular users. An aisle width of 18.30 m (60 ft) and a stall width of 2.50 m (8.33 ft) are adequate for standard U.S. cars. The respective dimensions for compact cars [i.e., shorter than 5.00 m (16.0 ft)] are 14.50 m (48 ft) and 2.90 m (8 ft), resulting in a 30% to 50% higher parking capacity for a given area.

The average area needed per parking space varies with the shape and size of the facility. With adequate circulation, 30.0 to 32.5 m² (320 to 350 ft²) per space for standard cars and 18.5 to 20.5 m² (200 to 220 ft²) for compact cars is required. Extensive landscaping or inconvenient geometry may increase these figures by 30% to 50%.

The design of a RRT station with major P+R and K+R facilities based on these principles is shown in Figure 6.48. For further details of design of outlying RRT station areas, see Vuchic and Kikuchi (1974).

6.5.5 Rail Transit Yards and Shops

Several factors influence the selection of rail transit yard locations. Minimization of deadheading distances (between a yard and line) is usually achieved when the yard is located on the outer section or at the end of each line, since inbound travel starts earlier in the morning than outbound, while the reverse is true in the evening. For day storage of trains, between morning and evening peaks, central locations minimize empty runs; therefore, storage tracks at different stations along the lines can be used. Further, the large space required for yards is much cheaper in the outlying than in the central urban areas. For environmental reasons and land-use impacts, outlying locations are also usually most desirable.

Functions which major rail transit yards have include the following:

- Shop for regular car maintenance, inspection, and minor repairs

- Track for car cleaning and washing, which may be enclosed in the shop building or be in the open, as shown in Photo 6.42
- Tracks for overnight and day storage of trains
- Tracks for cars waiting for maintenance
- Tracks for maneuvering and preparing train consists

A schematic layout of an RRT yard with designations of its individual sections and tracks is shown in Figure 6.49. In this specific case, the yard is located between tracks, in the extension of an outlying station. A more typical “terminal” type of yard with a large storage area and maintenance facilities is shown in Figure 6.50; Figure 6.51 depicts LRT yard in the city of Bochum, designed to meet the latest standards for efficient train maintenance and storage as well as dedication of 20% of area to green surfaces required in Germany.

General overhaul and major repairs of cars are usually performed at one major shop for the whole system. RRT systems with fleets of over 1000 cars perform overhauls at rates of several cars per week or per day, utilizing production procedures of major factories. The Coney Island and 207th Street Overhaul Shop in New York are good examples of facilities performing such large-scale activities.

6.6 OPERATIONS, PERFORMANCE, AND COSTS

This section discusses the operations, basic performance, and cost characteristics of rail modes. A description of different methods of vehicle control and, specifically, full automation of rapid transit trains is first given, with its implementation steps and evaluation of results.

6.6.1 Vehicle/Train Travel Control and Automation

As the transit mode carrying by far the highest volumes of passengers, the rail rapid transit system is de-

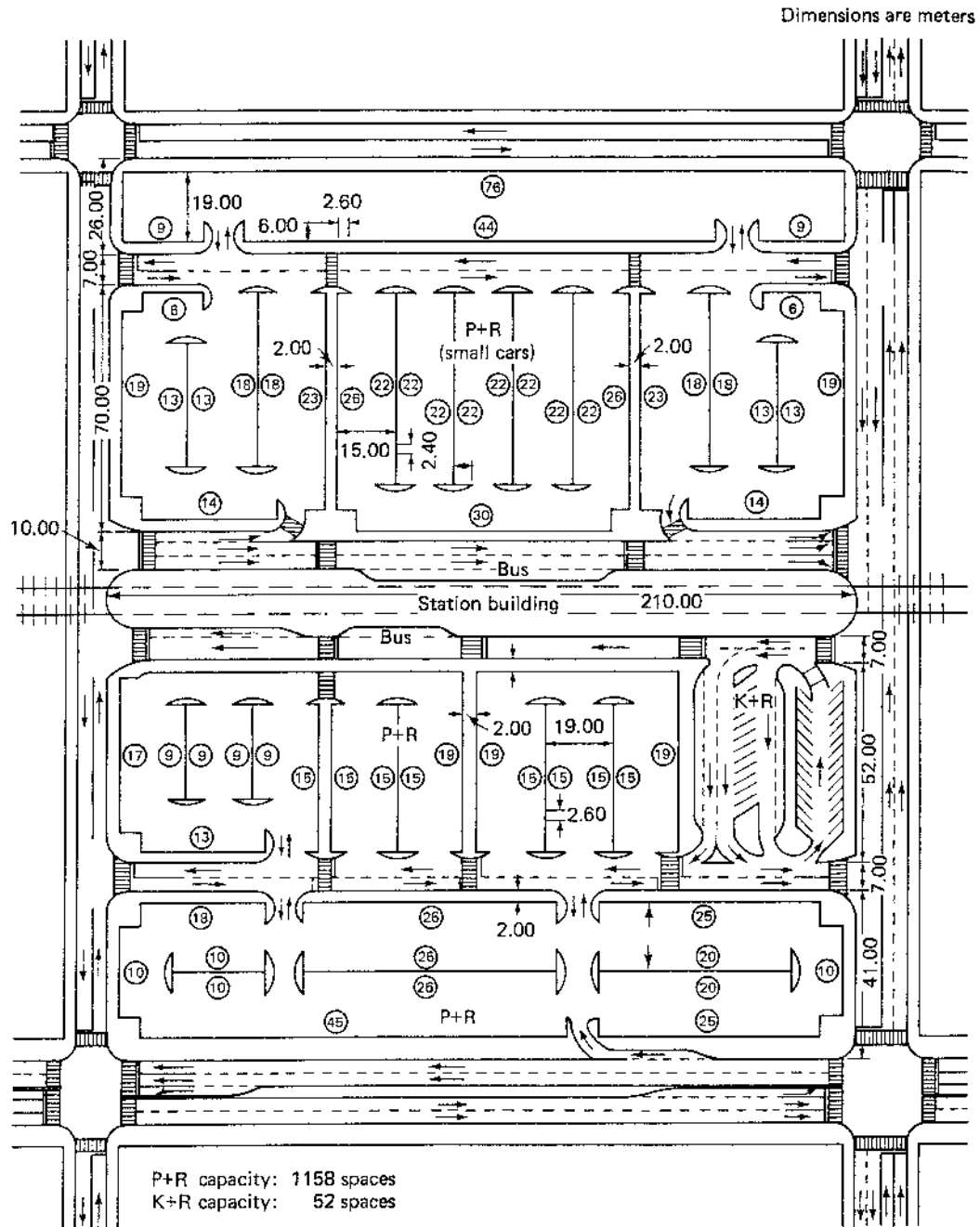


Figure 6.48 Suburban rapid transit station with pedestrian, bus, K+R, and P+R as feeders

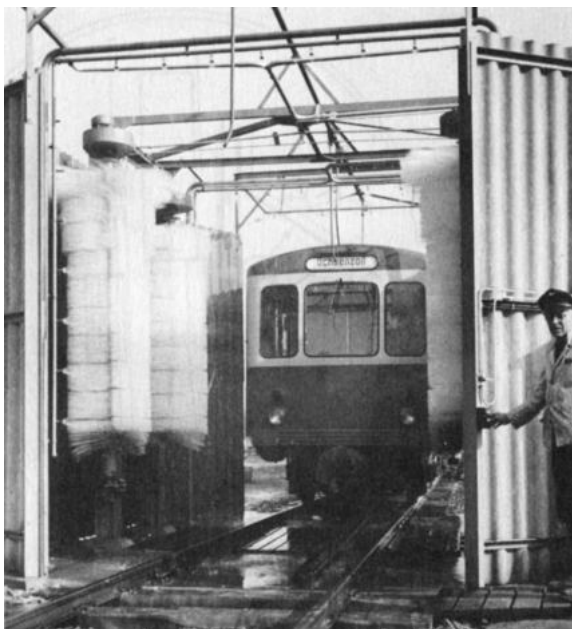


Photo 6.42 Automatic washing of rail cars (Hamburger Hochbahn AG)

signed for very high safety, speed, and reliability. The tracks are fully signalized and drivers' actions are either fully backed or replaced by automated fail-safe control systems. Reviewing all rail modes, the types of TU movement control can be grouped into four general categories:

1. *Manual/visual*, where the driver controls the TU without any assistance
2. *Manual/signals*, where manual driving is assisted by automatic signals showing occupancy of the track ahead. This type of signal control is referred to as an *automatic train protection (ATP)* system. The signals may be of two types:
 - a. *Permissive*, when the driver can drive through red (intentionally or by mistake) with impunity, as is the case with all street signals.
 - b. *"Forced stop"* type, which activate emergency brakes if the driver overrides red signal. These are used on rail systems on ROW category A. They are common on RRT and RGR, and on some LRT systems.
3. *Automatic train operation (ATO)*, in which the driver initiates an automatic driving process on each station-to-station spacing and only supervises train movement.
4. *Fully automated driverless trains*, which have no controls aboard requiring personnel.

All street transit and most semirapid transit modes—buses, streetcars, BRT, and most LRT—use type 1 and 2a controls. The ATP technology, particularly the 2b type, is used on rail (and other guided) modes, while automatic driving—types 3 and 4—is used only on guided systems with fully separated ROW (category A)—i.e., rapid transit by its technical definition (not BRT). Type 4 operation requires additional control elements over type 3, as described in Section 6.6.1.3.

6.6.1.1 Manual/Visual Control. Manual vehicle control, utilizing the driver's vision, is only as safe as the driver's capabilities and judgment. This is the control used in all street travel, and it is considered adequate for moderate-size TUs, such as buses, trolleybuses, streetcars, and most LRT transit units.

With visual control, vehicles can follow each other at any distance the driver chooses. This leads to low speeds when the capacity level is approached. Unless efficient supervision of boarding at stops is provided, delays may occur. Consequently, lines with visual control may have a rather high capacity (short headways), but it is achieved at a low level of service: reliability and speed may be unsatisfactory. For operation below capacity and with speeds up to 70 km/h, manual/visual control is usually adequate and efficient.

6.6.1.2 Signal Control. Modes with large-capacity TUs, such as RRT and RGR, require a higher degree of safety than visual control provides. The possibility that a single human (driver) error can cause an accident resulting in loss of life and large damage is unacceptable. Therefore virtually all RGR, RRT, and some LRT systems are equipped with ATP (i.e., signal systems that control the spacings between successive trains). Various control methods and equipment are used for signalization. The basic concepts underlying most of these are described here.

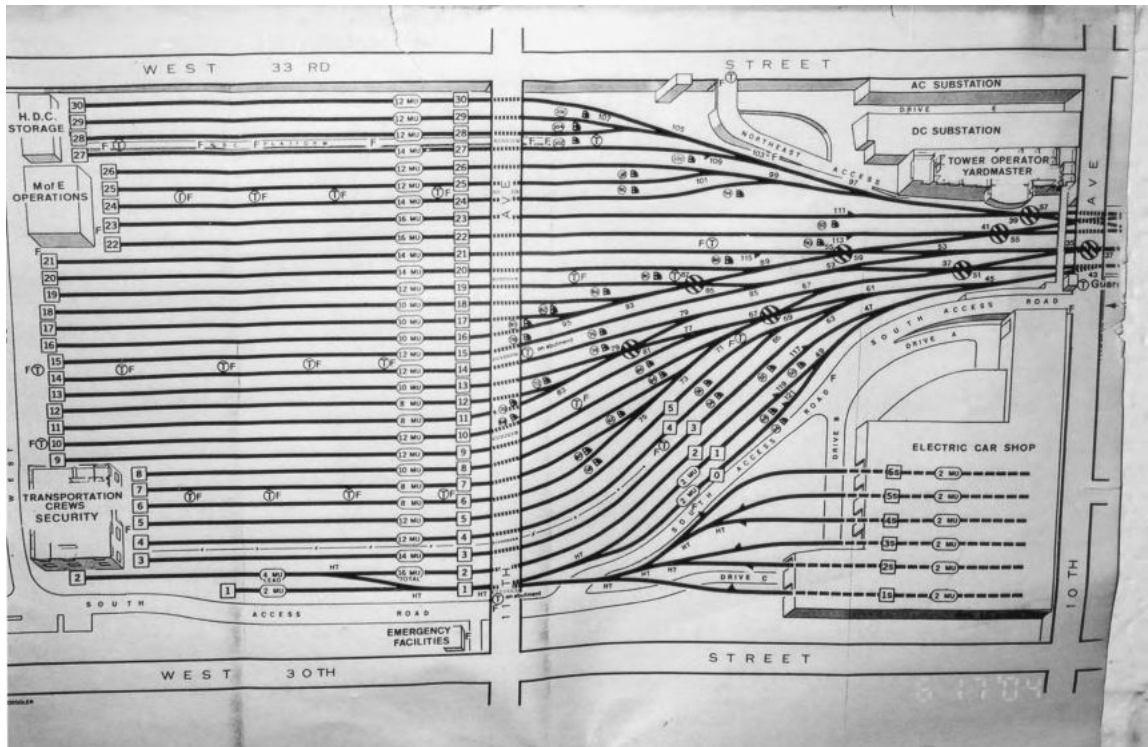


Figure 6.49 Schematic track plan of a regional rail yard (Long Island Rail Road in Manhattan) (Courtesy J. W. Vigrass)

YARD

- A BLOCK AREA
 - ROUTINE SHOP
 - MAIN SHOP
 - COMPLEMENTARY SHOP
 - STORES AREA
- B BLOCK AREA
 - MANAGEMENT HEADQUARTERS
 - OF MAINTENANCE DEPARTMENT
 - AND ELECTRONIC LABORATORIES
- BI BLOCK AREA
 - MAINTENANCE SHOPS
 - OF ELECTRO-MECHANICAL
 - EQUIPMENT
 - PERMANENT WAY EQUIPMENT SHOP

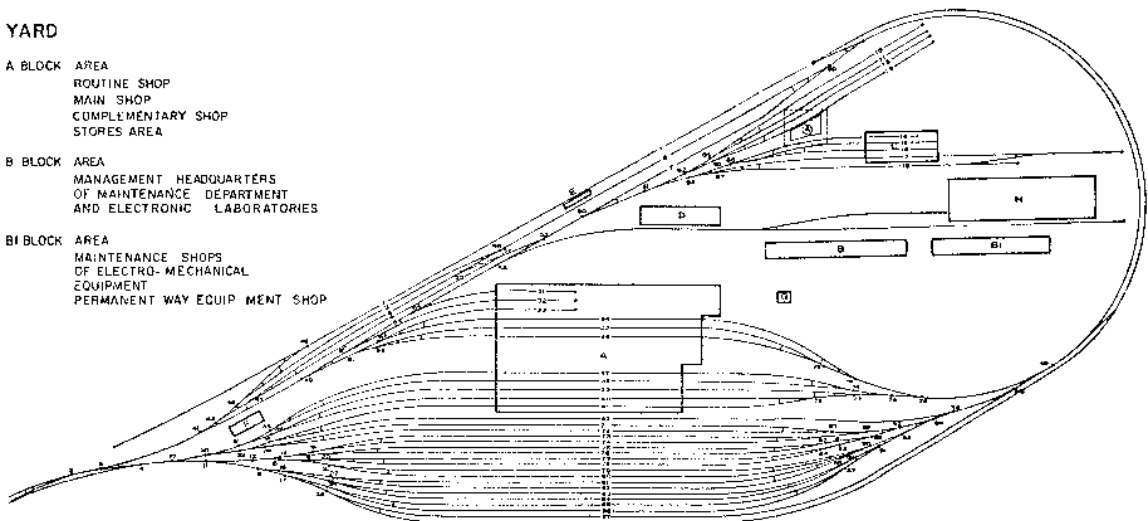


Figure 6.50 Rapid transit yard layout (Metro São Paulo)

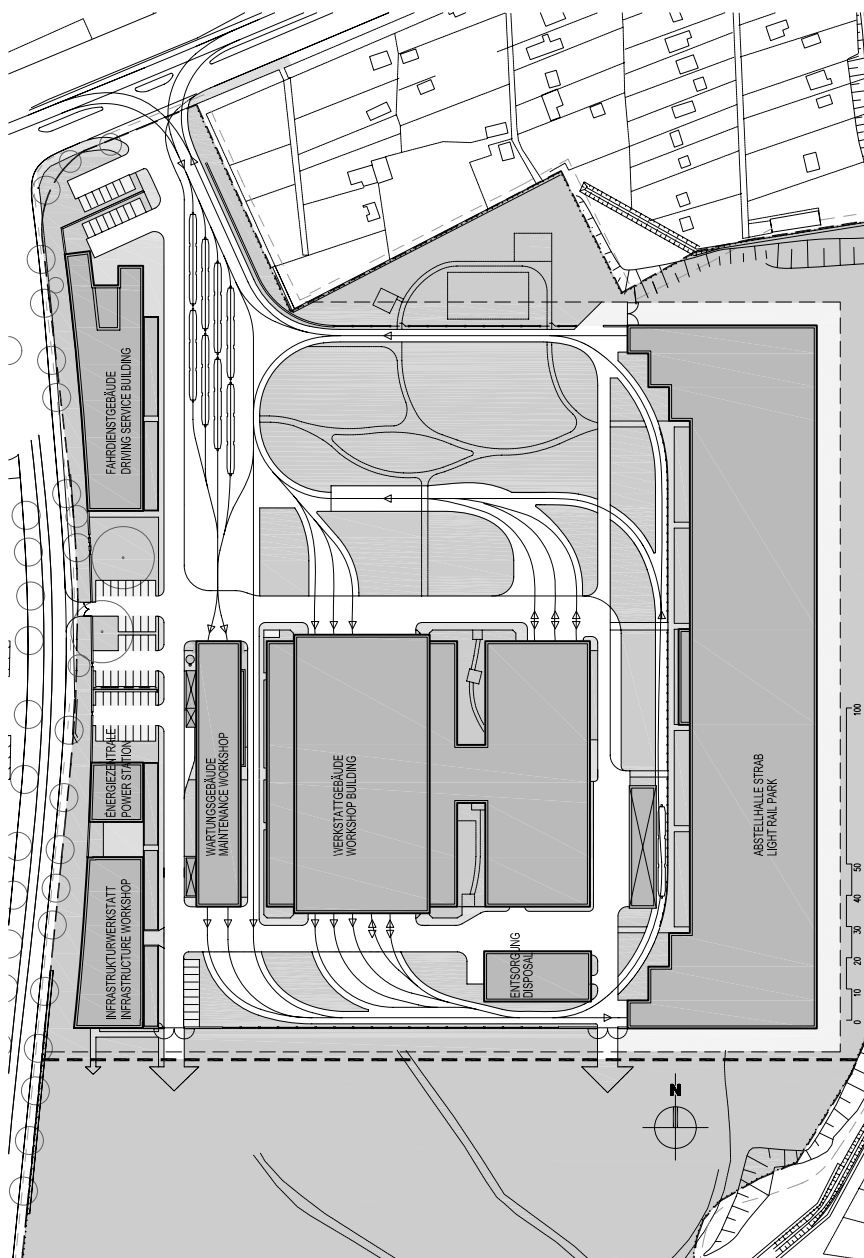


Figure 6.51 Layout of an LRT yard designed to meet the latest standards for efficient operations and environmental requirements in Bochum, Germany (Courtesy of VDV and Gestering, de Vries, Wurster, and Partner)

To guarantee safe separation of trains, the position of the *leading train (LT)* must be detected and shown to the *following train (FT)*. For this purpose, the track is usually divided into sections called *fixed signal blocks*. In a conventional system, the running rails within each block and between blocks are electrically insulated from each other. A low-voltage battery is connected to the two running rails in each block, forming an open circuit. As a train enters a block, its axles close the circuit, activating via a relay a circuit controlling the signals.

There are two general types of signal display, wayside signals and cab signals. *Wayside signals* are located along the track at block boundaries. *Cab signals*, utilizing continuous transmission of block occupancy information via the rails to each train, are displayed on the driver's control panel. Wayside signals are simpler and less expensive, whereas cab signals give the driver continuous information and are independent of weather and other possible visibility impediments. Cab signals are therefore increasingly used on rail lines.

Signals may utilize different light patterns or light colors to display usually three commands (or *aspects*). With color lights, these are red, stop; yellow, proceed at a limited (prescribed) speed; and green, normal speed.

Most LRT and a few RRT systems utilize permissive signals, which are only advisory: trains can be driven through red signals with impunity. However, the majority of RRT and RGR systems and some LRT lines utilize forced-stop signals. A magnetic (on older systems) mechanical device is located between or next to the rails at each signal location. When the signal is red, the device is active and creates a magnetic field. If a train passes over the device, a detector mounted beneath the car senses this magnetic field and activates the emergency brake, which the driver must report to the control center. Moreover, to release the brakes after the stop, the operator must break a lock, for which he is held responsible upon returning to the yard.

All the signals along the line are interconnected, so that when the presence of a train in one block causes its signal to display red, this automatically triggers a red aspect on the signal behind it and yellow on the next, while all subsequent signals remain green. This

sequence can be seen in Figure 6.52, which shows the travel of a LT and a FT over a six-block track section. The LT is shown on each line in its initial (a') and final (a'') positions for each set of signal indications. The FT is shown at the closest positions to the LT it can reach at both normal (b') and reduced (b'') speeds. For clarity, the influence of the FT on the signals is not shown.

The figure shows that the closest the FT can come to the LT at normal speed is two block lengths (b' and a' on lines I and III). At reduced speed, the minimum separation is one block length (b'' and a' on lines I and III). Thus this signal system always provides a distance between trains such that the FT can be stopped without collision even if it overruns a red signal.

The time-distance diagram in Figure 6.53 shows the same type of signal operation with different block lengths. Suppose that the block lengths D in case (a) are equal to the train stopping distance, and those in case (b) are $D/2$; the diagram shows that use of the shorter block lengths reduces the minimum separation between the LT and FT for full speed from $2D$ (if the LT stopped at a' , the FT could travel at full speed to b') to $1.5D$, while their minimum separation at reduced speed would remain the same, D .

Pursuing this analysis further, it becomes obvious that the shorter the blocks are, the more closely the trains can follow each other without reducing safety. The headway reaches its minimum value when the block length is zero (i.e., the FT continuously receives information about the exact position of the LT). In this case the FT can theoretically always maintain a separation equal to its stopping distance (in practice, this distance must be increased for reaction time, safety margin, etc.). Consequently, a *moving-block* signal system, providing zero block length, allows reaching absolute maximum line capacity. Although moving-block signals are used principally on automated systems, they can also be applied to manual operation, with the same capacity advantages.

Several different technical solutions are in use for moving-block systems. The concept used on some sections of the Munich S-Bahn and a number of other systems is quite simple to explain. This system has two cables, laid between rails and criss-crossed at regular

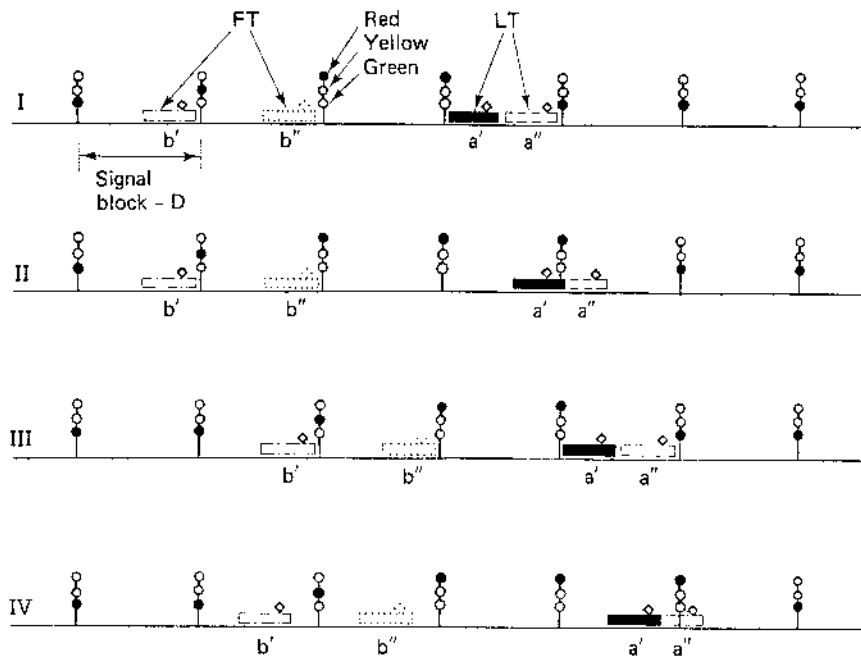


Figure 6.52 Train control with fixed-block signal system

spacings D (e.g., 100 m). The cables, called “line leaders,” are connected with a central control center (Figure 6.54).

Antennas are mounted beneath all train units. The antennas of the first and last cars of each train sense and count each criss-crossing of the line leader by the change in the direction of flux they emit. The count, transmitted to the control center—together with the train’s identification, length, weight, and so on—as a coded “telegram,” allows computation of the train’s location with respect to a fixed reference point. The control center receives this information from all trains on the line section it supervises, which is usually 10 to 12 km long; computes the positions, speeds, and braking abilities of each train; and transmits to each one a separate “telegram” with directives to accelerate, proceed at constant speed, coast, or brake. This information, transmitted back to the train via the line leader, is decoded on the train and displayed to the driver in his or her cab or directly used for ATO. The driver

thus has a continuous display of instructions for driving by means of an elaborate type of cab signals.

It has been computed that with this type of ATP control, minimum headways under 90 s can be operated on RRT and RGR lines (theoretically exceeding maximum frequencies of 40 TU/h), but in most cases such headways cannot be achieved due to station dwell times. Moreover, even when individual headways between trains can be shorter than 90 s, scheduled headways must always be longer than the minimum ones because there must be a reserve time to make up for headways which are longer than the minimum one. While the New York City Subway, London Underground, and several other metro systems have operated minimum headways of 90 s, Moscow Metro uses short blocks (even two or three within a station, where short headways are particularly critical). It also uses fast dispatching of trains, which shortens station dwell times, and signals displaying headway from the preceding train (Photo 6.43), so that headways as short as 70 s

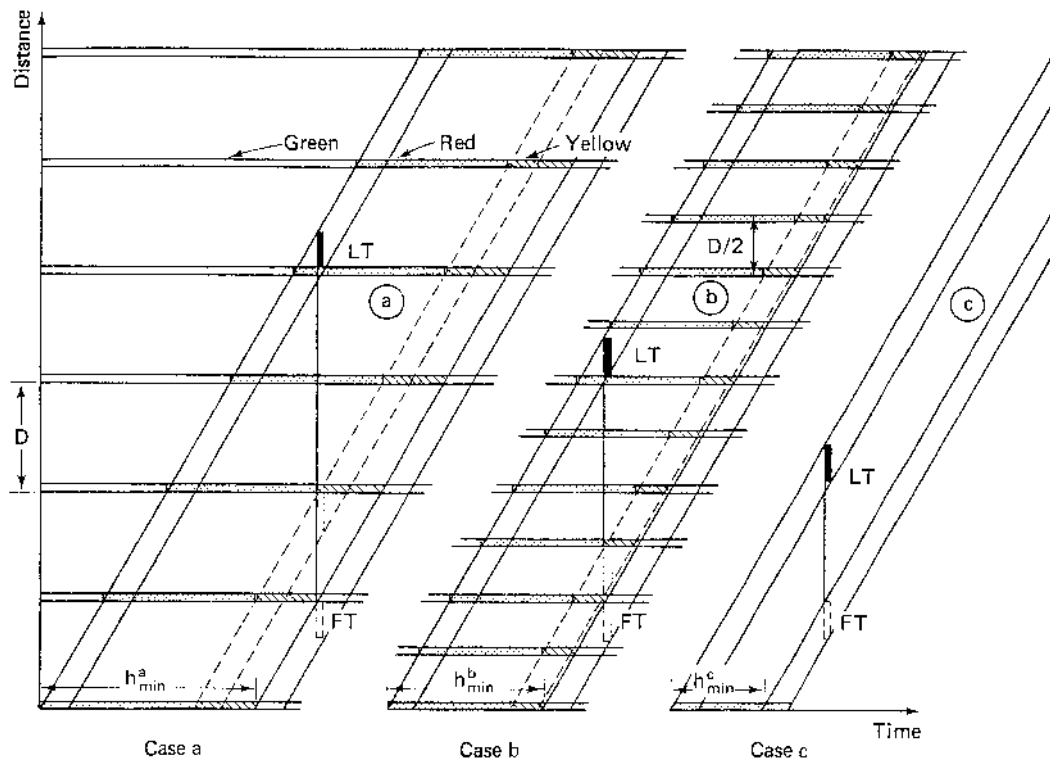


Figure 6.53 Minimum headways for block lengths D , $D/2$, and 0 (moving block)

can be achieved. The VAL AGT system, with short trains and somewhat higher braking rates, can reach minimum headways of only 60 s.

6.6.1.3 Automatic Train Operation (ATO). There are two degrees of ATO. *Semiautomatic operation* incorporates only initiation of train movement and supervision by a driver (type 3 in Sec. 6.6.1), who also performs other operations, such as the supervision of doors, delivery of passenger announcements, and handling of any problems or breakdowns. *Fully automatic operation*, type 4, is when trains operate without crew: *train control and operations* are automated, performed automatically, and supervised by a control center.

Fully automatic operation of transit TUs is the ultimate result of a long evolutionary process whose selected highlights are summarized in Table 6.10. When

the first rapid transit systems opened around 1900, doors were physically opened by a guard on each car. It was also considered that an employee must be present in each vehicle. The introduction of centrally controlled doors a few decades later allowed train crews to be reduced to two persons: a driver and one guard or conductor.

Train operation with a two-person crew was standard for many decades and is still used on a number of metro systems. With relatively small adjustments, this operation was replaced in Hamburg in 1957 by a driver-only crew, resulting in a significant reduction of labor costs. This type of operation is now used by most metro systems opened since the 1970s, as well as on some older ones. However, the last step in automation, driverless TUs, requires much more fundamental changes.

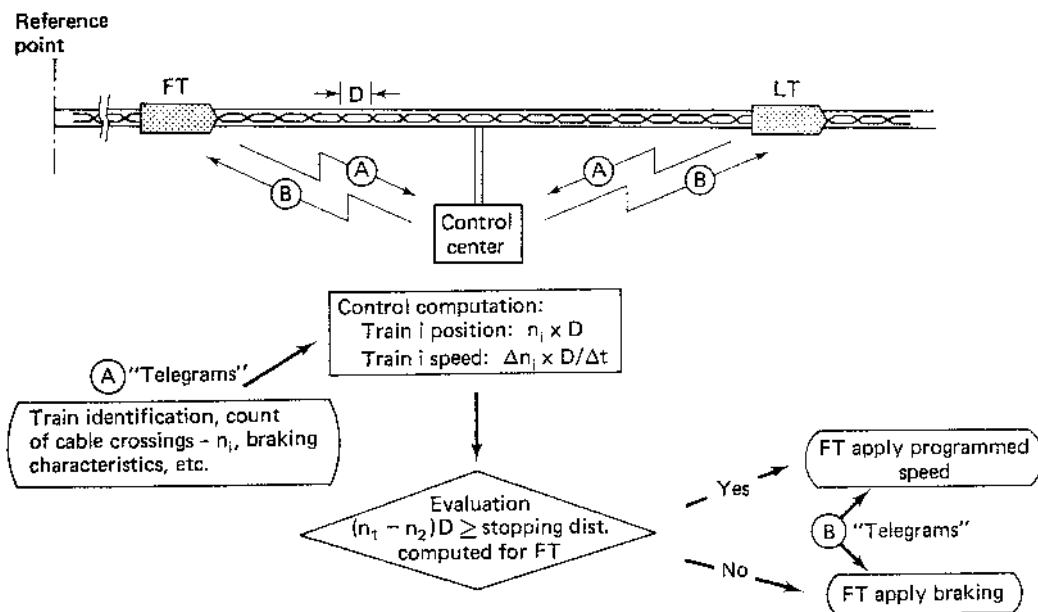


Figure 6.54 Train control with moving-block signal system

Like many other gradual automation processes, elimination of the last person of train crew—the driver—requires a more comprehensive set of changes and the introduction of new physical and operational elements in the metro system. This involves careful planning, higher investments, and new operational practices, such as change of supervision from the trains and stations to a control center that coordinates train operation, train dispatching from stations, public information, police, and other services.

A sine qua non for ATO is an exclusive, fully controlled ROW. ATO can therefore be applied only on RRT, on fully controlled RGR, and on LRRT and AGT lines. A number of RRT systems have developed different ATO technologies. The first full ATO in operation was the 42nd Street Shuttle of the New York City Subway. Today, most metro systems opened since the 1970s, and some older ones, operate with ATOs. Some of them (PATCO in Philadelphia) require the drivers to perform manual driving for one cycle run every day to retain his or her driving skills.

Fully automated driverless TUs have also been gradually introduced, initially mostly on APM and

AGT modes but then also on LRRT and RRT modes, as Table 6.10 shows. It is important to understand that full automation should not be considered as the goal but rather as a possible measure for achieving a more efficient transit system (better performance, lower cost, increased passenger attraction). Full automation can bring very important benefits on many systems, but it is not necessarily a desirable goal for all rail rapid transit lines. Evaluation of full automation as an option in rapid transit planning should therefore be carefully performed.

Figure 6.55 shows the main actions needed for the introduction of fully automated operation. The major problems to be solved are as follows:

- *Introduction of ATO and ATS systems* (see the next section).
- *Supervision of passengers* on station platforms, their boarding and alighting and *train dispatching* can be fully automated, but it must be monitored from the control center.
- *Track surveillance* for obstacles must be ensured. In tunnels and on aerial sections, the control of



Photo 6.43 Headway clock for maintaining short and reliable headways on Moscow Metro

ROW is virtually complete. But on at-grade sections and in station areas, improved control is required. Protection of tracks from intrusion by passengers can be achieved by infrared rays, by plates sensitive to any falling objects, or by platform edge walls with doors to which the trains' doors match when they stop.

- *Information for passengers* must be upgraded to be basically of the self-service type.
- *Contact with passengers* in cases of emergency. Although this problem exists today (passengers in rear cars often wait during breakdowns without any communication with the driver), better communication must be provided on driverless trains

for psychological reasons. This can be done by an intercom or closed-circuit TV system provided in each car. Thus security—including the detection of vandalism, smoke, or fire—would be improved significantly over the present conditions.

- *Opposition by labor unions* may be a serious obstacle on some existing systems. Through rational negotiations providing compensation accrued by increased ridership and consequent opening of other, more productive jobs, it should be possible to solve this problem.
- *Conservatism of management and regulatory bodies* represents, in some cases, another serious obstacle that requires time and effort to resolve.

Table 6.10 Evolution of automation on rail and other guided transit systems since 1900

City/Line	Year	Train Length			Crew Size	Operation-Innovation	Innovation
		Cars	Meters	Spaces			
New York Subway	1904	6	108	1100	7	Driver + 6 guards	2-Person crew
Paris Metro	~1930	5	71	750	2	1 guard/car → 1 guard/train	1-Person crew + platform attendant
Hamburg U-Bahn	1957	8	112	1100	1	Eliminate guard	(1), ATO
New York/Times Square Shuttle	1964	3	54	540	(1)	Driver sitting	1-Person crew, ATO
London/Victoria Line	1968	8	128	1480	1	Driver door control	Unattended stations
Philadelphia/PATCO	1969	6	124	1200	1	Central station supervision	1-Person, 10-car train
San Francisco/BART	1972	10	220	2160	1	Driver door control	Automated network in airport
Dallas-Fort Worth/Airtrans	1974	2	13	80	0	ATO, ATS; low capacity	Automated low-capacity transit
Morgantown	1975	1	5	21	0	ATO, ATS; very low capacity	Medium-capacity automated shuttle
Atlanta Airport/Westinghouse	1980	3	38	300	0	ATO, ATS; medium capacity	Automated guided transit
Lille/VAL	1983	2	28	172	0	ATO, ATS	Roving driver-attendant
Vancouver/SkyTrain	1986	4	51	440	0	ATO, ATS	Attendant on each train
London/Docklands LRT	1988	2	56	524	(1)	ATO, ATS	Fully automated regular metro
Lyon Metro Line D	1993	3	50	450	0	ATO, ATS	Fully automated regular metro
Paris Metro Line 14	1998	5	75	750	0	ATO, ATS	

Note: Some numbers are approximate.

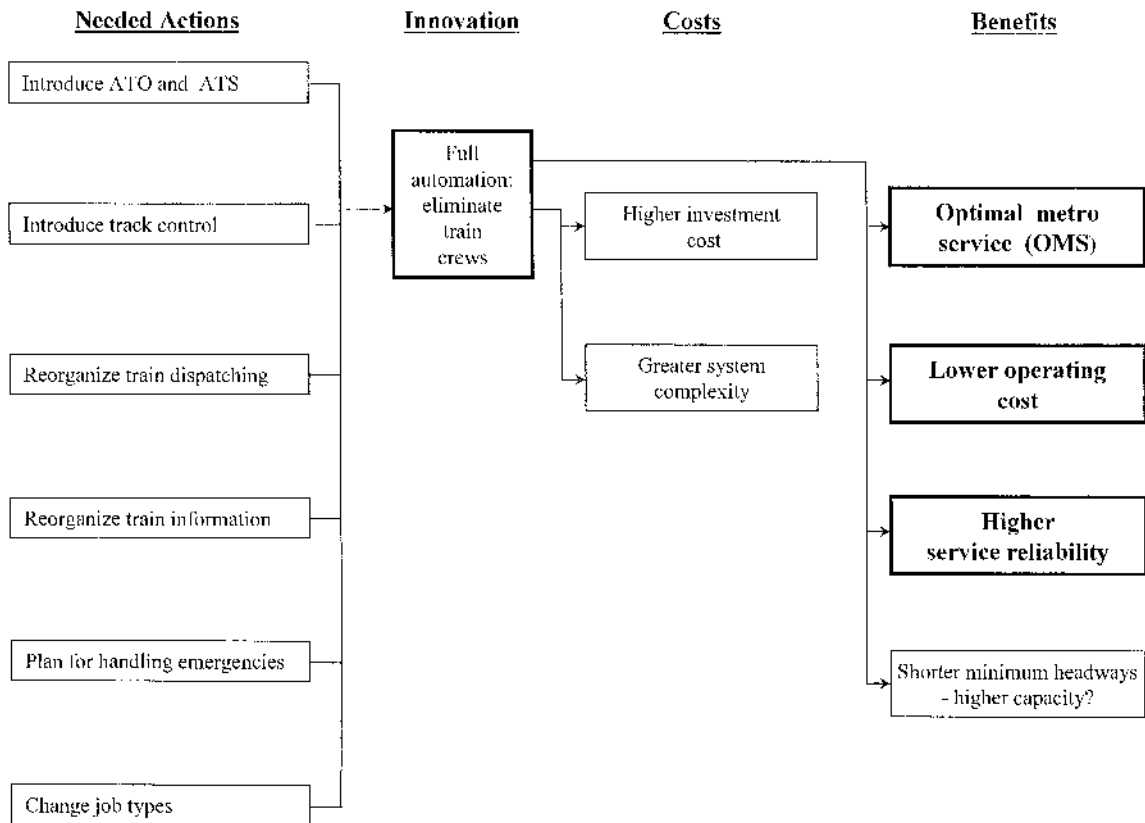


Figure 6.55 Evaluation of introduction of fully automated trains

The introduction of full automation poses two problems that must be planned for:

- *Higher investment cost.*
- *Greater system complexity*, which requires better-qualified personnel than conventional systems have.

The final column in Figure 6.55 lists the benefits accrued by full automation. The main ones are defined here.

- *Optimal metro service (OMS)*—the ability to introduce a high frequency of service at all times is by far the greatest benefit of full automation. It is not only very attractive to passengers, but also makes possible many variations in service, including the ability to couple and uncouple cars,

place them into or pull from the service at any time, route them to different lines or tracks, and use different stopping schedules. This specific feature and its positive impacts on the attraction of passengers, increased revenue, and reduced operating costs are shown in Figure 6.56.

- *Lower operating costs and higher reliability of service* are obtained from full automation of regularly operated trains. The above-mentioned benefits from the OMS are additional to these.
- *Shorter headways* may be a benefit on lines operating at capacity, but their significance depends on many local factors.

Reduced labor cost achieved by the elimination of the “last crew member,” sometimes believed to be the main reason for automation, may in many cases be

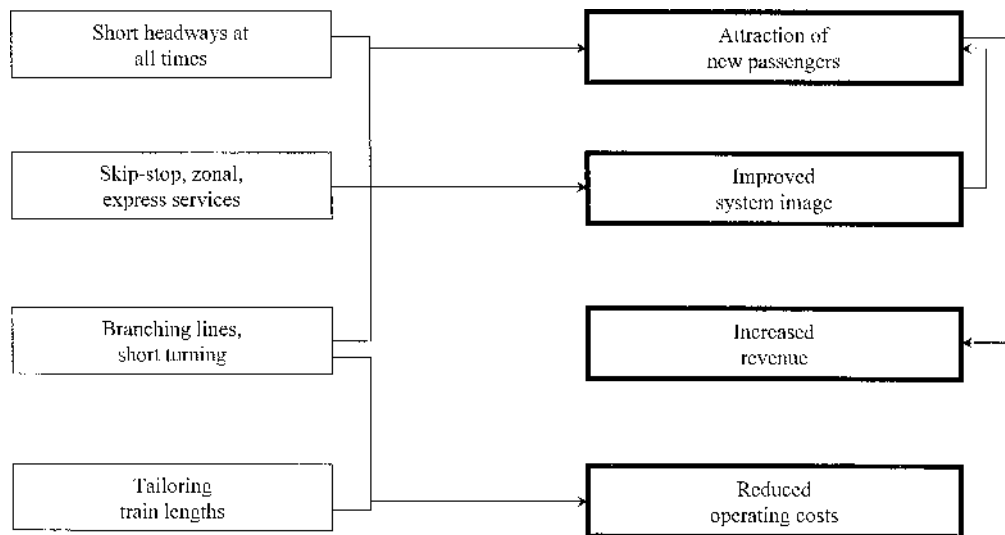


Figure 6.56 Optimal Metro Service (OMS)—utilization of metro automation benefits

much less significant than the resulting service improvements. Without crews, operating cost per car-km is constant regardless of train size. Thus an existing service with, for example, six-car trains operating at 7.5-min headways could be changed into service with two-car trains operating at 2.5-min headways without an increase in cost. Consequently, most RRT systems could offer service with 2 to 5 min. headways throughout the day (Photo 6.44). Significant ridership in-



Photo 6.44 An aerial station of Vancouver SkyTrain with bus transfers (Courtesy of Squeaky Marmot)

creases could be achieved. Peak-hour service would involve less change in headways but more savings in labor costs.

Rail systems, because of their technical simplicity, are actually more conducive to full automation than are the numerous AGT-APM modes, sometimes promoted as the only ones capable of such operation. Full automation would bring significant benefits to systems operating below capacity, which is the case in most cities. Moreover, it would make RRT much more attractive for those medium-sized cities that currently have surface transit of much lower quality.

6.6.1.4 Automatic Train Supervision (ATS).

Most rail transit systems have a center that controls operations on an individual line or on the entire network. The center has one or more boards and multiple computer monitors with layouts of track network. They display by different colored lights the positions of switches and train movements, occupancies of signal blocks, and train identification codes. These centers have automated control over settings of switches and signals within each interlocking, station, or other area with numerous interconnected tracks. All possible paths through an interlocking are preprogrammed, so

that when a train travels over a given path, all tracks along that path are free and switches prevent any possible contacts with trains that are on or may enter from other tracks.

Many recently built rail systems have on-line computer supervision of operations, which precisely controls movements of all trains. Thus BART's control was designed to compute schedule adherence of each train and recover delays by giving them instructions as to which of the six performance level programs to apply to speed up or slow down their movements and exactly time arrivals of trains at line merging points.

6.6.1.5 Review of Rail Transit System Automation. The preceding sections show that there are a number of operations in rail transit systems that can be automated. In addition to the described ATP, ATO, and ATS, which are major functions, there are minor functions that can be automated. They include passenger information display on platform and on trains, which can be preprogrammed in connection with ATO, as well as door operation, fare collection, and so on. Naturally, for fully automated operation, all these functions must also be automated.

For a clear review, the major elements of *rail transit automation* mentioned above are presented in a systematic form in the box on page 422.

6.6.2 Performance Characteristics of Rail Modes

Ranges of operating characteristics of different rail modes in Table 6.1 show that their performance generally increases from SCR over LRT and RRT to RGR. More detailed statistical data are given here for RRT and LRT, the two most widely used and actively planned modes.

6.6.2.1 Operational Characteristics. Basic network and operating data of 13 U.S. rail rapid transit systems are given in Table 6.11 (the 14th system, San Juan, PR, opened subsequently). These systems represent 11 metropolitan areas (New York includes the New York City Subway and PATH, Philadelphia includes SEPTA and PATCO). In addition to rapid transit

systems, most of these 11 metro areas have regional rail systems, while most of these and another approximately 20 cities have light rail and streetcar systems.

Table 6.11 includes network lengths, number of vehicles in service, number of passengers, and their average trip lengths. These data lead to two interesting observations. First, there is a distinct dominance of New York City (its Subway and PATH) by their size and characteristics. Rail rapid transit in the New York region used to amount to about three-quarters of the national rapid transit ridership. This share has been reduced through intensive building of seven new rapid transit systems since 1972. However, that share still remains high: the New York Subway and PATH now amount to 33.3% of national metro network length; they are served by 61.6% of vehicles and carry 66.6% of the nation's passenger trips.

Second, the rapid transit networks built since the 1970s are more extensive, serving not only central cities but also much larger regions. This is reflected in several indicators of service and passenger densities for two groups of systems. The older systems have average trip lengths between 6 and 10 km; on the newer ones these lengths are between 8 and 14 km, while the average trip length on BART, exceeding 20 km, is more typical of regional rail than of rapid transit systems. Due to the longer trip lengths on the new systems, the share of New York City in the national total is somewhat smaller on the basis of passenger-km than in passenger trips served: it is 60.2% as compared to 66.6%.

The density of offered service, measured by vehicles/km of network, is distinctly the highest on the two New York City systems with 13 and 11 vehicles per kilometer, while other systems with exception of Cleveland are in the range of 2 to 6 veh/km. Density of ridership, or network utilization factor measured by passenger-km/km of network, are similarly the highest in New York City (20 and 33 million passengers/km of network), between 10 and 15 on other older systems, and only between 2 and 5 million passengers/km of network on the new, longer and systems serving lower-density suburbs. A rather consistent passenger loadings of vehicles, expressed by the vehicle utilization factor (number of passenger-km/vehicle-km), shows the range of 13 to 28 prs-km/veh-km without a clear distinction between older and newer systems.

Automation of components: operates individual facilities on trains and in stations, such as:

- Door control
- Train departure
- Passenger information on platform
- Line designations and announcements on trains
- Fare collection
- Telephones for assistance and emergencies

Automatic train protection (ATP): prevents trains from following each other at less than safe distance. Types are:

<i>Control</i>		<i>Block</i>		<i>Signal</i>
Permissive	→	Fixed	→	Wayside
Forced stop	→	Moving	→	Cab

Automatic train operation (ATO): performs entire train travel, including the ATP function. Types are:

<i>Operation</i>		<i>Block</i>		<i>Signal</i>
Semiautomatic	→	Fixed	→	Wayside
Fully automatic	→	Moving	→	Cab

Automatic train supervision (ATS): controls movements of all trains on a line or a network. It may include:

- Switches
- Signals
- Communications
- Directives to ATO of individual trains

Greater lengths of the new systems is also reflected in their higher average speeds: older systems have operating speeds in the general range of 29 to 36 km/h, while the new ones range from 36 to 47 km/h, with BART again exceeding this range with 54.5 km/h.

Reliability of the rail transit systems depends on three major factors. ROW control is by far the most important one; that factor makes RRT and RGR the most reliable transit modes. LRT reliability varies with the degree of its separation from other traffic and its locations: it is essential that LRT lines be separated in the areas or locations of frequent congestion. For example, an underpass at a critical major intersection may increase reliability more than separation of a long section on which congestion seldom occurs. Reliability

of streetcars depends also heavily on traffic regulatory measures.

The second influencing factor is train departure control, which determines lengths of dwell times at stations t_s and thereby maintenance of schedule. The relationship between the volume of boarding/alighting passengers p_k and dwell time t_s is described in Section 4.4.4.2 and plotted in Figure 4.16.

The third factor is the technical reliability of the equipment. Rail systems with well-designed and well-maintained rolling stock and track rarely have breakdowns. Such rolling stock of all rail modes should have 92% to 95% of the vehicles available for service during every peak-hour period (vehicle availability coefficient of 0.92 to 0.95); 5% to 8% of the vehicles are typically

Table 6.11 Operating data for selected U.S. rapid transit systems

City/system	Network Length (km)	No. of Vehicles	Annual Passengers (unlinked trips) (000s)	Annual Vehicle km (revenue) (000s)	Average Trip Length (km)	Annual Passenger-km (000s)	Veh/km of Network	Annual Pass.-km/ of Network (10 ⁶)	Pass.-km/ veh-km	Operating Speed (km/h)
Los Angeles	25.7	70	30,870	8,692	7.96	245,733	2.73	9.57	28.3	36.4
San Francisco/BART	168.2	522	97,545	100,421	20.27	1,977,777	3.10	11.75	19.7	54.5
Washington/Wmata	166.2	750	250,660	93,711	9.68	2,426,387	4.51	14.59	25.9	40.5
Miami	36.2	103	15,638	14,671	12.54	196,135	2.84	5.41	13.4	37.9
Atlanta	77.3	184	69,089	35,500	10.61	733,127	2.38	9.48	20.7	42.4
Chicago	166.0	1,008	178,716	103,568	9.68	1,730,448	6.07	10.42	16.7	30.0
Boston	61.4	320	157,503	33,987	5.94	935,594	5.21	15.23	27.5	35.4
Baltimore	23.7	54	12,426	7,302	7.72	95,948	2.28	4.05	13.1	39.9
New York/PATH	23.0	259	66,517	20,317	6.97	463,795	11.25	20.14	22.8	29.8
Philadelphia/PATCO	25.3	84	9,150	6,528	13.99	128,077	3.31	5.05	19.6	46.7
New York City Subway	397.3	5,191	1,760,779	547,108	7.63	13,434,205	13.06	33.80	24.6	29.4
Cleveland	30.6	22	7,283	3,860	10.48	76,378	0.72	2.49	19.8	35.5
Philadelphia/SEPTA	60.3	276	88,083	26,385	7.17	632,137	4.58	10.48	24.0	31.5

Unless otherwise noted, all data from 2004 NTD

on regular maintenance, repairs, overhaul, or, sometimes with streetcars, undergoing body repairs from collisions.

Reliability performance, or schedule adherence, is measured by the percent of on-time arrivals (within 4 min of schedule) at a station. With LRT and SCR systems, reliability depends greatly on the type of ROW. This feature varies among systems, as can be seen in Table 6.12, from 100% in St. Louis, San Jose, and Edmonton to 50% in San Francisco and 41% in Philadelphia. Most LRT systems have partially separated tracks—ROW category B—on majority of their networks.

The reliability of rail systems may, however, be considerably lower than the quoted typical figures for various reasons. The operating agency may lack management and technical expertise or funds for adequate maintenance. Inadequate financing also leads to the postponement of track maintenance. When breakdowns on lines eventually begin to occur, recoveries from service interruptions may take excessive time. These factors often compound the reliability problem on systems with inadequate financing and obsolete operating practices.

Frequent equipment breakdowns have in some cities resulted from a different reason: the introduction of extremely, often unnecessarily, complex mechanical or electronic equipment in both rolling stock and control systems, as well as inadequately trained or experienced personnel. The low reliability of such systems is, however, by no means typical of rail transit modes.

Different methods of reporting accident statistics make comparison of transit modes with respect to safety extremely difficult. However, RRT and RGR systems generally have the highest safety records of all modes due to their full separation from other vehicles, fail-safe signal systems, and vehicles built to withstand collisions. LRT and SCR systems have safety records between that of RRT and RGR on one, and buses on the other side.

Energy consumption of rail transit is discussed in Section 3.7.

6.6.2.2 Service Quality. As already discussed, rail transit provides better *riding quality* than any other transit mode. RGR and RRT systems with good align-

ment, welded rails, air suspension in the trucks, and preprogrammed motor control offer what can be described as the ultimate in riding comfort. The sharper curvatures and shorter vehicles used by some RRT and LRT systems cause a somewhat lower but still very high riding quality.

With respect to vehicle interior, the spaciousness of rail vehicles allows the use of a larger space per seat and design of wider aisles than in buses. Sitting is therefore generally more comfortable, and standing is distinctly more acceptable than in buses.

Convenience of use of rail transit is limited by the extensiveness and density of its network. This problem can be alleviated by good integration of bus services with the rail system network.

A strong *image and identity* of rail transit, caused by the simplicity of its services and permanence of its lines, represents a major element of passenger convenience. This strong recognition contributes greatly to the much stronger passenger-attracting ability of rail as compared to other transit modes.

6.6.2.3 Impacts. The most significant single impact of rail transit is its strong *influence on land use and the form of cities*. The permanence of rail transit lines and stations generates the developments of land use that interact with and depend on high-quality transit service. Therefore, in time, stations generate their own patronage and “anchor” themselves at their locations. With good planning and urban design, this interaction can be used for the creation of attractive urban environments. In large cities, rail transit is a major element of their livability. However, unless planning and some controls exist, this feature of rail transit cannot alone guarantee that such development will take place. In U.S. cities, the surroundings of some RRT stations have greatly deteriorated because of numerous social and economic factors. Poorly maintained stations have often not only failed to prevent but even furthered urban decay under such conditions.

The ability of electrically powered transit vehicles to utilize any type of primary energy source is a significant advantage under the prospective shortages of oil supplies. Their lack of air pollution is also a valuable feature, since it makes electrically powered vehicles particularly well suited for deployment in

Table 6.12 Characteristics of North American LRT/streetcar systems

City/System	One-Way Line Length km	No. of Lines	% of ROW B and A	Double Track %	Ave. Stop Spacing km	Approx. Ave. Speed km/h	No. of Cars	Cars per km	Weekday Passengers (000s)	Service Productivity	
										pass./line km	pass./car
Baltimore, Central corridor	47.0	2	100	61	1.6	35	53	1.1	24.7	525	466
Boston, Green Line & Mattapan	41.5	5	97	100	0.5	22	215	5.2	230.8	5560	1073
Buffalo, MetroRail	10.4	1	100	100	0.8	20	27	2.6	22.6	2178	839
Cleveland, Blue/Green	25.0	2	100	100	0.6	30	48	1.9	15.1	605	315
Dallas, DART LRT	71.3	2	100	100	2.1	34	95	1.3	55.1	772	579
Denver, RTD LRT	25.6	2	100	98	1.3	23	31	1.2	31.4	1226	1012
Jersey City & Newark, NJT	24.0	3	> 99	100	1.0	28	45	1.9	25.5	1063	567
Los Angeles, Blue/Green/Gold	90.3	3	100	100	1.8	34	121	1.3	105.6	1169	872
New Orleans, streetcars	14.1	2	91	100	0.3	15	41	2.9	14.1	1000	344
Philadelphia, City & Suburban	55.6	7	41	91	0.3	18/26	141	2.5	84.1	1512	596
Pittsburgh, South Hills	30.2	4	81	91	0.5	26	55	1.8	27.0	895	491
Portland, MAX	61.9	2	> 99	99	1.1	30	78	1.3	80.0	1292	1025
Sacramento, RT LRT	43.6	2	89	77	1.1	34	56	1.3	29.4	674	525
St. Louis, MetroLink	61.5	1	100	97	1.4	43	65	1.1	44.0	716	677
Salt Lake City, UTA LRT	28.2	2	100	99	1.4	40	33	1.2	21.0	744	636
San Diego, trolley	73.6	2	100	99	1.4	30	123	1.7	84.5	1148	687
San Francisco, Muni	41.5	6	50	100	0.2	18	175	4.2	164.2	3956	938
San Jose, VTA LRT	49.5	3	100	96	1.1	32	50	1.0	25.0	506	501
Total United States	801.5	53	—	—	—	—	1462	1.8	1088.6	1358	744
Calgary, LRT	32.3	2	100	100	1.0	29	99	3.1	137.0	4246	1385
Edmonton, LRT	12.3	1	100	100	1.3	30	37	3.0	36.0	2921	971
Toronto, streetcars	79.6	10	11	100	0.2	15	248	3.1	307.1	3858	1238
Total Canada	124.2	13	—	—	—	—	384	3.1	480.1	3866	1250

Source: Schumann, J. and F. Loetterle, 2003.

medium- and high-density areas. It also represents a precondition for extensive operations in tunnels or in other enclosed areas.

It is pointed out that the high evaluation of most rail transit (particularly RRT and RGR) features is based on modern, well-designed, adequately financed, and competently operated systems. Aging equipment with inadequate maintenance of facilities and obsolete operating practices may result in lower riding comfort, less reliable service and less favorable image than described here. Actually, such inadequacies exist on several older rail transit systems, and for some people that has created an impression of rail transit which has little to do with the excellent characteristics of the present state of the art.

Construction of rail transit lines can cause considerable disruption along their alignments, particularly if the construction process is inadequately prepared and organized. In some cities construction of RRT tunnels and stations paralyzed major streets for up to 2 years, hurting many businesses and various other activities. In other cities, tunnel construction has been much faster, with virtually no negative impacts on activities: for example, construction of the LRT tunnel in downtown Edmonton required surface street interruption of only 14 weeks.

Measures to minimize the negative impacts of rail transit line construction should always be undertaken. But the entire effort is also made more acceptable if it is looked upon as a temporary inconvenience or harm that leads to a permanent improvement not only for transit passengers but also for activities in the areas served. Moreover, physical improvements that can be incorporated in street reconstruction when transit lines are built are often very significant for the city. For example, Market Street in San Francisco completely changed its character after reconstruction with BART; the Place de la Mairie in Montreal was developed in close coordination with the construction of the Montreal Metro; Mexico and São Paulo have obtained new plazas and public areas with their metros. Similar commercial stimulus and uplifting of center city core areas were achieved with construction of LRT lines in tunnels or in pedestrian zones in Cologne, Strasbourg,

Portland, Houston, and many other European and North American cities. All of these projects represent assets of permanent value for the cities, which easily justify the inconveniences of construction phases.

6.6.3 Rail Transit Costs

Construction of metro infrastructure, which gives rail transit its high performance and service quality, requires considerable capital investment. The ability of rail modes to operate large-capacity units, on the other hand, results in high labor productivity and low operating costs per unit of capacity offered. These features make rail transit a feasible solution where high service quality is required or where a large potential travel demand exists.

Since most of the new rail systems are either LRT or RRT modes, their costs are of greatest relevance here. Typical costs are presented, but they should be used only for orientation, since variations among cities and at different times are quite large.

6.6.3.1 Investment Costs. General estimation of rail transit investment costs can often be made by cost estimates for their components. Table 6.13 shows costs reported for selected recently performed projects, including representatives of the three major modes—LRT, RRT and RGR. General ranges of capital costs per line kilometer are from 10 to 30 \$M/km for LRT, 60 to 100 \$M/km for RRT (with a few systems being far below and far above this range) and only 1 to 4 \$M/km for RGR lines built on existing ROW and upgraded tracks.

Some comments on costs of major systems components follow here.

Right-of-way acquisition costs consist of land purchases for ROW and stations. They vary greatly, since tunnels and the use of public ROW, such as street medians, do not involve direct costs, while, other at-grade, cut, or aerial alignments, as well as stations require land. ROW costs are usually expressed in \$/km (mi); for stations, \$/m² (ft²), or \$/station of a given type and dimensions.

Table 6.13 Capital costs for selected rail transit systems in the United States

City	Length (km)	Cost (\$Million)	Unit Cost (\$Million / km)	Comment
Light rail				
Sacramento	29.5	176	6.0	First segment; 1987
Portland–East Line	24.3	214	8.8	No tunnel, few structures; 1986
St. Louis	29.0	351	12.1	Used extensive existing tunnel and a long bridge over Mississippi; 1993
Edmonton	13.8	221	16.0	33% in tunnel and a large bridge; 1978 to 1990
Los Angeles–Green Line	32.2	718	22.3	Mostly freeway median; 1995
Los Angeles–Blue Line	34.8	912	26.2	5% tunnel; many overpasses; 1990
Portland–West Line	29.0	944	32.6	4.8 km tunnel; many structures; 1999
Minneapolis	18.5	549	29.7	Opened in 2004
Rapid transit				
Washington, DC				
Green Line	10.5	900	85.7	
San Francisco				
Dublin branch	22.5	517	23.0	ROW in freeway median
Colma–SF Airport	9.0	1,270	158.8	Long tunnel and high aerial structures
San Juan	17.2	1,200	69.8	
Regional rail				
Virginia Railway Express	132.0	131	1.0	Existing railroad tracks purchased
North San Diego County	69.2	150	2.2	Existing railroad tracks purchased
Los Angeles				
Phase 1 & 2	1,213.9	1,623	1.3	Existing railroad tracks purchased

Source: Communication with John Schumann.

Permanent way construction costs also vary greatly among types of alignment. Grade-separated alignments generally have much higher costs than at-grade ones and often represent the largest single cost item of rail transit lines.

Aerial rail transit structures require approximately two to three times higher investment than at-grade alignments, while tunnel construction is at least two to three times more expensive than construction of tracks on aerial structures. In addition to the cost of line infrastructure, construction of rail lines typically involves considerable preparatory works (e.g., removal of various objects or buildings, relocation of utilities), and restoration of street and sidewalk pavements, as well as construction of plazas and landscaping where applicable.

Station construction costs vary among modes and positions with respect to the location, type (under-

ground, aerial, or surface) and surroundings. Underground stations are generally the most expensive because they involve two or three levels, stairways and escalators, corridors, and fare collection barriers. LRT stations usually involve considerably lower costs because their platforms are shorter, usually do not require fare collection barriers (self-service fare collection is more common), and, most importantly, do not require grade separation of pedestrian walkways. On most LRT lines, even on sections with full separation of tracks from streets, pedestrian crossings of tracks are provided at stations with adequate safety protection at grade, without any bridges or underpasses. Examples of these convenient and economic arrangements are found on LRT systems in St. Louis, Denver, Dallas, Cologne, and most other recently built LRT systems.

LRT stations along streets, particularly with low platforms, involve a much lower cost than do

controlled-access, high-platform stations. On the lines with low-floor LRT vehicles, construction of stops in streets is particularly simple and can be easily included in street reconstruction, since they require little more than a special curb layout.

Cost of constructing P + R facilities at outlying stations, computed on a per-parking-space basis, depends on the cost of land and type of facility. Parking lots are commonly used, but at very busy stations garages are built. Their cost is much higher, but they provide greater capacity per unit of land and allow the development of stores or apartment buildings in the immediate vicinity of the station. P + R garages have been built at a number of rail stations in the suburbs of San Francisco, Toronto, Washington, Atlanta, and other cities.

Track superstructure includes tracks, switches, crossovers, and related equipment. *Power supply* consists of substations, the distribution system, and third rail or overhead wire. *Control and communications* include the entire signal system along the lines, telephone and other communications, and emergency systems. Costs of all these components are usually expressed on a per lineal meter or kilometer basis. Other elements of control and communications, such as construction of the control center, its communications with vehicles, and public address system in stations and on vehicles, are computed separately because they are not directly related to line length.

The costs of control and communications are considerably lower for LRT than for RRT because most LRT systems have signalization at crossings but not along the lines. RRT systems are always fully signal-controlled and have fail-safe devices, ATO equipment, and a sophisticated control center.

Costs of *vehicles* depends on their design and complexity as well as on the number of vehicles ordered. As most rail vehicle orders are custom-made for each transit agency or city, orders of 20 to 30 cars cost considerably more per vehicle than orders of 100 or more, which are made by cities like New York, Paris, or Moscow. The range of LRT vehicle costs is greater than that of RRT vehicles because it includes a greater variety of types, from four to ten-axes, and from streetcars to high-performance LRT vehicles. The latter,

being equipped for both street and fully controlled operation, may be more expensive than RRT vehicles, but many recently ordered LRT vehicles also have higher capacity because of their length, which now often reaches 30 to 40 m or longer. In North America there have been considerable adoptions of the same LRT models: Siemens six-axle LRT vehicles have been adopted by about 10 cities (Calgary, Denver, Houston, Edmonton, Pittsburgh, Sacramento, San Diego, St. Louis, Valencia in Venezuela, and others). Similarly, Bombardier's BiLevel model regional rail car, designed initially for Toronto, has been purchased by transit agencies in Los Angeles (Metrolink), Miami (Tri-Rail), Seattle, Vancouver, Montreal, San Diego, and several other cities.

Costs of different types of rail transit vehicles are best compared through their costs per unit floor area (m^2 or ft^2) or per unit weight (t). These unit costs are rather constant for all vehicle types with similar performance and degree of complexity. Comparison of costs with nonrail modes, such as buses, should be based on unit floor area but also take into account the difference in vehicle life (two to three times longer for rail than for highway vehicles) and vehicle performance.

In a comprehensive review of the developments of LRT systems, Hondius (2005) concludes that since the 1980s, about three new LRT systems are opened every year. Car orders are in the range of 350–700 per year, and their prices vary from €1.4–€4.4 million (\$1.7–5.3 million) per car, amounting to the range of €28,000 to €45,000 per square meter of vehicles.

RRT cars are generally in the range from under \$2 million to over \$4 million, depending on vehicle size, type, and the number of vehicles purchased.

Maintenance and storage facilities include shops, yards, and administrative facilities. Their costs depend on the location and shape of the site, the type of maintenance that will be performed, and, of course, capacity.

Engineering and administration, representing all agency costs during the implementation of the facility, is commonly estimated at 25%, while *contingencies*, or unpredictable costs, are allocated initially at 25% but later decreased to 10% of the project costs.

It can be seen in Table 6.13 that unit costs for several components, such as permanent way and vehicles, are not greatly different for LRT and RRT. Yet, costs of LRT for most specific lines are usually considerably lower than the costs of RRT for the same line, because LRT can use a greater proportion of lower-cost alignment types than RRT. This is illustrated on a hypothetical example in Table 6.14, using the average values from Table 6.13.

Suppose that a 10-km-long line with 10 uniformly spaced stations is being planned. LRT and RRT with different ROW types, as shown in Table 6.14, are considered. Alternative I is entirely in tunnel, typical for very large cities, while II has a combination of ROW types more typical for RRT lines in medium-size to large cities. Alternative III represents a high-quality LRT that utilizes the same tunnel length as II, other types of controlled ROW on an additional 30% of length, and ROW with grade crossings on 40% of its length in suburban area. Alternative IV has no tunnels and utilizes ROW category B on 60% of its length. The last column in Table 6.14 shows that these different alignment compositions have a drastic impact on permanent-way and station construction costs. These costs cannot, of course, be used as the sole evaluation criterion, since the four alternatives would vary greatly in performance and passenger attraction, both decreasing from I to IV.

This hypothetical case is generally corroborated by various actual cases of rail transit construction. Systems that utilize low-cost at-grade ROW (street medians, railroad alignments, parklands, etc.), such as the LRT in Edmonton, Portland, Sacramento, and San Di-

ego, have had a drastically lower costs per kilometer than the systems with extensive tunneling, viaducts, and bridges, such as the LRT systems in Buffalo and Pittsburgh.

6.6.3.2. Operating and Maintenance Costs. The most common breakdown of rail transit operating costs is into the following five major categories:

- *Transportation or vehicle operations:* wages of all personnel involved in operation, such as drivers, supervisors, stations attendants, and scheduling personnel.
- *Power:* cost of electricity, which depends mostly on consumption, although in some cities the rate paid per kWh depends on the peak rate of consumption.
- *Vehicle maintenance:* expenditures for personnel and material necessary for the maintenance, repair, testing, and cleaning of cars. In some countries maintenance procedures are specified by law.
- *Permanent-way maintenance:* costs of personnel and material required to maintain the permanent way, including tracks, power supply, signals, and so on.
- *General and administration:* indirect operating costs, such as management, legal services, accounting, insurance, employee benefits, maintenance of buildings and grounds, and miscellaneous costs.

Table 6.15 gives a percentage breakdown of operating costs on four categories (transportation includes

Table 6.14 Investment costs of a line with different ROW categories^a

Line Alternative	Mode	ROW (Alignment) Type (%)				Total Cost (\$10 ⁶)
		Tunnel	Aerial	At Grade, Category A	At Grade, Category B	
I	RRT	100	0	0	—	1,200
II	RRT	30	50	20	—	740
III	LRT	30	0	10	60	580
IV	LRT	0	20	20	60	380

^aLine length 10 km, with 10 stations. Assumed unit construction costs per km including one station: tunnel, \$120 million; aerial, \$60 million; category A, \$40 million; category B, \$30 million.

Table 6.15 Breakdown of operating costs among selected U.S. rapid transit systems (2004)

City/System	Annual Operating Expenses (\$ 000)				Operating Expenses (% or total)				
	Vehicle		Non-Vehicle		Total	Vehicle		Non-Vehicle	
	Operations	Maintenance	Maintenance	Administration		Operations	Maintenance	Maintenance	Administration
Los Angeles	28,485.2	10,832.4	12,448.5	14,062.7	65,828.8	43.3	16.5	18.9	21.4
San Francisco/BART	155,805.6	68,416.5	77,260.7	73,541.9	375,024.6	41.5	18.2	20.6	19.6
Washington/Wmata	137,122.7	111,929.4	162,429.6	114,034.5	525,516.2	26.1	21.3	30.9	21.7
Miami	25,062.1	14,563.0	14,685.2	7,127.4	61,437.7	40.8	23.7	23.9	11.6
Atlanta	51,361.1	23,387.9	29,059.8	19,399.5	123,208.3	41.7	19.0	23.6	15.7
Chicago	175,124.5	56,564.6	104,596.8	63,578.0	399,863.8	43.8	14.1	26.2	15.9
Boston	98,724.3	31,443.0	57,387.1	26,692.4	214,246.8	46.1	14.7	26.8	12.5
Baltimore	18,250.6	6,796.7	13,680.6	3,082.7	41,810.6	43.7	16.3	32.7	7.4
New York/PATH	83,838.8	21,520.7	51,900.7	22,531.9	179,792.2	46.6	12.9	28.9	12.5
Philadelphia/PATCO	14,636.7	5,706.2	8,583.6	5,231.3	34,157.9	42.9	16.7	25.1	15.3
New York/RRR	1,138,484.7	429,419.2	657,741.9	311,994.0	2,537,639.7	44.9	16.9	25.9	12.3
Cleveland	7,617.8	5,474.1	9,589.7	1,187.5	23,869.1	31.9	22.9	40.2	5.0
Philadelphia/SEPTA	69,352.7	22,868.5	16,609.5	16,549.3	125,380.1	55.3	18.2	13.2	13.2

the first two items listed above, transportation and power) for seven U.S. transit agencies with each one of the three modes, light rail, metro, and regional rail, based on 2004 data.

It can be seen that transportation costs represent the dominant item among operating costs for all three modes. The fact that RRT has by far the highest labor productivity among all three modes is not reflected in the percentage distribution of costs among items. In general, the shares of costs among the four given categories are not distinctly different among the three modes. However, the high labor productivity of RRT mode is reflected in the lowest cost per car-km for this mode. Regional rail has the highest cost per car-km because most systems still have conductors, while all new LRT systems have driver-only crews. The high capacity of RGR vehicles would be reflected if the costs were expressed on a per space and particularly on a per-seat basis.

6.7 PRESENT AND FUTURE ROLE OF RAIL TRANSIT

The preceding sections of this chapter have shown that a very intensive development of rail transit technology has taken place in recent decades. The innovations have been not only in technological and engineering aspects, but also in system concepts: diversification of ROW types, methods of operation, intermodal integration, and, as a result, in creation of new modes and changing of their roles in urban transportation.

The traditional three rail modes—streetcars/tramways, metro and regional/commuter rail—have been expanded into a nearly continuous family of rail modes. Major trends with respect to rail transit modes can be summarized as follows.

- **Streetcars/tramways** have gone through major changes:
 - Drastic reduction or complete elimination from many cities and countries (the United States, Great Britain, Spain)
 - Stabilization, modernization and retention of this mode as the basic transit carrier in many

cities (in central and eastern Europe, Hong Kong, Melbourne, Toronto)

- Construction of new streetcar lines in central cities related to their revitalization and increased livability (New Orleans, Portland, Washington, DC, many French cities)
- **Light rail transit** has been developed by upgrading tramways and as new systems in many different forms to become the fastest growing rail transit mode (the United States, France, Canada, Great Britain, Ireland).

The Light Rail Transit Association has reported (LRTA 2006) that between 1980, when construction of new LRT systems started, until 2006, the total number of cities that opened new tramway and LRT systems worldwide reached 99.

- **Light rail rapid transit** has been developed as “mini-rapid transit” mode between LRT and metros, operated manually or as fully automated systems (Philadelphia–Norristown, London–Docklands, Vancouver SkyTrain, Kuala Lumpur).
- **Metro** mode has had a period of unprecedented growth, spreading from 17 cities in the early 1950s to about 110 cities worldwide in the beginning of the twenty-first century. This growth has happened in industrialized as well as in developing countries, and it includes several fully automated systems.
- **Regional rail**, following a major decline in North America after World War II, has also reached a period of rapid growth which continues, particularly in industrialized countries. Its innovations include diversity of traction (diesel and electric), network upgradings in central cities and in suburban areas, and ROW alignments and operations—from commuter rail to regional metros.
- **Tram-train** mode, a combination of light rail and regional rail, has been introduced since 1980s very successfully in several cities (Karlsruhe, Manchester, Saarbrücken), with likely introduction in more cities.

With respect to system appearance, operational efficiency, and quality of service, there is a great differ-

ence between the heavy rail transit equipment and sometimes noisy stations found in many cities around 1950 and the quiet, high-capacity, comfortable rolling stock operating on attractive transit systems in the beginning of the twenty-first century. In addition to its technical progress, several other factors have had a major influence on the role rail transit plays in cities. A brief review of the influencing factors during the last several decades is helpful for a prediction of the probable future role of these transit modes.

6.7.1 Trends and Impacts of Urban Population and Growth of Auto Ownership

The two factors that have had the strongest influence on transit ridership in general—growth of cities and increase in auto ownership—have also strongly influenced growing utilization of rail modes in recent decades. Observing general urban transportation trends in different countries, it can easily be seen that the growth of cities increases volume and density of travel in urbanized areas. How much of that increase goes to transit modes depends on auto ownership level, transit extensiveness, service quality, and efficiency, which are largely functions of transportation policies in different cities and countries.

The rapid increase in auto ownership was followed in different countries by some similar phenomena and policy decisions, including positive developments and system expansions as well as shortsighted actions that create long-term problems. In many cases major efforts are focused on construction and modernization of highway/street systems, parking, and related facilities. Transit systems are usually negatively affected by these developments: their modernization is given less attention than highway construction. Transit, specifically rail, is often neglected, or its ROW are taken over for street widening. This very costly mistake in the long run. These developments have in many countries had a major influence on the elimination of streetcars, which usually resulted in a decreasing role of transit in general. In the cities in which streetcar ROW were preserved and extended and the systems were upgraded

into light rail transit, rail transit has retained its important role.

As the increased use of the private auto leads to chronic congestion, even with expanded highways and streets, the fact that the auto alone cannot satisfy transportation needs of cities for physical, social, economic, and environmental reasons is eventually recognized (Newman and Kenworthy 1989, Vuchic 1999). The only solution to congestion relief and provision of service with adequate capacity, quality, and permanence is through creation of rail transit systems with separate, independent transit ROW, category B or A.

Consequently, increasing auto ownership has had a strong negative impact on the use of streetcar mode, but it has also led to the development of the light rail transit mode, increased use of regional rail, and in the most extensive construction of metro systems in history. From 1935 to 1950, the number of cities with metro systems was 17. During the 1950s, that number increased to 25, and in the following decade to 33 cities. That pace of construction accelerated further, so that by 1980 there were 55 cities with metros. During the next 25-year period, this number doubled: in 2006, approximately 110 cities have metros (this number depends on the classification of some systems that are “between” LRT and RRT or RRT and RGR). Total length of lines also grew rapidly, although not in the same proportion as the number of “metro cities.”

6.7.2 Objectives and Goals in Building Rail Rapid Transit Systems

The decision to build a rapid transit system, the dominant representative of rail modes, is a result of a number of considerations and can have different objectives. In some cases, one or a few objectives dominate this decision, but they are usually supported by a number of others. A brief review of the objectives and goals in building metros, spanning the period from the building of the first Underground in London in 1863 to the present, is given here. The objectives are classified in three categories and illustrated by examples of cities in which each goal was particularly emphasized.

The *immediate objectives* include:

- Increase in speed of transit travel (Brussels, Moscow, New York)
- Provision of adequate transporting capacity (London, Mexico, Moscow, Tokyo, Toronto-Yonge Street Line)
- Decreased operating cost through higher labor productivity on major lines than streetcars and buses (Hamburg, Munich, Atlanta)
- Relief from street congestion (Boston, London, Montreal, São Paulo) and excessive parking requirements (Cleveland, San Francisco, Washington)
- Provision of transit service with much higher reliability, safety, and comfort than surface transit can offer (Berlin, Philadelphia-PATCO Line, Vienna, Washington)

Some of these goals can be expressed and their achievement evaluated in quantitative terms (speed, capacity, reduced parking in CBD, etc.). However, that evaluation should not be considered as comprehensive and sufficient, since in most cases higher-level goals are important and often dominant reasons for metro construction.

Specific goals pursued through construction of metros are as follows:

- Strengthening of the central urban area through improved transit service (Boston, Philadelphia, Paris).
- Tying together a region separated by geographic barriers (New York, San Francisco, Rotterdam, Los Angeles).
- Stimulating development of major activity centers in outlying areas through their efficient connection with the central city (Amsterdam, Stockholm).
- Introduction of a high-quality transit service on a special line serving a residential, business office, medical facility, or university complex (LRT lines to Frankfurt Nordweststadt, University of Alberta campus in Edmonton, Houston medical complex).
- Rail links between center cities and airports have been built in a large number of cities since the 1980s. Regional rail lines serve these links in most cities, such as Frankfurt, Philadelphia, Hong Kong, Tokyo, Munich, Oslo, Rome, and both Paris airports. Monorail connects Tokyo Haneda Airport with the city, while Shanghai Airport line represents the first magnetic levitation (Transrapid) line in the world. Rapid transit links have been built to the Cleveland, London Heathrow, Chicago, and San Francisco airports, while in the United States several cities have built successful LRT airport lines: Baltimore, St. Louis, and Portland. This wave of rail airport links construction is expected to continue.

Clearly, these goals cannot be precisely quantified, but their direct economic and performance evaluations are usually a major part of the overall justification of investment.

The *highest-level goals* in building metros are, in most cases, to:

- Increase transit ridership, achieving higher mobility of population
- Provide a high level of transit service in individual corridors or throughout an urban area, stimulating its economic viability
- Attract passengers away from private automobiles and provide conditions for application of disincentives for automobile use in cities
- Create a better balance in urban transportation between public and private transportation, which results in an intermodal system with physically, economically, and environmentally superior performance than the systems relying on one mode only can provide
- Ensure a greater permanence of transportation service required for integration of land use and transportation
- Enhance the quality of urban development and create efficient and livable urban forms, which are a precondition for creation and permanence of great cities.

Since these goals are mostly qualitative, there is a tendency to underestimate them. However, they should represent an integral part of metro planning, and no evaluation of any rail transit project can be complete without a full recognition of its potential achievements toward these goals. Neglect of these aspects in planning may result in underutilization of the potential interaction of rail transit with overall urban planning.

This diversity of objectives and goals in building metros shows that a number of factors can favor its introduction in individual cities. The most significant factors are city size, form, and density. These factors determine volumes of travel along individual corridors or throughout the city and determine whether the investment in a metro is justified.

The condition of transit and traffic in the city also has a major influence. Narrow streets, traffic congestion, and an inability to provide any preferential treatment to surface transit are factors in favor of introducing grade-separated transit, i.e., metro or light rail.

Geographic features represent another important element in many cities. Hilly terrain, narrow valleys, bodies of water, and so on, make construction of transportation facilities very costly, so that application of high-capacity modes, such as metro, is the logical choice. This factor played an important role in Rotterdam (Metro under the Rhein and Maas Rivers), in San Francisco (Twin Peaks Tunnel and the BART tube under the bay and through Berkeley Hills), in Hong Kong (Mass Transit Railway under the Victoria Harbour), and in many other cities.

Finally, an important element is also the existence of a long-range transportation policy, coordinated planning, and stable financing of transportation facilities. Historically and worldwide, metros have always been constructed most intensively when there was a longer period of peace and economic stability, as well as in cities and at times when rational long-range planning for transportation improvements existed. Without these conditions, the improvements usually tend to be short range in character, involving minimum investment, but often with limited impact and low permanence.

6.7.3 What Size City for a Metro?

This question is often asked, but it is clear that because of many factors influencing feasibility and desirability of metros, it can never be given a precise answer. Until the 1950s a hypothesis existed that a population of one million represented a “threshold” for construction of metros. At that time basic policies toward the roles of private car and transit diverged and caused different decisions about transit planning. The cities that adopted orientation toward the private automobile developed extensive low-density suburbs which generated dispersed travel patterns that do not support high-performance transit service. During the 1990s, such cities as Detroit, Houston, and Seattle represented the most populous cities in any highly developed country that did not have any rail transit. As a rule, cities with populations of several million without rail transit have all their transit services far below the needs of such large urban agglomerations.

Opinions in countries that have consistently pursued modernization of transit have been that wider use of private automobiles should actually lower the city size that justifies building a metro system, since the high quality of its service is needed to attract auto drivers and create a balanced transportation system. Very successful metros systems have been built in Stockholm (population at the time of opening 750,000), Lisbon (900,000), and Rotterdam (700,000). Nürnberg and Oslo built their systems even before their populations reached 500,000, but these were exceptional cases influenced by specific local factors (topographic, political, financial, and other).

The “threshold” for use of other rail modes is considerably lower, since streetcars and light rail operate in some cities with populations of only 150,000 to 300,000. These modes are the main transit carriers in many cities with populations up to one or two million, overlapping the domain of the metros (Photo 6.45). Many cities with populations between 500,000 and two million, and some even considerably larger, utilize both LRT and RRT (Amsterdam, Brussels, Cleveland, St. Petersburg, Milan, San Francisco, Toronto).

A very significant development of rail modes has influenced and broadened this “overlap” of metros and



Photo 6.45 Light rail transit has become the basic transit network in many medium-sized cities (Courtesy of James Aslaksen)

light rail systems. In addition to the mentioned cities, an increasing number of cities have been constructing both of these modes in parallel. Thus, Baltimore built one metro and one light rail line in addition to its several regional rail lines. Los Angeles, which was without any rail services until 1990, has undertaken a particularly energetic development to dramatically improve its transit. Since 1990, the Los Angeles Region has built one 26-km long metro line serving 138,000 passenger trips per weekday, three light rail lines with total length of 90 km and a daily ridership of 137,000 passengers, and a new regional rail system with seven

lines with a total length of 824 km and a network length of 641 km serving 42,000 weekday passengers. Thus the region total daily rail ridership in 2006 is 317,000 persons.

With this trend of using different rail modes, many cities have built either metros or LRT systems as their main rail carriers, or in some cases both of these modes, supplemented by regional rail. This is particularly the case in many North American cities in which the service quality of new LRT systems is so high that they are competitive with the private automobile, and the very high line capacities that metros provides are

not needed. For example, LRT systems in St. Louis, Denver, and Dallas have long sections with ROW category A as well as maximum speeds as high as 100 km/h, and their P + R facilities clearly show that these systems attract many auto users.

It is interesting that the development and diversification of light rail has led to its reintroduction even in a number of megacities with extensive metros and regional rail systems. The new LRT systems are built mostly in the densely developed suburban areas, and they usually also feed and interconnect radial RRT and RGR lines. Examples of such new LRT systems include London's automated LRT system in the rapidly growing Docklands area in the eastern part of the city, which has much higher ridership than expected, and Croydon, also very successful LRT system west of the city. Paris has opened several LRT lines in the suburbs which are beginning to form a large circumferential corridor around the entire central city. In the New Jersey suburbs of New York City, the Hudson-Bergen LRT line has been built through a number of rapidly growing commercial and residential developments along the west bank of the Hudson River. The line draws attention by its rather unique operations of express trains during peak hours which use reverse running on some track sections and reaches speeds of 90 km/h with two min headways (Fazio 2002).

Consequently, the traditional question of the city size that justifies construction of metro has evolved into the question what city size justifies rail transit. This now includes not only metro, but also different forms of light rail and regional rail, and the threshold for rail transit has been lowered while the composition of rail modes has been broadened for cities of all sizes.

It is obvious from this discussion that these are only general observations rather than fixed rules about applications of rail modes according to city sizes. Because of other factors, numerous exceptions exist. For example, the Green Line, a four-branch LRT system in Boston (metropolitan area population 2.9 million), plays a more important role than any one of its three RRT lines. Honolulu (with a population of only 700,000)—owing to its corridor form, limited area, aesthetic and environmental concerns, large number of

tourists, and several other factors—represents a much stronger case for construction of rail transit than that of many other U.S. cities with considerably greater populations. Finally, the area served by the PATCO rapid transit line in Philadelphia has a population density of only 1300 prs/km² (3400 prs/mi²) and a very high auto ownership—conditions often believed to be strongly against the use of RRT; yet the large Philadelphia CBD, a toll bridge, and extensive P + R and K + R facilities make this line extremely successful both in attracting passengers and its financial results. The line has often had the best operating ratio of all rapid transit systems in North America.

6.7.4 Development of Rail Transit in the United States

The role of rail transit in U.S. cities has gone through several major phases. During the first decades of the twentieth century, rail transit in U.S. cities was in many respects more advanced and more extensively used than in any other country. The Great Depression and the introduction and wide use of private autos led to a drastic reduction of rail transit and near-disappearance of streetcars. Construction of rapid transit, intensive until the 1930s, ceased prior to World War II. That was followed by a massive highway construction program paid 90% by federal funds and no federal assistance to transit during the 1950–1970 period. The resulting crisis of transit was only a part of a broader crisis of cities due to suburbanization, extensive destruction of inner city areas for construction of freeways and parking garages, and other factors, well documented by Goddard (1996). Rail transit suffered particularly from inadequate financing, lack of modernization, and obsolete operating practices. There was intensive propaganda that, in the future, personal travel would be by private automobiles, with transit mostly assisting commuters during peak hours dominated the media.

The realization that such a simplistic view of urban transportation is not realistic and that cities cannot be economically viable or livable without efficient and attractive transit caused major changes in transportation

policies and programs from the late 1960s. The San Francisco Bay Area led with the progressive view that the region needed a high-performance transit system independent of highways. Voter approval of the plan for a rail rapid transit system and its financing through tax-based bonds in 1962 led to the construction of BART, in many respects the most advanced transit system in the world at that time. That success stimulated the planning of metro systems in other cities in subsequent decades.

Rail transit developments in North America in recent decades can be summarized as follows. Five U.S. cities had rapid transit in 1970 (New York, Philadelphia, Boston, and Chicago, with Cleveland opening one line in 1955), and another seven cities opened metros since that time: San Francisco, Washington, Atlanta, Miami, Baltimore, Los Angeles, and San Juan. Other North American cities opening new metro systems were Toronto (1954), Montreal (1967), and Mexico (1969), while Vancouver opened its SkyTrain “minimetro”—fully automated LRRT—in 1986, and Monterrey, Mexico an LRRT, in 1986. Thus, the number of metro systems in North America increased from four in 1950 to 16 in 2006, of which two are RTRT (Montreal and Mexico), one conventional and one fully automated LRRT.

During the 1970s, the evolving light rail transit system, used successfully in many European cities, was recognized as a mode with considerable potential for U.S. cities. Its new rolling stock and numerous operational concepts were used to modernize several major streetcar systems, mostly those operating in tunnels and other separated rights-of-way: Boston, San Francisco, Philadelphia, Pittsburgh, and others. This development was followed by a wide acceptance and construction of new LRT systems in 14 U.S., three Canadian and three Mexican cities. It appears that by 2010, there will be about 25 cities in North America with new LRT systems.

The regional rail mode has also had a renaissance in North America. The traditional commuter and regional rail systems in the regions of New York (Long Island Rail Road, Metro North, and New Jersey Transit), Chicago (Metra), Philadelphia (SEPTA), Boston

(MBTA), Baltimore-Washington (MARC), and San Francisco (Caltrain) have been joined since the 1970s by new systems in the regions of Miami, Northern Virginia, Dallas, Seattle, Connecticut, San Diego and a particularly extensive and successful Metrolink in Los Angeles (seven lines with total length of 822 km). Several other regions are planning to introduce RGR systems.

The many factors that influence development of rail transit in U.S. cities are summarized in the box on page 438.

The major improvements of bus systems in the form of BTS and BRT (see Section 5.4) can have two opposite impacts on rail. Use of extreme and incorrect claims that BRT can provide the same service as rail modes, BRT can be used to prevent introduction of rail. On the other hand, with transit planning conceived as a coordinated intermodal effort, a well-planned BRT system can be complementary and mutually supporting with rail, resulting in a more efficient transit system with an increased network competing successfully with automobile.

6.7.5 Present and Future Role of Rail Transit around the World

As mentioned in Section 6.7.1, metro systems have been constructed very intensively in many countries around the world since the 1950s, increasing the number of cities with metros from 17 to 110. A large share of RRT construction during the 1950–1980 period (nearly 40%) took place in western Europe, Japan, and North America (Pushkarev and Zupan, 1982). Tokyo, Seoul, Madrid and a number of other cities have drastically increased their metro networks and introduced many technical and operational innovations in recent decades (Photo 6.46). However, an increasing share of construction has subsequently been done in the newly urbanizing countries (Brazil, Egypt, India, China, Taiwan, Egypt, as well as in Hong Kong, Singapore, and other growing cities).

Several comprehensive studies of interactions between rail transit and urban characteristics (Pushkarev and Zupan 1982; Newman and Kenworthy 1989) have

Factors favoring modernization of the existing facilities and the construction of new rail transit systems:

- The view of transit service as only a supplement to private auto has been replaced by the concept of an integrated urban area transit system serving the entire city and region.
- Revitalization and increasing residential population in central areas of many cities (best examples: New York City, San Francisco, Boston, and Portland).
- Many city mayors, political and business leaders, as well as citizen organizations publicize very positive experiences with rail transit, increasing support by decision makers for rail projects in other cities. The strong positive impacts of regional metro systems in San Francisco and Washington; the vital role of the Metro North, Metra, and other regional rail systems; as well as the impacts on economic viability and livability in cities like San Diego, Portland, Denver, St. Louis and other cities are particularly well known.
- The notion that rail transit must be a high-performance/high-investment-cost regional system such as the San Francisco BART has been replaced by the availability of a broad range of many planning and design options of different rail modes that can be tailored to local conditions and requirements.
- Cities are increasingly recognizing the fact that modern transit is a basic component for their revitalization and progress; rail modes are the strongest symbols of such improvements. Rail projects generally appear in the cities that undertake energetic, far-sighted planning.

Factors representing obstacles and having negative impact on development of rail transit are as follows:

- Continued sprawl-type development in most urbanized regions.
- Both federal and local funds for transit investment are far from adequate, and they are still heavily highway biased (federal share for most highway construction is 80%, for transit 50%).
- Confusion and costly delays in planning in many cities are caused by promotion of various nonconventional technologies repeatedly proven inferior to rail (Monorail in Seattle, various proposals for PRT in Minneapolis, other modes in Pittsburgh, Houston, and so on).
- Strong antitransit lobbies using conceptually and factually false arguments focus their criticisms particularly on rail as the strongest element in creating balanced transit-highway intermodal systems (see Section 10.5).

a major significance for estimating the future development of rail transit. Namely, cities with rail and bus transit compared with those served by buses only have:

- Significantly higher transit riding habit (annual transit trips per capita). (see Vuchic 2005, Section 12.2)
- Considerably lower auto travel per capita
- Distinctly lower total energy consumption per capita

Although many other factors have influences on these statistical findings, there is little doubt that rail transit, through its characteristics, has a strong influence on transit use and the form of cities in the long run. Consequently, the future development of rail transit is closely related to the trend of growth and future characteristics of cities. If transportation policies and planning efforts are concentrated on serving growing cities and their economic vitality, expansion of rail transit should represent a major component of those efforts.



Photo 6.46 Rail rapid transit has been continuously expanded and innovated with new concepts in many cities; Tokyo and Hong Kong (shown here) are among the leading networks in many respects

Trends in governmental policies and the increasing energy problems make this course likely to be pursued in the coming decades.

As in Europe and North America, an increasing diversification of rail modes has occurred worldwide. As in the United States, cities in many other countries have upgraded existing or built entirely new light rail systems. Their central city sections have been built in many cities in tunnels or in pedestrian zones, and suburban sections have been built in about 30 German cities, 15 French, and 5 British cities. Other cities building new LRT have been those in Spain, The Netherlands, Switzerland, Ireland, Turkey, and many eastern European countries.

Major regional rail modernizations, and construction of entirely new lines, have also been undertaken



Photo 6.47 Regional rail, with strong trend toward bilevel cars, is being expanded in many large- and medium-sized cities (Courtesy of W. D. Volkmer)

in numerous countries. Particularly interesting developments are found in Paris (R.E.R.), Berlin, Munich, Frankfurt and Ruhr (S-Bahn), several Brazilian, and many Japanese cities. There is a strong trend in many countries to introduce bilevel cars for increased seating capacity (Photo 6.47). The recently developed tram-train concept, unifying the light rail and regional rail modes, is likely to be introduced in more urban regions in the future.

With respect to the dominant reasons for metro construction, cities around the world can be classified into two rather distinct categories. Cities in western Europe, the United States, and Canada build rail transit systems primarily to improve the *quality of their transit services*, to make them capable of attracting passengers from the automobile. Cities in Latin America, Asia, and to a large extent Russia and other members of the former USSR build metro systems primarily to provide the needed high capacity, i.e., *quantity of service* (improved service is, of course, always another important contributing factor).

The importance of both of these dominant requirements—quality and quantity of service—has increased in recent years. High auto ownership has resulted in the paralysis of cities; urbanization, particularly intensive in the developing countries, has created growing needs for higher-capacity systems than highway modes can provide. The result of these trends has been continuously accelerating construction of metro systems throughout the world, as discussed above.

In addition to the need for increased capacity and improved quality of transit services, several other aspects of metros (or rail transit in general) have an important role in the decisions about their construction. Introduction of a metro is always an important step in the development of a city. Its construction usually represents the largest and most significant public project ever undertaken by the city; it stimulates various planning activities and interest in civic progress in general. Its opening is always a major festivity: inaugurations of the Metro and other major rail systems in Brussels, London, Paris, and Vienna were made in presence of heads of the respective countries. (Photo 6.48).

The opening of rail transit lines results in a major reduction in energy consumption for transportation as



Photo 6.48 The importance of rapid transit is reflected in its opening celebrations: the Queen of England rides the inaugural train on the Heathrow Airport Extension in London, 1977 (Courtesy of London Transport Executive)

well as for other purposes. These savings increase with time through the impact of rail transit on urban forms. Moreover, the rail transit system becomes a landmark by itself, giving the city a certain special identity and image. There is a distinct pride in a city's being a "metro city." Most great world cities are recognized as such partly because of their metro systems: an important part of Paris is the Metro; of London, the Underground; of New York, the Subway; of Moscow, the Metropolitan; and of Berlin, the U-Bahn. Light rail is similarly a symbol of livable, pedestrian, and transit-oriented cities in San Francisco, Portland, Calgary, Cologne, Karlsruhe, and many other cities. The importance and value of rail transit thus considerably exceeds the direct physical and economic results of its operations. Regional rail usually represents a distinct symbol of a large region with its central city strongly connected with its surrounding areas. In addition to very large metropolitan areas such as Tokyo, London, and New York, good examples of this role of regional rail are Munich, Sydney, and Los Angeles as a new member of this category of urbanized regions.

EXERCISES

- 6.1.** List and explain the characteristics of rail modes caused by their (a) External guidance. (b) Rail technology, as distinguished from other guided technologies.
- 6.2.** There are opinions that LRT is seriously impeded by its grade crossings or street running, so that it can never have satisfactory speed, reliability, safety, and other performance elements. RRT has no such impedance and is therefore the superior mode. Others claim that LRT has a greater flexibility of alignment than RRT and that when grade crossings and street running are properly regulated, this mode can nearly match RRT in performance. Therefore, LRT is “better” than RRT.

Define the main characteristics of the two modes and compare them systematically to show which one of these two views, or a third view, is correct. The comparison should include, among other factors:

- Network extensiveness and configuration
- Possibility of staged construction
- Investment cost
- Capacity
- Reliability of service
- Operating speed

- 6.3.** a. Express the lengths of four-, six-, and eight-axle LRT vehicles in terms of l_t and l_o (see Figures 6.3 and 6.7).
 b. Assuming that $l_t = 7.00$ and $l_o = 3.80$ m for all three models, compute the average vehicle length per truck for each one.
 c. For what values of the ratio l_t/l_o is vehicle length per truck greater for articulated (six- and eight-axle) than for single-body cars?
- 6.4.** A rapid transit car has a wheelbase (distance between the axles in a truck) $l_a = 2.00$ m, body length $L = 21.00$ m, width $W = 2.90$ m, and truck center distance $l_t = 14.00$ m. The overhangs l_o are symmetric. Compute its ΔR_b^i and ΔR_b^o in a curve with $R = 125$ m.
- 6.5.** Described low-floor LRT and RGR vehicles. Compare them with conventional ones (with high floor) with respect to design, operations and changes they allow in platform design. Define their advantages and disadvantages. How can these changes influence alignment of LRT/RGR lines in cities?
- 6.6.** Define the three types of LRT/RGR low-floor vehicles by floor design. Compare them by their door locations, axle and truck designs and passenger accommodations.
- 6.7.** A rapid transit line has old rolling stock that should be replaced. It has been decided to make every reasonable effort to achieve higher operating speed with the new stock. List the major items that should be considered for improvement to achieve higher speed, such as body design and dynamic and operational characteristics. Discuss each item and explain how you would examine its feasibility (physical design and costs) for application on the existing line. Concentrate on rolling stock, but mention if some of its changes would necessitate other changes (e.g., departure control procedure).

- 6.8. You are asked to evaluate proposals to purchase two different types of rolling stock for a metro line which operates during peak hours eight-car TUs. One proposal is to purchase married pairs. The other is to purchase unit trains of eight cars which have jointed bodies, providing continuous interior (as Hong Kong has done). Develop a list of factors you would consider and mention elements that would be included in the evaluation of each factor.
- 6.9. Find the technical specifications for three different RRT vehicle models. Compare their dimensions, weight, and power characteristics (using the diagrams in Figures 6.12 to 6.16) and evaluate the suitability of each to the specific operating conditions on the line on which it is operated.
- 6.10. What are the differences between typical rapid transit and regional rail rolling stock?
- 6.11. Give technical details and describe the layout of two different bilevel RGR cars and compare their features.
- 6.12. Describe recent trends with respect to streetcar/tramway mode in one of the following geographic areas:
 - a. Western Europe (Germany, France, Switzerland, Benelux and others);
 - b. Eastern Europe (former USSR, Poland, Romania)
 - c. United States
- 6.13. (Closed book) Draw rail switches (a) Standard with elastic points and (b) Double slip switch. Show one position with solid and the other with dashed lines.
- 6.14. Describe the cut-and-cover and tunneling subway construction methods. Define the differences between them and the conditions that make each one superior to the other.
- 6.15. Compare the Paris- or Montreal-type RTMT with conventional RRT; list and describe its inherent advantages and disadvantages. On the basis of this comparison, define two sets of conditions under which each one would most likely be superior to the other.
- 6.16. Analyze the benefits and costs of complete automation of a rail rapid transit line. Include such elements as investment cost, operating cost, safety, passenger acceptability, line capacity, potential improvements of the level of service, and others.
- 6.17. Discuss implementation problems (changes and additions to infrastructure and operations) required for application of automation with driverless operation on an existing RRT line.
- 6.18. In most respects RRT has the highest performance of all transit modes. List the main physical and operational characteristics of this mode that give it each of the following features:
 - High capacity
 - High safety
 - High reliabilityBe sure to include all components, such as ROW type, station, design, vehicle characteristics, way control, and others.
- 6.19. Identify and describe major physical factors (topography, urban form and shape, etc.) that influence the suitability of rail transit for a given city.
- 6.20. Why has the role of RGR systems (increased ridership, improved and expanded services) in major cities, including those with freeway systems and very high automobile ownership (e.g., Chicago, Frankfurt, New York, Toronto), increased in recent decades?

- 6.21.** What factors in addition to transportation effects (e.g., user benefits) and costs (investment and operating) should be considered in analyzing the feasibility of rapid transit construction in a city? (Include both positive and negative, and temporary and permanent effects.)

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7

UNCONVENTIONAL CONCEPTS AND SYSTEMS: AUTOMATED GUIDED TRANSIT AND MONORAILS

The conventional transit technologies and operational methods, such as bus and rail systems, offer a wide variety of services in quantity and quality, which can satisfy most types of urban transportation needs. However, numerous innovations in transit technology and operations have been developed nearly continuously ever since the first transit services were built. Although recent inventions have not been as radical as those in the earlier stages of development, they have by no means been negligible. Contemporary transit systems based on conventional bus and rail technology are distinctly different from those built only a few decades ago. In addition, several unconventional systems and modes have found significant applications in many cities and specific functions, increasing the options of modes cities can select.

This chapter reviews different categories of urban transit and points to situations in which there is potential for improvements of conventional services. A number of innovative proposals are reviewed and their underlying concepts systematically analyzed. Then, recently developed unconventional modes are described and evaluated on the basis of this conceptual analysis. The emphasis is placed on the most significant unconventional modes, mostly in the category of automated guided systems, which have acquired an important place in the family of transit modes. Monorails, which enjoy the aura of “a future transit system,” are also included. Personal rapid transit (PRT), a hypothetical

mode, is covered in this chapter because it is often brought up as an option in urban transportation planning and causes considerable confusion.

Many transit system components reviewed here, such as types of guideways, wheels, vehicle design, propulsion and control, as well as operational methods, including ROW control, fully automated operation of TUs, and integration of different modes, are also presented in the chapters on highway, rail, and paratransit modes (Chapters 5, 6, and 9, respectively).

7.1 EVALUATION OF CONVENTIONAL SYSTEMS AND POTENTIAL FOR INNOVATIONS

The basic reason for the development of innovative technological and operational concepts is the need to improve the performance and quality of transit systems or to reduce their costs and negative side effects. This is particularly the case with services that are “between” or “around” the optimal domains of existing modes. Identification of the need for innovations, which is very important for directing research and development efforts, is presented next with respect to each major category of services.

Low-passenger-volume transit services, typically found in suburban areas, are provided primarily by conventional buses and vans of various sizes. They of-

fer adequate comfort and require low investment for the introduction or expansion of services. Diesel propulsion of buses, although improved in recent years, still has performance features that could be improved: air pollution and noise produced by most motorbus models are still objectionable.

The main problem with transit services for low-density areas is, however, the low productivity of vehicle operators in terms of produced passenger-km/driver-h. It is therefore difficult to provide a desired density of lines and frequency of service at a reasonable operating cost. However, the solution to this problem lies more in special organization of services (timed transfer system with common headways, use of ITS for control of paratransit services) than in technological innovations.

Medium-capacity lines are adequately served by buses, trolleybuses, and streetcars where passenger volumes are moderate and streets reasonably free of congestion. With higher passenger volumes (on the order of ≥ 1000 prs/h) and on streets with heavy traffic, higher-performance modes are needed. Bus lanes are a logical first step solution where the bus services are well organized and police enforcement is permanently effective to protect the lane from intrusions by other vehicles, parking, and stopping. A more permanent and higher quality of service that attracts more passengers can be obtained by LRT at a somewhat higher investment cost. Fully automated modes, discussed below, can provide even faster and more reliable service, but at a significantly higher investment cost and with difficulty in penetrating pedestrian-oriented urban centers.

Consequently, there is a distinct need for a transit mode that would have the physical characteristics and capacity of LRT but the speed and reliability of rapid transit. ROW A would also make fully automatic operation possible, thus allowing a high frequency of service throughout the daily operating period. In other words, a moderate-investment, medium-capacity rapid transit mode is needed for lines with moderate passenger volumes. The vast majority of current developments of unconventional modes focus on this category of medium-capacity automated rubber-tired or rail-based modes.

Short-haul transit in high-density areas sometimes requires a more reliable and more convenient service than street transit modes can provide. Thus short-haul represents another application for low- or medium-capacity automated guided modes (see Section 8.1).

High-density major corridors are most efficiently served by conventional rail modes that provide high speed, capacity, reliability of operation, safety, and passenger comfort. Modernization of some of the existing metro systems may be desirable to decrease their investment costs, but no major technological breakthroughs are needed.

7.2 ANALYSIS OF SYSTEMS COMPONENTS

Based on the above discussed evaluation of performance of conventional transit modes, their possible improvements and innovations can be classified in three general categories:

- Technological components.
- Operational concepts.
- Design of modes and systems.

The first two of these categories are analyzed in this section. Unconventional modes are described in Section 7.3 and evaluated in Section 7.4.

Technological components most relevant to system characteristics and performance include vehicle support and guidance (type of wheel and guideway), and vehicle/TU capacity. Their innovations include such items as improved design of ICEs for lower emissions, noise, and vibrations; increased efficiency and reduced size of electric motors; AC traction; remote control of trolley poles on trolleybuses; and modular design of vehicle bodies and components.

The following two sections present a systematic analysis of the basic elements of unconventional modes: types of wheel, guideway, and vehicle capacity.

7.2.1 Vehicle Support, Guidance, and Switches

Vehicles can have four basic positions with respect to *guideway* (see Figure 7.1). They can:

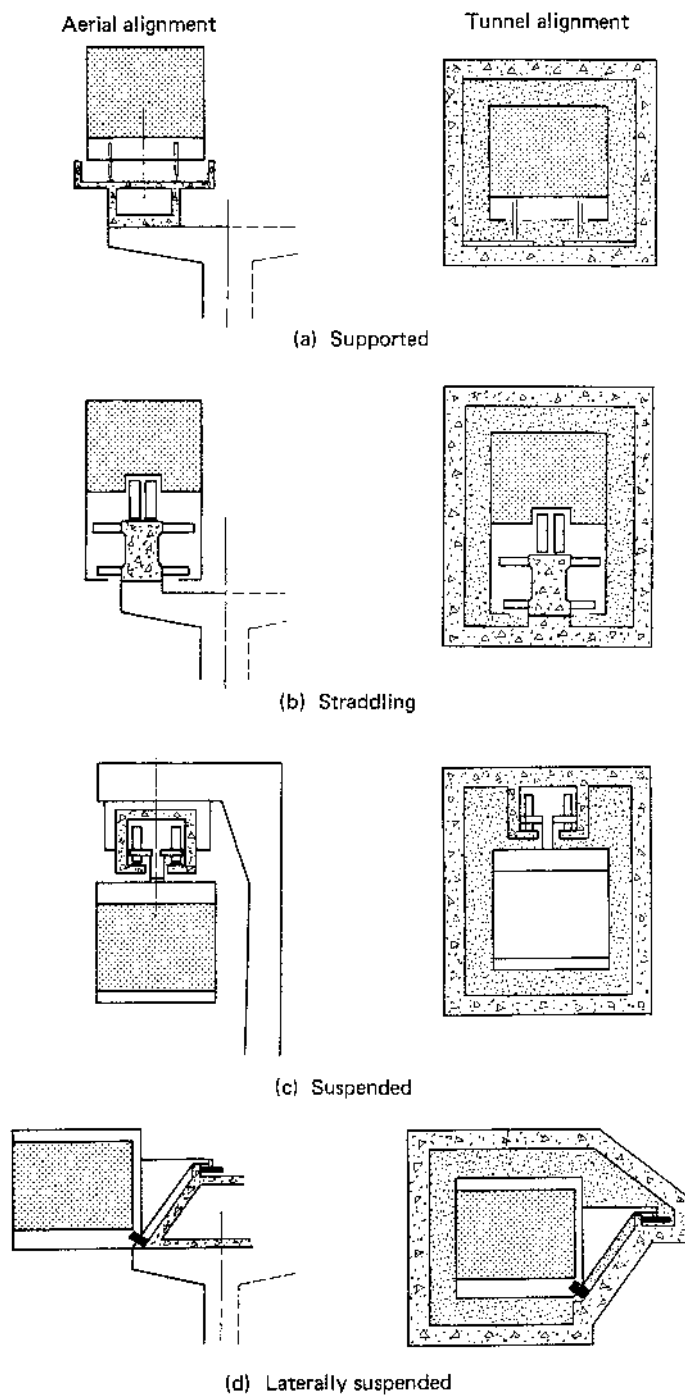


Figure 7.1 Different types of guideways by vehicle position

- Stand on it
- Straddle it
- Hang from it
- Be laterally suspended

Each one of these positions has a direct repercussion on the characteristics of the guideway as well as on the type of vehicle support and guidance.

Guideways on which vehicles stand and travel are by far the most common type. They include conventional rail and most rubber-tired guided modes. Their basic advantages are simplicity and the low position of the running surface.

Guideways that vehicles straddle have the advantage that they consist of a rather narrow single beam. The advantages of small profile and apparent “lightness” of the guideways are, however, countered by the complexity of their guidance and switching, discussed later. Most systems with this type of guidance are called “monorails,” although they have six sets of wheels running along six surfaces on three sides of the guideway (see Figure 7.1b). This technology is used by the majority of presently operated or planned monorail systems.

Guideways with suspended vehicles have a considerably higher structure than those supporting vehicles. An advantage of this type of guideway is that sway of suspended vehicles tends to compensate their lateral accelerations, so that they have a more comfortable ride in curves than supported vehicles do. This type of design is used by the oldest monorail system in the world, operating in Wuppertal, Germany, and shown in Photo 7.1.

Several suspended systems with different designs and rubber tires have been developed since the 1950s (Monocab in the United States, URBA and SAFEGE in France, Cabintaxi and H-Bahn in Germany). Their advantageous feature is that they have enclosed running surfaces, protected from weather along entire lines. Several suspended monorails are in operation, mostly in Japan, on transit lines (Chiba and Shonan), and for special purposes (e.g., in the Tokyo Zoo).

Several designs with lateral suspension of vehicles have also been proposed, but prototypes have not been built. The most advanced one has been the *Project 21*

system, developed by Lawrence Edwards. Its concept is shown in Figure 7.1d: the vehicles have angled supporting wheels and horizontal wheels that hold the vehicle laterally suspended. The main advantage of this system would be that a single beam carries vehicles in both directions on a line. The basic concept has a number of attractive features as well as some design/operational components that require further testing.

Support and guidance have a number of technological concepts and designs (see Figure 7.2), but only a few are efficient and practical. The simplest method of support and guidance is provided by conventional rail: since each wheel provides both support and guidance, the four or eight wheels that support a vehicle provide its guidance at the same time (Figure 7.2a). Rubber tires, utilized on many recently developed unconventional guided systems, must have separate sets of supporting and guiding wheels; thus they must have two and sometimes three times as many wheels as conventional rail vehicles of comparable or even considerably larger size and capacity. For example, rubber-tired rapid transit (see Sec. 6.4) has trucks with four large rubber tires for support and four small horizontal ones for outside lateral guidance in addition to the standard steel wheels [i.e., a total of 12 as compared with four wheels only on conventional rail vehicles (Figure 7.2c)].

The French VAL system has single-axle trucks with two supporting and four guiding rubber tires. The Bombardier CX-100 AGT system, developed originally by Westinghouse, has four double-tire supporting wheels and eight horizontal wheels against a central I-beam for guidance (i.e., a total of 16 tires). These and several other support/guidance designs are shown in Figure 7.2.

The simplicity, low rolling resistance, fast switching, and ability to have at-grade crossings or to operate in streets are some of the major advantages that make rail by far the best support/guidance technology for high-performance systems. For smaller, two-axle vehicles and alignments in constrained areas with many curves, however, rubber-tired support/guidance becomes superior to rail owing to the quieter ride in sharp curves and easier negotiating of steeper grades (better adhesion). For this reason, the majority of the recently



Photo 7.1 Schwebebahn in Wuppertal, Germany, the oldest operating monorail in the world

developed small- and medium-capacity guided systems have rubber tires.

Another support/guidance method utilizes contactless magnetic suspension and guidance and a linear induction motor (LIM) for propulsion. Either repulsing or attracting magnets can be utilized. This method is used on the M-Bahn transit system developed in Germany (Figure 7.2g). It is technically feasible but has been used only in a few cities. The same basic technology, but at a drastically different scale, is used by the Transrapid Magnetic Levitation (MagLev) System designed for very high-speed intercity transportation, which presently operates on one line in Shanghai,

China, between a terminal in the center city and the airport.

Air-cushion levitation can also provide vehicle support and guidance: a vehicle has a pad and a specially contoured surface that corresponds to the contour of the guideway. Pressured air streams blown from the vehicle create a separation between the vehicle pad and the guideway, so that the vehicle levitates at a certain usually very small (on the order of 1 cm) distance from the guideway.

Both of these two support/guidance methods have the advantage that they have no wheels and no physical contact between vehicle and guideway. Resistance is

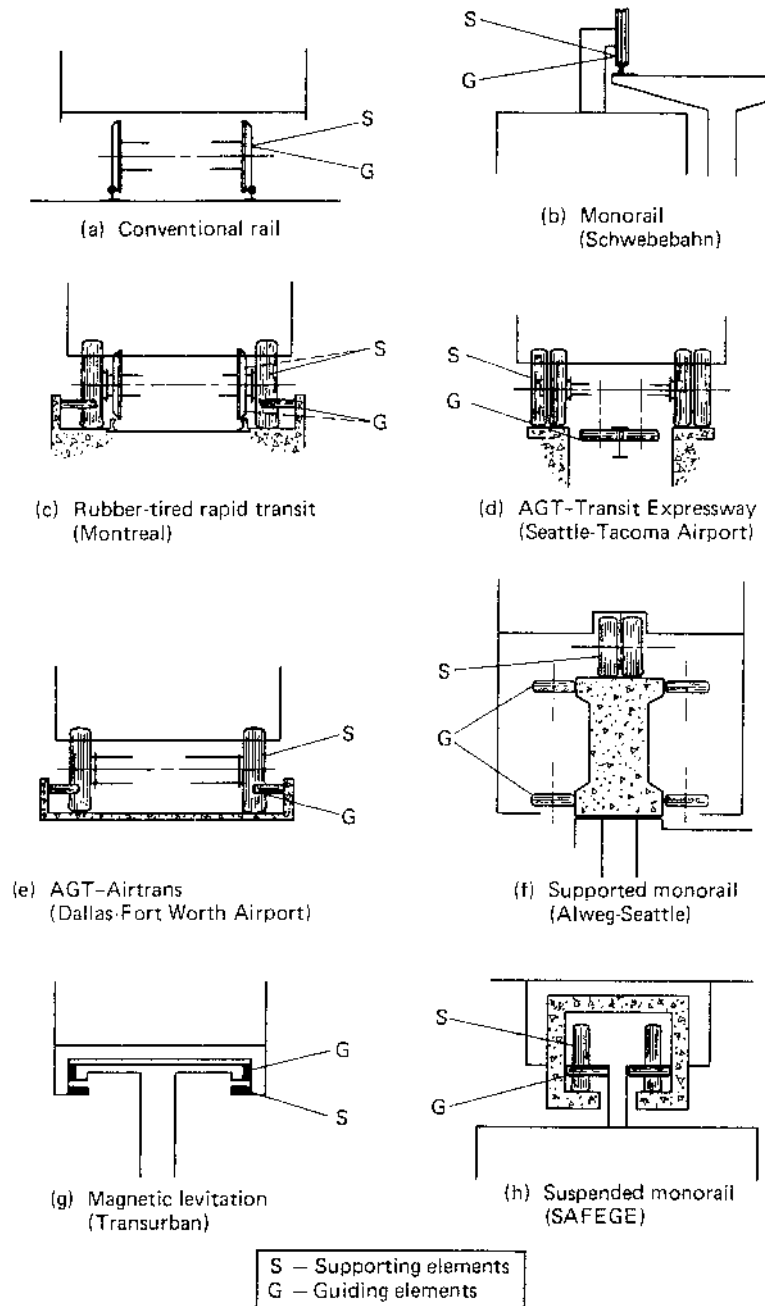


Figure 7.2 Different vehicle support and guidance technologies

therefore extremely low, their suspension is good, but they require precisely constructed guideways and involve continuous energy consumption. Actually, it has been estimated that MagLev vehicles use more energy for vehicle suspension (for powering the supporting magnets) than rail vehicles need to overcome rolling resistance up to approximately the speed of 120 km/h. It is therefore likely that magnetic levitation would increase power consumption at speeds used in transit operations.

Related to support and guidance is the type of *vehicle propulsion*. Various proposed modes utilize several different types of propulsion, but by far the most appropriate one is by electric motors. Among unconventional propulsion systems applied for several proposed modes is the above mentioned LIM, used on the M-Bahn system, and pneumatic pressure used on the Uniflo system. Neither of these two is competitive in cost/performance characteristics with conventional electric motors at the present time.

Switches for converging/diverging of guideways represent an important element of these modes. The basic requirements for switches are that they provide safe, fast, and comfortable vehicle travel; that their position can be quickly changed; and that they allow the design of various guideway configurations (turning out at different angles, several switches close to each other, crossovers, slip switches, etc.). Therefore, switches influence the design of stations, yards, and networks as well as the type of operations.

Each type of support/guideway technology has a different type of switch. Several basic types are shown in Figure 7.3.

Conventional rail has an extremely simple switch with two elastic movable points. Its position is changed in approximately 0.6 s, it allows high-speed travel through switches with small angles, and it is safe for approach from either converging direction regardless of the switch position.

Systems that straddle guideways usually have stub-type switches: the entire beam bends into one or the other position (Figure 7.3b). This switch provides continuous guidance, but its change requires several sec-

onds. It can be approached only from the directions to which the switch is set.

Systems with central guidance have switching by changing the position of the guiding I-beam (Figure 7.3c). The position is changed quickly (2 to 3 s). Approach is possible only from the directions to which the switch is set.

Systems with lateral guidance by rubber tires have several different types of switches. One consists of "sinking" guideway sections within the switch area: the guideway remains continuous for the selected direction, while the guideway section leading to the other direction is lowered to be flush with the riding surfaces. This switch was tested on prototype systems but not on an operating transit system.

Another type of switch has no guidance in the diverging area, but vehicles have wheels automatically steered to the left or right, thus following only one of the guiding surfaces. This represents a basically different principle of switching: the switch is passive and has no moving parts, while each vehicle "chooses" the guideway it is directed to follow. This switch has been in use on the Morgantown system, which has a rather low maximum speed (48 km/h).

The concept of an "on-board switch" (i.e., on vehicles, without moving parts on the guideway) has a major advantage over movable switches in that it involves no switching time: vehicles can follow each other closely and switch into different directions. Thus operation with very short headways is possible. A simple design of on-board switching is with an arm on the vehicle that can be stretched out to hook with the guideway on either side in the switch and steer the vehicle in that direction.

Although all these types of switches provide safe travel, some do not satisfy the requirements for a fast and comfortable ride. Even more significantly; none of the switches can match rail in the diversity of guideway configurations: different switching angles, switches close to each other, and so on. Finally, none of the guideways except rail can have at-grade crossings by other traffic or simple crossovers of guideways themselves. This imposes a limitation on the design of stations with storage tracks, yards, and entire networks.

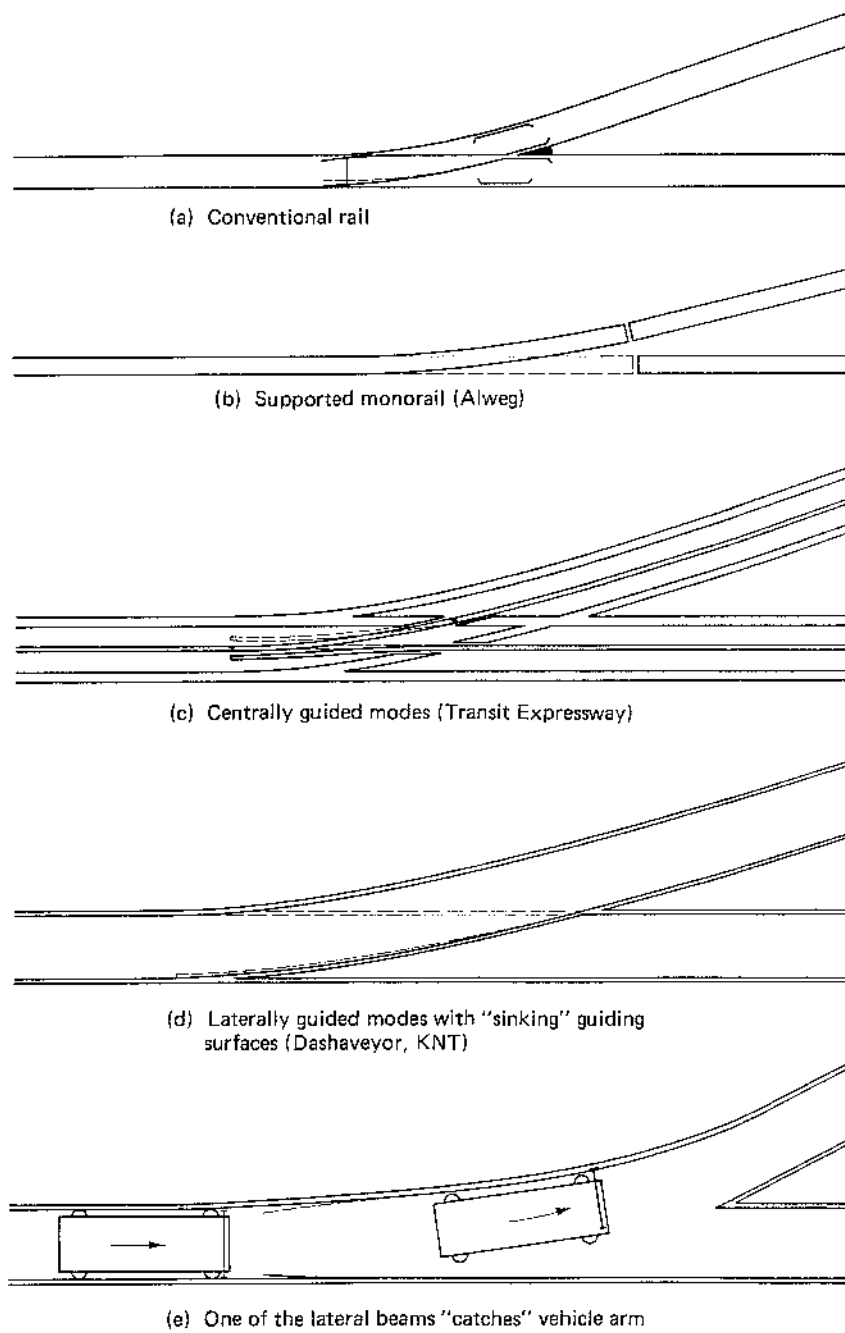


Figure 7.3 Different types of guideway switches

7.2.2 Vehicle/TU Capacity

Vehicle cross-sectional profile, length, and resulting capacity are important characteristics of guided transit modes, since they affect their capacity, costs, operational features, and line surroundings. To have low tunneling costs and little negative impact if operated above ground in dense urban areas, the vehicle profile should be minimized. But to provide adequate capacity and passenger comfort, vehicles should have large dimensions, particularly length and width. Thus, as with most vehicles used in cities, it is desirable to have transit vehicles that are “large inside but small outside.” The compromise between these two requirements must be found on the basis of system usage and characteristics of the served area. For example, regional rail systems have large free profile on their lines. Since passenger comfort in their vehicles is very important because they typically serve long trips, a large profile and in many cases double-decker cars represent the optimal choice. On rapid transit lines that operate in tunnels optimal vehicle and train sizes depend on maximum passenger volume and trip lengths.

Determination of optimal capacity of vehicles for new transit systems is not always well understood. There was a tendency in the development of unconventional modes to design small-capacity vehicles. Several such systems have been designed with small cross sections to reduce ROW space requirements but compensate small vehicle capacity by provision of high service frequency. During the 1970s, the Morgantown system, Rohr’s P-Series Monorail, the French Aramis, and Krupp’s Kompaktbahn all of which were intended for intraurban applications with short trips, had small profiles and capacities between 12 and 21 spaces, while the Airtrans vehicles had 40 spaces. Among the AGT systems that have been later adopted and built in several cities, the French VAL was designed for use on lines with tunnels (Lille, Toulouse) with a width of only 2.06 m. These vehicles require a smaller tunnel cross-section, but their space for passengers is very limited and they are much less capable of accommodating standing crowds than transit vehicles with widths of at least 2.20 m but usually 2.65 m. However, several other modes, also intended for reg-

ular transit lines, have dimensions similar to those of rail vehicles. Thus, Bombardier’s AGT vehicles are 2.84 m wide and 3.36 m high, dimensions larger than those of many rail vehicles, and their capacity is up to 100 spaces (mostly standing).

The diagram in Figure 7.4 shows the relationships among service headway (and its inverse, service frequency), TU capacity, and the resulting line capacity. AGT systems have rather diversified applications, but several factors can be analyzed to define boundaries on the required capacity of their TUs. The critical condition for which every system must be designed is the peak hour or, more precisely, the maximum passenger volume expanded to hourly volume. In most cases, it would be difficult to justify an investment into an exclusive ROW and a fully automated system if its design capacity were less than 2000 sps/h (or actual passenger volumes between 1500 and 1800 prs/h). This value, shown on the diagram by a dashed line, can be assumed to be the lower boundary for line capacity, and it requires TU capacities greater than 50 spaces. The maximum line capacity for AGT modes is the limit between the domains of AGT and rail modes, LRT and RRT. In many cases rail modes are used for any volumes down to 2000 sps/h, so that their domains overlap. But for design capacities above 8000 sps/h (passenger volumes of 6000 to 7200 prs/h), rail modes are clearly superior to AGT under all realistic conditions. The feasible domain for AGT can therefore be assumed to be on lines with capacities between 2000 and 8000 sps/h.

Another factor influencing TU capacity is the headway. It is logical to assume that the longest headways that would be acceptable on an automated system are about 5 to 6 min (longer headways would defeat one of the basic benefits from automation). The shortest average headway is, on the other hand, limited by the operating feasibility of the control system to 90 s. Shorter headways can be achieved only if off-line stations are provided on the critical links, which is not likely to be feasible in typical urban applications.

These four boundaries of AGT applications are plotted on the capacity-headway (frequency) diagram in Figure 7.4. TU capacities that are functions of line capacity and service headway are also plotted. The di-

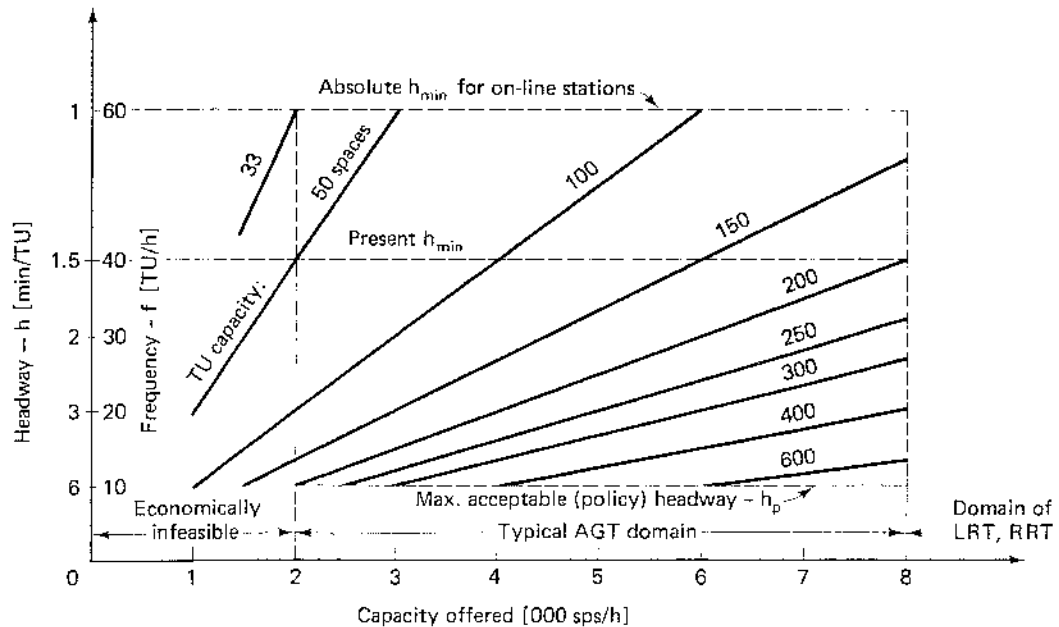


Figure 7.4 TU capacity of AGT modes as a function of frequency of offered line capacity

agram shows that the minimum TU capacity in the defined range of applications, for a line that operates at 60-s headways and offers a capacity of 2000 sps/h, is 33 spaces. For the most common applications, such as headways of 2 to 4 min and capacities between 3000 and 5000 sps/h, TU capacities must be about 100 to 250 sps. Since the smallest TU should not require coupling of vehicles, the minimum vehicle capacity for the AGT mode should be in the range of 35 to 50 spaces. These relationships have been corroborated in practice by the developments during the 1980s and 1990s: most AGT systems built during the 1980–2000 period have capacities in the range of 80–100 spaces, so that they are larger than many AGTs from the preceding generation. Since most AGT systems operate on short lines as people movers, they have very few seats, so that, for example, a vehicle with dimensions of 11.20 m $\times$ 2.70 m (Mitsubishi's Crystal Mover) has a capacity of 100 spaces, and the manufacturer offers single units as well as articulated two- and three-car units with capacities of up to 300 spaces.

The rapid transit mode, regardless of its specific technology and manual or automatic operation, always requires large vehicles and TUs, with capacities between 120 and 250 spaces and TUs of one to ten cars.

Operational concepts include such elements as moving-block control of guided systems; lower-cost tunneling methods; track construction for lower maintenance; dual-mode systems operations, and fully automated (driverless) TU operation. The last two are discussed here because of their direct relationship with many unconventional transit systems.

7.2.3 Dual-Mode Operations

The concept of dual-mode vehicles or operation is rather broad and applies to many combinations of different transit services, such as street, partially and fully reserved ROW (C, B and A categories), types of vehicle control, etc. Table 7.1 presents a review of different types of dual-mode operations and abilities of different transit modes to operate these combinations.

Table 7.1 Dual-mode capabilities of different transit modes

<i>Category and Dual Features</i>	<i>Guidance: Driver Steered/ Guided</i>	<i>ROW Category: Street/ Separate (C, B, A)</i>	<i>Hybrid Propulsion: Electric/ ICE</i>	<i>Operation: Manual/ Automatic</i>
<i>Transit Mode</i>				
Auto/taxi		x	x	
Bus		x	x	
Guided bus	x	x ^a		
Dual mode bus		x	x	
Trolleybus		x	x ^b	
Light rail transit		x		x ^c
AGT/APM				x ^d
Metro-rail rapid transit				x
Regional rail			x ^b	x

^a Exclusive roadways for this type of vehicle are used only for sections of lines.

^b Special vehicles.

^c Automatic operation is possible only for LRRT or sections of LRT with ROW A.

^d Manual operation is possible but not foreseen for economic reasons.

The table shows that several conventional modes have dual-mode capabilities. For example, a conventional bus can operate in mixed traffic as well as on exclusive ROW. LRT has not only the capability of utilizing any ROW type (C, B, or A) but also manual or automated operation (the latter on ROW sections with category A only).

Vehicles capable of operating on two different ROW types, under two different regimes, or with two different propulsion systems offer no-transfer service over both types of facilities or networks. However, to have the ability to operate under two regimes, vehicles must be more complicated and therefore more expensive and often less efficient than vehicles designed for only one type of operation. The basic rule for evaluation of dual-mode transit systems is given in the box.

For example, a dual mode bus—with both ICE and electric propulsion—provides no-transfer service be-

tween low-density suburban areas where ICE vehicles require lower investment than trolleybus, and high-density streets in city center where electric traction is superior to ICE; however, the dual-mode buses have a higher purchase price and operating costs than either regular buses or trolleybuses on their respective optimal line sections. The relative importance of these two characteristics would determine the feasibility of such vehicles in a specific application (this example is found in the Seattle CBD and the Boston Silver Line).

To sum up, each dual-mode feature increases the diversity of a mode's application at the cost of a more complicated vehicle and less efficient operation on one or on both types of travel. Dual-mode systems are feasible when the diversity is more beneficial than the inefficiencies that it causes. This is the case with bus and LRT modes, the most diversified dual-mode technologies presently in use. For example, LRT vehicles

The feasibility of dual-mode transit systems under specific conditions depends on whether their advantages of continuous service between two different regimes outweigh the disadvantages of their greater complexity and cost.

can be considerably simpler, lighter, and cheaper if they have to operate on streets only (streetcars) or on ROW A only (LRRT) than when they are designed to operate on both or all three ROW categories.

A good example of this fact is found in the San Francisco Muni Metro operations, where five lines operating as streetcars on ROW C and B converge into two tunnels approaching the trunk line along Market Street. Initially, convergence of the five branches resulted in extremely short headways and very low speeds on ROW C on Market Street. When that section was put into a tunnel (ROW category A), the system was upgraded into an LRT: the single cars and two-car trains from the branches were coupled at two convergence points into two- to four-car TUs, which then operated at high speeds on the trunk lines in the new trunk tunnel. The high speeds were possible because the coupling resulted in longer headways than merging of individual cars from all branches had previously created. The additional costs of dual-mode features and coupling-uncoupling operations were clearly outweighed in this case by the radical improvement in service: speed and capacity on the trunk are more than doubled over those on the branches; reliability, comfort, and safety are also greatly increased. Later, fully automated train operation (ATO) was introduced on the trunk section which enabled running of one- to two-car TUs at shorter headways while maintaining high speeds and avoiding the somewhat complex operation of coupling the cars into trains. Again, the investment in ATO was outweighed by the benefits from dual mode operation—manual driving and ATO.

It should be mentioned that the concept of a *Railbus*—bus operating on streets as well as on rail tracks—attracted considerable attention and development efforts during the 1920s. The same attempt was made again by the Port of New York Authority for an “intermodal connection” to the Kennedy Airport, and under DOT sponsorship in several other cities in the late 1960s. However, none of these efforts could produce a satisfactory street-rail dual-mode vehicle because of mechanical problems in rubber-tire traction on rails (extremely low adhesion coefficient under wet conditions), suspension, braking, etc. These attempts were later abandoned.

Another effort to develop dual-mode buses, undertaken in West Germany and Japan in the mid-1970s, led to the successful development of the guided bus, called in Germany O-Bahn (see Section 5.2.2.8).

7.2.4 Fully Automatic Operation

Driverless operation is a *sine qua non* for all guided modes with medium-size vehicles serving medium-volume lines, since the main purpose of not using large vehicles with lower cost per space is to provide a higher frequency of service. That is possible only if the vehicles/TUs are automated, because manual operation would make their operating costs so high that they would in many cases be rendered economically infeasible.

Physical and operational feasibility of fully automatic operation of transit TUs requires three basic features: first, that vehicles operate on fully protected ROW (category A) to prevent obstacles; second, that they are physically guided (by the guideway); and third, that they have electric propulsion. Specific guidance technology, vehicle size, and other physical features of transit systems have no direct influence on their conduciveness to full automation.

As discussed in Chapter 6, many conventional rail systems—metros and LRRT—now utilize ATO, and an increasing number of new systems are fully automated (i.e., have no crew members). However, because operation of TUs without crews is more important for intermediate than for high-capacity guided modes, the first driverless operation of a complex transit system (network with many stations and different routings of vehicles) was the Airtrans system, opened in the Dallas–Fort Worth Airport in 1974. The first such system applied to transit service in a city was the Morgantown AGT system, often misnomered as a “PRT,” opened in 1975. Subsequently, the number of AGT systems, rubber-tired as well as rail systems, accelerated, so that in 2006 there were over 40 AGT systems in operation. Most of them operate as APMs in airports, but an increasing number also serve transit lines.

Several unconventional modes were intended to operate with on-call stopping, i.e., the TUs would only

stop when requested by passengers, as is done on many bus and streetcar lines. However, this feature may be used only with small vehicles that operate at very short headways, so that many vehicles would find stations without passenger demand for stopping. As experience has shown that most AGT and APM systems require rather large TUs (one to three vehicles with 80- to 100-space capacity), the probability of no passenger calls at some stations becomes very small. Therefore most APM systems at airports and other locations and all fully automated rail systems operate with precisely scheduled stopping plans. Some transit systems have some TUs that do not stop at some stations but on a precisely scheduled and announced basis, such as skip-stop, express trains, zonal service, etc. (For detailed description of these operations see Chapter 2 in Vuchic 2005.)

7.3 UNCONVENTIONAL MODES AND SYSTEMS

New transit systems and modes have always been an area of lively activity. In most cases new modes are being developed with the intention of introducing the innovative basic technological and operational concepts discussed above. In some cases, however, new modes are incorrectly perceived as the best potential solutions to deficiencies in transit services caused by various errors in planning, financing, and organization of transit systems (several monorails and PRT systems are good examples). The former reasons for development of new modes are, of course, the only valid ones; the latter—attempts to connect inadequate planning and operations through introduction of different technology—cannot lead to success.

Ever since the introduction of the first mechanized transit systems toward the end of the nineteenth century, numerous inventions of urban transportation systems have been made. Although the conventional modes of urban transportation—such as automobile, bus, and rail modes—are highly efficient and need only further improvements of components, the number of proposals for entirely different modes has not subsided. Inventions of new mechanical components and methods of operation have resulted in introduction of new

systems, referred to here as “unconventional modes,” which have enhanced the family of transit modes.

Unconventional modes utilize different designs of the basic system components described above, such as vehicle support, types of wheels guidance and propulsion, different vehicle sizes and, particularly, fully automatic operation. The monorail concept, with vehicles guided by a single rail or beam, has drawn attention since the end of the nineteenth century. A particularly lively period of “new mode” developments occurred in the 1960–1980 period, with the introduction of computers and automatic vehicle operations. These innovations have been introduced by many inventors and private manufacturers. Governments in the United States, Germany, Japan, and some other countries have supported these innovations and related research and development. Among many new concepts and systems, some have been brought to successful implementation and wide use; others have not proven competitive with conventional modes. Naturally, like in any innovative process, some of the concepts are unrealistic and are not likely ever to be used as real-world systems.

This section describes four groups of unconventional modes. The most widely used mode, automated guided transit (AGT), is presented first, followed by monorails, which have somewhat specialized applications. The third category are several less known systems. Finally, personal rapid transit (PRT) a theoretical system, frequently proposed but never applied, is also discussed.

7.3.1 Automated Guided Transit and Automated People Movers

The largest and most significant category of unconventional systems consists of electric, guided, fully automated modes. Through their development since the 1970s, these systems have been given several different names. AGT is the professionally most correct term. Automated people movers (APM) is a widely used and popular term, as is people mover systems (PMS). Group rapid transit (GRT) was the term used for a government-sponsored program exploring a theoretical automated system with extremely short headways that did not prove feasible. All these terms are used inter-

changeably by various groups. One of the first automated systems, in Morgantown, West Virginia, is often referred to as a PRT system, which it is not (see Section 7.3.4).

To emphasize two major roles of these systems, the first two of the quoted names for this mode are used here for the two application categories:

1. AGT are systems which are used on regular transit lines in cities
2. APM are systems used on short lines performing as shuttles or loop lines in major activity centers, such as airports, campuses, and amusement and convention centers

Their characteristics are given in the box.

Many of these proprietary systems are used for both functions—AGT and APM—but in most cases systems used as APM systems, operating on short lines, have lower speeds and fewer seats (often nearly exclusively standing passengers) than AGT systems.

By applications, there are many more APM than AGT systems. As of 2005, there are APM systems at 26 airports around the world, ranging in length from 0.7 km in Pittsburgh to 10 km in San Francisco, with most in the range of 1 to 4 km. The busiest is the 3.9-km line connecting all air terminals at Atlanta Hartsfield Airport, which carries 225,000 passengers per day.

Other APMs serve amusement parks (the Walt Disney World monorail is particularly well known), university campuses, hospital complexes, sport grounds, and others.

The downtown people mover (DPM) systems in Miami and Detroit, using rubber-tired and rail technologies, respectively, represent an overlap between APM and AGT types by their functions. The 7.1-km-long Miami Metromover system is particularly elaborate, serving with 21 stations as a distributor for two metroline stations and convenient connector throughout the downtown area (Photo 7.2).

Applications of AGT systems to regular transit lines started during the 1980s with opening of a VAL line



Photo 7.2 Miami downtown people mover

The basic elements of both AGT and APM systems are as follows:

- Exclusive, category A, ROW and stations.
- Most AGT systems use two-axle rubber-tired guided vehicles, but some are four-axle rail vehicles, in a few cases supported by magnetic levitation.
- Conventional electric propulsion and, in a few cases, linear induction motors
- Fully automated, centrally controlled operation, without drivers, which allows operation of many small TUs at short headways involving the same cost as operation of few large TUs at long headways.
- Central control of operations, which allows easy change of train consists to adjust TU sizes to passenger demand.
- Most of these systems, with the notable exception of those using rail, are proprietary.

Table 7.2 Bombardier AGT/APM systems

<i>System</i>	<i>Setting</i>	<i>Opened</i>	<i>Length [km]</i>	<i>No. of Stations</i>	<i>No. of Cars</i>
Tampa	Airport	1971	1.5	10	24
Seattle–Tacoma	Airport	1973	2.7	8	45
Miami	Airport	1980	0.8	4	6
Atlanta–Hartsfield	Airport	1981	3.9	7	73
Orlando	Airport	1981	2.4	8	24
London–Gatwick	Airport	1982	1.4	4	8
Las Vegas–McCarran	Airport	1985	1.4	4	10
Miami Metromover	Urban	1986	7.1	21	29
Singapore	Airport	1990	1.3	6	3
London–Stansted	Airport	1991	3.2	3	9
Pittsburgh	Airport	1992	0.7	2	6
Denver	Airport	1994	3.9	8	27
Frankfurt	Airport	1994	3.8	3	18
Kuala Lumpur	Airport	1998	1.3	2	6
Singapore–Bukit Panjang	Airport	1999	7.8	14	19
Houston–George Bush	Airport	1999	1.1	3	12
Rome–Leonardo da Vinci	Airport	1999	1.1	2	4
San Francisco	Airport	2003	10	9	38
Dallas/Fort Worth	Airport	2005	8	10	64
Madrid–Barajas	Airport	2006	2.7	2	19
Beijing–Capitol	Airport	2008	2	2	11
London–Heathrow	Airport	2008	0.67	3	9

in Lille, Kobe New Transit, and several similar lines in Japanese cities (Osaka, Yokohama, and others), and the SkyTrain in Vancouver. The Docklands Light Rail line in London can also be considered an AGT system, although it has train attendants for fare control and contacts with the passengers. Other VAL lines have been opened in Taipei (Taiwan), Toulouse and Rennes (France), and Turin (Italy). Fully automated LRRT lines in Kuala Lumpur and Copenhagen followed. Line D of the metro in Lyon is not referred to as AGT but also functionally belongs to this category. Thus, there is now a virtual continuum of fully automated systems from such AGTs as the Miami DPM, the VAL in Lille, the Metro Line D in Lyon and Metro Line 14 in Paris, proceeding to the fully automated rail rapid transit Northeast Line in Singapore (see Section 6.6.1). An increasing number of rail and rubber-tired AGT lines are expected to be built in the future.

In further text, this entire family of modes are referred to as AGT and described by vehicle manufacturers.

Among the great number of proposed AGT systems developed by various government and manufacturers' initiatives since the 1970s, the most successful and best known are described briefly below. Their technical data are presented in Table 7.2. Many of these data do not necessarily represent fixed values, since they vary among different installations of the same system or change as the systems are developed further.

Bombardier's CX-100 AGT system was developed by Westinghouse Electric (initially known as the Skybus) as a major research and development effort with extensive testing. The first system was built in 1971 at Tampa International Airport, followed by Seattle–Tacoma International Airport in 1973 and then by close to 20 airports worldwide by 2005. In addition to its dominant role as airport APM, it has AGT applications, such as Miami DPM, a feeder line to RRT in Singapore, and others. Several vehicles and guideways of this mode are shown in Photos 7.2 and 7.4.

The CX-100 vehicles have a modified bus chassis with two axles and eight supporting rubber tires (Fig-



Photo 7.3 Miami DPM guideway penetrates CBD (Courtesy of Westinghouse Electric)

ures 7.5 and 7.6). Its weight, tare of 14.9 t and gross 22.2 t, results in high axle weight—up to 11.1 t, but only 2.8 t per tire. The guidance is obtained by eight small horizontal tires running along a vertical steel I-beam in the center of the guideway. Switching is achieved by movement of this beam (Figure. 7.4c). In most applications, vehicle interiors provide only longitudinal seating and high standing capacity, but a higher seating capacity is possible where operating conditions require it. Most existing Bombardier CX-100 lines, being short shuttles, operate only one- to three-car trains, but the system is designed for up to ten-car TUs, which would provide a capacity adequate for any AGT application.

A review of the Bombardier AGT and APM systems in operation and their sizes is presented in Figure 7.2.

Siemens' VAL system, a product of MATRA, was first built in the city of Lille as a regular transit line. Its 12.7-m long vehicles have two axles. Rubber tires

are used for both supporting and guidance wheels. The guidance mechanism, the guideway itself, and the switches are all rather elaborate. Similar to CX-100, use of two axles for 12.7-m-long vehicles results in high axle loadings (7.5 t tare, 11.0 t fully loaded) and a greater weight per tire, 5.5 t.

The VAL line in Lille, opened in 1983 (Photo 7.5a), was the first driverless AGT line in the role of regular transit in the world. Its stations have platform-edge doors that open simultaneously with car doors (Photo 7.5b). To reduce tunneling costs, its vehicles were designed with a body width of only 2.06 m, narrower than that of any rail vehicle. This small width and longitudinal individual seats result in constrained standing in the aisle (Photo 7.5c). This limit of vehicle capacity is partially compensated by very short headways: the central control and rubber-tire technology make possible operation with minimum headways as short as one minute (average headways are longer). The line in Lille provided reliable service and proved to be very



Photo 7.4 Bombardier AirTrain (variant of CX-100 model) AGT vehicle at San Francisco Airport (Courtesy of Bombardier Transportation)

successful, so that it was followed by construction of another line. The two lines have a total daily ridership of 190,000 passengers.

Lille was followed by construction of a 10-km-long VAL line, mostly in tunnel, in Toulouse, France, opened in 1993. It carries 150,000 daily passengers. Rennes, France, opened a VAL line in 2002 (Photo 7.6). VAL has also been built as APMs in Chicago O'Hare and Paris Orly airports.

The highest-capacity VAL was built in Taipei. To cope with passenger volumes usually requiring RRT mode, the all-aerial 10.9-km-long Taipei line has 2.56-m-wide vehicles and is operated by four-car TUs. However, that system was beset by a number of contractual, technical, and operational problems (Parkinson and Fisher 2000).

Advanced Light Rail Transit (ALRT) is a fully automated rail transit system developed by Canada's Ur-

ban Transportation Development Corporation (UTDC), now part of the Bombardier family (Parkinson and Fisher, 2000). Custom-designed for the line in Vancouver (Photo 7.7), it has a linear induction motor (LIM) propulsion and steerable axles. One reason for the use of LIM was to keep the vehicle profile low. This allowed use of an abandoned railway tunnel for two tracks placed above each other. LIM uses about 25% more energy for vehicle propulsion than a conventional rotary motor, but it has traction advantages: since the wheels are not used for traction, the problems of adhesion and negotiation of steep gradients is reduced or eliminated.

The 21.4-km-long Vancouver line, named the SkyTrain, opened in 1986 as the first major driverless transit line in North America. For reliability and a customer-friendly environment, roving attendants are assigned to the line to patrol stations, provide

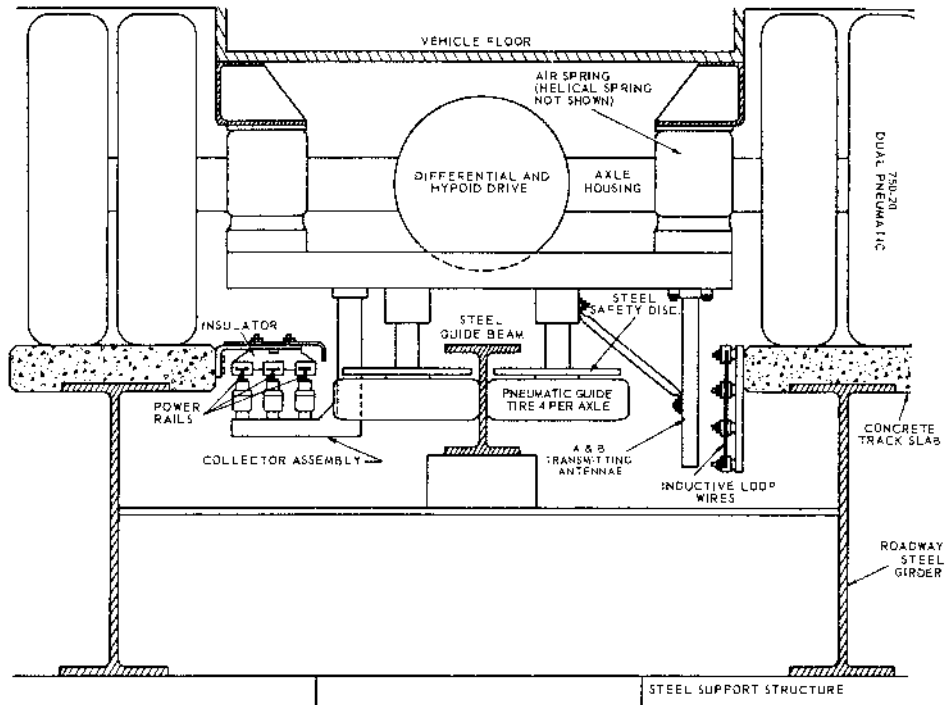


Figure 7.5 Bombardier CX-100 vehicle and guideway (Courtesy of Westinghouse Electric.)

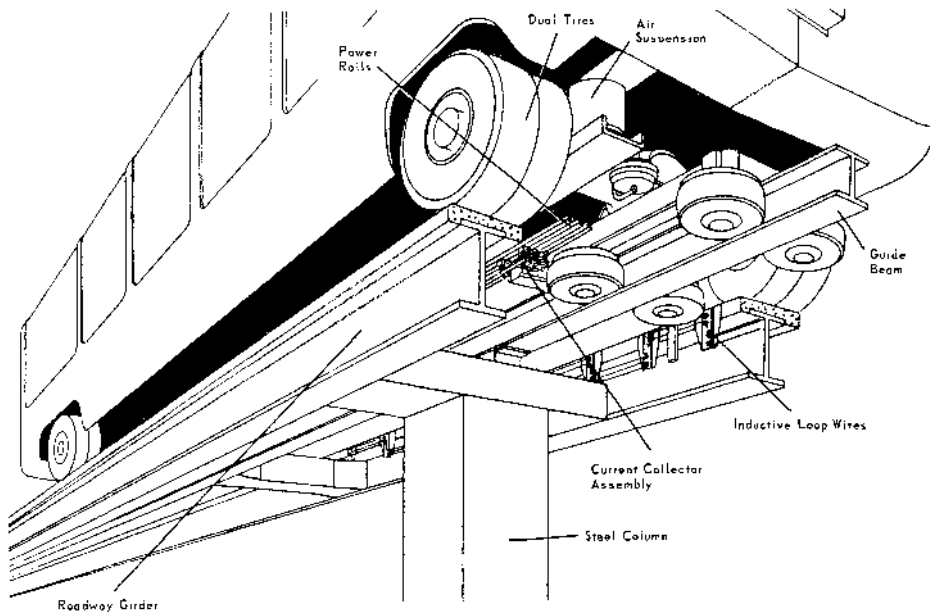


Figure 7.6 Undercarriage of the CX-100 vehicle (Courtesy of Westinghouse Electric.)



a. Two-car train approaching station



b. Platform doors



c. Vehicle interior

Photo 7.5 VAL in Lille, the first AGT on a regular transit line train



Photo 7.6 Two-car (married pair) unit of Siemens VAL in Rennes (Courtesy of Steven Jeremy)

information, and intervene in any operational problems. Unlike VAL's stations with walls with doors, the SkyTrain stations have no platform-edge walls, and possible intrusions on the track are detected by vibration-detecting plates along the tracks, which automatically stop an incoming train if an intrusion occurs. The stations appear much more open than stations with platform walls of most other AGT systems.

The SkyTrain line is operated with up to four married-pair TUs, providing an offered capacity of 26,000 sps/h, which is at least twice greater than most rubber-tired AGT systems can offer. The line has been highly successful, attracting 135,000 daily passengers. Subsequent extensions, in 1990, 1994, and 2002, brought its total length to 50 km, more than double its initial length, with over 200,000 daily passengers.

The same UTDC technology, but with manual driving, has been applied for the Scarborough feeder line to the Toronto Subway and for the driverless Detroit DPM. Another application of this system was for a major ALRT line in Kuala Lumpur, Malaysia. Opened in 1998 and 1999, the line has a length of 29 km with

24 stations. It is mostly elevated, but it also has an at-grade section of 2.3 km and a tunnel of 4.4 km.

The latest application of the UTDC/Bombardier system has been the line serving Kennedy Airport in New York City and connecting it to the Long Island Rail Road and the New York City Subway networks, thus representing a combination of AGT and APM functions (Photo 7.8). The line is programmed for very fast operation (not the case with many APM systems) and has been considered as very successful and well received by passengers.

Airtrans AGT, developed by LTV/Vought Corporation, was the first fully automated transportation system on a network in the Dallas–Fort Worth Airport in 1973 (it was replaced in 2005 by the Bombardier's CX 100 on a simplified network, a single two-way loop). Vehicles supported and guided by rubber-tired wheels have a 40-space capacity and operated in two-car trains on fixed schedules. However, since all stations are off-line, a number of different routings were operated, providing some nonstop travel between various terminals. With small vehicles and low speed (27 km/h), Airtrans



Photo 7.7 Vancouver SkyTrain, high-capacity rail AGT, or a minimetro system (Courtesy of Bombardier Transportation)

was applicable for limited-circulation systems rather than for regular transit lines. Its simple and fast switching (see Figure 7.3e) allowed it operation on complicated networks.

The *Kobe New Transit (KNT)* system, developed by Kawasaki, is used on a 6.4-km-long line that connects a new urban development, Port Island, with a railroad station in Kobe. This AGT mode, shown in Photo 7.9, consists of two-axle rubber-tired vehicles with four supporting and four guiding wheels. Each vehicle is 8.00 m long, 2.39 m wide, and has a tare weight of 10.5 t. Its total capacity, assuming 0.20 m²/standee, is 53 spaces. Guidance is achieved by horizontal rubber tires against outside guide beams, visible in the guideway cross section in Figure 7.7. The line is operated

with six-vehicle trains operated at a minimum headway of 2.5 min, offering a total capacity of 7632 sps/h. The trains are driverless.

Similar AGT systems have been built in several other Japanese cities: Osaka (the *New Tram*), Yokohama, Tokyo (Yurikamome Line) and others. Several of these systems use technology based on the Airtrans system design.

Crystal Mover AGT, developed by Mitsubishi Heavy Industries, has been adopted for an AGT line in Singapore. Its vehicle is shown in Photo 7.10.

The Japanese AGT systems operate with permanently coupled four- to six-car TUs. Constant TU length at all daily hours actually does not utilize one of the main advantages of AGTs: tailoring TU size to



Photo 7.8 UTDC/Bombardier AGT system with LIM propulsion for JFK Airport in New York (© 2004 Hal Dick)

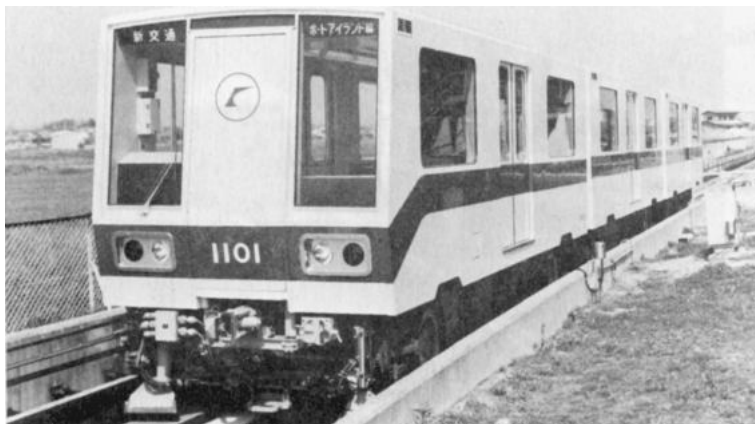


Photo 7.9 KNT's attractively designed two-axle vehicle

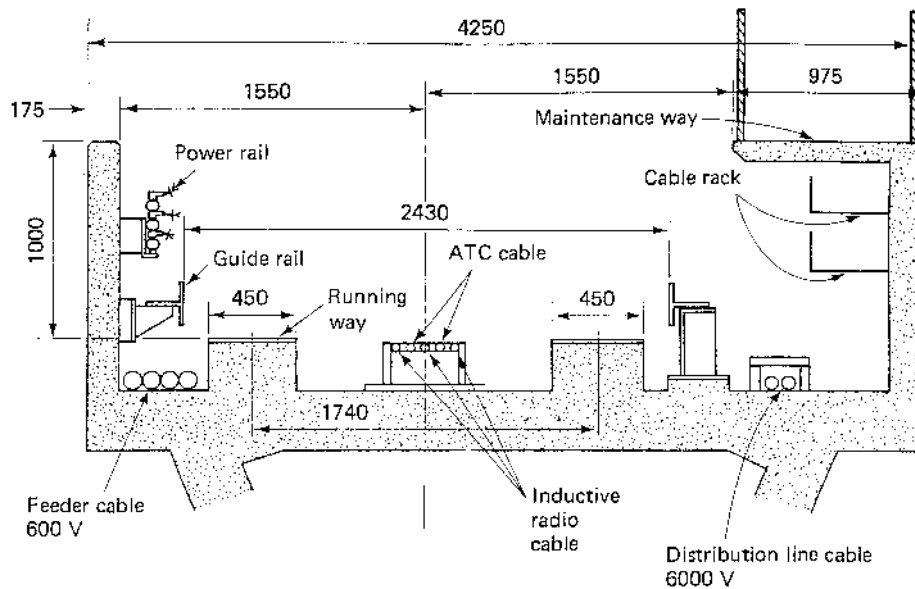


Figure 7.7 Cross-section of the KNT's guideway (Courtesy of City of Kobe.)

fit passenger demand and increase coefficients of utilization (load factors), thus decreasing operating costs per offered space.

Table 7.3 presents the basic technical data of selected AGT/APM systems and a monorail.

Among numerous other AGT systems, several deserve mention.

The *Morgantown AGT system*, built as a demonstration project sponsored by FTA (then UMTA), utilizes vehicles developed by Alden and the Boeing Company. The system represents an unusual "mixture" of PRT and AGT. Although often referred to as a PRT system, its eight-seat vehicles are too large for that purpose; the system is actually operated as a typical AGT system (vehicles carry different travel groups together). Standing is acceptable because of very short trip lengths.

The vehicles ride on four rubber-tired wheels and have four horizontal guiding wheels. Switching is on-board, achieved by turning supporting wheels toward one of the sides. Although it is simple and causes no delay, it is designed for limited speed and requires careful cleaning of the guideway in that area. The entire guideway is heated in inclement weather; this requires high energy consumption and operating costs.

Following corrections of initial technical problems, the Morgantown system has achieved a high degree of service reliability. Its operational experiences have been valuable, but its technology has not been used for any other AGT system.

M-Bahn or *Magnet-Bahn* was developed in Germany and built on one short line in Berlin and one in Birmingham Airport. Both performed satisfactorily but the Berlin line was discontinued due to its displacement by another project, and the Birmingham line was replaced by a different system. M-Bahn utilizes magnetic levitation for vehicle support and LIM for its propulsion. However, the United States government continues to support research and development projects for this mode.

H-Bahn consists of 56-space vehicles magnetically suspended from a simple overhead guideway (several other vehicle sizes have also been developed). Propulsion is obtained by an LIM. Two vehicles can be coupled in a train and operate at 80-s headways. By its general design, the H-Bahn is rather similar to the Schwebebahn monorail in Wuppertal (see Section 7.3.2), but it has the advantages of an extremely light guideway and very low noise. The system was devel-



Photo 7.10 Mitsubishi Crystal Mover AGT vehicle (Courtesy of Mitsubishi Heavy Industries)

oped jointly by Siemens/DUEWAG under the sponsorship of the German Ministry for Research and Technology. One of its vehicle designs is shown in Photo 7.11. An H-Bahn line operates at Düsseldorf Airport.

This review of the selected AGT systems shows that there are a considerable number of technologies with diverse guideway types, support and guidance methods, vehicle sizes, and other elements. Yet, many AGT modes have a number of joint features, such as two-axle rubber-tired vehicles of medium size, low to moderate speeds, and full automation. These features compared with conventional rail technologies can be evaluated as follows.

1. *Rubber tires* for support and guidance, resulting in:

- + Superior adhesion (important for acceleration and climbing abilities) when protected from rain and snow.
- + Lower noise in curves.
- Elaborate guideways (at least four contact surfaces) and switches.
- Need for open-air guideway heating in inclement weather, involving high energy consumption.
- Rubber-tired guided vehicles have a distinctly lower riding comfort than rail.

2. *Two-axle support*, which, in comparison with four-axle rail and rubber-tired vehicles, results in:

- + Use of smaller vehicles where low passenger volumes are served.

Table 7.3 Technical characteristics of several AGT/APM systems

Model	Vehicle							Theoretical			
	Support	Guidance	Length × Width (m)	Weight Empty (kg)	Weight/ Area (kg/m ²)	Capacity: Seats/ Total	Weight/ Space (kg/sp)	Motor Power/ Supply	Cars/ Train	Maximum Speed (km/h)	Line Capacity (sps/h)
Bombardier CX-100	4 double tires	8 horizontal tires on center beam	12.75 × 2.85	14878	409	8/100	149	Two motors DC/ 600 VAC	1–3	70	11,500
Siemens VAL- Lille	4 single tires	8 horizontal tires on side guidebeams	12.70 × 2.08	13850	524	22/90	154	Two 120kW DC/750VDC	1–2	80	10,800
Bombardier Mark II-New York-JFK	Two 2 axle trucks (8 steel wheels)	Conventional rails	17.60 × 3.20	24000	452	25/160	150	Linear induction /750 VDC	1–4	100	27,000
Airtrans-Dallas- Fort Worth 1974	4 single tires	4 horizontal tires on side guidebeams	6.48 × 2.24	5350	369	16/40	134	One 56kW DC/480VAC	2	27	4,800
Kobe-Portliner	4 steerable tires on 2 axles	4 horizontal tires on side guidebeams	8.00 × 2.39	10500	549	16/53	198	Two 90kW AC/3 phase 600VAC	6	60	7,632
Mitsubishi CrystalMover- Singapore	4 steerable tires on 2 axles	4 horizontal wheels on side guiderails	11.20 × 2.70	14300	473	18/105	136	Two 80kW	2	70	12,600
UTDC SkyTrain- Vancouver	Two 2 axle trucks (8 steel wheels) with steerable axles	Conventional rails	17.40 × 2.65	21500	466	42/130	165	Linear induction / ± 325 VDC	4–5	90	28,000
Bombardier Mark VI Monorail	4 double tires	16 horizontal tires	11.80 × 2.64	8,000	257	84/224	36	Two 110kW AC/750VDC	3–6	85	13,440



Photo 7.11 Modern monorail system—Las Vegas (Courtesy of Bombardier Transportation)

- + Simpler vehicle mechanics
 - Lower riding comfort
 - In most cases, higher axle loadings
 - Lower capacity
3. *Medium-capacity vehicles* with a large proportion of standees. This is advantageous for short-haul APM but not acceptable for AGT on regular transit lines.
 4. *Low to moderate speed* (40 to 60 km/h), adequate for short-haul services. Several systems are designed with higher speeds (up to 90 km/h) where line operations require them.
 5. *Fully automated operation*, involving considerable technical complexity of vehicles and control systems but allowing high-frequency service even for low passenger volumes. This is a highly significant basic innovation that contributes to improved services of all guided transit modes with ROW category A.

7.3.2 Monorails

Monorails encompass many different transit systems with the common feature that their vehicles ride on or are suspended from a single rail or beam. The first monorail was opened in Wuppertal, Germany, in 1901. Called Schwebbahn (“Hovering Railway”), it was built along a narrow valley of the river Wupper, which

is the “spine” of the city. Suspended mostly over the river (Photo 7.1), the Schwebbahn actually represents the only true “monorail” in the world: its cars have trucks above them, each with two double-flanged wheels behind each other, riding on a *single rail*. The Schwebbahn has had a very safe and reliable operation and enjoys great popularity due to its unique design and scenic visibility. In recent decades, some reconstructed sections of the line have been built with a concrete structure to reduce the noise produced by the old steel structures. Articulated 6-wheel vehicles have been introduced to replace the old 4-wheel rolling stock.

From their early appearance, monorail systems have acquired an image of the “transit of the future,” being shown dashing as a hanging train or riding on a narrow beam above urban streets. This latter type, straddling on a concrete beam, is the monorail system developed by the Swedish industrialist Axel Wenner Gren in the 1950s and named Alweg. That model, with subsequent improvements and modifications, is now the most common type among the several dozen monorails operating in the world. Most monorails are in Japan (Photos 7.12 and 7.13), but some are also operated in the United States and other countries (Photo 7.14).

There are two basic types of monorails:

- *Supported (straddling) monorails* running on a concrete beam with two trucks, each with four supporting and eight guiding rubber tires running along six surfaces along the beam. The vehicle body is above the wheels, in some models with wheel boxes placed under the supporting wheels in the passenger compartment. Long side skirts cover the guiding wheels (Figure 7.1b).
- *Suspended monorails* hang from a guide beam, which may be a single rail or an enclosed tube with four running surfaces, two for supporting and two for guiding wheels. Thus the trucks run along protected surfaces inside the beam and carry the vehicle body, which is suspended through a slot in the beam, as shown in Figure 7.1c.

All monorails consist of one or, most often, three- to six-car TUs and have exclusive ROW, so that they functionally belong in the rapid transit category of

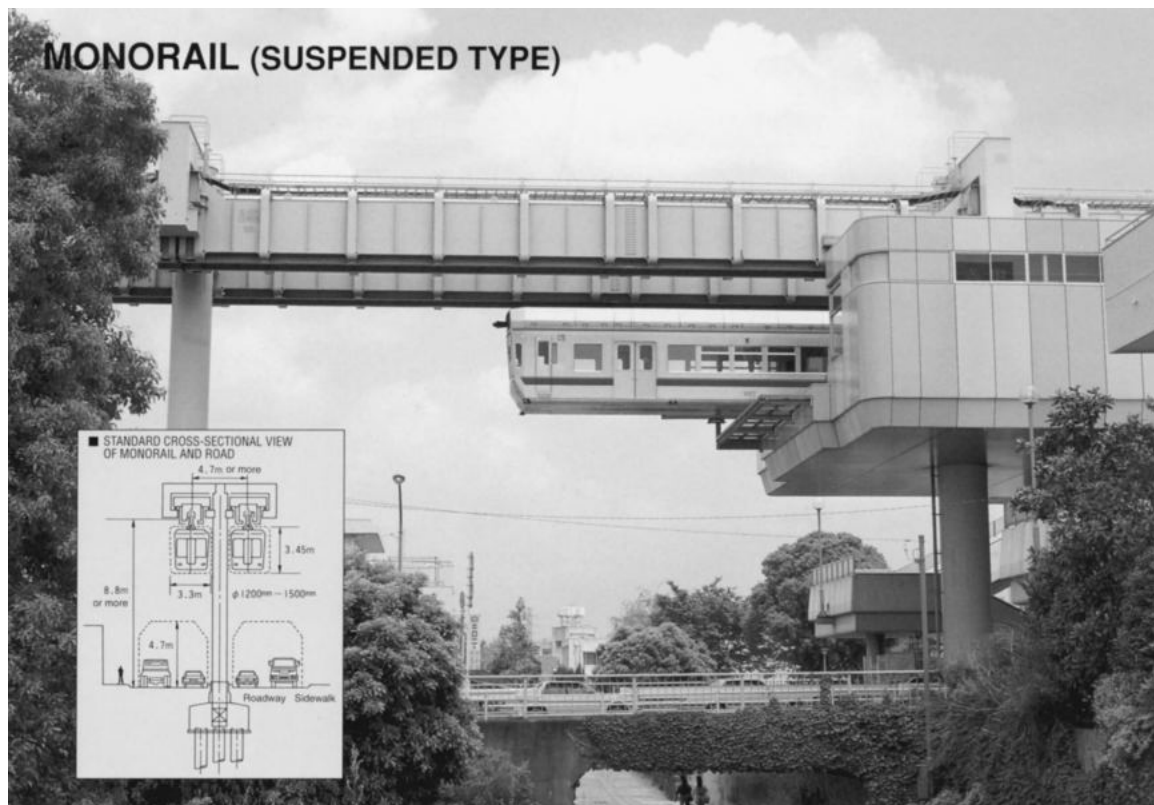


Photo 7.12 A suspended monorail (Courtesy of Mitsubishi Heavy Industries)



Photo 7.13 A supported monorail in Japan



Photo 7.14 Monorail on a CBD loop in Sydney (Courtesy of Greg O'Beirne)

modes. One of the most heavily used monorail lines in the world, between Hamamatsucho and Haneda Airport in Tokyo, has six-car trains with Alweg technology, while the most recently opened monorail in the United States, the Bombardier-built line in Las Vegas, operates four-car trains. Operating with headways of 2 to 3 min, monorails can have capacities similar to those of moderate-sized RRT systems.

With ROW consisting of a single beam, supported monorails have a small, unobtrusive infrastructure with a considerably smaller profile and shadow than conventional rail aerial lines. The single guideway, however, requires a more complicated wheel mechanism, which makes the vehicles much taller from the skirts

to the roof than rail vehicles. With a much higher total vehicle profile, monorails are not suited to tunnel alignments. The aerial alignments are a part of their attraction and visibility in the city, but the acceptability of trains traveling between tall buildings is lower than is often imagined. Objections to trains taking air space and passing by windows of buildings are not much less than those to aerial alignments for rail systems. With respect to stations, monorail has very similar requirements to rail, so that they face the same problems in fitting their elevated stations in center city areas.

Rubber-tire support gives monorails advantages over rail vehicles in negotiating steeper grades and curves. The Haneda Airport Line in Tokyo demon-

strates how monorail guideways can better follow various constrained alignments.

Mechanically, monorail guideway switches consist of a movable beam, which is much more complicated, slower, and requires larger space than rail switches. Crossing of guideways is even more complex, so that any guideway layout with switches and multiple beams, such as larger stations and yards, are very complex and require large areas. This is one of the reasons that all monorail installations consist of single lines only; there are no monorail networks of several lines anywhere in the world.

In summary, monorails can operate efficiently and be acceptable to urban environment on single lines in wide boulevards, green areas or along bodies of water, utilizing aerial structures. They are not suited to tunnel or surface alignments, to urban streets with tall buildings, or for networks of more than single lines. Thus, monorails can be used efficiently as APM systems in open areas and in tourist areas where their exotic appeal is an asset.

Planning and discussions about monorails are often controversial because there is a considerable difference between their popular appeal and rational engineering analysis and comparison of their features with those of conventional rail modes (see Section 10.4.3). The latter are almost never favorable for monorails, so that their applications are mostly found in areas with special character and tourist appeal.

The difference between emotional support and engineering/economic system evaluation of monorails has been demonstrated by the developments in Seattle during the 2000–2005 period. A transit planning process and several popular referenda for its financing during the 1990s led to the adoption of a plan for construction of a long light rail line as well as improved bus and regional rail services. Influenced by the propaganda against rail transit produced in most U.S. cities, the promoters of monorails claimed that a monorail network would be a more effective and attractive mode for Seattle, which has operated one shuttle monorail line built for the World's Fair in 1962. The grassroots movement resulted in two popular referenda that proposed construction of a 14-km-long monorail line and sources for financing it, both totally unrelated to the already adopted transit plan for the region.

The claims were brought up that with its aerial alignment, monorail would be easier to build than a partially tunneled LRT line and that it would be more attractive for the city's central area. As the planning proceeded, however, design difficulties proved to be much greater than foreseen. Aerial structures and stations in city streets with tall buildings, large stations, and other installations were criticized and their redesign escalated the costs. To keep the costs moderate, construction of a single-beam section was considered—a feature not suitable for a busy transit line that needs reliable operation with short headways, which is particularly inconvenient for monorail's switching characteristics. Following many efforts to manage the required financing, a plan was developed for the sale of bonds, which would be repaid over 40 years for a total cost of about \$11 billion. This plan caused a political uproar and a call for another referendum, at which the entire plan was rejected. This case demonstrates the mentioned differences between popular support for monorails and factual planning—that is, technical and financial analyses of that mode.

The failure in Seattle does not mean that monorails have no future in urban transportation. They will continue to have a certain appeal and it is likely that monorails of different designs will be used for special applications, such as certain APM services (airports, amusement parks, shuttles in major activity centers) and in tourist-oriented cities.

7.3.3 Personal Rapid Transit (PRT)

The PRT concept is based on the premise that the best way to provide transport in cities and attract automobile drivers to a transit system is to match its service by a system that offers high-frequency service among many points in the city without transferring. To achieve this, a PRT system is supposed to work as follows.

An extensive network of elevated automated guideways with many stations is provided throughout a city or a section of it. A great number of small (three- to six-seat) vehicles operate on the guideways automatically, directed by a control center. Each passenger or a related group traveling together comes to a station and records its desired destination. A vehicle comes

within a short period of time. Boarding and alighting of vehicles is done on an off-line guideway, so that, during the process, other vehicles can bypass the station without stopping. This allows all vehicular travel to be station-to-station without any intermediate stops. The movement and routing of vehicles is fully automated and computer-controlled. That control supervises merging and diverging areas and enables short spacings of vehicles on the guideways, so that the capacity of the lines could reach, based on some theories, 3000 to 5000 vehicles per hour. The vehicles would be capable of traveling at high speeds (80 to 100 km/h).

Because of the low vehicle weight, the guideways would be light, aesthetically unobtrusive, and cheap to construct. At intersecting points, they would be connected by ramps similar to those in freeway interchanges, so that vehicles could switch from one guideway to another (the reason for building these as aerial structures above urban intersections has never been satisfactorily explained). Some stations would have facilities for U-turns of vehicles.

Computerized control of the system distributes the vehicles, responding to passengers' calls, and routes empty vehicles to the areas of anticipated future demand.

Various PRT systems have been developed by researchers and manufacturers in different countries during the wave of interest in "new modes" of the 1970s. To mention a few, the *Jetrail* system was built by Stanray Corp. for the Love Field Airport in Dallas in 1968 and operated until 1974, when the city opened a new airport. It connected one station in the parking lot with two stations within the terminal building. The total length of a circular guideway was 2.5 km. The mode consisted of vehicle cabins suspended on an overhead "I" profile on which two rubber tires ride and two horizontal smaller wheels provide guidance. The maximum speed was 32 km/h. The system represented an attraction, but it has not been considered for any major urban application.

The *Monocab* system, initially developed by Varo Corp. and later taken over by Rohr Corp. and demonstrated at the Transpo Exhibition in Washington in 1972, consisted of six-seat cabins suspended from an overhead guideway. Running surfaces for two rubber tires and two guidance rollers per axle are within the guideways.

The *Cabtrack* system, developed in Great Britain and proposed at one time for application in the city of Gothenburg, Sweden, was claimed to have a capacity of 5600 cabins per direction per hour. This claim, based on computer simulations, was disputed by virtually all professionals experienced in transit systems operations.

Similarly unrealistic claims (capacities of 2000 to 15,000 sps/h and 0.5 s headways) were made for the *Aramis* system, developed by MATRA Company in France and for the *Cabintaxi* PRT system developed, in turn, by the DEMAG and MBB firms under the sponsorship of the German Ministry of Research and Technology.

Parallel with these attempts by various industries and research institutions to develop PRT systems, this concept attracted very intensive academic activities. Hundreds of theoretical papers, reports, and several international symposia discussed endless design and operational details of the PRT concept. Many theoreticians developed algorithms for optimal vehicle distribution, control of merging areas, operation of off-line stations, and so on.

An even more serious phenomenon has been that the PRT promoters, because of their emotional attachment to that mode rather than rational analysis of its feasibility, have misled the population as well as political leaders and thus postponed progress on transit modernization in many cities, such as Minneapolis, Denver, Seattle, Gothenburg, Copenhagen, and others. In Chicago during the 1990s, the Regional Rail Metra's board financed extensive planning of a PRT system as a feeder at a suburban station until it was realized that if the passenger volume for such a line would be sufficient to justify the required high investment, an AGT mode would be much more efficient than PRT. The entire proposal was then canceled. The latest developments are the proposals for construction of a PRT demonstration line in Cardiff, Wales, and as a shuttle for a parking facility at the Heathrow Airport in London, "to introduce this transit mode of the future."

Because of the failure to produce any real-world demonstration or plausible proof that such a system can operate satisfactorily, these activities subsided during the 1980s but were revived again since the 1990s. In 2006, nearly 40 years after the PRT concept was

introduced and no progress toward its implementation had occurred, there are over 20 Internet websites about PRT. This can be explained only by a strong emotional appeal of the concept of ubiquitous cabins gliding through the air over city streets.

The main reason for such absence of any progress in implementing PRT system is simple: *the basic concept of PRT is inherently unsound*. It combines small vehicles, ideal for low-density travel, with complicated, electronically controlled guideways that are feasible only for heavily traveled routes. Consequently, in suburban areas where a vehicle carrying two to six persons would be optimal, construction of guideways is economically infeasible; on major arterials, where large passenger volumes might justify the construction of guideways, small vehicles are highly inefficient and cannot provide the required capacity. Consequently, the combination of the two features—small vehicle and complicated guideway—is paradoxical and makes the *PRT mode impractical under all conditions* (Vuchic 1996).

How is it possible that this concept should attract so much interest and even government support for development in several countries? The explanation lies in the fact that the positive features of PRT are often exaggerated while the negative ones are overlooked. Thus, although it is true that PRT resembles the positive characteristics of the private auto more than any other transit mode, it is also true that due to this similarity PRT has the severe limitations of auto use in urban areas: low capacity, very high cost and energy consumption per space-km, and extremely large space requirements for stations, guideway interchanges, and vehicle storage areas. Aerial guideways and station, in urban streets would be highly objectionable, not even considering the legal requirement for accessibility by the disabled.

With respect to operating costs, PRT would be several times more expensive than an AGT rubber-tired or rail system. This can be shown by a simple comparison of these modes.

Suppose that a transit line has stations 1, 2, 3, . . . , n . If, for example, 30 persons in parties of two travel from station 1 and 10 persons to each of stations 4, 5, and 6, they would use 5 vehicles to each of the three

stations, or a total of 15 vehicles on a PRT system, but only 1 vehicle on an AGT or conventional rail system. Although the PRT vehicles would be smaller, their operating costs would not be proportionately lower: the use of 15 instead of 1 vehicle would involve several times higher operating costs. Incidentally, the persons traveling to station 4 would experience the same travel time on PRT and AGT systems, while the other persons would have to accept one and two additional stops in traveling by AGT or conventional rail mode as compared with PRT (i.e., slightly longer travel times).

This comparison can be expanded to the overall operation and performance of the line. Compared with an AGT system whose vehicles stop at all stations with a certain frequency, the PRT system would have to provide up to $(n - 1)$ times more vehicle trips to offer the same frequency for passengers from station 1 to all other stations. To provide the same frequency for travel between any two stations, the PRT system would have to provide up to $(n - 1)^2$ times more vehicle trips. Uneven distribution of passenger travel among stations would produce factors smaller than $(n - 1)$ and $(n - 1)^2$ but still quite large, particularly for extensive networks (large n). Operating costs of the system (as well as the speed and reliability of service) would be closely correlated with the latter factor, $(n - 1)^2$.

Thus the main objective of the PRT concept—to match the positive features of the private auto such as privacy and direct station-to-station travel—cannot be achieved without also experiencing the major drawbacks of the auto/highway system in urban areas, such as high costs, large space requirements, low capacity, and poor reliability. Consequently, PRT is an unrealistic concept rather than a “future transit mode.”

7.4 EVALUATION OF UNCONVENTIONAL MODES AND NEW CONCEPTS

For evaluation of any proposed unconventional transit mode, the following fact is useful to consider in the box on page 475.

Although many modes have been developed sufficiently to satisfy the first condition, only a limited number have satisfied the second. Experience with the

To become a full member of the family of transit modes, a new mode must fulfill two conditions:

1. Be technologically and operationally sound
2. Have a performance/cost “package” at least equal to that of an existing (conventional) mode

modes developed and implemented in recent decades has led to the following general conclusions:

- *APM mode* has found a significant number of applications as short-haul systems in airports, urban centers, amusement parks, campuses, and similar developments; their implementation is likely to continue to grow in a diverse set of roles.
- *AGT mode* used for regular transit lines has been introduced in many technological forms, including rubber-tired and rail vehicles. Its implementation is likely to grow further, particularly if automated LRT systems are included in that category. In comparisons among BRT, LRT, and rubber-tired AGT modes for medium-capacity lines, the first two modes are likely to be superior for most applications over AGT, as such studies already showed in Baltimore, Buffalo, Manchester, Pittsburgh, and many other cities.
- *Dual-mode systems* in a broad sense, including bus and rail lines on different ROW categories, will be increasingly used, but dual-mode ICE-electric buses and guided-steered buses will be used only in special situations.
- *PRT mode* is not likely to have any application in urban transportation.
- *Rapid transit systems* may also have a few unconventional technologies for special reasons, but

the proposed modes are not at all likely to change the present dominance of rail technology, LRT, and RRT for guided modes.

Technical innovations that would bring further benefits to the existing and new transit systems include:

- The introduction of fully automated, driverless operation on existing rail rapid transit lines.
- Fast coupling and uncoupling of vehicles during operations on lines and eventually also during vehicle motion
- Greater use of off-line stations allowing various skip-stop, partial express, and other accelerated services on two-track guided transit lines
- Further standardization and modular construction of body components and various subsystems (motors and controls, brakes, communications, etc.) while allowing diversity in certain vehicle specifications (both bus and rail), such as width, length, and motor power

These and many other innovations are likely to contribute further to continuous modernization of transit systems that have already had major impacts on improvements of transit operations and service during the recent decades.

EXERCISES

- 7.1. The dual-mode concept generally provides benefits from operating the same vehicles under two different regimes, but at the cost of greater complexity of vehicles and operation. Compare these benefits with costs for the following modes:
 - a) Railbus (assuming that the concept were physically feasible)

- b) Guided bus (with lateral wheels on special guideways)
- c) LRT, operating on ROW categories C, B, and A
- 7.2. Compare suspended with supported guided transit technologies.
- 7.3. State and explain the differences between rubber-tired and rail-guided transit technologies.
- 7.4. All rubber-tired AGT modes have two-axle vehicles. Discuss their advantages and disadvantages in comparison with four-axle guided vehicles.
- 7.5. A two-axle AGT vehicle has the following dimensions: overall length $L = 10.0$ m; distance between axles $l_t = 6.0$ m. Compute the required inside clearance widening ΔR_b^i and outside clearance widening of this vehicle in a curve with a 20.0-m radius. For what revised wheelbase l'_t of this 10-m-long vehicle would one get that $\Delta R_b^i = \Delta R_b^o$ when $R = 20$ m? (Hint: Note that the centerline of the vehicle deviates from the track centerline by the same distances as the vehicle sides from the vehicle profile on straight alignment. Figures 6.3 and 6.7 are useful).
- 7.6. Describe off-line stations, their purpose, and their method of operation. What are their good features? What are their limitations?
- 7.7. Using the theory of urban transportation modes (Section 2.3), explain the inherent paradox of the PRT concept: automated small cabins on a highly complex network of grade-separated guideways.
- 7.8. Define and analyze conceptual (primarily type of operation) differences between PRT and AGT.
- 7.9. Which characteristics give AGT modes several advantages over rail for small-scale operations (short lines, light to medium passenger volumes) but make rail superior as system size increases?
- 7.10. Compare the Bombardier CX-100 with the Morgantown AGT system.
- 7.11. Compare the Bombardier CX-100 with the Siemens VAL.
- 7.12. List and describe the advantages and disadvantages of an Alweg-type (supported) monorail as compared to RRT.
- 7.13. Describe two ALRT systems, such as the SkyTrain, London Docklands, Copenhagen and New York City Kennedy Airport AGT.

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8

SPECIALIZED TECHNOLOGY SYSTEMS

Several types of urban transportation cannot be effectively served either by automobile or by paratransit and regular transit. These special types of transportation services include travel within geographically small areas, connections between two or a few discrete points in metropolitan areas, and transportation over various natural barriers (hills, rivers, bays, etc.). The modes providing these types of specialized services are described here.

8.1 SHORT-HAUL AND SHUTTLE TRANSIT SYSTEMS

The central business districts (CBDs) of medium-sized and large cities, suburban centers, university campuses, airport complexes, fair and exhibition grounds, and similar major activity centers (MACs) generate large volumes of short trips within their areas, which are usually rather small (0.5 to 3.0 km in diameter). Most of these trips are best performed by walking. However, for trips longer than 400 to 800 m (a 5- to 10-min walk), it is often desirable to provide a transportation service to reduce the time and increase the comfort of movement. Transit systems for these short trips, which usually operate as lines of 1 to 3 km in length, are referred to as *short-haul transit systems*. For example, such services are provided in the CBDs of many cities by buses, streetcars, APM systems (Miami, Detroit), or other modes.

Because of the short trip lengths, passengers require that the service be frequent: long waiting is not acceptable. Speed, on the other hand, is not very important, since high speed can usually reduce travel times

on such short distances by only a few minutes. Capacity requirements vary but may often be rather high because of sharp peaking of demand.

A broad variety of modes are used for short-haul travel. Their basic characteristics and therefore their optimal applications vary considerably.

8.1.1 Pedestrians and Pedestrian-Assisting Modes

Walking is and will remain the basic mode of travel for short trips. It is always “instantly available,” involves no terminal times (which make the automobile and some transit modes unsuitable for this application), and has an extremely high capacity (5000 to 6000 persons per meter of walkway width per hour in transportation corridors; on a street sidewalk with less orderly two-way movement, the corresponding values are 2500 to 3000 prs/m/h). The limitations of walking are discomfort and low speed (3.8 to 5.0 km/h). Discomfort is often caused by an unpleasant environment: dangerous street crossings, air pollution from auto traffic, congested narrow sidewalks, no weather protection and steep grades.

Careful planning and design of streets, including weather protection, sitting areas, escalators, and the provision of integrated pedestrian walkway networks on regular streets, pedestrian streets, enclosed passageways, and malls can not only eliminate unpleasant features but also create a human-oriented urban environment that is pleasant and *attractive* for walking. This is particularly the case in CBDs. Recent recognition of the importance of such an environment for

the vitality and economic health of the entire city has caused a radical change in transportation policies in many cities, particularly in western and central Europe. Efforts to maximize the vehicular capacity of every street have been replaced by efforts to separate vehicular from pedestrian flows and create exclusive pedestrian zones or extensive networks of walkways (Belgrade, Munich, Portland, Rotterdam).

The other limitation of walking, its low speed, can be solved only by mechanical means. The range of technologies serving this purpose can be classified in four major categories. One category, continuously moving systems, assists pedestrians. The other three are various modes of vehicular technologies.

Continuously moving systems, which assist pedestrians in their walking, include moving sidewalks and escalators. Their speed is usually somewhat lower than walking speed (see Section 6.5.3.4). Pedestrians using these systems have a choice: stand on the belt and reduce walking effort but not save any travel time (or even increase it) or walk and save time without a change in effort.

There are several inventions that can improve the performance of moving sidewalks. Some of these inventions have been applied for a few commercial installations and they may have some potential for future applications.

- *Lateral entry/exit* can be provided by a short parallel belt along a sidewalk, moving at the same speed, as Figure 8.1a shows.
- *Double-speed sidewalk* can be obtained if at each end short normal-speed sidewalks are provided (Figure 8.1b). Pedestrians step on the normal-speed one, then transfer to the main belt, experiencing the same acceleration. Toward the end of the facility, the reverse process takes place.
- *High-speed moving sidewalk*, developed by the British manufacturer Dunlop, is an S-shaped continuous system named Speedaway, which has normal moving sidewalk speeds (e.g., 2.5 km/h) at the beginning and end, while its middle section moves at three to five times higher speed, or up to 12.5 km/h. Acceleration and deceleration between walking and maximum speeds are gradual,

achieved by changing the direction of individual components (“platforms”) of the belt (Figure 8.1c and d). (This system is described in Dunlop.) Otis and Westmont manufacturers also produce a variety of moving sidewalk types, but the most significant progress has been made by the Paris RATP agency, which has installed and tested a high-speed moving sidewalk. People board a moving sidewalk which travels at a normal speed of 3 km/h; then they arrive at an accelerating section where they stand, while the belt accelerates to a steady speed of a section traveling at 9 km/h, where they can stand or walk. Close to the end, the belt slows down from 9 to 3 km/h. Then people step off it, as from common moving sidewalks.

The basic characteristics of the pedestrian-assisting systems include continuous service, high capacity and comfort, adequate safety, and the ability to carry people between different elevations. However, low speeds limit their applications to short distances (the longest moving sidewalks are about 200 to 300 m long; the longest escalators negotiate vertical distances of some 25 to 30 m). Since they require a continuous, uninterrupted path, they cannot accommodate at-grade crossings. Another, often dominant disadvantage of pedestrian-assisting modes is their very high cost. In addition to their high investment cost, they usually involve appreciable operating (particularly maintenance) costs. Since it is not feasible to collect fares for the use of continuous systems, financing must be provided from other sources.

Consequently the pedestrian-assisting systems cannot be used as transit systems, but their role in very short haul passenger transport within transit and airport terminals (Photo 8.1) and other large building complexes for pedestrian convenience is rapidly increasing.

8.1.2 Short-Haul Transit Modes

Three categories of transit modes that can be utilized for short-haul services are described here.

Regular transit services, which are often supplemented by special shuttle or loop lines. Among its typ-

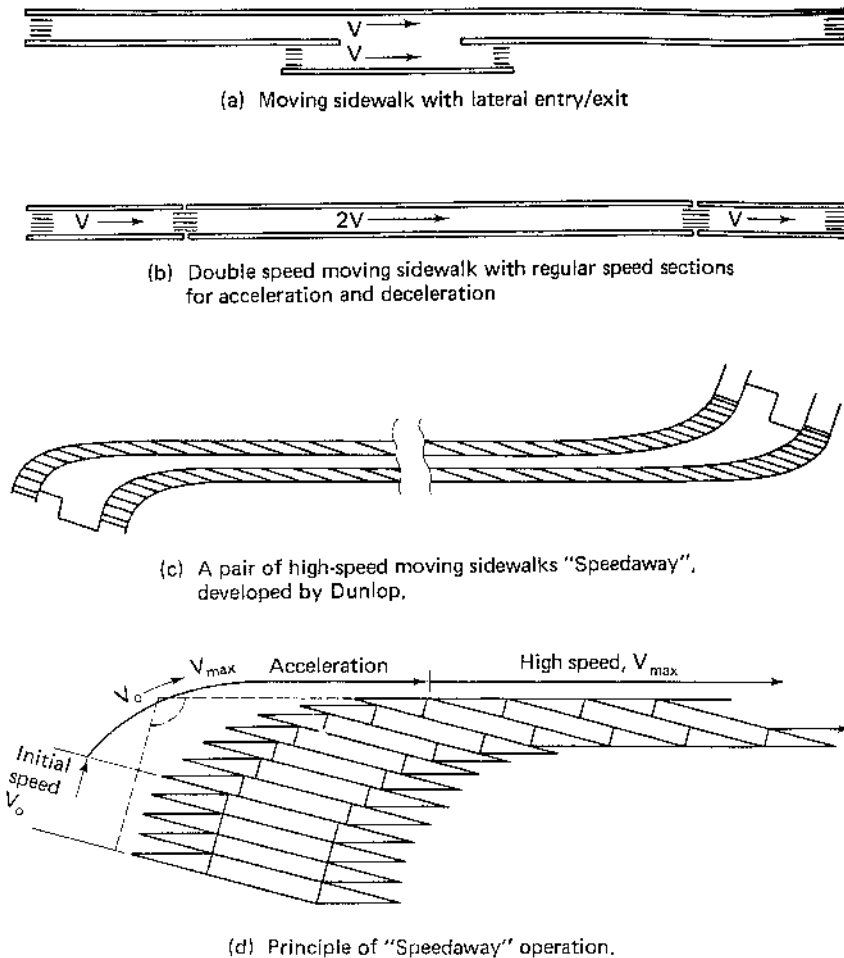


Figure 8.1 Unconventional and new concepts of moving sidewalks.

ical examples are bus "shopper specials" and "cultural loops"; the CBD streetcar in Tacoma, Washington; subway "shuttle lines," such as the Times Square–Grand Central Terminal Subway Shuttle in New York; and Waterloo and City Line in London are examples. The conditions for successful deployment of transit for short-haul travel are that it offers high frequency of service, preferably a dense network with adequate information for passengers, and low fares. In large cities, these requirements usually necessitate vehicle designs that allow rapid boarding/alighting (high ratio of doors to vehicle capacity) to avoid excessive delays to

through passengers, rapid fare-collection methods, and graduated fare structure.

APM modes operate as short-haul transit systems in many locations, particularly in and around airports, university campuses, and fairgrounds. The technology of these systems varies greatly, from 20-space rubber-tired "cabins" (Morgantown) to rail rapid transit trains (Montreal Expo), as described in Section 7.3.2.

As mentioned, the demand for short-haul travel is substantial in many CBDs. The potential for APM applications for this function varies greatly with local conditions and the designs of such systems. The down-



Photo 8.1 Moving sidewalk in London's Heathrow Airport

town people movers (DPMs) in Miami and Detroit are successful, but there are few such systems because a major portion of CBD travel demand consists of dispersed short trips, for which people are usually sensitive to the fare level, so that only nominal fares can be charged. Because of their fully controlled ROW, APM stations are more similar to rapid transit stations than to those of street transit. Therefore they cannot be as close to each other and as easily accessible as bus or LRT stops. Another factor influencing the feasibility of APM systems for short hauls is the relationship of their lines and terminals to transit stops, particularly to rapid transit stations, railroad and bus terminals, and large garages as well as major office buildings, stores, and other traffic generators.

Aerial guideways for APM systems allow them to penetrate some inner-city areas and buildings but pre-

vent them from entering various environmentally sensitive zones, narrow streets, and so on. Actually, positive experiences with recently constructed rail and rubber-tired guided systems on aerial structures in some cities may reduce opposition to them and greatly enhance the potential for uses of APM and conventional rail systems in CBDs as well as throughout urban areas.

“Elephant trains” are trains of light rubber-tired trailer cars with benches for passengers towed by a diesel-powered tractor. These trains are steered by the driver in the tractor. The trailers follow basically the same path, but only at limited speeds: usually three to five trailers can be driven at speeds of up to 40 km/h.

As low-speed open vehicles, elephant trains are primarily suited for short sightseeing routes on separate paths (which may be shared with pedestrians), as ex-

emplified by many services in parks and boardwalks along sea coasts (e.g., Atlantic City), or as collector/distributor short-haul systems in large parking areas, such as in Disneyland and Walt Disney World. They are not suited to street operation because of their length, limited steering precision, and incompatibility with fast traffic.

8.1.3 Significance of Short-Haul Transportation

The impacts and importance of short-haul transportation, particularly for CBDs, are often underestimated. In many cities, inadequate short-haul service represents a major deterrent to transit use and creates pressures for provision of extensive parking in the immediate vicinities of all major buildings. This, in turn, results in auto-oriented environments that discourage walking and destroy the unity of entire center-city areas. If, on the other hand, CBDs and other MACs are designed as unified areas with ubiquitous mobility (i.e., easy travel among all points within them), these centers can be extremely efficient for conducting business as well as attractive for work, shopping, recreation, other activities or just strolling. Such ubiquitous mobility can be achieved only by careful planning and deployment of various short-haul transportation services, ranging from attractive pedestrian streets to transit lines. These systems must be closely coordinated with regular transit services in the area and parking facilities located, preferably, along its periphery. Short-haul transportation can thus be a significant element in designing central cities that provide all the unique elements for urban activities in a human-oriented environment.

Recognizing the importance of good short-haul transportation for the economic and environmental vitality of MACs, city governments or private businesses often provide special funds to support low-fare or free short-haul services. The rationale for financial support from sources other than fares is that it is neither practical nor agreeable to the public to pay significant fares for short trips in an area, whether they be vertical (elevators) or horizontal (short-haul). A good example of free services are the fare-free zones in Portland and

several other cities. A common arrangement is that fare collection on all transit lines in the city is done upon entering for inbound trips and prior to exiting for outbound trips. The CBD is then a zone in which there is no fare collection at all, so that trips within that area are free. Weekly and monthly transit passes with unlimited travel on certain lines or throughout the city, which are used extensively in many European cities, can also provide “free” short-haul travel.

8.1.4 Point-to-Point Shuttles and Lines

Demand for travel between different activity centers within urban areas—such as CBD, outlying MACs, airports, and so on—often justifies the introduction of some form of public transportation service for nonstop connections between two or more of them. The most common technologies applied for this type of service are limousines, vans, buses, and rail transit (RRT and RGR).

Limousine vehicles represent an “extended version” of the standard passenger automobile. They usually have 11 seats and a separate luggage compartment. Their relatively small capacity is well suited to many services between individual points and airports, their most common application. Passenger comfort in limousines has several deficiencies, particularly for longer trips: no change of position is possible and the vehicle is dark at night, not allowing reading.

Vans, which have larger doors for easier entry and exit, are more practical for point-to-point transportation and have replaced limousines in most cities.

This type of limousine or van service is often well patronized despite its typically high price because of the high speed of point-to-point travel as well as the fact that for many travelers the only other alternative is the even higher-priced taxi service.

Standard buses are often used for nonstop point-to-point service. They are usually specially equipped with luggage space and have softer seats than regular transit buses. They offer greater rider comfort than limousines and vans. In most cases, fares for this type of service are higher than regular transit fares but lower than limousine/van fares.

Helicopters, with their very high speeds (110 to 150 km/h) and ability to fly close to a straight line, can provide much faster transportation than any other mode. However, since they can land at very few points within an urban area, their applications in urban transportation are limited to very few point-to-point services. Although many futurists predicted a major role for helicopters in urban transportation, the applications of these vehicles are severely limited by their high cost, low reliability in inclement weather, and high level of noise. Helicopters were used in a few cities (New York, Los Angeles, San Francisco, Chicago, Philadelphia) between airports and various locations within their metropolitan areas, but few of these services were successfully operated for extended periods. Some were banned because of noise or safety problems, others closed because of financial failure.

Rail transit, either rapid or regional, provides in some large cities express service that represents a direct transportation link between two or several major urban activity centers. Rapid transit in New York has several such lines, regional rail systems in Tokyo, Kobe, and Osaka have a number of such express runs either on four-track lines or on two-track lines with off-line stations (local trains stop on side tracks while expresses run through). The monorail line in Tokyo from Hamamatsuchō to Haneda Airport, although with different technology, actually functions as a point-to-point rapid transit service. Two regional rail lines operate as high-speed shuttles to Narita Airport in Tokyo. Similar exclusive express regional rail lines have been built in London—Heathrow Express—and in Oslo, Rome, Hong Kong, Philadelphia, and a number of other cities. Their number has been rapidly increasing.

In review, for high-speed connections between center cities and airports and among other distant points with low-to-moderate passenger volumes, vans and buses on arterials are commonly used. For this type of line with heavy passenger volumes, rail transit is the most efficient mode due to its speed, comfort, and reliability. However, rail transit lines connecting airports to city centers are often justified not so much by the volumes of passengers as by the airport's visibility, image, and importance as a critical intermodal link.

8.2 TERRAIN-SPECIALIZED TECHNOLOGIES

Hilly terrain and bodies of water present in many cities obstacles to the use of conventional road and rail vehicles and require the application of specialized technologies. A considerable number of different technologies are now in use in different cities for service on steep alignments, along rivers, or across lakes and bays.

8.2.1 Rail Systems with Auxiliary Traction

Rail passenger vehicles utilizing wheel adhesion for traction can operate efficiently and safely up to gradients of approximately 10%. Although there have been operations on gradients up to 15%, these may have serious operational problems. Highway vehicles, particularly trolleybuses, can operate in areas without snow on gradients of up to 15% and exceptionally 18% (e.g., San Francisco), before serious problems occur. For steeper alignments a different traction system and sometimes external propulsion must be utilized. Some of these systems, such as cable cars, can have not only at-grade crossings, but they can operate on streets with regular traffic signals and mixed traffic.

8.2.1.1 Cog Railways. The limited ability of rail systems to operate on steep gradients due to wheel-rail adhesion of only $\mu = 0.25$ to 0.35 (see Section 3.4) can be overcome by cog railways. Introduced in the nineteenth century with steam engines, most cog railways are now electrically powered. Vehicles on this system have a geared wheel on each powered axle engaged with a continuous linear vertical gear (rack) installed along the track center. The connection between the gear and the wheel rack is permanent—i.e., on the entire line—or on some lines the rack in the track center exists only on steep sections of a line. The vehicle or train can travel without gear-wheel engagement and then come to a section with a rack in the track center and engage its gears for negotiation of a steep section. When a flat section is reached, the gear is disengaged again without slowing down. The geared connection



Photo 8.2 Meter-gauge cog railway with bicycle trailer in Stuttgart (Courtesy of Gabriel Tompkins)

transmits accelerating and braking forces, enabling rail vehicles to travel on gradients of 15% to over 30%.

This traction method is used on a number of mountain railroads with extremely steep gradients: Mt. Washington Railroad, one of the oldest in the world that still uses steam engines for tourist purposes, reaches 37%. The Corcovado Line in Brazil has 30%, while Pilatusbahn in Switzerland, the leading country in technology and applications of special modes for hilly terrain, reaches 48%, although with a special gearing arrangement (Risch and Lademann 1957, Chap. VII).

Electric cog railways are also used for urban and suburban transit. Several examples of such lines are found in Europe. Stuttgart has an old but recently renovated and extended 2200-m-long line that overcomes a 250-m difference in elevation and has a maximum

gradient of 17.8%. It has four-axle cars, one powered axle in each of the two trucks being equipped with cogwheel. The Riggerbach system is used, which has the rack in the track center at the same elevation with the tops of the rails (Photo 8.2). This enables not only track crossings but also track alignment in streets with mixed traffic. The fleet consists of three bidirectional cars, each car pushing a light aluminum trailer that can carry up to 10 bicycles uphill. They are not carried downhill because the driver would not be able to supervise them. Maximum speed is about 20 km/h, and 10-min headways are operated in peak hour periods.

The Dolderbahn Line in Zürich was opened in 1973. Two years later Lyon opened the first 600-m-long section of a line that is partly in tunnel and has gradients up to 17.4%. It has a transfer station with the Metro, which was opened in 1978.

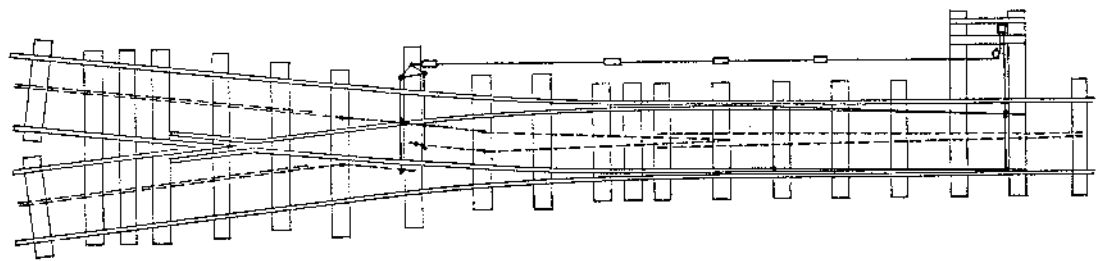


Figure 8.2 Cog railway track switch, system Abt with gear over rail head (Source: Risch and Lademann, 1957.)

There are several types of cog railway track switches. The Abt type, which can be used only on reserved ROW because its rack line is higher than the tops of the running rails, is shown in Figure 8.2.

8.2.1.2 Cable Cars. Probably the best-known technology of rail transit with auxiliary traction is the world-famous system of cable cars presently operating only in San Francisco (Photo 8.3). Invented by Andrew Hallidie in 1873, cable cars were introduced rapidly in several cities in the United States, Australia, and several other countries. However, upon the invention of electric streetcars, cable cars were quickly replaced by their much faster, more advanced successors (see Section 1.2.4). One exception to their full extinction is San Francisco. On many of its extremely steep streets (up to 21%), cable cars operate safely. With their constant

speed of 15 km/h, cable cars are much slower than conventional transit vehicles on flat terrain; but on very steep streets the difference is much smaller and they have significant advantages over other transit modes.

The line lengths and gradients of the three cable car lines in San Francisco are given in Table 8.1.

Since the first two lines have a 1.2-km-long joint trunk section, the total network length is 7.2 km. These lines have two major roles: they function as important transit lines, carrying thousands of regular passengers every day; they also represent an extremely popular tourist attraction. Approved for preservation by a popular referendum in 1956 and given the status of “National Historic Landmark” in the 1960s, cable cars are a famous symbol of San Francisco, considered by many as one of the proudest and most beautiful world cities.

Cable cars are passive vehicles: they do not have motors or power. They have conventional rail wheels on steel tracks, but in the middle of their track there is a slot to an underground channel through which a cable moves continuously at a speed of 15 km/h. The cables consist of four independent closed loops for the three lines propelled by four 375 kW stationary electric motors (formerly a steam engine) located at a central



Photo 8.3 San Francisco cable car ascends Hyde St. (Courtesy of Richard Panse)

Table 8.1 San Francisco Cable Car lines characteristics

Line	One-Way Length (km)	Maximum Gradient (%)
Powell and Mason	2.6	17.5
Powell and Hyde	3.4	21.3
California	2.4	17.5

powerhouse. The channel has an open slot from the surface through which a steel bar from the car, called a “grip,” is lowered to engage the cable. The driver, or “gripman,” handles the grip and engages it to the cable for both traction on uphill and level streets and for steady braking on downhill streets. To stop the car, he must disengage the grip from the cable and apply manual brakes: brakeshoes on wheels and, on steep locations, wooden track brakes. A two-axle car on a manually operated turntable at its terminal is shown in Photo 8.4.

8.2.1.3 Funicular Railways. The technology most commonly used for transit service on lines with very steep gradients is the funicular railway, better known simply as “funicular” or, in some U.S. cities, as “inclined plane” (Chattanooga, Tennessee) or “incline” (Pittsburgh). Funicular is a shuttle line consisting of a pair of rail vehicles (or short trains) permanently attached to two ends of the same cable. Both units thus move simultaneously, the one going up utilizing the gravity force of the other, descending unit. A traction motor, located in a building at the top of the line (Photo

8.5), must therefore only add power for acceleration, overcoming of resistances, and compensating uneven loads in the two vehicles when they occur. The cable runs over rollers located in the center of the track.

Funicular railways often have straight alignments, but curves with radii of 200 m, exceptionally even as short as 50 m, can be negotiated with cable rollers in a slanted position. Transitional curves and superelevations are not needed because of the system’s moderate speed. Gradients vary between 10% and 100%, but only mild vertical curves (2000 m radius) are used. Maximum line lengths, determined by the mechanical limitations of traction, are about 2400 m; vertical differences of up to 1000 m can be negotiated. Longer lines are divided in two sections; for example, the Parnassus Line at Davos, Switzerland, has two sections 1893 and 2226 m in length and vertical differences of 622 and 449 m, respectively (Schneigert 1966, p. 221).

Short funicular lines and lines with large cars that carry automobiles have two parallel tracks, one for each car. Such lines require wide ROW and often a large supporting structure on their steep alignments. Long lines have a single track, which simplifies align-

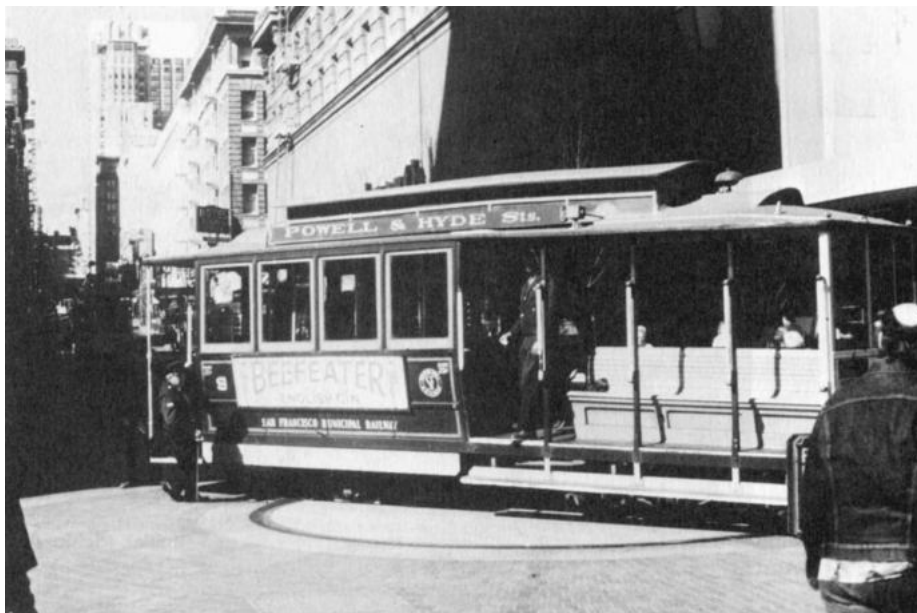


Photo 8.4 San Francisco cable car on its turntable

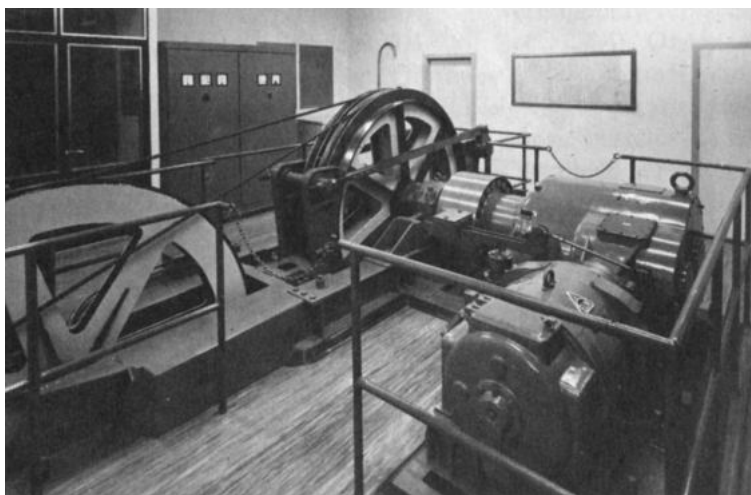


Photo 8.5 Traction motor and cable arrangements for a funicular (Schlossbergbahn, Graz, Austria, courtesy of Grazer Stadtwerke AG)

ment selection and requires much lower investment costs. The two cars meet at the middle point, where a two-track passing turnout is provided.

To allow passage of the lower car across the rail on which the upper car travels, vehicle guidance and switches in most cases use the design known as the Abt system. Each car has wheels with double flanges on the outside rail in the turnout track and wide cylindrical wheels without flanges on the other. Thus the car is guided to the track on the side of the flanged wheel, while the flat wheel crosses the gaps in the rail through which the cable passes (Figure 8.3 and Photo 8.6). The other car is guided by the opposite rail and thus goes to the other track, achieving the bypassing at the turnout.

The vehicles vary greatly in size. In most cases they are small cabins with 20 to 40 spaces in a single compartment, but there are vehicles with up to 160 spaces in two to four compartments with floors at different levels: the cars, being always on a rather constant steep slope, are designed with compartments in a stepwise pattern. In a few cases inclines carry both passengers and automobiles [Johnstown (Pennsylvania)]. At one time, an incline in Cincinnati was carrying streetcars (Photos 8.7 and 8.8).

An interesting funicular line has been in operation in Haifa, Israel, since 1959. This 1.75-km-long line is in a tunnel that is straight (no horizontal curves) but has gradients up to 15.5%. Its six stations are located symmetrically with respect to the middle point of the line, so that the two trains stop at stations simultaneously. Trains consist of two cars, each 15.00 m long and 2.40 m wide, with a capacity of 160 sps and four doors per side for fast boarding/alighting. An interesting feature is that the vehicles have rubber tires. This is a questionable choice of technology: the main potential advantage of rubber tires, their high adhesion, is not utilized in cable traction, while their main disadvantage—higher rolling resistance—creates greater tractive power requirements than rail wheels would have. The line has an operating speed of 30 km/h, a capacity of 1900 sps/h, and carries about six million passengers annually.

Although not as famous and venerable as the more than 130-year-old San Francisco cable car system, the funiculars also have a strong appeal with both citizens and tourists and contribute significantly to a city's "personality." Even after their long neglect and closings in U.S. cities, the "inclines" in Chattanooga and Johnstown are well known. However, the "capital of

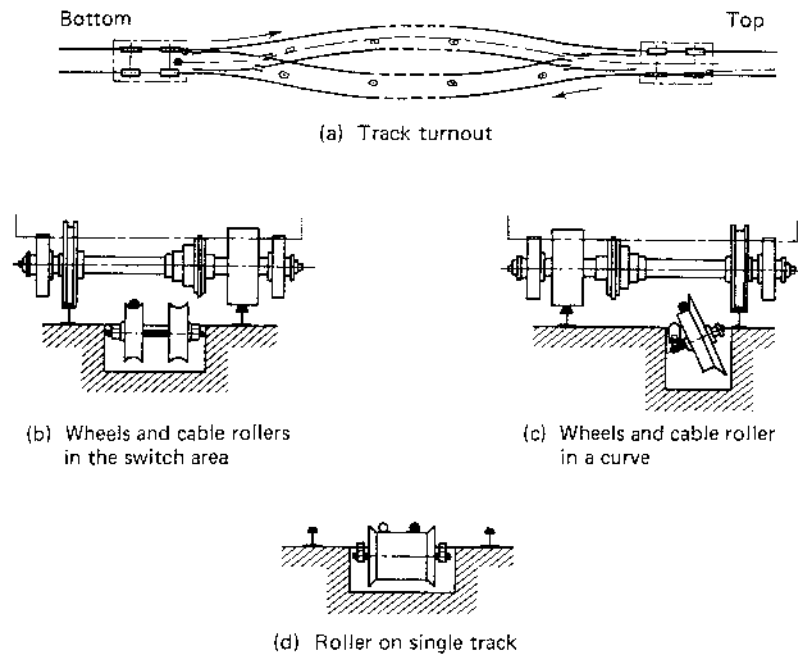


Figure 8.3 Funicular track components (Source: Risch and Lademann, 1957.)

funiculars” in North America is certainly Pittsburgh (Photo 8.9).

Lying on the Monongahela and Allegheny Rivers joining and creating the Ohio River, Pittsburgh has many steep hills, which give magnificent views but present serious obstacles for travel. The first incline in the city, Monongahela, was opened in 1870 and the second in 1884, followed by many others and reaching the peak with no less than 17 inclines operating until 1930, when the increasing use of private cars began to decrease their passenger loads, leading to their closure. At present two inclines, Monongahela and Duquesne, restored and designated as national landmarks, remain in operation and enjoy great popularity.

Similarly, funiculars in Graz, Ketchikan (Alaska), Lisbon (three lines with different technologies), Lyon, Paris (Montmartre), Salzburg, Singapore, Wiesbaden (using water supply at the top of the line for propulsion of the line), and many other cities enjoy considerable popular appeal. Several of them have survived pressures for closing due to financial problems only be-

cause of strong public insistence to retain them as unique facilities, often connecting historic or other touristically attractive areas (Salzburg, Zagreb). A number of funiculars do, however, provide essential service among several stations: the lines in Haifa, in Hakone near Yokohama, Peak Tram in Hong Kong, and three funiculars in Lisbon (Photo 8.10) with three different traction designs are good examples.

The largest set of funiculars in the world which operates as an important component of an urban transit system is found in Naples, Italy (Photo 8.11). The city is situated on hilly terrain, including two major plateaus with altitude difference of about 170 m. Four funiculars with individual names and designations f 1 to f 4 were built between 1889 and 1931. They provide direct, short but very steep links serving large passenger volumes between the two plateaus. While one line—Mergellina—operates only single cars with capacity of 60 spaces, the Centrale line has three-car trains with a total capacity of 450 spaces. Its cars have many doors along the platforms with steps, allowing



Photo 8.6 Switch and turnout for a single-track funicular (Hakone, Japan)

rapid boarding and alighting, so that the line has an hourly capacity of 5400 persons. The four lines carry a total ridership of 55,000 passengers per day between these plateaus and intermediate stations. Technical data about these four lines are given in Table 8.2 on page 492.

The city's difficult topography has led to the construction of another unique transit facility: Metro Line 1, going from the sea level to an elevation of 235 m, has a tunnel alignment making a full loop with a radius of only 160 m and gradient of 5.5% to overcome this great climb. Despite its steep alignment, the line has



Photo 8.7 Double-track funicular for passengers and automobiles (Johnstown, PA) (Courtesy of Richard Clarke)

an operating speed of 35 km/h and soon after its opening in 2002 it carried about 90,000 daily passengers.

8.2.1.4 Comparison of Rail Modes with Auxiliary Traction. These three modes differ greatly not only by their technology but also by their operations and service performance. Their basic characteristics important for transit planners are as follows.

Cog railways consist of individual TUs that usually operate on urban transit lines as single vehicles, but the same technology is used for regular intercity trains with many trailer cars. TUs are electrically powered and travel along lines in the same manner as streetcars. They usually have ROW A, but some models, like Stuttgart's, have a cog-rack design that allows them to use ROW C also. The line capacity depends on TU capacity and scheduled headways that are not constrained by their special technology.

Cable cars are single unpowered uni- or bidirectional vehicles that obtain propulsion and most braking from a continuously moving underground cable. The cable housing is flat, so that cable cars can and mostly

do run on ROW C in mixed traffic. Their line capacity also depends on vehicle capacity (which can be considerably increased by passengers standing on outside running boards), and on headways. The cable is designed to provide sufficient traction not only for short headways but also for the bunching of cars that occurs on special occasions or due to traffic conditions on streets.

Funiculars are different from these two systems in many respects. Like cable cars, the vehicles have no power but are permanently tied to the cable, which balances the two cars so that they always travel simultaneously. They usually serve only as shuttles between two stations at different elevations, but they can also have symmetrically located pairs of stations along the line.

The service frequency and capacity of a funicular line depend on its travel and terminal times, because its headway is always half of the cycle time. Since travel times in each direction T_o and terminal times at each terminal t_t are equal, the cycle time T is:

$$T = 2(T_o + t_t) = 2\left(\frac{60L}{V_o} + t_t\right),$$

$$\left| \frac{T, t}{\min} \right| \left| \frac{L}{\text{km}} \right| \left| \frac{V}{\text{km/h}} \right| \quad (8.1)$$

V_o being operating speed. The headway is:

$$h = \frac{T}{2} = \frac{60L}{V_o} + t_t, \quad \left| \frac{h}{\min} \right| \left| \frac{T, t}{\min} \right| \left| \frac{L}{\text{km}} \right| \left| \frac{V}{\text{km/h}} \right| \quad (8.2)$$

Thus, the headway increases with line length L , but it is inversely related to speed. Line capacity C is a linear function of vehicle capacity C_v and number of cars per TU, n (which may be one to three) and inversely related to headway h :

$$C = f \cdot n \cdot C_v = \frac{60 \cdot n \cdot C_v}{h},$$

$$\left| \frac{C}{\text{sps/h}} \right| \left| \frac{F}{-/\text{h}} \right| \left| \frac{n}{\text{veh}} \right| \left| \frac{C_v}{\text{sps/veh}} \right| \left| \frac{h}{\min} \right| \quad (8.3)$$



Photo 8.8 Funicular in Cincinnati, which carried streetcars with passengers (Courtesy of Cincinnati Historical Society Library–Cincinnati Museum Center)

Funiculars thus have two limitations on line length. First, cable length becomes inefficient on long lines due to physical friction; second, service headways become long and line capacity decreases with line length, so that the system becomes less attractive and less productive.

A summary review of characteristics of three rail modes with auxiliary traction is given in Table 8.3.

It should be mentioned that in spite of the popularity of cable cars, it is not likely that any new systems will use that technology. Cog railway and funicular modes may be expected to be built in additional cities with hilly topography.

8.2.2 Aerial Tramways

Suspended passenger cabins pulled by a closed-loop cable can also be used to overcome steep gradients or, most commonly, deep valleys, ravines, or bodies of water. These systems are used extensively in mountainous regions (the Alps, the Rockies), but in some cases they are used in the immediate vicinity of cities [Atlanta–Stone Mountain, Rio de Janeiro, Innsbruck (Austria), Caracas–Avila], or as shuttle transit lines within cities (Portland was building one in 2006).

The best-known aerial tramway with the largest cabins used as an urban transit line is the Roosevelt Island–Manhattan Line in New York City, opened in



Photo 8.9 Double-track funicular providing transportation and impressive views for passengers in Pittsburgh



Photo 8.10 Lisbon

1976. This line, providing the fastest and most convenient connection between the island and Manhattan over the navigable East River, was a part of the entire planning concept for the design of the island as an integrated, nearly vehicle-free environment (Ozerkis 1975). The basic technical data about the Tramway are as follows (Tomaseti and Ozerkis 1975):

Line length:	945 m
Number of stations:	2
Maximum height:	76 m
Clearance over East River:	41 m
Cabin capacity:	125 passengers + 1 operator
Maximum speed:	7 m/s (25 km/h)
Cycle time:	10 min
Line capacity:	1500 sps/h



Photo 8.11 Naples (Courtesy of Kristina P. Ho)

Table 8.2 Funiculars in the city of Naples

Characteristic	Line			
	f 4—Montesanto	f 3—Centrale	f 2—Chiaja	f 1—Mergellina
Length [m]	825	1270	536	570
Climb [m]	168	170	161	147
Stations, including terminals	3	4	4	5
Avg. gradient [%]	20	13	29	16
Max. gradient [%]	23		29	46
Speed [m/s]	7	7	7.5	3.5
[km/h]	25.2	25.2	27.0	12.6
Travel time [min/s]	4' 25"	4' 20"	3'.08"	7' 0"
Cars per train	2	3	2	1
Train capacity [sps.]	300	450	300	60
Max. line capacity per direction [prs./h]	3600	5400	4500	480
Year of opening	1891	1928	1889	1931

Table 8.3 Design and operating characteristics of three rail modes with auxiliary traction

<i>Characteristic</i>	<i>Cog Railway</i>	<i>Cable Car</i>	<i>Funicular / Incline</i>
Propulsion	Electric motors on vehicles	Stationary electric motor propels traction cable for lines	Stationary electric motor propels cable affixed to two vehicles or trains
Cars or TUs	Independent, self-propelled	Independent cars grip or release cable for traction and braking	Cars without motors, fully dependent on cable
Line length	Unlimited	Unlimited, network possible	Single line with 2 vehicles; length < 2 km
Stations	At any point	At any point	Two or more, but symmetric in relation to terminals
Headways	Any physically possible	Any physically possible	Half of cycle time, increase with line length

A sketch of the machinery of the Roosevelt Island Tramway is shown in Figure 8.4. Its high-capacity vehicle traveling over the East River is pictured in Photo 8.12.

With respect to line characteristics—length, stations, headway/cycle time relationship, and line capacity—aerial tramways have the same features and limitations as the funiculars.

8.3 WATERBORNE TRANSIT SYSTEMS

Rivers, lakes, seacoasts, bays, and other bodies of water within or adjacent to cities, often major obstacles to transportation, can also in some cases be utilized as ways for transit services that offer more convenient and even faster travel than land-based systems. Most of these waterborne systems using large boats powered by diesel motors (or sometimes steam engines) can be classified in two ways:

1. By type of vessels: monohulls, catamarans, hydrofoils and, much less used, small waterplane area twin hull-SWATH ships and hovercraft
2. By type of service: passenger ferries (carrying passengers and bicycles), auto ferries, and water taxis

The following text will describe both vessel types and the across-the-water transit services provided in many cities.

8.3.1 Types of Vessels

Ferryboats vary greatly in sizes and capacity. There are 15-m-long ferryboats for 50 persons, but most have rather large capacities, ranging from several hundred to several thousand passengers. The largest boats in the United States are operated in Puget Sound (Seattle), where some auto ferries are 140 m long, while boats operating on the Staten Island Ferry line to Manhattan are 102 m long and can accommodate up to 6000 passengers.

Monohull ferryboat speeds range between 20 and 32 km/h (12 and 18 knots), which are rather low compared to highway and rail vehicles, but their direct lines across large bodies of water can sometimes offer similar or even faster service than any competing mode between points served. High-speed catamarans and hydrofoils provide much greater speeds, in the general range of 60 to 100 km/h (35 to 55 knots). Ferries generally offer low-cost, reliable, comfortable, and often scenic travel, although these features can be affected by weather conditions.

Most ferryboats are powered by diesel, diesel-electric, diesel-waterjet, and in some cases also by steam engines. Diesel engine power typically ranges from 1500 to 10,000 kW (2000 to 13,000 HP).

Types of ferryboats and their designs vary with the types of services they operate. These can be grouped in two categories. First, ferryboats are used for short across-the-water connections, and such boats are designed for fast docking, unloading, and boarding of

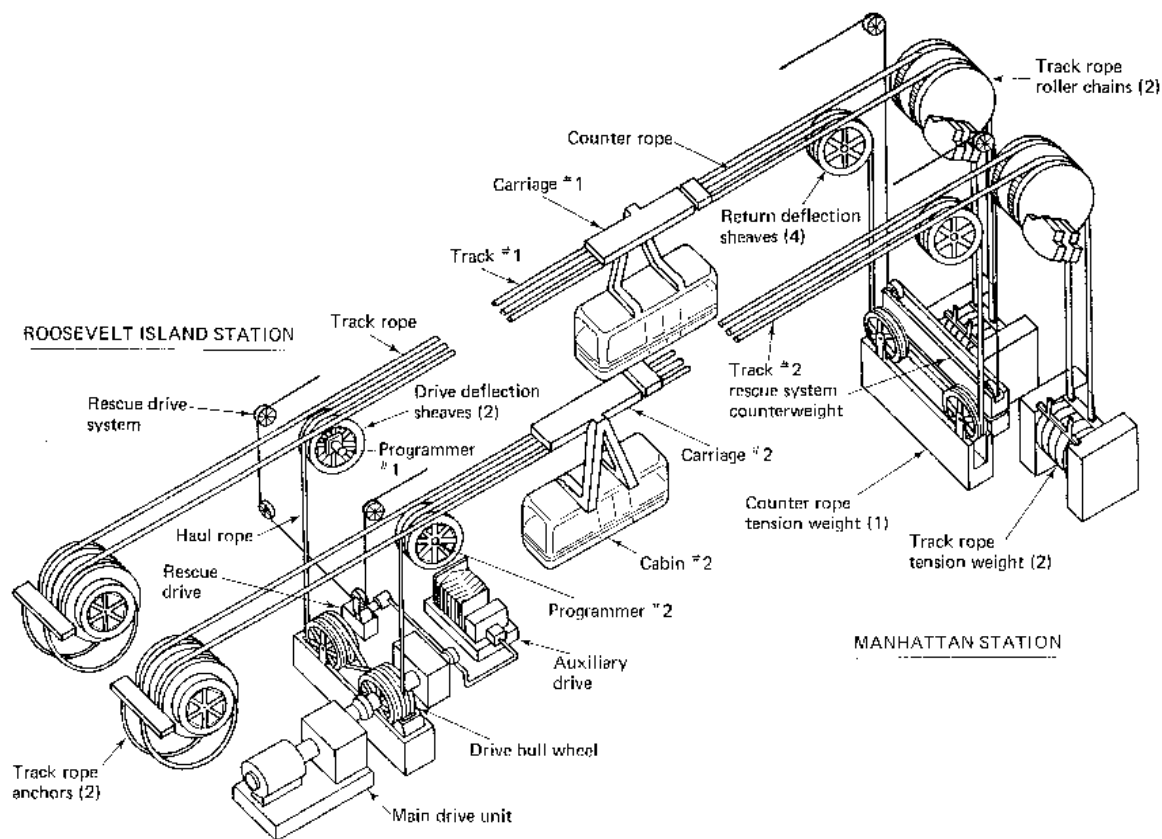


Figure 8.4 Aerial tramway system schematic (Courtesy of David I. Ozerkis, VSL Corporation, Los Gatos, CA.)

passengers. Second, they serve medium-to-long lines connecting islands, various points across major lakes or bays, or along rivers and seacoasts. In these cases vehicle speed plays a more important role, and use of catamarans and hydrofoil ships has been increasing on these lines in recent years.

For lines connecting islands or crossing straits without close alternative connection by highway, considerably larger, mostly monohull ferries carrying automobiles and buses are used. On intercity links (e.g., on several sea crossings to islands in Scandinavian countries), passenger train cars are also carried (Photos 8.13 and 8.14).

8.3.1.1 Conventional (Monohull) Vessels. Most passenger ferryboats are conventional boats now often referred to as monohulls to distinguish them from cat-

amarans. They usually have several decks, providing enclosed compartments as well as open balconies. Auto ferryboats are much greater by displacement and deck areas for storing vehicles and easy drive-on and drive-off arrangements.

8.3.1.2 Catamarans. These vessels have two parallel hulls that support the body bridging them, and each has one or more decks. They are more stable than monohulls and also more maneuverable, because of their widely spaced propellers under the two hulls. Their capital and operating costs are higher than those of monohulls. Catamarans have been increasingly used, particularly for longer ferry lines.

A special design for higher-speed operations is a SWATH vessel, which also has two hulls, but these hulls are submerged, while holding the body above the



Photo 8.12 Aerial tramway to Table Mountain in Cape Town, South Africa



Photo 8.13 Vancouver SeaBus, providing frequent transit service (Courtesy of Ben McNealy)



Photo 8.14 High-speed hydrofoil (Courtesy of Kawasaki Heavy Industries, Courtesy of James Aslaksen)

water surface. Their design reduces drag and allows higher speeds than are possible for monohulls and catamarans. SWATH ships provide a smoother ride in rough waters, but they consume more fuel. This type of vessel has had limited applications in urban regions so far.

8.3.1.3 Hydrofoils. Also known as Surface Effect Ship or SES, the hydrofoil is a surface-effect boat that has two supporting floats under its hull. At low speed the boat's hull is in the water, but during acceleration the floats lift the boat out of water, resulting in much lower resistance than a conventional boat would have. This allows the hydrofoil to travel at much higher speeds: it has cruising speeds in the range 70 to 100 km/h (40 to 55 knots). When slowing down, the hydrofoil gradually descends until its hull is in the water again.

Hydrofoils provide a high-speed service, but at higher cost than conventional boats. Because of their operating method, they need a certain distance to develop cruising speed, so that they cannot be effective on short intraurban routes. Hydrofoils are therefore utilized mostly for connections between cities and their distant suburbs or surrounding towns. They are operated, for example, between Lausanne (Switzerland) and Evian-les-Bains (France) across Lac Lemman. They are also used to connect Belgrade, Budapest, Buenos Aires, Moscow, Naples, St. Petersburg and other large



Photo 8.15 Staten Island Ferry, transporting both passengers and automobiles and providing the only direct link to the CBD (New York, Courtesy of James Aslaksen)

Table 8.4 Selected North American ferry routes and ridership

Region	One-Way Route Length (km)	Average Weekday Passengers	Max. Boats in Service
Boston (MBTA)	72.4	5,200	12
New York (NYC DOT)	16.7	60,900	4
New York (Port Authority)	5.5	8,900	4
New York, Circle Line (private)	20.1	29,700	n.a.
New York, Waterway (private)	88.5	35,000	n.a.
San Francisco (Golden Gate)	69.2	6,200	5
Seattle (Washington State)	395.5	40,700	28
Vancouver (SeaBus)	6.4	14,700	2

Source: TRB, 2003, TCRP Report 100. *Transit Capacity and Quality of Service Manual*, 2nd ed.



Photo 8.16 Hong Kong ferry (Courtesy of Thomas Abrahamsson)

cities with their neighboring towns on islands, along rivers, or on seacoasts. Several of these services, such as those in Naples and St. Petersburg, are urban and regional, while others have a more intercity type of service.

8.3.1.4 Hovercraft. These vehicles ride on an air cushion created by air pressure under a specially designed vehicle skirt. Their propulsion is usually provided by air propellers. Since they have no physical contact with the surface, they are capable of traveling over ground as well as over water. In principle, this can be a significant advantage, but it is more than offset by the serious limitations of the vehicle. One is its imprecise guidance, which limits its ground travel to wide, open, flat areas. Further, a hovercraft produces very high noise levels, and its operating costs are high. Finally, the vehicle is highly sensitive to waves. Even on relatively moderate waves, the hovercraft's ride becomes extremely rough.

8.3.2 Ferryboat Services

Ferry systems are not a common mode of urban transit because they are limited to cities with large water bod-

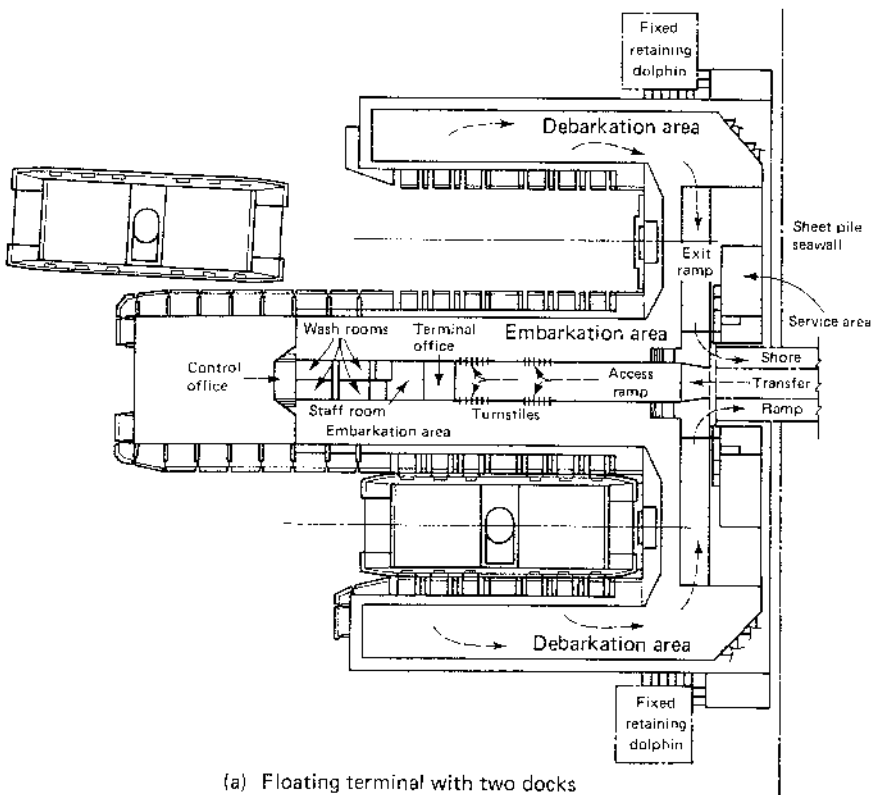
ies. However, in many such cities, ferries represent a unique and extremely important mode. The best illustrations of this important role and extensive use of ferryboats are, for example, the ferries of Seattle, Hong Kong and New York (Photo 8.15).

The data about ferryboat operations in selected North American cities, shown in Table 8.4, show the substantial line networks and numbers of served passengers that this mode provides.

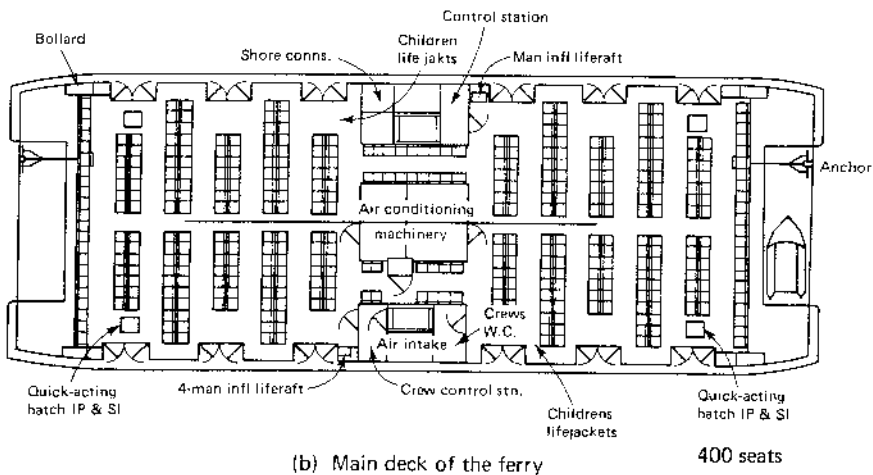
Examples of ferries used for crossing rivers or straits are found in New York (the Staten Island Ferry) Vancouver, and Hong Kong (Photo 8.16). Crossing of bays is found in San Francisco, Seattle, and Sydney. Services along lakes, rivers, and numerous canals that have influenced the unique shapes of cities are typified by those of Amsterdam and Bangkok, while Venice, with its unique geography, uses different types of boats for its entire transit network. Moreover, various types of boats are often used in cities for sightseeing: New York has a unique 3-hour boat ride around Manhattan, Paris along the Seine, and Berlin along the Spree, while Rotterdam and Hamburg have tours of port facilities. In Amsterdam and London, low boats for sitting only are used for cruises along narrow urban canals, under low bridges, and through various parks.

During the period of heavy auto orientation and neglect of all transit except standard buses in the United States and Canada, ferries appeared to be destined for abolition with the exception of a few cases where it is physically impossible to find any substitute for them, as in Boston, New York, and Seattle. However, with the diversification of transit modes resulting from more balanced urban transportation policies since the 1970s, the importance and potential for increased uses of ferries has again been recognized. One example of their revival is found in San Francisco: ferry service between Marin County and San Francisco—which had ceased to operate when the Golden Gate Bridge was opened in 1937—was introduced with new terminals, park-and-ride, and bus transfer facilities as well as new boats in 1970. At present, two ferry lines between Marin County and San Francisco carry about 2 million passengers per year.

An example of coordinated system design for shuttle ferries with fast docking and rapid passenger



(a) Floating terminal with two docks



(b) Main deck of the ferry

Figure 8.5 Burrard Inlet Ferry: dock and vessel layout

exchange, used in several cities (Hong Kong, Sydney), is exemplified in North America by the ferry service developed in Vancouver (Case 1976, Sullivan and Spratt 1978). The Lions' Gate Bridge between Vancouver and North Vancouver became overloaded, and additional capacity for travel between the two areas was needed. Buses on an exclusive lane were implemented in 1967, but the rapid increase in passenger volumes gradually brought capacity problems, affecting the reliability of service. Since construction of another bridge would have involved extremely high costs and both physical and environmental problems, the British Columbia Provincial Government's Transit Services Division decided to introduce a ferry across the Burrard Inlet; this ferry service named SeaBus, incorporates a number of new concepts and has many features of rapid transit operation.

The northern terminal of the SeaBus is a focal point for many bus lines from northern suburbs; the southern terminal provides transfers with many bus lines and the Skytrain–LRRT line, designated as advanced light rail transit (ALRT). Schedules and fares of the bus lines, Skytrain, and SeaBus are integrated. Each terminal has a floating structure with two docks (Figure 8.5a) to provide easy docking regardless of the tides, which fluctuate as much as 6 m. The ferries fit precisely in each dock and have six double doors on each side. Passengers embark from the central portion of the terminal, while those arriving disembark into its outer corridors, as the figure shows. This one-way passenger flow allows for a complete exchange of 400 passengers (the seating capacity of the boat) in 90 s.

Ferryboats are symmetric bidirectional catamarans (Figure 8.5b) with the same dynamic performance in both directions. After embarkation, a boat immediately accelerates to 25 km/h (13.5 knots) and crosses the

3.2-km-long distance across the inlet in less than 10 min. Thus cycle times of 30 min are easily achievable, resulting in a capacity of 1600 seats/h per direction by two boats.

The catamaran vessel has the following vital statistics:

Length × breadth	34.30 × 12.65 m (112 ft 6 in. × 41 ft 6 in.)
Depth to main deck	3.51 m (11 ft 6 3/4 in.)
Draft loaded	2.03 m (6 ft 8 in.)
Machinery	4–12V–71 NA Detroit Diesels
Output	4 × 400 Bhp
Propulsion method	4 propellers with right-angle drives
Generators	2 × 120 kW (Detroit Diesel)
Service speed	25 km/h (13.5 knots) 90% MCR
Capacity	400 seats + 4 crew members.

Source: Sullivan and Spratt, 1978.

Acceptance of this line has been excellent. Soon after its opening in 1977, weekday ridership stabilized in the range 10,000 to 15,000 passengers per day, with considerably higher volumes on special occasions.

Water taxis are usually small boats providing different types of taxi and charter paratransit services.

Reviewing the different waterborne modes used for certain transit services, it is obvious that at present conventional ferryboats maintain the dominant role but that new technological and operational concepts, from vessel design to intermodal coordination and joint fares at landing points, are being introduced in many cities with water bodies. Such waterborne systems are likely to be further developed in the future.

EXERCISES

8.1. Short-haul transportation in CBD:

- What are typical service requirements for it (speed, frequency, comfort, etc.)?
- Why is it important (i.e., what are the major problems in city centers if short-haul travel cannot be performed easily and conveniently)?
- List the modes that can be used for it.

- 8.2.** Compare the cog railway to funiculars with respect to:
- a) Gradients they can negotiate
 - b) Line lengths
 - c) Performance, particularly capacity and frequency
 - d) Energy consumption
- 8.3.** What line characteristics influence the choice between single- and double-track funiculars?
- 8.4.** Briefly describe aerial tramway and the roles it plays in urban transportation (conditions and types of lines).
- 8.5.** For some connections in cities, water transportation is the only physically feasible transit mode. Under what conditions do you see a potential for using these modes as an alternative or supplement to land modes, such as bus or rail? Give some examples of cities where ferryboats providing the only service and of those offering alternative means of travel.
- 8.6.** What characteristics (problems) limit applications in urban transit of:
- a) Hydrofoils
 - b) SWAT
 - c) Hovercraft
- to very special cases only?

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9

PARATRANSIT

Bus and rail transit, unconventional and specialized transit modes, were presented in Chapters 5 through 8. This chapter describes paratransit, representing modes of semipublic and public transport which by ownership and types of service are classified “between” private transport and conventional transit (see Section 2.1). Paratransit includes several different modes that vary in their operational and physical characteristics as well as in age: the oldest, the taxi, was introduced before regular transit; the recent ones, such as dial-a-ride and other hybrid services with properties of both paratransit and fixed-route transit, continue to be under development and evaluation.

9.1 DEFINITION AND CLASSIFICATION

There are a number of definitions of paratransit based on several different criteria. The broadest but rather imprecise definition is that paratransit represents all types of urban passenger travel “between” the privately owned and operated automobile on the one hand, and conventional transit with fixed routes and schedules on the other. By this definition, paratransit includes not only taxi, jitney, dial-a-ride, and subscription commuting services but also car rentals and car-pools. The last two, however, neither represent systems (they are types of ownership and vehicle use, respec-

tively) nor are they available for semipublic or public use.

The most logical and precise definition of paratransit is the *functional* one, on the basis of the service it offers and the type of usage (see Section 2.1 and Table 2.1). On this basis the definition is as shown below.

Consequently, paratransit is characterized mainly by the type of usage, ownership, and type of operation rather than by technology: its vehicles vary only in size and body design, but they are all, with very few exceptions, ICE-powered highway vehicles. The exceptions include, for example, water-taxi and rented suburban trains (e.g., Toronto).

Individual paratransit modes can be classified and defined on the basis of several characteristics:

1. *Type of usage*: services of paratransit modes may be available to different groups. This is a very important characteristic and it divides the modes into three basic groups, the last two representing paratransit by its functional definition:
 - *Modified uses of private transportation*, travel available only to vehicle owners. Therefore these modes of travel do not represent public transportation or paratransit in its precise definition.
 - *Semipublic paratransit*, representing regular subscribed travel, an arrangement similar to a

Paratransit is urban passenger transportation service mostly in highway vehicles operated on public streets and roads in mixed traffic; it is provided by private or public operators and it is available to certain groups of users or to the general public, but it is adaptable in its routing and scheduling to individual user's desires in varying degrees.

Generic Category		Private Auto (Rental Car)	[← Semipublic Paratransit → ← Public Paratransit →] Paratransit (broad definition)							Regular Transit
			Carpools	Vanpools	Subscription Bus	Car Sharing	Taxis	Jitneys	Dial-a-Ride & Hybrid Services	
Characteristic	Type	Mode								
Type of usage	Private									
	Semi public									
	Public									
Vehicle (system) ownership	User									
	Employer, school, etc.									
	Individual operator									
Service type by routing	Transport agency									
	Personal									
	Partially personal									
Method of getting service	Fixed route									
	Always available									
	Fixed schedule									
Trips served	Prearranged									
	On street/by phone									
	Regular only									
Vehicle driver	All									
	User									
	Partially trained driver									
Vehicle capacity	Trained driver									
	≤ 6									
	7-15									
Parking at each trip end	≥ 16									
	Required									
	Not required									

Figure 9.1 Basic characteristics of paratransit modes

specialized club. This service is usually available to all persons from an organization, school, factory, or neighborhood but not to the general public. Its predominant uses are for commuting to work, transporting children to/from school, and serving the demand of private groups for hiring one or more vehicles with operator on a temporary basis.

- *Public (regular) paratransit*, available at any time and provided to any person who pays an established, usually publicly regulated fare.
2. *Ownership of vehicles or systems*: paratransit vehicles may be owned and service provided by an organization unrelated to transportation (e.g., factory or school), by an individual who also operates the vehicle (taxi or jitney driver), or by a transport agency (taxi company or transit agency).
 3. *Service type by routing*: some modes give individual users door-to-door service, others adjust

it partially to the user's travel; a third group of modes has fixed routes to and from which users must walk or travel.

4. *Method of getting service*: user may have paratransit service available at fixed (or very frequent) schedules, such as jitneys; the trip may be prearranged, as, for example, with subscription buses; or, it must be obtained by "hailing" the vehicle on street or calling it by telephone (taxi).

Other significant characteristics of paratransit services include type of served trips (regular only or all types), vehicle operator (user, partially trained driver, or professional driver), vehicle capacity (up to 6 spaces in private cars, 7 to 15 in vans, and more than 16 in minibuses), and parking requirements.

These main characteristics are shown in Figure 9.1 for all paratransit modes, as well as for the special uses of private modes which are sometimes included into a

broadly defined paratransit. Private auto and regular transit are included to show the relationship of paratransit with them.

9.2 MODIFIED USES OF PRIVATE TRANSPORTATION

Two special uses of the personal automobile, considered by some to be paratransit modes, perform roles similar to those of taxis or vanpools. They are car rentals and carpools.

9.2.1 Car Rentals

When individuals rent cars for a certain period (day or week), and drive wherever they desire, their travel does not differ in any way (physically, by routing, or availability to others) from travel by private automobile. The only difference in use, that they can be picked up and dropped off in any city, does not make rental car a separate mode. The difference in the type of vehicle ownership has little bearing on their functional characteristics. Since it is in no way available to any other party, *travel by rented cars represents private transport* rather than paratransit.

9.2.2 Carpools

Although they are not paratransit, carpools are discussed here because of their overlapping role with paratransit and transit for some categories of urban transportation.

Carpooling is another special use of private automobiles (i.e., prearranged travel of two to five individuals by private cars of one or several members, usually for regularly performed trips). Costs are shared on some mutually agreed upon basis. Carpools have a domain of travel that is functionally limited but not necessarily negligible by volume. They can generally be organized only among persons who (1) travel at the same time, (2) travel from the same general origin, (3) travel to the same general destination, and (4) return at the same time. Only in special cases can carpooling

be organized if some of these conditions do not exist: pick-up or drop-off of passengers at other places deviates from conditions (2) and (3), and one-way carpooling from condition (4). In most cases all four conditions are met, however. These conditions limit applications of carpools almost exclusively to work and school trips performed on a regular, usually daily, basis. Despite this limitation, however, carpools are used extensively in low-density urban areas with large employment centers where transit service is inadequate. This is a typical situation in many U.S. cities, particularly in southern and western regions of the country.

Although organization and use of carpooling can be strongly encouraged and assisted by various governmental or employers' policies, the agreement on carpooling is entirely a private one among the participating parties, and there is no public jurisdiction over it. *Since carpools are not available to any other parties, they also represent a private mode of transportation*, not paratransit in its strict definition.

Carpools provide a much more efficient type of travel than individual use of private automobiles from the societal point of view. A carpool with n persons involves nearly n times fewer car-km than travel of the n persons in separate cars (sometimes circuitous routing to collect/distribute members decreases this ratio). It thus reduces travel and parking costs, traffic volume on highways, energy consumption, air pollution, and other direct and indirect negative effects of auto travel. To its participants, however, its characteristics include some disadvantages. Although carpooling offers considerable financial savings, it also has less or no flexibility by comparison with the private auto for travel in any direction at any time. In comparison with public transport, carpools are much more limited and offer lower LOS in several respects: their "frequency of service" is once per day, between two points (rather than over a network), and with the same partners. Therefore carpools can compete with transit only for the commuter trips that fit these conditions. They can supplement but not substitute for either the auto or regular transit service.

Factors favoring the use of carpools include:

- High concentration of jobs, schools, or major special events (CBD, major office or factory

complexes, campuses, stadia), as well as of employees' (or students') residences

- Lack of good transit service or high fares
- High cost of parking
- Congested highways

Since some of these factors, such as congested highways, do not directly induce individuals to switch from driving alone to carpooling, various incentives should be used where carpools are socially desirable for lower congestion, less pollution and energy consumption, parking area requirements; and so on. There are several types of incentives, such as:

- Service provided in organizations with large employment (offices, factories) that matches addresses of employees interested in carpooling, helping them to contact one another.
- "Cashout" programs when employers do not provide free parking but pay employees a certain monthly amount for transportation expenses. Employees can then use that for parking, join a carpool, use transit, or purchase a bicycle, thus having a greater choice and reducing car use (Shoup 2005).
- Reserved street or freeway lanes, or bypass lanes on frequently congested ramps for exclusive use by carpools [actually for high-occupancy vehicles (HOV)—autos with four or more persons and buses].
- Higher parking rates for vehicles with fewer than three or four occupants.

Carpools are difficult to supervise (it is usually not known which vehicles can be considered carpools), and they are not very stable (parties may discontinue the arrangement at any time for any reason). Moreover, their social value with respect to the reduction of pollution, energy consumption, and parking area requirements as compared with private automobile transportation are usually considerably lower than those of transit modes. Carpools should therefore be encouraged where they are likely to attract riders from auto drivers, but they should not be encouraged where

they would compete with transit services. Such competition would have double negative consequences: increased negative impacts caused by the diverted passengers and reduced transit service (due to lower patronage) for the remaining transit passengers.

9.3 SEMIPUBLIC PARATRANSIT

Some organizations with large numbers of employees located in areas without adequate transit service (usually in auto-oriented suburbs) organize commuter service for their employees. In some cases, neighborhood groups and schools organize a subscription-type transit service. These services are semipublic since they are not available to the general public, although they are available to any member of certain employee, student, or neighborhood groups.

9.3.1 Vanpools

The concept of commuter vanpools organized by employers was initiated during the 1970s. The employer provides 7- to 15-seat vans and organizes groups of commuters from the same general areas to join in commuting pools. One of the participants accepts the responsibility of driving and vehicle maintenance; as compensation, this person has the van for private use at other times. Costs of vanpool commuting are usually shared by the participants on a monthly basis. They include operating, parking, and maintenance costs of the van as well as its depreciation unless the employer absorbs it by purchasing the vans.

To be successful, vanpool commuter services should be organized so that they bring benefits to most or all directly participating parties: commuter-riders are freed from the problems of operating and, in some cases, owning automobiles; the volunteer-driver has the free use of the van at nonworking times, thus compensating for the extra driving and van maintenance; and the employer has reduced parking requirements and traffic volumes at the plant. Many successful vanpool services have been planned with careful distribution of these benefits to all the parties.

Vanpools as a mode have characteristics similar to those of carpools in that they involve lower costs and more negative concomitant effects than the private automobile where there is sufficient demand for them; but they are not as efficient in those respects as transit where the latter has sufficient demand. Compared with carpools, vanpools are more economical, they can be used by nondrivers, and they are better organized; on the other hand, they require a formal organization for their initiation, operation, and financial arrangements.

Vanpools are most effectively used by large employment centers in suburban areas that are dependent on auto access only. They can be counterproductive if their routes duplicate transit services. In addition to diversion of transit passengers, vanpools can in such cases lead to an “exclusive club” type of service that is covertly used to separate its users from a different class of users delegated to transit buses; the more people are attracted to vanpools, the less pressure there is to improve transit. The segregation between the two groups thus tends to increase.

Good examples of large vanpool commuter services are those organized by King County Metro for Boeing and other large factories in the Puget Sound (Seattle) region and PACE’s system in the suburbs of Chicago.

Offering comfortable travel to and from work for regular employees, vanpools serve as an efficient commuter transit mode. As such, they provide only a fraction of the service regular transit would provide (i.e., to many locations at all times and to all potential users). The initial failure to coordinate land-use and

transportation planning (i.e., locate a large employment center where transit can serve it) cannot be fully corrected. Given such a development, however, the vanpool program represents a significant improvement over total dependence on the auto, not only in terms of user costs and convenience but also in reduced space requirements, and negative side effects, and improved mobility.

9.3.2 Subscription Buses

Another kind of “commuter pooling” is sometimes provided by individual organizations (companies, government agencies, schools, or residents of an area) for regular travel of a group of persons, usually for commuting between a major employment center and a residential area. The service may be provided by the employment organization or hired from a bus operator. For example, an organized group of residents collects subscriptions from commuters and leases one or more buses on a permanent basis from a private or public bus company to provide fixed-route, fixed-schedule trips. The characteristics of subscription buses and their advantages and disadvantages in comparison with private auto on one hand and transit on the other, are similar to those of vanpools except for the following differences listed in the box below.

The second advantage in the list is particularly significant. When the demand is sufficient to justify lease of more than one bus run per day, two or more depar-

Subscription buses compared with vanpools:

- + Require less organization by participants, since the employer or a transport company provides the driver, maintains the vehicle, and so on.
- + When demand is high, they can provide several runs during the day rather than a single trip.
- + Organized by operating companies, they require fewer security precautions.
- Require a larger group of commuters.
- May have limitations due to involvement with a bus company, its labor union, legal requirements, and so on.

tures are available to participants, so that they can make some changes in their travel when necessary. If on some days uneven bus loadings occur, they can be handled as standing overloads; vanpools do not have this feature, since they cannot accommodate standees.

Examples of subscription buses being later upgraded into regular transit services are found in Reston, Virginia, the suburbs of Washington, DC, Ottawa, and the Marin County suburbs of San Francisco.

9.3.3 Car Sharing

A growing number of cities—such as Dresden, Paris, Philadelphia, Seattle, Zürich, and hundreds of others—have organizations that provide hourly car rentals to their subscribers from a number of locations in the city. Specially selected, often environmentally friendly cars, including several sizes, are used for the fleet. Although vehicle access varies among car sharing systems, in newer systems subscribers are typically issued a personal electronic key to all vehicles in the entire fleet. To drive, subscribers book via Internet or phone, walk to the nearby car-share station (often located at transit stations like a taxi stand), and unlock a car using their personal key. Usage is logged via on-board computer. Later, the subscriber is automatically billed. Hourly and distance-based rates cover the costs of insurance, vehicle, gasoline, maintenance, and reserved parking.

Various service models exist (e.g. open-ended reservations, “instant” or no reservations, one-way trips, provision of keys via lockboxes, etc.), although the modes’ basic features of very short term, self-accessing, nearby auto mobility remain the same.

This type of service has found excellent response from many urban residents who do not use cars regularly but from time to time or for special trips. For such uses shared cars are more economical and convenient than owning a private car, finding parking for it, paying for insurance, etc.

By their function in urban transportation, the car-share systems have been found to be more complementary than competitive with transit because they enable a sizable number of residents not to own cars but to use transit supplemented by shared cars. The hourly and distance fees, which shift auto costs from

fixed costs to variable expenses, enable travelers to save money by driving less and thus encourage more judicious decisions. Overall, the effect of car share in most cities has been to reduce the number of private cars and car-km driven, thus reducing traffic congestion, parking demand, and air pollution. At the same time, transit usage has increased, supporting the upgrading of services.

PhillyCarShare in Philadelphia has been an excellent example of a successful non-profit car sharing system. The organization carefully planned its car fleet selection and locations for stations or “pods,” information, and marketing strategies. After the system’s establishment in 2002, the organization has continued to analyze its users and their habits, adjusted several types of rates, and their structures (amounts of membership fees, rates per hour, methods of collecting the charges, etc.), and performed research for potential future customers, including individual neighborhoods and college students, and has further potential for coordinating car sharing and transit usage. Only 1½ years into PhillyCarShare’s program, the City of Philadelphia became a subscriber. PhillyCarShare became the first system worldwide in which government employees and local residents shared vehicles by the hour in a major car-reduction effort. The project replaced 330 municipal vehicles, saving the city government \$2 million annually, and residential members sold or avoided purchasing roughly 1400 vehicles, saving about \$5.5 million annually versus car ownership. Residential members also report driving about 50% fewer kilometers and more often walking, bicycling, and taking taxis and transit.

9.4 PUBLIC (REGULAR) PARATRANSIT

Three different modes represent public paratransit (i.e., service adjustable to individual user’s desires that is open to the general public): taxis, jitneys, and hybrid (dial-a-ride) services.

9.4.1 Taxis

The taxi is the oldest form of public transportation, stemming from for-hire horse-drawn coaches in west-

ern cities, rickshaws in Far Eastern cities, and, similar vehicles.¹ For their introduction, taxis require lower demand than any other public mode. Therefore they are operated in many small towns as the only mode of public transportation.

Taxi vehicles are always designated either by color, by sign on the door or the roof, or by some other special symbol. In some cities taxis are specially designed vehicles. In London they have a separated passenger compartment, easier entry than standard passenger cars, and easily accessible luggage space. Some U.S. cities use specially designed taxis with easy entry/exit.

Taxis offer service either at taxi stands—specially designated areas usually in the vicinity of major taxi trip generators such as hotels, transit and railroad stations, airports, theaters, and stadia—or by cruising streets with a sign showing that the vehicle is available. Most taxi systems have a dispatcher who is in radio contact with the entire vehicle fleet and assists in its distribution throughout the service area. He or she also handles telephone calls for service. An automatic vehicle location (AVL) system is increasingly used, both for efficient dispatching and enhanced security.

The service taxis offer is entirely individualized: the user is transported wherever and whenever he or she wishes. This feature makes taxis unique and gives them a certain role in cities of all sizes. Various business trips, night trips, or travel to special locations and special services (carrying luggage, emergencies) can be served by taxi better than by any other public mode. The necessity to have a driver for such individual trips makes taxis inherently labor-intensive and much more costly than other modes.

Taxi services are regulated by public bodies with respect to some or all of the following items:

- Entry of new drivers and vehicles into the taxi fleet or licensing of drivers
- Driver training and competence

- Area in which each taxi company can operate
- Locations of taxi stands
- Rates
- Vehicle safety standards

Control of entry, which has a major influence on the number and role of taxis in a city, varies from no control (e.g., Washington, D.C.) to a fixed number of licenses (New York has had approximately 11,800 licensed taxis since 1937). Weak control of entry results in a much greater number of taxis and usually lower rates but also lower control of rates actually charged, less control of vehicle safety, and lower driver earnings than with the strict regulation of entry.

Taxi systems in different cities also vary widely with respect to driver training. At one extreme, some cities do not require any special driver training, safety awareness, knowledge about the city, courtesy, etc.; at the other extreme, each candidate can become a taxi driver only after successfully completing a training course that includes safety aspects, intervention in emergencies and courtesy as well as thorough familiarity with the city, its streets, and its landmarks. The best example of the latter case is London.

Strict public regulation and control of taxi fares are particularly important. If no adequate control exists, overcharging of passengers is a frequent and highly objectionable phenomenon inherent and deeply entrenched in this mode of transportation in many cities of the world, from New York and Mexico City to Cairo and Rome (Photo 9.1). The problem is particularly difficult, since a large portion of taxi passengers are not regular users and many are nonresidents. Fares are usually dependent on a combination of trip length and time. In a few cities (Washington) zonal fares are used: the city is divided into zones and fares are determined by the number of zones traversed. However, this problem of overcharging has been successfully solved in many cities by introduction and regulation of meters which clearly display the amount passenger has to pay.

Compared with private automobiles, taxis have slightly higher social costs with respect to congestion, air pollution, and noise, since they perform more vehicle-km per passenger-km of travel and often delay traffic during pickup and dropoff of passengers. But they have a significant advantage in requiring virtually

¹ Some nonmotorized forms of taxis are presently used in many cities for sightseeing: horse-drawn coaches in New York, Philadelphia, and Vienna; rickshaws in many Asian cities; tricycles in Honolulu.



Photo 9.1 Taxi in Philadelphia (Courtesy of Christopher Puchalsky)

no parking; only taxi stands occupy certain street or off-street areas. It is difficult to compare taxis with transit, since they perform quite different types of service and have different roles in urban transportation, but the main characteristics of this mode can be summarized in general terms shown on the following page.

In some cities taxis can pick up and drop off other passengers along the way while carrying one party. This practice modifies and decreases the importance of the first positive feature above. However, if lower rates apply for such service, the importance of the first negative feature listed above may also be decreased.

In many cities in Germany, The Netherlands, and some other countries taxis are integrated with transit in several ways. Taxis are sometimes used to replace buses at times of very low ridership, as in late evenings. Joint fares are sometimes used, despite organi-

zational and accounting problems of such setups. It has been found that cost reduction can be achieved when the number of bus passengers is small enough to be carried by one or two taxis. However, as soon as more taxis must be used, the cost advantages disappear.

9.4.2 Jitneys

In many cities in developing countries—particularly in Latin America, Africa, and the Middle and Far East—substantial portions of public transportation are performed by various types of jitney services. They are known under different names: *publicos* in San Juan, *por puestos* in Caracas, *jeepneys* in Manila, *dolmus* minibuses in Istanbul, group taxis and minibuses in South Africa.

From the passengers' point of view, *taxis have the following positive and negative features* in comparison with other modes:

- + Fully personalized service: travel at any time from/to any place (door to door).
- + No need to own, drive, or park a vehicle.
- + Service, in most cases, easily available.
- + Very convenient for transporting luggage.
- The highest price of all modes.
- Reliability uneven: at certain hours or in certain areas unavailable.
- Insecurity about being overcharged for the trip where fare meters are not used.
- Some drivers refuse to take passengers for less remunerative trips than others they expect to obtain.

Jitneys are passenger automobiles, vans, or minibus-type vehicles (capacity from 5 to 15 seats) driven by individual private vehicle owners or operated by a number of companies along predetermined routes (often major streets or avenues), sometimes with limited distribution from the route alignment on demand of individual passengers toward the ends of routes.

Jitney vehicles are usually distinguishable either by signs or color, or they are vehicles of unique design (e.g., Hong Kong, see Photo 9.2). Their organization varies greatly among cities. In some cities they are owned by hundreds or thousands of individuals or small companies and have little coordination. There are even fights among different groups competing for customers and service areas. In other cities, individual jitney owners and operators are coordinated by an umbrella organization for joint vehicle purchases and maintenance as well as service coordination. It is typical in many Asian, African, and Latin American countries for jitneys not to have high standards of safety and reliability; the maintenance of their vehicles and qualifications of their drivers are lower than those of public transit agencies, where these are reasonably well organized.

A special problem with jitneys is that they are not a system: in cities like Lima, Mexico City, and Manila, their number is not known and they cannot be organized into a high-quality transit network service. As a consequence, any substantial upgrading from the cha-

otic jitney services to a high-quality bus or rail system requires full control of jitneys, followed by their elimination.

Jitneys usually serve rather heavily traveled corridors. Because of their small capacities, they operate in large numbers and provide frequent service with few stops. In some cities (e.g., Mexico City, Caracas) they have designated stop locations; in most other cities, they stop anywhere along the street. This creates a considerable safety hazard and disturbance to other traffic.

Typical jitney services characteristics can be described as follows. Their *service frequency* and *speed* are higher than those of buses at most times of day. Their *regularity* and *reliability* are usually much lower, because during periods of low demand (e.g., late evenings) jitney owners tend to avoid providing the service.

The *comfort* of jitneys also varies considerably, but it is generally much lower than in modern transit vehicles. Many jitney vehicles have boarding/alighting as slow as passenger cars. All passengers are seated, but overcrowding, even up to 50% over the legal number of seats, is common in some cities (Lima, Manila). Riding comfort also varies. In a few cities with passenger cars used for jitney operations (Mexico City, Cape Town), comfort is good. In many other cities (Manila, Atlantic City) jitney vehicles are various types of vans or jeeps with hard suspension and seats, in some cases even hard benches. (Photo 9.3).



Photo 9.2 Specially designed and painted jitney vehicles in Hong Kong (Courtesy of Huafang Cui)

Compared to transit buses in the same cities, jitneys often offer distinctly different comfort. In some cities, jitneys always provide seats, while buses are heavily overcrowded (typical for many Asian cities); in others, jitneys are often overcrowded while spacious, air-conditioned buses have more seats available (San Juan). This factor, together with other service features and fare levels, often results in separation of the two services into two different classes: one for the “better-off” population, the other for low-income passengers.

The *fares* for jitney services are either the same or higher than those for buses. They are determined by public regulatory bodies, but, like taxi drivers, jitney drivers have in some cities a tendency to overcharge

uninformed passengers (the phenomenon sometimes deceptively called “flexible pricing”).

Traffic congestion is often intensified by jitneys. Operating in large numbers and stopping frequently at any location along the usually busy streets they serve, jitneys are major contributors to the chaotic traffic conditions typical of many cities in which they operate (Caracas, Damascus, Istanbul, Manila). In this respect they have a much stronger negative impact than buses.

The *economics* of jitneys, observed externally, appear to be superior to those of buses or conventional transit in general. They operate in most cases on a self-supporting basis, while transit in the same cities usually receives public financial assistance. This



Photo 9.3 Manila jitney (Courtesy of Michelle Lyles)

difference is, however, caused by the fact that jitney owners' average hourly earning is much lower (typically about half) than the wages of transit personnel. The former are private operators, often *without any training*, many of whom may also hold other jobs; the latter are trained professional drivers whose wages are determined by established pay scales or labor union contracts. In many cases the economic situation of jitney operators is so marginal that a failure of a regulatory agency to approve an increase in fares as costs increase may result in a rapid decrease in jitney fleet size because many individuals are forced out of business.

In conclusion, in many developing countries, jitneys provide a service similar to that of regular transit buses on the same or similar routes. Contrary to some beliefs, they usually do not serve very low density routes: their primary areas are moderately or heavily traveled cor-

ridors. Their main advantage is frequent and fast service, but in all other respects (reliability and regularity of service, safety standards, comfort, information about services and fares, etc.) they represent a service that is of lower quality and lower permanence than a competently operated regular transit system. Moreover, jitneys are usually not easily accessible to other than regular captive users.

In the United States, jitneys were operated in large numbers in several cities around 1915, but they were prohibited by regulatory agencies in most cities by the early 1920s. The reasons for this prohibition were logical. The conditions of operation of jitneys parallel with streetcars were typical for all competitive operations of private enterprise and public utility. Regular transit vehicles (streetcars) were obliged to operate on exactly specified routes, including heavily as well as lightly traveled ones, with announced headways

throughout the day. Thus they operated services with various financial results, including a number of non-remunerative ones. They had to provide public service under specified conditions.

Jitneys, on the other hand, concentrated on serving the most financially lucrative routes: busy routes during busy periods, often collecting passengers at street-car stops. Claiming that they represent a “free enterprise system,” jitney organizations collected the “cream of the crop” of the transit business, leaving the uneconomical services to transit. They claimed higher efficiency of operations, neglecting to mention the differences in the extent of provided services, in reliability and safety standards, as well as in earnings of drivers and other personnel. As in the case of some other utilities, such uneven competition is not tolerable, since it leads to the gradual deterioration of transport services in the city as well as to economic problems of operators and many negative impacts of reduced mobility.

During the 1980s, there were numerous proposals that public transportation should be deregulated to make regular transit services and operations similar to those of jitneys. Opening the doors to “free competition” (actually only private competitors would be free of obligations) would, it was argued, lead to efficient services and elimination of the need for public financial assistance. These proposals were implemented in British cities except London in 1986, and they led to the results transit professionals had predicted: reduction of deficits but a loss of ridership of over 30%, caused by deteriorated, uncoordinated services and higher fares.

As the opponents of deregulation in Great Britain had warned, its implementation recreated the very problems that forced the introduction of regulation some 60 years earlier. Its promoters also ignored the fact that the experience of recent decades has been that urban public transportation is best provided by fully integrated and coordinated services of all modes, rather than through unregulated competition of numerous competing companies and modes, only one of which (public agency) is legally required to meet certain obligations. This results in chaotic services for passengers

and in an increased total cost of transportation. (For more discussion and list of other references on this topic see Vuchic 1999 and Vuchic 2005, Chapter 9.)

Consequently, jitneys have an important and sometimes even dominant role in urban transportation where:

- Labor is very cheap.
- Regular transit offers inadequate level of service or it is very costly to operate due to excessive wages, obsolete labor rules, or corruption.
- Requirements for regularity of service, comfort, safety, and so on, are not high.
- It is desirable to have two types of transit service with different performance/quality and different fares, similar to intercity railway and air transportation, to meet two different markets. This is the case in many developing countries where regular transit has very low fares, largely for social reasons, but it is overcrowded and of such quality that it cannot attract any person who owns a car or other type of vehicle (choice rider). A higher quality of service, such as high availability of seats, air conditioning, etc., can attract choice riders even at considerably higher fares. A similar phenomenon of two service types is found in some cities of industrialized countries: buses, trains, or boats are sometimes offered with guaranteed seating, express runs into the city or to the airport, and so on, at a higher fare.

Since these conditions seldom exist in European and North American cities, jitneys at present have practically no applications on either of the two continents. Among very few jitney services in the United States are a single line in Atlantic City (Photo 9.4), and a large jitney system in Puerto Rico.

Some interesting developments that illustrate the relationship between transit and unregulated jitneys took place during the late 1980s and early 1990s. In some U.S. cities, such as New York and Miami, large unregulated jitney operations developed during the 1990s. In the case of Miami, these were later integrated into the regular transit network by hiring many of the jitney



Photo 9.4 Jitney vehicle in Atlantic City

operators as drivers. In the case of New York, they were attractive when the transit agency required separate fares for subways and buses. With the introduction of Metrocard, which integrated intermodal fares, the demand for jitneys subsided. These cases demonstrated that jitneys attract passengers when regular transit fails to provide convenient and reasonably priced services. The appearance of illegal jitney services should therefore be seen by transit planners as evidence of shortcomings in the regular transit network.

In Mexico City, transit bus services deteriorated during the 1980s. Under strong financial constraints on the city with the drop in the value of the peso in 1994 and pressures by the World Bank, which promoted “self-supporting” transit, regular transit was deregulated, leading to the introduction of a huge number of buses and minibuses (jitneys) operated by many companies and individuals (Photo 9.5). There are no statistics about these services, but rough estimates are that

there are 25,000 to 30,000 of them. They replaced buses on many lines and even attracted passengers from the Metro. However, the low quality of services with respect to safety, reliability, and increased traffic congestion led to the introduction of a very successful BRT line and efforts to return to high-capacity buses on fewer but better-organized lines than jitneys can offer.

Jitneys are extensively used in many other developing countries as a supplementary (or competing) service with regular transit. Photo 9.6 shows minibuses typical for African cities. Their use reduces but does not obviate the need for higher-performance transit modes such as bus and rail transit. This has been shown by the recent construction of RRT systems in such cities as Caracas, Hong Kong, New Delhi, São Paulo, and many others; LRT systems in several Egyptian and Turkish cities; and BRTs in São Paulo, Curitiba, and Bogota. All of these high-performance systems required substantial investments, but they re-



Photo 9.5 Mexico City minibus

sulted in the upgrading of entire transportation systems and improved quality of life in these cities.

9.4.3 Dial-a-Ride and Other Hybrid-Type Services

Even low-density areas with fully saturated auto ownership have a certain demand for travel by public conveyances. However, that demand is so dispersed that regular transit bus service cannot provide a minimum service frequency at a reasonable cost/revenue ratio. In some suburban areas, bus operations are also difficult because of poor street network designs. The construction of many enclosed suburban areas and dead-end streets makes transit service by regular bus lines very difficult. Although taxis can serve this demand, their fares are too high for regular everyday trips. Dial-a-ride (DAR), route deviation, and other services with variations in methods of obtaining, scheduling and routing them represent a mode designed to meet this demand and thus fill the gap between the



Photo 9.6 Minibuses for suburban and intercity transit in Stellenbosch, South Africa.

types of services that taxis can offer on the one hand and regular bus services on the other. As travel density increases, the hybrid services become more expensive and operationally inferior to fixed-route (usually regular bus) services.

A DAR system consists of a control center, facilities for vehicle maintenance and garaging, and a fleet of vehicles that serve a geographically delineated area (Photo 9.6). The vehicles may be physically the same as taxis (i.e., passenger automobiles), vans, or small-to medium-sized buses, seldom exceeding 20 to 25 seats. Most passenger trips are ordered by users calling the control center by telephone and informing it about their trip origin, destination, and desired departure time; a few services, such as those distributed from a transit station, can be organized by direct communication between passengers and the driver. Subscription service, where passengers request the same service on a regular (e.g., daily or weekly) basis, is also possible on most DAR systems.

There are two distinct types of routing of DAR vehicles:

- *Many-to-many*, or travel among dispersed points within the service area
- *One- or several-to-many* (and vice versa), where radial travel to one major generator (airport, suburban rail transit station, CBD of a small town, major activity center, etc.) is served.

Many-to-many is a more diversified service, but it is more costly than several-to-many because it has a 1.5 to 2.0 times lower passenger-km/vehicle-km ratio.

DAR operates as follows. Service area of the system, its method of operation, fares, telephone number of the control center, and other pertinent information are announced to the residents or visitors in the area. Persons who want to travel (as soon as possible or at a later specified time) call the center and inform it about the desired trip. Initially, a dispatcher in the center, who had a good knowledge of the area and traffic conditions in it, recorded this information on cards or some other filing system and scheduled the vehicles under his or her control to pick up and drop off as many passengers on a single trip as is possible without exceeding a reasonable circuitry of travel for any one passenger. At present, call taking is increasingly separated from dispatching with information technology linking the two.

It has been hypothesized that the dispatching can be better performed by computer than manually as

soon as the fleet reaches five to six vehicles. Practical experience in several towns has shown, however, that this boundary between computer and manual dispatching is considerably higher than initially believed, for two reasons: first, the ability of a well-trained, capable dispatcher to schedule multiple trips had been underestimated; second, it was very difficult to prepare computer programs that included not only details of the street network but also varying traffic conditions at different times. This problem has been ameliorated with the introduction of automatic vehicle location (AVL) or the geographic information systems (GIS), which provide continuous information on locations of all vehicles and traffic speeds. Experience and studies have shown that with these monitoring devices, the boundary between manual and computer dispatching is in the order of 30 vehicles (Lave et al. 1996).

The main positive feature of DAR is that it usually provides door-to-door service for a lower fare than that of taxis. This is possible, however, only due to ride-sharing by several passengers, which in turn imposes a certain delay and circuitry of travel for most trips. A good illustration of this problem is found in Ann Arbor, Michigan, on one of the best-known DAR hybrid systems. The former transit system consisting of bus routes was replaced by a combination of fixed routes and DAR services. The system is considered to be successful because it had a substantial increase in ridership, but some riders believe that uncertainty in vehicle arrival times, telephone (waiting) problems, and circuitous routings are unacceptable trade-offs for the door-to-door convenience of DAR (Photo 9.6).

Reliability and directness of DAR service can be increased, of course, by the deployment of more vehicles, but this increases the already high costs of DAR services: as of 2006, the typical cost of providing DAR service amounts up to \$35 per passenger trip for many-to-many services. A practical and ethical question sometimes arises—that is, whether in competing for the same funds, a service provided in suburban areas with higher incomes and very high auto ownership should receive proportionally greater public assistance (in dollars per passenger or per passenger-km) than the regular transit serving the vital central areas, which

contain a much higher proportion of lower-income groups and have a much lower level of auto ownership.

The Americans with Disabilities Act of 1990 (ADA) mandates that complementary demand-response (DAR) service be provided to 0.75 mi (1.2 km) on either side of a fixed route for those who cannot access either the fixed-route stop or board a fixed-route vehicle. Other countries have since passed similar laws.

The experiences from a number of DAR systems during recent years show that DAR can be the optimal mode in providing the following four general types of services:

1. Special services for the disabled. In some cities it has been found that the DAR type of service for the disabled can be of higher quality as well as less costly than regular transit with specially designed vehicles. It should be mentioned here that the category of passengers who require specially equipped vehicles is sometimes referred to as "elderly and disabled." This term is incorrect, since the vast majority of elderly persons (defined as those aged 65 and older) regularly use conventional transit services without difficulties. Actually, a well-designed transit system (with adequate pedestrian accesses to stations, reliable escalators, low-floor vehicles, etc.) provides mobility for the elderly that is much better than any mobility a specially designed system can provide except in small cities and suburban areas. The elderly who cannot use regular vehicles are included in the category of disabled persons, defined as those who cannot negotiate stairs or escalators, board or alight from transit vehicles, stand in a moving vehicle, or walk more than 75 m. If DAR service is provided for the disabled in an area without regular transit service (small towns or suburban areas), it is often advantageous to also make them available to the general public, so that both demands for travel are satisfied by the same system.
2. Exploratory service in areas not served by transit. This can often result in the promotion of transit usage and later introduction of permanent hybrid or regular transit services.
3. Late-night or all off-peak service, substituting very lightly traveled bus routes in low-density areas.
4. Permanent service as an independent system in small cities, as a transit service in suburban areas coordinated with regular bus lines serving the central city (Ann Arbor), or as feeders to suburban rail transit stations (Toronto region). How extensive these services can be depends largely on financing.

For many-to-one, average loads are considerably greater, so that the average cost per passenger trip is lower. Many recently introduced types of transit operations, referred to as hybrid services, combine operating features of demand-driven paratransit and fixed route transit, and they involve lower costs than DAR. These include:

- Services along fixed routes that serve certain stations but may deviate between them to serve individual passengers by request. This is known as route-deviation service
- On-call services that follow fixed routes and operate only when there is at least one request
- On-call services for the disabled leading to accessible stations of rail lines

These hybrid services are, of course, quite different from hybrid propulsion and other dual-mode transit systems.

9.5 EVALUATION OF PARATRANSIT AND ITS ROLES

The present significance, possible improvements, and potential role of paratransit can be best evaluated on the basis of a careful review of its inherent physical and operational characteristics.

9.5.1 Characteristics of Paratransit

The broad range of modes included in paratransit have a great variety of characteristics. While at one extreme carpools can hardly be distinguished from the private automobile, jitneys and hybrid modes offer services

similar to those of bus transit. Yet, observing this entire group of modes, the following characteristics can be established.

The *service is adjustable* to the desires of individual users or groups to various degrees; taxis offer a fully personalized service; jitneys, at the other extreme, make only minor deviations in stopping and sometimes in routing for individual passengers.

With the exception of user-driven modes (carpools, vanpools, and car sharing), the typically small-capacity paratransit vehicles result in *low labor productivity* (seat-km or person-km per driver-hour).

As a combination of personalized service and labor-intensive vehicle operation, most paratransit modes (taxis, DAR) involve a *much higher operating cost per space-km offered than regular transit modes*. Because of this characteristic, paratransit can be operated with reasonable economy in two different forms: first, as a highly priced personal service (taxi) and, second, with regular fares but high passenger turnover and very low drivers' wages (jitneys in developing countries or user-operated vanpools). Regular fares can be applied for public paratransit modes only with substantial public assistance (DAR).

Small vehicles make paratransit well suited for low passenger volumes. Transporting one or two persons a given distance can always be done more efficiently by a taxi-type vehicle than by a 45-seat bus. Only special conditions may distort this inherent operating and economic relationship between the two modes. One such special case is when buses needed for transport of large volumes of passengers during peak hours are available for service at other times: their marginal operating cost may then be lower than the average cost of operating paratransit vehicles. On the other hand, small vehicles make paratransit inferior to regular transit for high passenger volumes. Consequently, under normal conditions paratransit has advantages over regular transit for low passenger volumes, but the relationship between the two modes shifts in favor of buses (and, later, rail) as passenger volumes increase.

Operation on streets and highways without special facilities gives paratransit several advantages as well as several drawbacks in comparison with transit modes that can or must utilize separate ROW. Operation on existing facilities in mixed traffic allows the *introduc-*

tion of paratransit without any significant investment in fixed facilities and thus involves *no delays due to construction*. This is a very significant advantage, particularly for situations in which short-term improvements of transportation are needed.

The disadvantages of using existing facilities are, however, also very significant, particularly where a permanent improvement of public transportation is required. As long as paratransit (or any other public transport mode, for that matter) operates in mixed traffic, it *cannot offer a higher LOS than private automobile*: it is subject to the same congestion, delays, safety hazards, and so on, as auto traffic. Separate lanes and roadways for transit buses and paratransit vehicles, operated in several U.S. cities, partially offset some of these disadvantages because they reduce the probability of congestion and delays.

9.5.2 Potential Improvements

In many cities different actions can be undertaken that would result in increased use of paratransit and improved urban mobility in general. Most of these actions are of an organizational nature; only a few concern hardware changes. The most important of these actions are discussed here.

Transportation planning and regulatory agencies should *treat paratransit as an integral component of a coordinated urban transportation system*. Instead of the currently prevailing attitudes that paratransit is generally "allowed to happen" but not carefully planned and coordinated, planning agencies should intensify their efforts to determine the potential short-term transportation improvements that paratransit can offer as well as to define the optimal role of paratransit in relation to auto on the one hand and transit on the other in long-term transportation development. Paratransit should not duplicate and compete with transit; rather, it should complement and support it.

Changes in regulations that are needed actually vary widely among cities. In many cases legal restriction on the number of taxis should be relaxed or eliminated, but control over the quality of drivers and safety and comfort of vehicles should be intensified. In some cases rates or fares for paratransit may be made more

diversified to better respond to the nature of the demand, but strict control of their implementation must be retained and often improved. Control over individual competing paratransit services must be retained to achieve the best coordination instead of wasteful competition among modes or agencies.

Coordination among modes can also be advanced by the *introduction of a transit federation or brokerage agencies*, which have the specific task of optimally allocating to different operators those services for which they are best suited. This applies primarily to small towns and cities.

Publicity and information about paratransit should be intensified for two purposes: first, to inform the public about the services, particularly because of their rather invisible and “flexible” nature (many routes and no fixed schedules), and second, to create a better image for these modes and eliminate the feeling that paratransit is “inferior” to private auto.

Favoring of paratransit over private auto use can be introduced through two sets of measures. First, provide priority treatment for paratransit where this is feasible (special lanes, reduced parking rates). Although limited in scope and difficult to enforce, these measures may be helpful in many situations. Second, introduce various disincentives for private auto use (elimination of private cars from certain streets and areas, higher tolls and parking rates).

Vehicle designs improving the efficiency of paratransit is a neglected but important measure. Most paratransit vehicles today are modified versions of vans or new bodies on truck chassis. Purpose-built vehicles are rare, probably due to absence of the large orders needed to sustain mass production. A number of various special features can be introduced. For example, taxis should have easier entry, accessible luggage compartment (as in London), better signage, shorter body for easier maneuvering in traffic and while parking, and so on.

9.5.3 Present and Potential Roles of Paratransit

Summarizing the preceding discussion, primary applications of paratransit can be classified into the following categories by the type of service they provide.

1. *Fully personalized high-fare public transport service*, offered by taxis in all cities. It parallels transit, but does not compete strongly with it because of differences between the two service/price “packages.”
2. *Basic public transport service in small cities* that do not have regular transit systems.
3. *Supplementary service to transit* (car sharing, DAR, leased buses or trains for groups, etc.) provided by paratransit in the form of suburban feeders or substitution of lightly used lines in the late evening periods and on Sundays. However, public paratransit is seldom a more economical alternative to transit along moderately busy and heavily traveled corridors during peaks or other daily hours. The marginal cost of carrying additional riders by transit during peaks is always lower than the operating cost of paratransit modes because of the previously discussed labor intensiveness of the latter. Semipublic paratransit modes that are operated by users (vanpools) utilize “free labor” and can therefore sometimes have lower costs, particularly if transit agency has high wages and obsolete labor rules (e.g., no part-time drivers).
4. *Airport shuttles*, such as vans, minibuses, and buses, play an important role in providing access to airports from a number of focal points or MAC’s, such as CBD, shopping malls, convention centers, and others. This is particularly the case in North American cities with high air travel volumes and typically large low-density suburbs. These paratransit services can provide more links to airports in their suburban locations than regular transit lines, and if properly organized, they can replace many private shuttles provided by dozens of hotels, stores, business and shopping centers, etc.
5. *Specialized services*, such as those for the disabled, which can be provided by paratransit (subscription vans, DAR or hybrid services) better than by any other mode. Although more expensive than regular transit on a per space-km basis, paratransit can usually offer both lower total cost and higher LOS for the personalized service dis-

abled persons require. Hybrid services that carry the disabled with other passengers also serve the social goal of “mainstreaming” the disabled.

6. *Commuter travel*, provided by semipublic paratransit modes (vanpools, subscription buses) and by carpools for major employment centers at locations that transit cannot conveniently serve. Paratransit can thus reduce the problems of total dependence on private automobiles created by deficient city planning and poor coordination between land use and transportation.
7. Considerable potential exists in *coordinating school and university bus services and with both paratransit and transit*. It is sometimes possible to use school buses for subscription services at various times (Miller 2001). On the other hand, a substantial portion of school trips can be served by transit. This is a standard practice in most European countries. In some cities, schoolchildren represent up to 30% of total transit patronage. Thus transit has additional riders, children become more familiar with their city and its transportation system, and the need for operation of special school buses is greatly reduced or eliminated. In the United States, however, this is a standard practice only in central

parts of large cities, while the suburbs and smaller cities have enormous school bus fleets that involve high costs and have very low daily utilization. An extreme case is found in California, where the Highway Patrol does not allow transit buses to enter school grounds.

Major transfers of schoolchildren traveling from special school buses to public transport services could in many areas result in significant reductions of school costs, improvements of paratransit and transit services, and many other positive consequences. In some cities, such transfers could be organized rather easily; in others, this could be achieved only if transit services and information about them were first improved and carefully prepared for this additional category of passengers.

In all its applications, the greatest benefit can be obtained from paratransit if it is carefully coordinated with other modes, particularly with regular transit. Indeed, this is the purpose of hybrid services: their integration and bridging of the separation between regular transit and paratransit. In particular, paratransit feeders to accessible transit routes and transit routes that permit deviations for the disabled or for other riders under certain conditions are likely to be increasingly used.

EXERCISES

- 9.1. Define semipublic paratransit, describe its characteristics, and list several of its modes.
- 9.2. Utilizing the case of Reston subscription buses, describe how a single commuter bus service can grow into a regular bus line through a series of incremental changes. Describe major developmental steps that would logically result from ridership increases.
- 9.3. Analyze taxi service in a city you know well and determine whether it is adequate with respect to:
 - a) Availability (how easy it is to get a taxi on the street or by phone at all hours)
 - b) Level and structure of fares
 - c) Condition of vehicles (comfort, safety, cleanliness)
 - d) Training of drivers (driving manner, courtesy, knowledge about the city, fare collection)
 If you find deficiencies, propose measures to improve them.
- 9.4. Describe car sharing and explain how it is used. What types of trips does it serve? What are its typical subscribers? How does car sharing relate to transit and to car ownership?

- 9.5.** Describe the dial-a-ride (DAR) mode, list its characteristics, and define its optimal types of applications.
- 9.6.** A medium-sized city has for many years operated several bus lines without much change or any marketing efforts. You are asked to promote public transportation by any modes and means you consider appropriate to improve population mobility and decrease the use of private automobiles. Assuming that you have moderate funds for improvements, describe the steps you would undertake. Focus on the introduction of paratransit modes (vanpooling, taxi, DAR) and their full coordination and mutual support with the regular bus lines (existing or expanded and restructured services).

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10

CHARACTERISTICS AND COMPARISONS OF TRANSIT MODES

The evaluation and selection of transit modes affects the type of network and services, and it is therefore usually the central phase of the transit planning process. Its importance is great not only with respect to investment costs and system performance but also by the impact the transit system will have on the future shape and character of the city and the quality of life in it. This is particularly the case with respect to high-performance modes, specifically rail and other systems with their own infrastructure, which is permanent and therefore has much stronger impacts on areas they serve and on the entire urban region than transit modes operating in street traffic.

The basic mode characteristics were presented in Section 2.3. Chapter 12 in Vuchic (2005) also has a description and comparisons of modes. Because of importance of this topic, this chapter has some overlaps with the two mentioned references. It focuses particularly on medium- and high-performance modes, which generally correspond to modes utilizing ROW categories B and A, respectively. An evaluation of the increasing use of fully automated systems is also given.

In the last section there is a discussion about the progress in planning the increasingly complex and diverse transit systems, and about misinformation and attacks on transit by special interest groups and ideological extremists. The need for rational systems approach in mode selection is pointed out in the closing.

10.1 BASIC ELEMENTS OF TRANSIT MODES

Most comparative analyses and selections of transit modes focus on medium- and high-performance transit systems, because they involve substantial investments and permanent commitments. The basic elements considered in this process can be grouped in three categories:

- **Level of service (LOS)** required for passengers;
- **Performance cost package (PCP)**; and
- The **role transit should play** in the city's functioning and development.

These categories underlie the discussion of this section, which presents a review of transit mode characteristics related to their physical and operational features, which are defined in Section 2.1 and applied in the description of evolution of urban transportation modes in Section 2.2.1. This material is developed here in more specific detail for application in the comparison of medium- and high-performance modes.

10.1.1 Significance of Right-of-Way Categories

In most cases, the ROW, or travelway, is the most fundamental transit system element, because it strongly influences each mode's PCP. Moreover, the ROW type interacts with the other two elements, system technology and service/operation.

Transit modes with ROW category B compared to those with category C have the following advantages (+) and disadvantages (–):

- + Considerably higher performance: speed, reliability, capacity, riding comfort, safety, etc.
- + Ability to operate trains of two to four vehicles (rail systems only).
- + Stronger identity and image, which, combined with higher performance, results in higher passenger attraction.
- + Lower operating costs per passenger.
- + When rail technology is used, these modes are electrified, providing high vehicle performance and no air pollution, so that they can be operated in tunnels.
- They require space for their ROW.
- They involve higher investment.
- They may require special signals or other control and priority measures.

Street transit modes, operating on ROW category C, represent the basic type of transit, exemplified by **buses, trolleybuses, and streetcars or tramways**. These modes require low to moderate investment. In addition to vehicles, items requiring investment on bus lines are equipment at transit stops and, in some cases, signs/signals provided specifically for transit vehicle operations and their priorities over other traffic. Trolleybuses also require investments in overhead wires, while streetcars also need more substantial investment in tracks.

Street transit performance depends greatly on traffic conditions along its lines: if there is congestion, service is unreliable. Operating speed is always lower than the speed of other traffic because of the time transit vehicles lose at passenger stops.

As a result of such performance and the lack of permanent distinguishing features of these services, street transit is generally not competitive with respect to speed and reliability with auto travel on the same streets. The balance between the two modes can be maintained to some extent by providing transit priorities at intersections and other critical locations as well as by parking restrictions or charges in the served areas.

Modes having ROW category B, including LRT and BRT, represent **semirapid transit**. Since most or

all of the ROW for these modes have infrastructure, their construction involves considerably higher investment costs than street transit. However, the performance of semirapid transit is also much better than that of street transit due to very low interference by other traffic. Particularly important for passenger attraction is the fact that most semirapid transit modes, particularly LRT, have a **distinctive, separate and permanent ROW** and therefore a **much stronger image** than street transit. The differences between the two ROW categories are summarized above.

Most modes with ROW category A represent **rapid transit**: independent guided systems with high-capacity trains, usually operated at short headways. This group is known also as metro [and in individual cities as subway, subway-elevated, MRT (mass rapid transit), U-Bahn, etc.]. In most cases these use rail technology and high-capacity trains.

Systems with ROW category A generally have similar differences from ROW B as B has over C, but expressed to a greater extent (see the box on page 523).

Transit planning varies greatly among the three basic mode categories. Street transit systems, not involving much infrastructure, are generally planned in the short term and can be relatively easily extended or modified. Semirapid and rapid transit systems, however, involve infrastructure planning and construction,

Features of transit systems with ROW category A compared to those with category B have the following advantages (+) and disadvantages (–):

- + They are free from any obstacles, systems on ROW category A have the highest performance (speed, reliability, capacity) of all modes.
- + All rapid transit systems utilize electrically propelled guided technologies with very high dynamic performance.
- + The absence of any interaction with other traffic and the use of automatic train protection results in the highest safety among all transit modes.
- + Exclusive ROW allows the operation of long trains with multiple doors at platform level, resulting in rapid passenger exchange and short dwell times.
- They require by far the highest investment costs, due to exclusive facilities along entire line length.
- Rapid transit line alignment is more geometrically rigid, requiring mostly the use of tunnels or aerial structures in central cities.
- Stations are grade-separated, may require land purchase and involve longer access to stations than LRT on ROW B, which can penetrate pedestrian areas.

which require substantial financing and take time. Those systems are permanent, and can have major positive impacts on the city. Their efficient design is therefore very important. The mistakes, such as an alignment that results in inefficient operations or has undesirable impacts on the surroundings, may have permanent negative consequences.

Inherent differences among the basic characteristics of transit modes grouped in the three ROW categories are expressed by simple descriptive terms in Table 10.1.

Some transit modes, such as most rubber-tired AGT systems and specialized modes such as funiculars, have

ROW category A, but they are not classified in the rapid transit class because they have small or medium capacities (500 to 10,000 sps/h, exceptionally higher) and are operated with small vehicles and short trains. Moreover, many AGTs have only moderate speeds.

The terminology used for transit concepts and modes requires clarification. Technical terms for transit modes utilizing ROW categories C, B, and A are, respectively *street transit*, *semirapid transit*, and *rapid transit*. Popular designations, often intended to enhance popular image, confuse these technical definitions. For example, several cities in the United States have “rapid transit agencies,” which operate regular

Table 10.1 Characteristics of transit systems with different ROW categories

Characteristics	ROW Category		
	C	B	A
System performance: capacity, speed, reliability, safety	Moderate	High	Very high
Investment cost	Low	High	Very high
Level of service	Moderate	High	Very high
Image/identification	Moderate	Good	Very strong
Passenger attraction	Moderate	High	Very high
Potential impact on urban form	Weak	Strong	Very strong
Full automation possibility	None	None	Full

buses only. The Dallas Area Rapid Transit (DART) operates an LRT system and a network of regular bus lines but not rapid transit. Similarly, several cities in Germany use the term *U-Bahn* (rapid transit) for LRT (Stadtbahn) systems to improve their image.

The currently strongly promoted bus rapid transit (BRT) refers to buses operated in semirapid transit mode. Technically, that is *semirapid bus transit* system (BTS). By strict definition, no bus system is rapid transit because none has ROW A on its entire length.

Thus, popular names of transit systems sometimes deviate from their technical definitions. Distinct names are also sometimes adapted for “personal designations” of some transit systems. For example, the term *metro*, standing for *metropolitan railway*, is also the “personal name” of Metro systems in Paris, Moscow, and Washington, as is *MAX* for the LRT in Portland, Oregon, and *Metrolink* for the St. Louis LRT and the Commuter Rail in Los Angeles.

10.1.2 Transit Systems Technology

The four basic technical elements that influence system performance and interact with ROW category and system operations are reviewed here, emphasizing their operational characteristics.

10.1.2.1 Vehicle Guidance. With respect to guidance, transit systems are classified into two very distinct categories: vehicles steered by driver and vehicles/TUs physically led by the guideway. The steered technology systems include mainly paratransit vehicles and buses. Being road-based systems, they can operate on nearly all streets and need investment only for vehicles and little special infrastructure for their physical movement. Bus services can be quickly introduced, modified, or suspended. These factors reduce the need for long-range planning of driver-steered transit systems.

The flexibility of driver-steered vehicles is advantageous on urban streets, because it is conducive to mixing with other traffic and use of any street without investments. That allows these modes to give excellent area coverage and provide extensive services through-

out cities. On the other hand, a lack of fixed facilities is also a strong disadvantage with respect to their performance, image, and passenger attraction. Many potential passengers are apprehensive about using buses operating on a complicated interwoven network. Exclusive bus lanes, trolleybus overhead wires, and especially the tracks of streetcars and other rail modes give LRT and RT lines a strong image, which gives passengers a better orientation in travel. Transit line image becomes particularly strong with independent metro lines. For example, many visitors to Mexico City, Moscow, Paris, or Washington use only the metro networks, transferring to buses only where the metro network does not extend. This attraction is not only caused by the higher level of service that rail systems offer but also by their strong image and easy orientation.

Another limitation of steered technology systems is that they are labor-intensive and have no economies of scale. They can be operated as single vehicles only (exceptionally, there are cities that operate trolleybuses with trailers or in double traction—Lausanne, St. Petersburg, Kiev—but in many countries transporting passengers in trailers is prohibited for safety reasons). Therefore for each additional vehicle, an additional driver is required.

Although road-based transit vehicles do not need a special infrastructure for their movement, it is desirable to provide infrastructure components for their operation in busy corridors, such as designated bus lanes, special signals with priorities, bus-stop bays, signs, etc. When passenger volume is so great that special busways are required, replacement of buses by rail technology systems becomes a logical alternative that should be examined.

Guided vehicle technology (mainly rail) systems, compared to steered highway vehicles, require a considerably higher investment for guideway construction and usually electrification, but they have major physical, operational, and economic advantages (see the box).

In conclusion, construction of a guided (rail) system to replace a steered (bus) system requires investment, but it leads to a transit system of considerably higher

Guided transit systems compared with bus (driver-steered) systems have the following features:

- + Ability to use larger vehicles and operate trains, thus greatly increasing line capacity, providing lower operating costs per space, and offering economies of scale with increasing passenger volumes.
- + Electric traction can be used, bringing major benefits (see below).
- + Guided modes have higher overall performance: speed, capacity, reliability, and safety.
- + Automated signalization provides a fail-safe operation, preventing accidents due to driver error.
- + They require narrower ROW.
- + With exact ROW delineation, no air pollution, or noise, guided systems are better suited to operation in pedestrian areas.
- + Operation in tunnels is feasible without excessively wide cross sections.
- + They provide much better riding comfort.
- + When combined with ROW A, guidance makes fully automated driving possible.
- They require separate ROW (B or A) involving much higher investment cost (except for tramway/streetcar mode).
- They require higher investment due to track/guideway and station construction as well as electrification.
- Their networks are much more limited, requiring transfer facilities and involving more transfers.

quality that attracts a significantly greater number of passengers.

Consequently, buses and minibuses are superior to guided systems for light- to medium-volume passenger transit lines. Their lower investment cost outweighs all advantages of guided systems. For high present or potential passenger volumes, however, guided technology systems represent a superior solution with respect to passenger attraction, economic efficiency, and positive impacts on the city's form and character.

10.1.2.2 Guided Vehicle Support. While all highway vehicles ride on rubber tires, guided systems have several possible types of support and guidance:

1. Steel wheels on steel rails, which is by far the most dominant
2. Rubber tires for support, supplemented usually by the same number of additional horizontal tires for guidance against side or center guiding rails (RTRT, monorails and most AGT systems)

3. Magnetic levitation, used only on a few transit systems

A summary comparison of the two commonly used vehicle support technologies is given on page 526.

For the reasons shown in this comparison, rail technology is by far the dominant one for high-capacity metro systems, while AGT modes, mostly with small-to-medium vehicles (capacities 30 to 100 spaces including standees) and short trains have advantages for shuttle lines in airports, exhibition grounds, and similar activity centers and on short transit lines, such as center-city distributors. Rail and rubber-tired systems overlap by performance on some medium-performance regular transit lines.

10.1.2.3 Propulsion. Most transit systems are powered by different types of internal combustion engines (ICE), usually diesel, or by electric motors. The introduction of compressed natural gas (CNG) or liquid natural gas (LNG) engines on transit buses helps lower

For guided transit modes, rail systems compared with rubber-tired systems have the following features:

- + Rail systems can utilize ROW categories A, B, or C; rubber-tired systems can use only ROW A.
- + Rail vehicles have two to three times fewer wheels with lower resistance, resulting in lower total resistance, energy consumption, and heat production.
- + Rail tracks have very simple switching and crossing mechanisms, while rubber-tire guideways require more space and grade separations in yards. Rail systems are therefore much more conducive to efficient line branching, network, station, and yard layouts. Monorails and AGT systems operate mostly on single lines.
- + Rail systems can use larger vehicles and operate at higher speeds than rubber-tired systems.
- + Rail vehicles provide considerably better riding comfort.
- = Acceleration and braking are similar because they are limited by passenger comfort.
- Rubber-tired systems can negotiate sharper curve radii and higher gradients than rail; this allows them to have more flexible line alignments.
- Rail vehicles produce more noise and vibration in sharp curves.

their emission of air pollutants. Similar to the differences among ROW categories and steered versus guided systems, ICE propulsion requires lower investment but has lower performance than electric propulsion, as the following comparison shows (the same comparison with more emphasis on mechanical than on system aspects is given in Section 3.4.8).

In general, electric propulsion is superior in TU performance in the absence of negative environmental impacts (particularly in high-density areas in cities), in making operation of transit lines in tunnels feasible, and in making pedestrian zones attractive. Again, the lower-investment diesel-powered vehicles are optimal for lightly traveled transit lines. As passenger volumes increase, the investment in electrification becomes economically justified and higher-performance electric traction can be introduced, usually together with the introduction of rail systems with ROW categories B or A. A summarized review is given in the box.

As one of numerous campaigns against high-performance transit in the United States, discussed in Section 10.5.3, there have been claims that electric traction does not have advantages over diesel traction

in considering air pollution caused by electric rail versus diesel bus modes. For a rebuttal of this claim, which contradicts extensive scientific analyses and real-world experiences about the advantages of electric traction, see Puchalsky (2005) and Vuchic (2005, Section 12.1.2.3).

10.1.2.4 Transit Unit Control. All transit modes operating on ROW categories C and B are manually driven, with advisory signals only. Some guided modes use automatic train operation (ATO), which is usually introduced to optimize the travel regime with respect to propulsion, braking, and travel time. Fully automated, driverless transit systems were initially used as APM and AGT systems, but now they are being increasingly introduced as regular transit lines. They use rail or rubber-tired guided technology on ROW category A lines: LRRT and metro modes. The characteristics of automated transit systems are summarized in the second box on page 527.

Clearly, the greatest advantage of fully automated train operation comes from the fact that with it, the cost of operating trains is proportional to the number

Electric compared with ICE propulsion of transit systems has the following differences:

- + Produces higher acceleration and higher operating speed.
- + Allows multiple-unit propulsion and operation of trains.
- + Regenerative braking recovers energy, thus reducing its consumption.
- + Produces no noise and vibration, as most diesel engines do.
- + Produces no air pollution, whereas diesel buses do.
- + Absence of pollution and good dynamic performance makes use of tunnels possible.
- + Electricity can be produced from any primary energy source, thus reducing oil dependency.
- Requires additional investment for electrification of lines, construction of substations, etc.
- Power failure stops all vehicles on a section of line.
- Service is limited to electrified lines, requiring more transfers to feeders.

Fully automated train operation compared with driver-driven systems has the following features:

- + Very frequent operation of short trains is feasible even during off-peak periods.
- + Quick adjustment of TU sizes and schedules to changing conditions is possible.
- + Driving regimes can be optimized for all conditions.
- Fully automated operation requires ROW A.
- Investment cost is considerably higher.
- The presence of a crew member is often desirable anyway for security, passenger information, etc.
- Mechanical and control systems are more complex and require more expensive maintenance.

of cars; therefore long trains, which are more economical when drivers are used, can be replaced by a greater number of short trains without any cost increase. Thus, frequent operation of short trains is feasible even with a much lower passenger volume than on regular transit lines. This feature lowers the boundary of feasible application of high-performance guided transit. The benefits from full automation are thus particularly important on medium-capacity systems. On metro systems with long trains, the presence of an operator is usually desirable for supervising passengers, handling service interruptions, and other reasons. Moreover, the cost of an operator represents a much lower percentage

of operating costs than on medium-capacity systems. Operation without train crews is therefore not as beneficial on high-capacity systems as it is on medium-capacity guided and typical AGT systems. For this reason fully automated operation was first introduced on small-capacity APM and AGT systems. However, the second potential benefit of fully automated operation is the ability to change train sizes according to passenger volume on a line. A line controller can remotely couple or uncouple trains, adjusting the offered capacity to meet the demand, so that a high average load factor can be achieved. This results in a significant reduction in operating costs, particularly on heavily

traveled metro systems where shortening of train consists during off-peak hours can bring significant reductions of operating costs.

These advantages of automation have gradually been accepted by transit systems operators. It also became clear that the advantages of full automation are not related to system technology: the same factors are equally valid for rail as well as rubber-tired guided modes. The first application of fully automated, driverless operation applied to a regular rail transit system was the SkyTrain in Vancouver, which was opened in 1986 and has been extremely successful, largely due to its operation at 2- to 5-min headways throughout the day and its ability to operate different train consists. The SkyTrain was followed by fully automated LRRT lines in Docklands/London, and in Copenhagen and then by driverless metros in Lyon, Paris (RTRT), and Singapore (RRT). This trend toward automated LRRT and RRT modes is likely to accelerate in the future.

10.1.3 Interdependence of ROW and System Technology

A matrix of the three ROW categories and three groups of technology by vehicle guidance (highway steered, partially and rubber-tired guided, and rail), with a special mode category added, is presented in Table 2.2. That table shows that the ROW category and system technology with respect to vehicle guidance are interdependent. On ROW category C, the steered modes—buses—are used mostly because their flexibility of movement and low investment cost are usually more important than the advantages of vehicle guidance. Streetcars/tramways also operate on ROW category C, but to effectively utilize their advantages of guidance, they usually need good traffic engineering and regulation coupled with enforcement.

On the other hand, systems operating entirely on fully separated ROW are always guided. Strictly speaking, there are no bus rapid transit lines (i.e., bus systems operating entirely on fully separated busways) because, for collection and distribution, they are always extended onto surface streets. The reasons for the use of guided modes on exclusive ROW are obvious: once TUs operate on exactly specified paths, flexibility

of movement is not needed, while the advantages of guided technology—such as narrower paths, operation of trains, electric traction, and fail-safe signal control—are very advantageous. Since ROW category A is in most cases provided for a smaller network length of heavily used lines, the benefits of these guided systems features can outweigh the higher investment cost for their additional infrastructure construction and equipment.

The basic relationship between investment costs of the three ROW categories and mode performance were analyzed in Section 2.3.6 and presented with numerous technical details in Figure 2.7. The same type of diagram, but with a simpler overview of transit modes grouped by ROW categories, is shown in Figure 10.1. The box for each ROW category shows generally the area where the PCP for the systems in that category belongs. ROW category C, street transit, requires distinctly lower investment than medium- and high-performance modes using ROW categories B and A, respectively. The diagram shows the problem that occurs when a city uses only buses on streets and rapid transit: the former has relatively low performance, while the latter requires large investment. A large area of medium-performance modes at medium investment levels is provided mainly by LRT, BRT, and AGT modes with their relative PCP positions, as shown.

It is pointed out here that this diagram—as well as most tables, figures, and comparative statements about modes given in this chapter—is general rather than numerically precise. Most numbers are given in ranges, which encompass most transit systems. In many cases there may be examples that are outside the quoted values, but those are usually exceptions and their values usually apply only under certain specific conditions. The descriptive statements about mode characteristics and their mutual relationships are those drawn from exact physical facts and actual experience from many transit systems.

10.1.4 Review of Technological and Operational Features

Following the classifications of modes by their ROW and technology, an overview of the technical compo-

Table 10.2 Technical components of transit modes grouped by ROW categories^a

<i>Mode Category</i>	<i>Characteristic</i> <i>Category</i>	<i>ROW</i> <i>Category</i>	<i>Mode</i>	<i>Support and</i> <i>Guidance</i>	<i>Propulsion</i>	<i>TU Control</i>	<i>Cars</i> <i>per TU</i>	<i>TU Capacity</i> <i>(spaces)</i>	<i>Line Capacity</i> <i>(sps/h)</i>
Street transit		C	Bus, Trolleybus	Road/steered	ICE, electric	Driver/visual	1	80–125	3000–6000
		C	Tram	Rail/guided	Electric	Driver/visual	1–3	100–300	10,000–20,000
Semirapid transit, medium performance		B	BRT	Road/steered	ICE	Driver/visual	1	80–180	6,000–24,000
		B	LRT	Rail/guided	Electric	Driver/signal	1–4	100–720	10,000–24,000
		A	AGT/APM	Guided	Electric	ATO	1–6	50–480	6,000–16,000
Rapid transit, high performance		A	LRRT	Rail	Electric	Signal/ATO	1–4	100–600	10,000–28,000
		A	Metro	Rail	Electric	Signal/ATO	4–10	720–2500	40,000–70,000
		A	Regional rail	Rail	Electric, diesel	Signal/ATO	1–10	150–1800	25,000–40,000

^a Exceptional characteristics, such as guided bus and diesel LRT, and extreme values found in a few cases are not included.

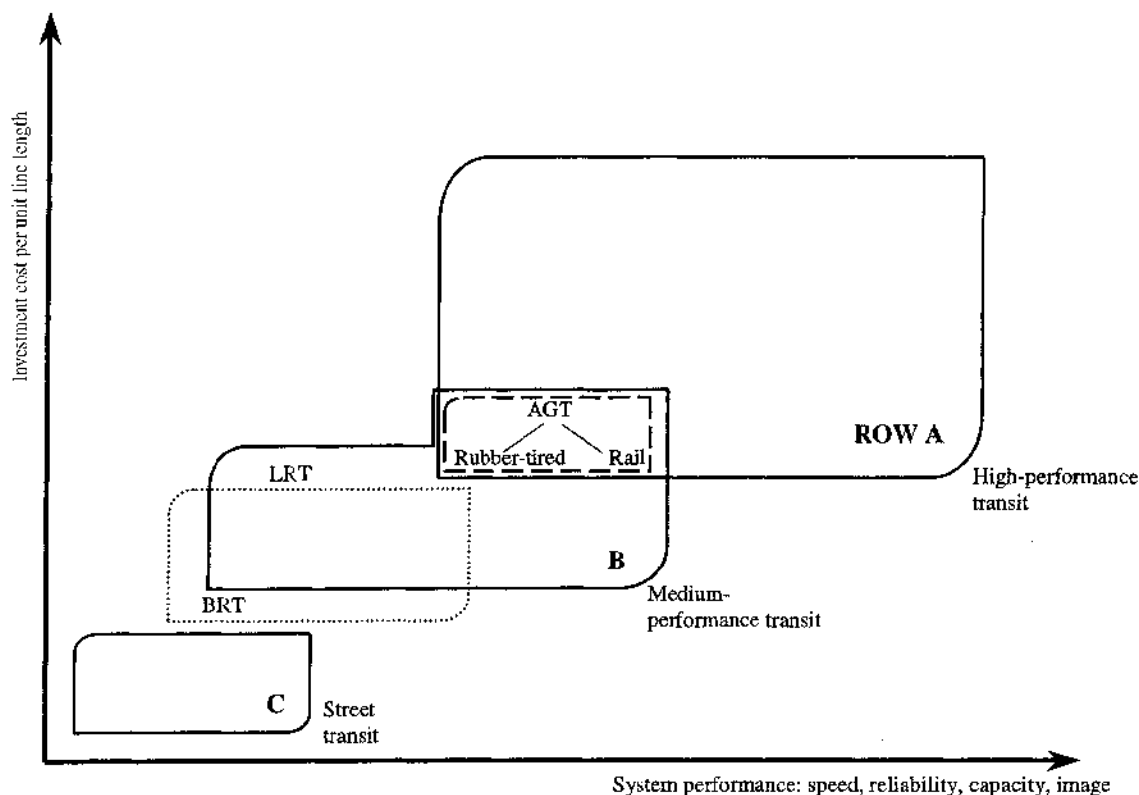


Figure 10.1 Performance-cost packages (PCPs) of different generic classes of transit modes

nents of major transit modes, including their guidance, propulsion, control, and vehicle and line capacities, is presented in Table 10.2.

Most of these elements, grouped in the ROW-technology-service/operation or RTS groups, are presented graphically in Figure 10.2. The diagram shows the sequence of upgrading the system components. Each component has two or three "steps," from lower to higher performance. The interdependence of some components is shown by arrows in the right-hand column. For example, operation of long trains requires ROW A, guided technology, and, with few exceptions, electric propulsion.

This diagram shows several basic transit modes as lines connecting a series of components. Regular buses on ROW category C (RB) can be considered as the

"basic system" that utilizes steered rubber-tired small-capacity (< 100 spaces) vehicles. A variation of bus technology is BRT, which utilizes category B ROW and often has medium-capacity (articulated) vehicles (> 100 spaces).

Most modes with ROW categories A and B, on the other hand, have guided vehicles, steel rails, and electric traction. They operate large vehicles and medium-length to long trains.

Metro or RRT has all the highest elements except that, with a few exceptions, it does not have fully automatic operation (crewless trains). AGT modes are an interesting combination of these components. They have ROW A, rubber-tired electric vehicles that are guided and automatically driven, but also small capacity and short trains. These features are determined for

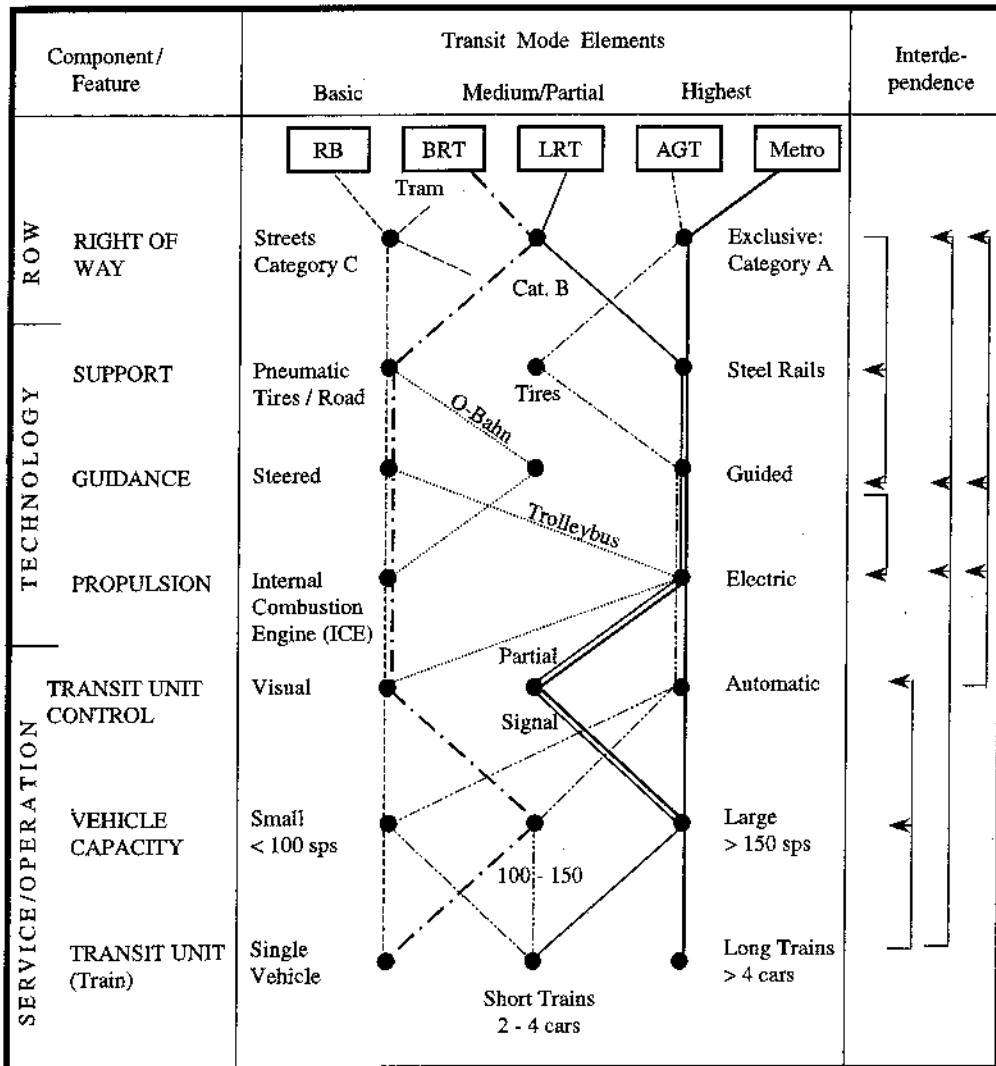


Figure 10.2 Graphical presentation of the physical and technological features of different transit modes

reasons discussed above: serving medium passenger volumes with medium-capacity TUs makes automation necessary for their economic feasibility.

It is emphasized that the modes with basic components (ROW C, steered, small vehicles without signal control) and low PCPs should not be considered “inferior” to those with higher PCPs. They are better

suitable only for transit services that have lower passenger volumes and require lower speeds or less comfort, etc., and where the higher PCP modes are not physically or economically feasible.

A great variety of transit technologies and modes can be considered in planning high-performance transit. However, in many cities the planning process has

been complicated, sometimes confused, and greatly lengthened by considering an excessive array of systems. Often, proposals and political pressures for the construction of specific modes, including proprietary ones, create this problem. Actually, in practical planning, the selection usually comes down to three or four modes, each with some technical or alignment alternatives. Therefore brief descriptions of virtually all operational transit systems are given in the next sections, grouped into two generic categories: (1) medium performance modes, mainly semirapid transit (Section 10.3), and (2) high-performance modes or rapid transit (Section 10.4). In each category the most common systems are compared against each other with respect to their main characteristics. A subsequent section discusses regional transit modes, followed by a brief review of the trends in transit mode utilization.

10.2 MEDIUM-PERFORMANCE TRANSIT MODES

The most common role of medium-performance modes is the basic transit system in medium-sized cities, where network extensiveness is more important than the very high capacity and performance offered by rapid transit. For example, LRT is the main carrier in dozens of cities with populations between 200,000 and 2 million in Germany, The Netherlands, the United States, Canada, and other countries. BRT systems serve as the main transit lines, for example, in Curitiba, Brazil; Bogota, Colombia; and Ottawa, Canada; while Lille and Toulouse in France and Vancouver, in Canada use the AGT mode for their main lines. Many large cities with rapid transit also deploy medium-capacity modes for complementary networks. Examples of these roles are LRT systems in Boston, Budapest, Moscow, Prague, San Francisco, and many other cities.

Medium-performance transit generally consists of three modes: BRT, LRT, and AGT. Their characteristics relevant for comparison with other modes are described in the following three sections.

10.2.1 Bus Rapid Transit

This mode of buses—upgraded through provision of separate infrastructure (ROW and stops/stations), ve-

hicles and operating methods—is described in Section 5.4. Its development followed numerous attempts to improve bus services. As described in Section 5.4.2, these developments included many successful innovations and some failures, resulting in valuable experiences that are relevant to the evaluation of BRT and its comparisons with other modes. The main experiences are summarized here.

1. Bus services are generally upgraded when several lightly traveled lines with long headways are replaced by fixed lines with reserved lanes, fewer but more distinct stations, and frequent service.
2. The main obstacles to upgrading bus services have often been organizational and political rather than technological.
3. The provision of separate bus lanes in roadways must be followed by their continuous policing and protection from pressures by lobbies to share their facilities with other vehicle categories, mainly HOVs and general traffic.
4. The most serious setback for upgrading of bus services has been the downgrading of busways and bus lanes into HOV facilities. That resulted not only in the deterioration of bus services but also virtually destroyed the image of BTSs. It took introduction of a distinct BRT concept with its own infrastructure to demonstrate that buses can be used on a medium-performance, semi-rapid transit systems.
5. Most steps in bus upgrading—such as provision of ROW category B, stations, trunk lines with transfers from feeders, and a stronger image—make bus line services more similar to those of LRT, although rail infrastructure and technologies remain more distinctive than those of buses on bus lanes. Compatibility of BRT with other street traffic is in this respect a liability.
6. Successful BRT systems are found in cities that have very strong planning, good traffic engineering, and a clear policy of prioritizing modes on the basis of the number of persons they carry. Ottawa and Curitiba illustrate the importance of these conditions. In most U.S. cities these ele-

ments are missing, Pittsburgh and Portland being positive exceptions.

7. The successful application of BRT in developing countries are also a consequence of the fact that the labor intensity of this mode is not a serious problem because of low wages and social policies aimed at increasing employment.

There are other fundamental differences between BRT systems in developing countries and those in industrialized countries. In developing countries, BRT is typically introduced as an organized, well-controlled bus system operated with high-frequency bus services and offering primarily high capacity, often with heavily loaded buses. In industrialized countries, BRT is provided as a transit mode with a higher quality of service than regular buses offer and with distinct vehicles and infrastructure that can compete with the private automobile. As on all transit systems, passenger volumes on BRT systems in developed countries are much lower than those in developing countries.

Since the mid-1990s, intensive promotion and publicity have been given to the BRT mode, particularly by the Federal Transit Administration of the U.S. Department of Transportation. BRT is presented as a new, highly promising concept. This promotion is a logical development, because most of the existing bus services in U.S. cities need improvements, at least to the level of BTS mode (for definitions of bus systems and their designations, see Section 5.1.3).

In many other countries, regular bus services also suffer from excessive complexity and poor image. In developing countries with unregulated services, the problems are even more serious. Buses provide services on many poorly marked lines, have no schedules, and are not coordinated with rail systems. Maps of these lines usually do not exist. Their service quality and safety are often low, and government regulations either do not exist or are not enforced.

In conclusion, the development of the BRT concept and system is significant not only because it greatly improves bus services and efficiency but also because it leads to the treatment of bus service as a system, to its integration and coordination, and to a much stronger image of transit. Functionally, BRT has become a

medium-performance mode of distinctly higher quality than regular buses.

10.2.2 Trolleybus System

Most trolleybus systems operate under similar conditions as regular buses, using ROW category C. However, due to their several characteristics, they have in certain conditions similar or even greater potential to be upgraded into a medium-performance mode than ICE buses. This is shown by a systematic comparison between the two modes given in the box below.

Several of these disadvantages are eliminated by dual-mode (electric-ICE powered) vehicles.

This comparison shows that trolleybuses have very significant advantages over ICE buses for many applications, but they require higher investment and more sophisticated operations. The fact that most benefits go to the users and quality of life in the city while the disadvantages impose costs and greater efforts on the operating agency has been the reason for many closures of trolleybus systems.

However, several factors may lead to a greater use of trolleybuses and upgrading them into medium-performance systems, similar to BRT. First, environmental concerns and higher standards for clean air and reduction of noise will continue to favor trolleybuses, particularly in pedestrian-oriented center city areas. Second, innovations in electric traction have made trolleybuses even more energy efficient than before. Finally, dual-mode bus-trolleybus vehicles, although more complicated than either ICE buses or trolleybuses, are finding some new types of applications. These include trolleybuses operating with overhead wires on trunk lines branching out in suburbs to non-electrified streets with automatic lowering and raising trolley poles to wires. Such dual-mode or hybrid electric-ICE buses now operate in several cities. They have been recently introduced in environmentally sensitive central area of Rome; they operate in short tunnels in Seattle and Boston and nearby Cambridge. Finally, various innovative preferential treatments for trolleybuses are operated in Zürich and several other Swiss cities.

Trolleybuses compared to ICE buses have the following advantages (+) and disadvantages (-):

- + Better performance (acceleration, speed, grade climbing ability) and other advantages of electric traction;
- + No exhaust and much lower noise along their lines;
- + Ability to operate in tunnels;
- + Greater acceptability in pedestrian areas and streets due to their superior environmental features;
- + Stronger and very positive image, largely due to their infrastructure (overhead wires);
- + About twice longer functional life;
- Considerably higher investment and vehicle purchase costs;
- Overhead power lines at junctions can be visually objectionable;
- Slower operation through line divergence points and crossings of overhead wires;
- Dewiring of trolley poles is disruptive to service if it occurs often;
- Loss of electric power stops entire line;
- Services limited to streets with overhead wires only.

10.2.3 Light Rail Transit Systems

Since the development of LRT by the upgrading of tramways during the 1960s and later construction of new LRT systems in dozens of cities, this mode has become the dominant representative of medium-performance or semirapid transit, playing a large role between services offered by regular buses and those of rapid transit or metros.

10.2.3.1 LRT Development Process. As described in Chapter 6, LRT is a very diversified transit mode, which has seen, since the 1960s, a virtually continuous stream of innovations in vehicle, ROW and station designs, operational concepts, and the roles that LRT lines play in different cities. An overview of the most significant innovations that led to the creation of LRT is presented in the box on page 535.

These developments of LRT, its description and implementation in European countries, and its construction in many North American cities are described in an extensive technical literature. Particularly good sources are the proceedings of ten National Conferences on LRT organized by the Transportation Re-

search Board and Federal Transit Administration, seven similar conferences organized by the International Association of Public Transport (UITP), as well as Girnau (1999) and Vuchic (1985 and 2005).

Interestingly, the trend was from streetcar-type systems for in-city services to higher-performance LRT systems for longer, higher-performance lines. However, in recent years some new trends have occurred. Following the invention of low-floor cars in the mid-1980s, tunnels in central cities have been foregone in some cities by placing LRT lines in transit malls (Calgary, Sacramento, and Portland) and thus utilizing the LRT system as a focal element for CBD activities. LRT has actually been successfully used as a symbol of a city's rejuvenation, vitality, and enlightened planning.

Even more recently, during the 1990s, there has also occurred a certain revival of streetcar-type services. Thus, the new rail systems in a number of French cities have most elements of LRT, but they operate on streets and center city areas with functions falling between LRT and traditional—although technically greatly modernized—tramways. A similar development has occurred in some U.S. cities. The best known is the extremely popular Streetcar Line F in San Francisco,

Major steps in the development of LRT into the dominant medium-performance mode:

- Consolidation of extensive streetcar networks into fewer, higher-quality LRT lines.
- Systematic replacement of ROW category C by categories B and A.
- Integration of tunnel, surface, and aerial alignments on the same lines.
- Intermodal integration with buses and metros.
- Development of high-quality rails, switches, and track structures that provide virtually perfect riding comfort, making LRT one of the quietest transit modes.
- Articulated vehicles offering spacious comfort, operate in one- to four-car trains.
- Change from unidirectional streetcar-type vehicles to bidirectional, metro-type rolling stock.
- Self-service fare collection allows rapid boarding/alighting on all doors and use of any fare type.
- Low-floor (0.30 to 0.40 m above top of rails) vehicles facilitate boarding/alighting of all passengers and meet the needs of the disabled.
- Because of increased TU capacity, single-person crews, and increased operating speeds, the productivity of the operating personnel has increased from tramways to LRT trains by about 20 times, drastically reducing operating costs (see Vuchic 2005, Section 12.2.2.4).
- Operation of LRT in central cities is performed effectively in tunnels or, in some cities, by direct running in pedestrian malls and zones.
- Integration (track sharing) of LRT with regional rail lines for services to suburbs and nearby cities.

crossing the entire CBD on Market Street and extending to Fisherman's Wharf. In Portland, Oregon, the very successful high-speed LRT lines have recently been supplemented by a typical streetcar line. Referred to as a "streetcar," this line has become a symbol of redevelopment and fashionable living in the center city.

10.2.3.2 Types of LRT Systems and Their Applications. As the preceding sections show, LRT systems have a number of different forms because they can be adjusted to functional system requirements, local conditions, and relationships to other modes in the city. In the box below, a broad range of LRT systems, including their "neighbors" on the lower-performance side (streetcars) and on the higher-performance side (LRRT and ALRT), are listed as a set of nine different types with examples of cities in which they are used.

10.2.4 Automated Guided Transit Systems

With the introduction of computerized train controls during the 1970s, a number of manufacturers devel-

oped automated systems with different arrangements of rubber tires and their running and guiding surfaces, named automated guided transit (AGT) or automated people movers (APM). These systems, described in Chapter 7, were proven physically and operationally feasible, but their economic and functional feasibility led to their further evolution with respect to vehicle/TU size, technology, and types of applications.

The experience with the development of AGT modes and their implementation can be summarized as follows.

- Most of the initial AGT system designs used small cabins, vehicles with 30 or 20 spaces or even PRT with 3 or 4 spaces for individual parties only. With this size, most of the proprietary systems were designed with rubber-tired guided technology.
- Vehicle sizes later increased, reaching capacities of 50 to 100 spaces, and TU consists of one to four cars for APMs and four to eight cars for some AGT applications are used. The reason for

Main categories of Light Rail Transit systems and its neighbors, streetcars and minimetro modes (with ROW category A only):

1. Conventional tramways: Moscow, St. Petersburg, Toronto
2. Upgraded conventional tramways: Amsterdam, Melbourne, Oslo, Vienna, Zürich
3. New tramway systems: Grenoble, New Orleans, Portland Streetcar, Valencia (Spain)
4. LRT networks developed from tramways: Berlin, Boston, Cologne, San Francisco, Stuttgart
5. New LRT systems: Birmingham, U.K., Calgary, Dallas (Photo 10.1), Denver, Nantes, San Diego
6. LRT systems in suburbs of megacities: Hong Kong (Tuen Mun), London (Croydon), New York (Hudson-Bergen), Paris (Bobigny and other circumferential lines)
7. LRT/regional rail integrated systems, sometimes popularly known as RLRT mode: Bern, Karlsruhe, Manchester, Saarbrücken
8. Light rail rapid transit (LRRT): Essen-Mülheim, Manila, Göteborg (Line 8), Philadelphia (Norristown Line)
9. Automated light rail transit (ALRT): Copenhagen, Kuala Lumpur, London (Docklands), New York (JFK Airport), Vancouver (SkyTrain)

this is obvious. Any transit system justifying investment in an AGT must be able to offer at least 2000 sps/h. As the diagram in Figure 7.4 shows, with TU capacity of 50 spaces, this service would need operating headways of 1.5 min, requiring extremely reliable operation. TUs with 100-space capacity would require headways of 3 min, which is still very satisfactory for passengers.

- Most applications of automated transit systems have been in short shuttle and loop lines in airports, amusement parks, and fairgrounds as well as on university campuses and in hospital complexes, etc. For these applications, two-axle rubber-tired vehicles have advantages over other modes because they can negotiate tight curves and steep gradients and have good performance because of their electric traction.

Another reason for the rather extensive use of automated systems in these functions, increasingly referred to as APMs, is that they are planned and constructed as a part of the areas or facilities they serve. Like elevators in buildings and subway stations, APMs in airports and campuses are usually considered

as a part of the overall investment and operation of an airport or fairground; no fares are charged and no separate economic feasibility is analyzed.

- AGT systems have been built as regular transit lines, mostly in French cities (Siemens' VAL system) and in a number of Japanese cities, where they were financed by highway authorities. Paradoxically, most of these AGT systems are operated with fixed TUs, not using one of the greatest advantages of automated systems—adjustment of TU size to passenger volumes.
- A very successful AGT system operates as a downtown people mover in Miami, distributing passengers from the Metro and bus lines throughout CBD and its surroundings (Photo 10.2).
- AGT systems have had an indirect but interesting impact on conventional rail transit systems. Most transit operators were very skeptical toward the concept of fully automated, crewless trains. Interest in eliminating “the last crew member,” i.e., operating trains without drivers or attendants, is not so important on full-size regular metro systems because the productivity of the driver on



Photo 10.1 Light rail transit (Dallas, courtesy of James Aslaksen)



Photo 10.2 *Automated guided transit (Miami)*

such systems is already very high. However, on metro systems with moderate passenger volumes and on LRRT systems, this option is very attractive for the same reasons as on AGT systems: operation of short headways and changes of train lengths, which automation makes feasible and results in much better service as well as a ridership increase without any increase in operating costs.

As it became obvious that fully automated train operation was not limited to rubber-tired systems, but was applicable to all guided systems—and many cities wanted to build medium-capacity rail systems—the concepts of AGT and LRRT converged into ALRT, so that rail systems became joint members of AGT as well as conventional rail systems. As listed in the preceding section, the number of ALRT systems has now been increasing, and it is likely that its growth has only started.

- Full-size metro systems have been using ATO for several decades, but in recent years several new metro lines operating without crews have also been implemented (see Section 6.6.1).

A brief chronology of significant developments in the introduction of fully automated transit systems, starting from small-capacity rubber-tired AGT systems to automated LRT and full-size RRT systems is presented in Table 10.3.

10.2.5 Comparisons of Medium-Performance Modes

As shown in Chapter 2, as a result of numerous inventions and developments of transit systems, there is now a virtually continuous set of transit modes that make up the “family of transit modes.” They range from the bus, trolleybus, and streetcar modes of the street transit category to medium-performance transit modes including BRT, guided bus, a series of LRT variations, and medium-capacity AGT systems. There is a clear distinction of high-performance modes by their exclusive use of ROW category A. However, the AGT systems span across this division: they have ROW category A, but most AGT systems belong to the medium-performance category because of their considerably smaller capacity and lower comfort level than those of rail rapid transit. LRRT also spans this range, because its versions—which are fully automated—can be considered the highest-performance AGT, while at the same time, automated or not, LRRT represents a form of medium-capacity rapid transit, or minimetro.

In spite of this near continuum in performance among modes, comparisons of medium-performance modes are not simple because specific technological modes differ in many basic physical and operational features. Comparisons of all major medium-performance modes are presented here. Individual characteristics of modes are defined by numerical values, usually in ranges; by descriptions; and by qualitative evaluations.

10.2.5.1 Light Rail Compared to Buses. The first comparison, given in Table 10.4, includes three modes: regular bus or bus transit system—typical bus systems used in most cities around the world, BRT and LRT. Their characteristics are grouped in three categories: system components, lines and operational components, and system characteristics.

This table shows that the elements in which BRT differs from RB (or BTS) are ROW category, somewhat larger maximum vehicle capacity (if double-articulated buses are used), different line designs and stop spacings, higher investment, and higher passenger attraction. LRT has more significant characteristics that

Table 10.3 Chronology of significant developments in the automation of guided transit systems

City/Line	Year	Train Length:			Crew Size	Operation Line Capacity	Innovation
		Cars	Meters	Spaces			
Dallas-Fort Worth/Airtrans	1974	2	13	80	0	ATO, ATS Low	Automated network in airport
Morgantown	1975	1	5	21	0	ATO, ATS Low	Automated low-capacity transit
Atlanta Airport/Westinghouse	1980	3	36	420	0	ATO, ATS Medium	Medium-capacity automated shuttle
Lille/VAL	1983	2	28	172	0	ATO, ATS Low-Medium	Automated regular transit
Vancouver/SkyTrain	1986	4	51	440	0	ATO, ATS Medium	Roving driver-attendant
London/Docklands LRT	1988	2	56	254	(1)	ATO, ATS Medium	Attendant on each train
Lyon Metro/Line D	1993	3	50	450	0	ATO, ATS Medium	Automated rubber-tired metro
Paris Metro/Line 14	1998	6	90	866	0	ATO, ATS High	Automated rubber-tired metro
Singapore/Northeast Line	2002	6	138	1353	0	ATO, ATS High	Fully automated rail metro

Table 10.4 Comparison of regular bus, bus rapid transit, and light rail transit characteristics

Characteristic \ Mode	Regular Bus (RB) or Bus Transit System (BTS)	Bus Rapid Transit (BRT)	Light Rail Transit (LRT)
System components			
ROW	C	B (C, A)	B (C, A)
Support	Road	Road	Rail
Guidance	Steered	Steered	Guided
Propulsion	ICE	ICE	Electric
TU control	Driver/visual	Driver/visual	Driver/signal
Vehicle capacity (spaces)	80–120	80–180	100–250
Max TU size	Single vehicle	Single vehicle	1- to 4-car trains
Max TU capacity	120	150	4 × 180 = 720
Lines/Operational elements			
Lines	Many	Few	Few
Headways on each line	Long/medium/short	Medium/short	Medium/short
Stop spacings (meters)	80–300	200–600	250–1000
Transfers	Few	Some/many	Many
System characteristics			
Investment costs/km	Very low	Medium	High
Operating cost/space-km	Medium	Medium	Low
System image	Variable	Good	Excellent
Passenger attraction	Limited	Good	Strong
Impacts on land use and city livability	Low	Moderate	Strong

are superior to those of BRT: it is an electric rail system with much larger TUs and fewer lines with higher service quality. LRT requires even higher investment than BRT but has a much stronger image, passenger attraction, and positive impacts on the city. The three modes are rather different as PCPs, increasing from RB to BRT and then to LRT. Therefore RB dominates applications on lines that require basic service. As higher investment is made to obtain higher performance modes, BRT and LRT represent two distinct steps, with considerable differences among all three of them.

Focusing now on the commonly made comparison of LRT and BRT, the main differences between them are described by a series of statements (see the box on page 541) defining the advantages and disadvantages of the former with respect to the latter mode.

Among these differences between the two modes, the *higher passenger attraction of LRT, a so-called rail factor*, is of considerable importance. The introduction of LRT to replace bus services in a major corridor usually results in significant increases of transit ridership not only on that line but on the entire transit system. The building of an LRT line, when it is done together with reorganization and upgrading of bus network and improved integration of the two modes, in many cases results in a reversal from declining to increasing transit ridership. This phenomenon occurred in San Diego, Calgary, Sacramento, Denver, and other cities. In some cities, despite the switch of passengers from buses to LRT in the same corridor, introduction of the new mode resulted in such increases in transit usage, including the use of buses as feeders, increased so much that the total bus ridership in the city actually increased.

The impacts of different mode choices and related transportation policies can be seen quite clearly by comparing developments in two capital cities of large states, Columbus, Ohio, and Sacramento, California, between 1987 and 2000.¹ These two metropolitan areas are very similar in their city and regional population

sizes and in being capital cities; also, both have many office employees and government-related activities. Ohio State University in Columbus has a large student population, which represents a sizable potential transit ridership.

According to statistical data from the Federal Transit Administration, Columbus served 17.5 million annual transit passengers in 1987. With improvements in its bus system, this ridership increased by the year 2000 to 18.7 million, or by 7%. Sacramento invested in construction of an LRT network and used its opening to reorganize bus lines as LRT feeders serving a number of timed transfer system points, thus creating an integrated, balanced transit network. As a result of these improvements, transit ridership—which, in 1987, with 14.0 million annual trips, was lower than in Columbus—grew to 28.1 million trips in year 2000 (i.e., a 101% increase).

These statistics show that Sacramento experienced a drastically different, much more successful development of transit than Columbus during the 1987–2000 period. Four major events can be credited for that success. First, LRT was built, introducing a service of much higher quality than had been offered by regular and express bus services. Second, LRT was integrated in the main street in the city as a pedestrian/transit mall. Third, the bus network was reorganized to feed LRT as the trunk line in two major corridors. And fourth, a timed transfer system (Vuchic 2005, Section 4.5) was introduced, greatly improving the intermodal and intramodal connectivity of the entire transit network. Thus, the introduction of the LRT in Sacramento not only attracted more passengers to rail than buses had served but was also the catalyst for improved transit service quality, more efficient network structure, and a stronger image for the entire multimodal network.

The impact of the new LRT system, its use as an element of increasing city's enhancements for pedestrians, and the concomitant upgrading of bus services into an intermodal system has drastically upgraded the quality and role of transit and the city's livability. Columbus is still planning an LRT system, while Sacramento, enjoying the popularity of its initial LRT line,

¹ This comparison of Columbus and Sacramento was obtained from John Schumann by direct communication.

LRT, compared to BRT, has the following advantages (+) and disadvantages (–):

- + Because of its rail tracks instead of roadway lanes, separate ROW (B or A) for LRT is easier to design and due to different technology requires no physical protection and police enforcement as do bus lanes and busways.
- + Because of its electric traction, LRT has better vehicle performance than BRT.
- + LRT produces no exhaust along the line and much lower noise than BRT (except that in a few cities, on high-speed LRT lines, trains are required to use horns at grade crossings).
- + LRT is often designed to serve as the central element for access and image of livable pedestrian areas in central cities; a busway with high-frequency bus services is much less compatible with pedestrianized areas.
- + LRT can use tunnels, BRT cannot.
- + LRT vehicles are more spacious and comfortable and have better riding quality than buses.
- + LRT has a stronger image, it is more popular and attracts more riders.
- + LRT has a stronger positive impact on urban development than BRT (Photo 10.3).
- Investment costs for LRT are higher than those for BRT.
- For the first LRT line in a city, introduction of new technology requires more extensive construction of infrastructure as well as new equipment, and it involves longer implementation.
- LRT services are limited to track networks and involve more transfers than buses.

opened another LRT line after the year 2000 and extended the original line to the neighboring city of Folsom in 2005.

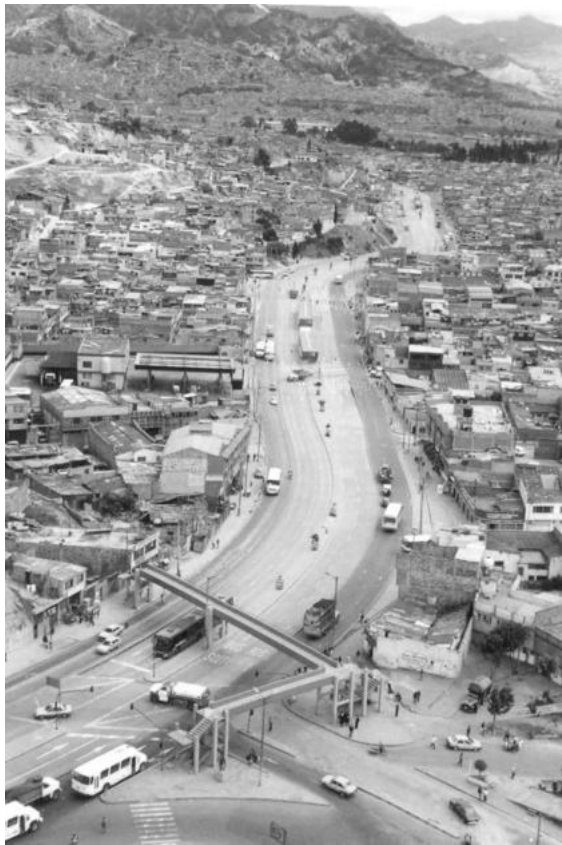
Portland, Oregon, experienced a similar growth of transit passengers when it introduced an LRT system. Transit ridership in 1987, the year LRT opened, was 42.0 million passengers on buses and 5.9 million on LRT. In 2003, there were 62.7 million passengers on buses and 26.1 million on LRT. Total annual ridership increased from 47.9 to 88.9 million (i.e., by 86 percent).

Most cities that have introduced the LRT mode in recent decades recorded similar increases in the number of passengers. Typically, a new LRT diverts bus passengers and **attracts a substantial number of new transit users**. The rail factor is seen not only in ridership trends but also in the fact that transit has a stronger image and plays a much more important role in the cities that have built rail systems—such as San Diego, Calgary, Portland, St. Louis, Dallas, Denver,

and Salt Lake City—than in their peer cities that continue to rely on buses only, such as Detroit, Cincinnati, and St. Paul.

For a summary of the differences between these two modes, their major characteristics are listed and described in Table 10.5. The superior mode with respect to each characteristic is listed in the last column.

The summarized evaluation and comparison in this table again show that BRT and LRT are different in many respects. Generally, BRT requires a lower investment and shorter implementation time than LRT, but LRT provides higher service quality, attracts more passengers, and has stronger and more permanent positive impacts on its served area as well as, often, on an entire city. BRT has physical limitations because, in cities with high density where exclusive busways or lanes cannot be provided, it cannot enter the urban core. LRT can do that either by using tunnels (with higher investment) or by operating on various types of ROW B, including running through pedestrian areas.



(a)



(b)

Photo 10.3 An example of basic differences between BRT and LRT (a) The extremely wide corridor of TransMilenio BRT in Bogotá provides high capacity, but separates the city and requires very long pedestrian access to stations (Courtesy of TransMilenio BRT) (b) LRT trans in Karlsruhe operate on high-speed railway lines, but also penetrate into pedestrian zones, enhancing their accessibility and livability (Courtesy of Mario Semmler)

Table 10.5 Comparison of main BRT and LRT features

Characteristic	Mode	Bus Rapid Transit (BRT)	Light Rail Transit (LRT)	Superior Mode
Vehicle performance and passenger comfort		Good	Excellent	LRT
Investment cost		High	Very high	BRT
Implementation time		Short	Medium	BRT
Operating cost		Lower for low passenger volume	Lower for high passenger volume	~
System image and passenger attraction		Good	Excellent	LRT
Air pollution and noise		Considerable	No direct pollution, very low noise level	LRT
Interaction with land development		Limited	Very good	LRT
Contribution to livable urban environment		Limited	Excellent	LRT

The present strong promotion of BRT often includes some misconceptions about its relationship to LRT and even with rail rapid transit, which can generate confusion, particularly among lay public. Three such misconceptions are discussed here.

Misconception I: BRT can provide the same services as LRT at a much lower cost. The preceding comparisons of the two modes clearly show that bus and rail modes provide services with many fundamental differences, which are reflected in the types of services offered, the structure of investment and operating costs, the system's physical separation from highway traffic, and the permanence and impacts of the system on the surroundings. Overall, BRT is easier to implement; in developing countries with low labor costs, it involves lower operating costs than LRT, but it also offers inferior service quality and image, and it is much more difficult to separate from general traffic (particularly in U.S. cities). LRT is superior in many features of service quality and passenger attraction, and it plays a much stronger and more permanent role in urban development and pedestrian-oriented urban design than BRT.

Many technical papers about BRT, as in JPT (2002), recommend that BRT should approach the features of LRT. Thus, the more similar a BRT system is to LRT, the better its performance. Some differences between the two modes can be reduced, but most cannot be eliminated. The measures that upgrade buses to acquire some features of LRT—such as higher quality of ROW design, larger stations, and very sophisticated vehicles—require additional investments, however. Upgrading of BRT then reduces its advantage over LRT with respect to lower investment costs.

Misconception II: Rail modes do not attract more passengers than buses because their attraction depends on service parameters such as speed, reliability, and comfort, in which buses can match rail. This statement is self-contradictory. If it is claimed that passenger attraction depends on service parameters, this actually proves that LRT has a substantial advantage over BRT because of its inherent higher service parameters than buses. In other words, the fact that passenger attraction

depends on service parameters actually proves that LRT is superior to BRT with respect to passenger attraction. Real-world experiences with different passenger attractions by these two modes, described above, prove that.

Misconception III: LRT is superior to BRT in all applications. The fact that LRT provides a higher quality of service does not by any means make that mode better suited to all applications than BRT. Although the optimal domains of BRT and LRT partially overlap, there are situations in which each one of these modes is either superior or the only one that is feasible. Here are a few examples:

- There are situations where BRT's advantages in lower investment cost and easier implementation are more important than the greater comfort and capacity of LRT, even if, in the long run, LRT would represent a superior PCP (this is the case in many developing countries).
- Some medium-sized cities that need medium-performance transit but cannot justify the investment and complexity of using a different transit technology for a single line may find BRT to be the only feasible solution. A good example is Eugene, Oregon.
- In many central cities with a high density of activities and narrow streets, creation of pedestrian streets or zones can be greatly enhanced by LRT lines, while busways with high frequency of buses would be detrimental to the area's livability. Here LRT is the obvious choice.
- In central cities where congested streets prevent reliable transit services, tunnels may be the only solution. LRT is clearly superior to dual-mode or other bus types for many physical and operational reasons.
- The higher passenger volumes and the higher-performance infrastructure are required on a transit line, the stronger is the case for LRT. In extreme cases, such as the SilverLine BRT in Boston, where a tunnel was built for a cost of about \$350 million per kilometer, the use of bus vehi-

cles—which are inferior to rail with respect to traction, capacity, safety, and comfort and which require larger tunnel installations—represents a gross underutilization of the investment.

In conclusion, BRT and LRT are quite different modes and each has a significant domain in urban transportation. Any publications that attempt to prove that one of these modes is always superior to the other, or that one has no place in urban transportation are based on distorted facts and biased conclusions and have no professional validity.

10.2.5.2 Light Rail Transit Compared to Automated Guided Transit. This comparison is rather difficult to make because AGT and APM cover a very broad range of modes. If AGT represent mostly small-to medium-capacity rubber-tired systems, usually referred to as APMs (see Chapter 7), the differences between the two modes are summarized in the box.

In some countries, particularly in France and Japan, which have several AGT producers, there have been intensive debates about mode selection between LRT and AGT. LRT has been selected in most cities in Eu-

rope and North America, usually because of its considerably lower investment cost and greater physical ability to fit into an urban environment without either tunneling or using aerial structures (which are not acceptable in high-density areas). In many Asian cities, particularly in Japan and Singapore, AGTs have prevailed when sizable funds were made available and cities were not so environmentally sensitive that aerial structures would be objectionable. Overall, LRT systems are used in many more cities and have much more extensive networks than rubber-tired AGT systems. Rail AGT systems, ALRT, are discussed in the next section.

10.3 HIGH-PERFORMANCE MODES

The basic feature of high-performance transit service is operation on ROW category A only. With exclusive use of protected ROW, guided modes represent the logical technology, because guidance allows the use of high-capacity electric trains with signal control. By far the most dominant modes in this category are the RRT and regional rail systems. This section, however, in-

LRT systems compared to rubber-tired AGT/APM systems have the following advantages (+) and disadvantages (–):

- + LRT is not limited to ROW A only: it can also utilize ROW categories B and C.
- + LRT can fit into urban and pedestrian zones and enhance their environment; AGT must be fully grade-separated, usually on aerial structures.
- + LRT requires a much lower investment cost (usually two to three times lower) per kilometer of line than AGT.
- + Rail vehicles offer considerably better riding comfort than two-axle rubber-tired guided vehicles.
- + LRT has a good image and is usually a popular symbol in city streets.
- + Rail systems are generic, produced competitively by many manufacturers; AGT modes are proprietary, produced by one supplier only.
- LRT cannot be operated automatically unless it has only ROW A.
- LRT has lower speed and a much lower frequency of service than AGT.
- LRT has somewhat lower safety than AGT.
- LRT schedule cannot be as quickly adjusted to unexpected changes, as can AGT.



Photo 10.4 Light rail rapid transit (Manila, courtesy of Laz'Andre F. Cawagas)

cludes several other high performance modes, starting from LRT operating exclusively on ROW A, rubber-tired rapid transit and monorails, to the highest-performance mode, regional rapid transit.

10.3.1 Light Rail Rapid Transit Modes

This group of modes includes systems which have modified LRT rolling stock operating on alignments with ROW category A over their entire length. When these LRT trains are operated by drivers, the mode is known as Light Rail Rapid Transit—LRRT. The same mode but with fully automated operation and no crew members is known as Automated (or Advanced) Light Rail Transit (ALRT). The fact that it is automated indicates that this system has only ROW A, i.e., it actually represents an automated LRRT.

10.3.1.1 Light Rail Rapid Transit (LRRT). Rolling stock of this mode differs in several ways from the regular LRT stock. The trains have high operating

speed and fail-safe signalization, the same as metro systems. LRRT stations usually have prepayment of fares and high platforms for fast passenger boarding and alighting at all doors. Thus, LRRT can be considered as the highest type of LRT or as a smaller-scale RRT, sometimes referred to as minimetro.

There are not many LRRT systems because in most cases when passenger volumes are large, transit lines are built with ROW A, and in such cases long trains and other metro features are used. Only in special cases is this highest type of ROW provided for lines that carry only moderate passenger volumes. Individual lines of this mode exist in Philadelphia, (the Norristown Line); Göteborg, Sweden; Manila, Philippines (Photo 10.4); Frankfurt and Essen-Mülheim, Germany; and Toronto–Scarborough (with linear induction motor propulsion).

With the growing demand for high-quality transit services, it is likely that there will be increasing use of the LRRT mode in the future. Conversion of commuter railway lines to this mode is a logical step to achieve



Photo 10.5 Automated light rail transit (Vancouver SkyTrain, courtesy of Jonathan Cote)

considerably lower operating costs and higher levels of service by replacing labor-intensive railroad-type regime with one-person crews and greater service frequency of transit-type regime.

10.3.1.2 Automated Light Rail Transit (ALRT).

This mode is a fully automated version of the LRRT, or it may be considered as an AGT system with rail technology. It involves a higher investment cost than LRRT because of automation and certain operational provisions necessitated by such operation (platform supervision, detection of objects fallen on track, emergency procedures, etc.), but its operating costs are lower, even for operation with shorter headways than LRRT, because drivers' wages are not involved. Without train crews, the operating cost of, for example, four single-car trains is the same as that of one four-car train (at four times longer headways). The other benefits of full automation, discussed in Sections 6.6.1 and 10.1.5, also apply in this case. The first ALRT system, SkyTrain, opened in Vancouver in 1986, is the best-known example of this mode. Operating up to four-car

trains at headways as short as 1.5 min, the theoretical capacity of the SkyTrain exceeds 26,000 sps/h, considerably greater than capacities of rubber-tired AGT systems. The SkyTrain (Photo 10.5) has propulsion by linear-induction motor, but that feature is independent of the basic system concept and its automation. The same type of ALRT with conventional electric motor propulsion is used on Detroit's Downtown People Mover, a collector-distributor loop in the CBD.

Another major ALRT system is the London–Docklands system, a line planned and built as a part of a major urban development in the Docklands area. It has been subsequently expanded into a network. Each train on this line has an attendant, but it can still be considered as ALRT because driving is automatic and the attendant is on the train only to assist passengers with information and fares. Since the year 2000, ALRT lines have been opened in Copenhagen and Kuala Lumpur, and several others are being planned.

ALRT is a mode that will have increasing importance in the future, because the technical and operational problems of automatic driving have been solved

and tested and a high quality of service (mainly short headways) is increasingly important for passenger attraction on all high-performance transit systems.

10.3.2 Rail Rapid Transit/Metro

RRT represents the highest-performance transit mode with the lowest operating cost per space-km. As explained in detail in Chapters 4 and 6, RRT elements designed to achieve such performance include the largest vehicles and longest TUs (except for some RGR systems), fully protected ROW, stations with high platforms for rapid passenger exchange and easy transfer to other modes, and fail-safe signal control or fully automated driving. In all these elements metro is designed for higher performance and more efficient operation than other modes. The most important single element for high capacity is the large size of TUs. Metro trains with capacities of 1000 to 2000 or more spaces can carry much higher volumes than LRT trains with capacities of 300 to 750 spaces or buses with 80 to 180 spaces in spite of the shorter headways at which other modes can operate.

Implementation of metro systems requires very high investment cost and involves extensive construction as well as disruption of areas along future lines. The construction is usually more comprehensive than the building of the metro infrastructure alone because most

cities use metro construction as an opportunity to rebuild entire corridors or include the development of plazas, buildings, or entire commercial subcenters as a coordinated effort. The metro system has virtually unlimited life and exerts a strong, permanent impact on mobility of population, urban form, and a city's livability. Evaluation of the feasibility of a metro system and its comparison with other modes should therefore always include the related urban reconstruction and development.

A summarized comparison of the metro with its closest widely used neighbor in the family of modes, standard LRT, is presented in the following box.

This comparison shows that RRT has a significantly higher PCP than LRT. The differences in these features between typical RRT and other medium-performance modes are even greater.

The dominant reason for the decisions of dozens of cities to build new metro systems has been to provide high transporting capacity in major urban corridors and networks. The selection of RRT as the basic mode to transport large passenger volumes on transit networks in cities like Beijing, Hong Kong, Munich (Photo 10.6), Osaka, and Washington has been logical and easy because no other mode comes close to meeting such requirements. However, in an increasing number of cities, metros are being built not only for greater capacity but also to provide high-quality service. The

RRT/Metro compared to LRT has the following advantages (+) and disadvantages (-):

- + With ROW A only and full signal control, metro has higher speed, reliability and safety.
- + Due to longer trains and rapid passenger exchange at stations, metro has much higher line capacity.
- + With its high performance and strong image, metro has stronger passenger attraction.
- + The distinct image of its stations and system permanence give metro more powerful positive impacts on urban development than any other transit mode.
- Metro requires a substantially higher investment cost, causes more disruption during construction, and requires longer implementation time than LRT.
- Metro requires more rigid alignment than LRT and cannot penetrate pedestrian areas at grade.
- LRT is more conducive to construction in stages, utilizing different ROW categories, while metro is limited to ROW A only.
- For a given amount of investment, a city can obtain 2–3 times longer lines of LRT than of metro.



Photo 10.6 Rail rapid transit (Munich, courtesy of Peter Specht)

reason for these objectives is the growing expectations of high-quality transit services and the need for such services to attract urban auto users. Improved mobility, intensified economic activities, and enhanced urban livability are, of course, additional factors leading to such investments and efforts to build metro systems.

In conclusion, although RRT is a mode with extensive infrastructure, it provides many variations and different choices with respect to its ROW positions, types of stations, rolling stock, and performance to fit a variety of local conditions. The more than 100 rapid transit systems operated around the world illustrate a wide range of options that the designers of new rapid transit systems can use. The role of conventional metros with more innovations is likely to continue and increase as the growth of cities advances around the world.

An example of metro innovations is illustrated in Photos 10.7a and 10.7b: some metros which handle very large passenger volumes, such as Tokyo, Hong Kong, and London, have introduced full or partial

walls along station platforms to increase safety. Their appearance is different—more constrained—but acceptable. Temperature control is easier. The need for them depends on the local conditions, such as ability to handle passenger crowds safely, incidence of suicides, etc. Another innovation that will undoubtedly be increasingly used is fully automated operation, which is discussed again below.

10.3.3 Rubber-Tired Rapid Transit and Monorails

Among many technological variations used in metro systems, the rubber-tired rapid transit (RTRT) type is most commonly used. This system is actually the same as RRT in all functional features but uses different support and guidance technology. Thus, RTRT represents a “technical subalternative” of the rail rapid transit mode. Its description and evaluation, given in Section



(a)



(b)

Photo 10.7 Innovations in rail rapid transit: platform doors; a. full and b. half (Tokyo)

6.4, show that RTRT has been used successfully in several cities (Paris, Lyon, Montreal) but that its advantages in lower vibration, better adhesion, etc., in most cases do not outweigh its disadvantages in higher cost and power consumption, smaller vehicle sizes, lower maximum speeds, and others. For a complete comparison, see Section 6.4.3.

The most common type of monorail, the rubber-tired Alweg-design, is also in many respects functionally the same as RRT, but its support and guidance are more fundamentally different than those of RTRT. The single-beam guideway gives the monorail its popular image of the “transit mode of the future,” as well as some of the serious disadvantages in the guideway design and operations. As described in Section 7.3.2,

monorails are technically feasible and operate under special circumstances, as on aerial alignments with sharp curves and steep gradients, amusement parks, etc., but they come out as inferior to conventional RRT in virtually all comparisons for mode selection. Moreover, monorails are not used for other than single lines because of their complicated switching. The reasons for frequent differences between popular interest in monorails and their much less favorable evaluation in technical mode selections are discussed in Section 10.1.4.

10.3.4 Review of Guided Modes and Their Automation

The preceding sections have shown that rail and other guided transit modes have benefited greatly from a number of technical and operational innovations which include vehicle/TU sizes, guidance technology, propulsion, and automated train operation (ATO). For evaluation and selection of modes and their characteristics, an understanding of these features is very important. For that purpose, different classifications of these basic features and transit modes have been given.

Interestingly, very intensive developments and promotions have taken place with medium-performance modes, particularly LRT and the very labor-intensive BRT. At the same time, there is a clearly growing interest and investment in fully automated modes at the opposite end of the labor/automation ratio: such modes can provide very frequent service utilizing automation rather than labor.

Due to the increasing interest in automated operations, an overview of the modes which can be fully automated is presented in Table 10.6. It includes many categories of modes with the three basic characteristics for automation: ROW A, physical guidance, and electric traction. Typical systems in different categories of high performance modes with added AGT modes are listed, with two or three representative cities where they are used, starting from conventional, manually driven systems to the latest fully automated (driverless) RRT systems.

Table 10.6 Classification of RRT, ALRT, and AGT systems by design and operation with respect to automation

<i>Category</i>	<i>City</i>	<i>Support/ Guidance</i>	<i>Propulsion</i>	<i>Driving</i>	<i>Crews</i>	<i>Line Capacity</i>
Conventional RRT	New York Subway	Rail	EM	M	D+A	V. high
	Mexico Metro	RT	EM	M	D+A	High
Upgraded conventional RRT	Hamburg U-Bahn	Rail	EM	M, ATO	D	High
	Moscow Metro	Rail	EM	M, ATO	D, A	V. high
Contemporary RRT (since 1970)	San Francisco BART	Rail	EM	ATO	D	V. high
	Munich U-Bahn	Rail	EM	ATO	D	High
AGT (shuttles)	Atlanta–Hartsfield	RT	EM	FA	N	Medium
	Singapore MRT	RT	EM	FA	N	Low
AGT (urban)	Lille VAL	RT	EM	FA	N	Low
	Taipei VAL	RT	EM	FA	R	Medium
LRRT	Philadelphia–Norristown Line	Rail	EM	M	D	Low
	Toronto–Scarborough Line	Rail	LIM	ATO	D	Low
ALRT	Vancouver	Rail	LIM	FA	N	Medium
	London–Docklands	Rail	EM	FA	A	Medium
Automated Metro/RRT	Lyon Metro Line D	RT	EM	FA	N	Medium
	Paris Metro Line 14	RT	EM	FA	R	High
	Singapore–NE Line	Rail	EM	FA	N	High

Abbreviations: A = attendant; ATO = automatic train operation; D = driver; EM = electric motor; FA = fully automated; LIM = linear induction motor; M = manual; N = no crews; R = roving attendant; RT = rubber-tired.

The sequence of these modes in the table generally follows their historic evolution. As the table shows, there has been an increase of automation, starting from driver-controlled ATO on rail transit followed by the introduction of AGT systems as shuttles and then on several regular transit lines. At the same time, conventional rail systems introduced full automation without a driver, first on ALRT and then on RRT.

A note of caution about transit systems with automatic operation is called for here. Fully automated train operation, without drivers, is expected to be increasingly used. However, its advantages are more important on medium-capacity modes than on large rapid transit systems such as those of New York, Hong Kong, and Mexico, where the presence of a person—driver or attendant—is desirable for many reasons and the cost of an employee in a train carrying hundreds or thousands of passengers is easy to justify. Thus, fully automated train operation is not necessarily a desirable target for all rapid transit systems.

10.4 REGIONAL TRANSIT MODES

As cities grow into metropolitan areas or urbanized regions, there is an increasing need to provide regional transit systems. These are characterized by long lines from the central urban area to suburbs and other cities within a radius of about 100 km. In large metropolitan areas, there are also lines among suburbs. Station spacings are long, so that travel speed on regional network is considerably greater than on urban transit. Serving mostly long trips among central city and regional major activity centers, regional transit is usually superimposed on regular transit, which serves local travel within central city and suburban areas.

Regional transit services are provided by bus, LRT, and commuter/regional rail modes. Regional express buses, operating in mixed traffic or on special lanes, cannot be defined as high-performance modes because they perform commuter services only and their reliability is dependent on traffic conditions. Yet they are briefly included here because of their important role as

the only mode providing regional services in many cities.

10.4.1 Regional Buses

To provide regional service at speeds competitive with auto travel in U.S. metropolitan areas, buses must usually utilize major arterials and freeways. Most U.S. cities have more extensive freeway networks than their counterparts in other countries, and their express buses represent the most common and often the only regional transit.

Typically, regional express buses run on streets in suburban areas and then get on a freeway for fast travel (very often without intermediate stops) into a center city, where they again travel on streets for distribution of passengers, transfers to other lines, etc. There are extensive networks of express bus lines utilizing HOV facilities in a number of cities, most notably Dallas, Denver, Houston, Los Angeles, Minneapolis, and Seattle. A large network of regional buses is operated also in the New Jersey suburbs of New York City, supplementing the NJT regional rail lines also serving that region. In New York City, these lines terminate at the Port Authority Terminal, the largest bus terminal in the world.

Most regional bus lines in U.S. cities represent commuter transit rather than regular transit. They offer very limited if any services during off-peak periods. Among the exceptions to this are three leading bus systems in North America: Ottawa, Pittsburgh, and Portland. These systems are mentioned in Section 10.3.1.

10.4.2 Commuter Rail

In many cities around the world, railway lines going through suburbs and entering the city have been used for commuter trains, bringing mostly daily commuters into and out of the city. These lines typically terminate in stub stations on the fringes of central city. For example, London has about a dozen stations where commuter lines operated by British Rail and its successors terminate and connect with the Underground (metro)

lines. Commuter rail lines terminate in similar stub stations in Boston, Chicago, San Francisco, and Paris.

Commuter rail plays an extremely important role in bringing workers into large cities of both industrialized countries (Buenos Aires, Milan, Moscow, New York City, Osaka, Tokyo), as well as in developing countries (Cape Town, Johannesburg, Mumbai, São Paulo, and many others).

Commuter rail systems in many cities represent by far the most efficient mode for bringing and returning extremely peaked loads of daily commuters from suburbs. They offer high speed, good comfort and reliability, and high line capacities. Their disadvantages are that their headways are long and irregular, making their use in off-peak hours difficult or impossible. Moreover, in some cities, the railway agency is not sufficiently interested in these services because its main focus is on intercity passenger and freight trains. With the increasing demand for high-quality regional transit, the trend has been to upgrade commuter rail into regional rail lines or networks.

10.4.3 Regional Rail

These railway systems belong either to the railway, or to the transit agency. They are specially designed as regional passenger rail networks, running through the central city and providing better coverage than radial commuter lines, which serve only one or a few central stations. Moreover, the growth of polycentric urban areas with major activity centers in the suburbs creates a demand for high-performance transit networks that provide links among such suburban centers rather than only radial lines to the center city. These polycentric links are provided mostly by buses, but in several cities there is an increasing interest in upgrading such circumferential or tangential lines to rail systems. The highly successful link between Sacramento and San Jose in California is tangential to San Francisco, although it connects these two large cities as well as Oakland. Similar lines are being considered in Chicago, Los Angeles, and Philadelphia.

Typical regional rail networks are the S-Bahn systems in Berlin and Hamburg, JR lines in Tokyo and

other Japanese cities (Photo 10.8) and RER in Paris. As described in Chapter 4, many cities (Brussels, Oslo, Paris, Philadelphia) have upgraded their commuter networks into regional rail by connecting stub-end terminals across central cities, electrifying the lines, and integrating them with regular transit.

As in the case of other “neighboring modes,” there is no sharp “boundary” between commuter and regional rail modes. Yet typical commuter rail systems, such as diesel-traction TriRail in Miami and Metrolink in Los Angeles, are very different from typical regional rail lines, such as the electric Hamburg S-Bahn, Paris RER, and Sydney City Rail. The former, commuter lines, operate several inbound trains in the morning and outbound in the afternoon; the latter, regional rail lines, operate with 5- to 20-min headways throughout the day. Regional Rail in Philadelphia and the Long Island Rail Road fall in between these two modes.

Both commuter and regional rail modes are strong candidates for expansion or introduction in many cities, particularly in North America, due to their extensive suburban developments and congested freeways.

10.4.4 Regional Rapid Transit

Several cities or urbanized regions in the United States such as the San Francisco Bay Area, Washington, Philadelphia and Atlanta, which decided in recent decades to build high-performance transit systems, designed

rail systems having networks similar to those of regional rail: long lines into the suburbs with long station spacings, high operating speeds, and heavy reliance on bus feeders, park-and-ride, and kiss-and-ride. Unlike regional rail, however, these regional rapid transit lines penetrate the center city through tunnels and have a number of stations in the central area with extensive transfers to other transit modes, including LRT and buses. Another feature of these systems is that their operation is the same as that of RRT: enclosed stations with high platforms allowing short headways and high capacity. These systems thus represent regional rapid transit, or an actual “bridge” between regional rail and metro modes. In a way, these systems have metro-type in-city networks extending into regional rail suburban lines.

10.4.5 Trends in Regional Rail Transit Development

With the rapid spatial growth of cities and urbanized areas, regional transit is growing in importance, and it has been the scene of intensive developments. Major developments in this group of transit modes are listed and briefly described here.

1. **Activation of abandoned railway lines or shared use of freight railway lines for transit services.** These actions require investments as well as organizational arrangements for shared use of tracks. In some cases, as in Los Angeles, the transit agency has purchased hundreds of kilometers of lines from freight railroads.
2. **Upgrading of commuter rail into regional rail lines.** This involves introduction of regular headways, usually of 10- to 20-min, which greatly facilitate transfers and integration of lines of the same mode or among modes.
3. **Integration of regional rail with city transit.** This includes such activities as joint stations, coordination of schedules, joint fares, and integrated information and marketing.
4. **Building connecting lines between stub-end railway stations at the fringes of city centers.** With excellent results from these connections



Photo 10.8 Regional rail transit (Japan)

built in Munich, Oslo, Paris, Philadelphia, Zurich, and other cities, this type of project is considered or planned in several other cities, such as Boston, London, and New York.

5. **Upgrading of diesel to electric traction.** Electric traction not only improves train performance but also allows tunnel alignments and use of shorter trains with multiple unit (MU) cars instead of locomotive-towed trains.
6. **Development of self-powered diesel passenger cars** capable of running on railways as well as on transit lines. This rolling stock, designed for a one-person crew, enables low-cost operation on regional railway lines with low-to-medium passenger demand, expanding the feasible domain of regional rail services at its lower end.
7. **Physical integration of regional rail with metros:** joint use of tracks by different operators, used in several Japanese cities.
8. **Regional light rail transit (RLRT), or integrated LRT with regional rail and even with intercity rail services.** Examples are Karlsruhe, Saarbrücken, and several other cities in Germany; Manchester in Great Britain, and the RiverLine in southern New Jersey.

With the increasing need for high-performance regional transit services, further developments and innovations in this field should be expected in the future. The last item listed above—integration of LRT with RGR lines—is a particularly promising development because it leads to utilization of extensive railway tracks in many cities by LRT trains, which can provide higher frequency services at much lower operating cost than regional rail trains. That concept deserves a special comment.

Traditionally, regional rail tracks and networks were physically separated from rail transit systems and had different traction motors (different voltages), signal controls, and operating rules. With the obvious potential benefits from integration of LRT and RGR networks, several solutions were applied in different cities under different conditions. In Manchester, UK, entire RGR lines were taken over by the transit agency, extended through city streets and operated as LRT lines.

In several U.S. cities, such as San Diego and cities in southern New Jersey, LRT services utilize railroad tracks, but with a strict time division between the two types of rolling stock.

The only truly integrated operation of LRT, RGR, and long-distance trains on the same tracks has been achieved in Germany. This successful integration was a result of a comprehensive effort to achieve compatibility of wheel profiles, traction systems, braking capabilities, and signal systems. In developing the signal systems and safety aspects, the focus was primarily on prevention of collisions rather than on minimizing the possible damages. This regional LRT (RLRT) system has been extremely successful and no serious safety problems have been experienced. Thus, a systems approach to the problem of compatibility of two different rail modes resulted in a coordinated effort that devised technical, operational, and management/legal aspects and regulations. The highly successful introduction of the RLRT system in Karlsruhe resulted in the implementation or planning of similar systems in Saarbrücken, Luxembourg, Kassel, and several other German cities.

The concept of RLRT attracted considerable attention in the United States because many U.S. cities have railroad lines that could be used for LRT services. So far, only a time-sharing type of operation by the railroad and transit systems has been implemented. Railroad lines are under the jurisdiction of the Federal Railroad Administration (FRA), which maintains very rigid safety standards designed for intercity freight trains. The standards require much higher buffeting strength of cars than in Europe so as to minimize damage in the event of collision. These standards therefore impose vehicle designs that LRT rolling stock cannot easily match without adopting extremely heavy and expensive vehicles. These regulations should be revised to be more appropriate for LRT/RGR compatibility in urban areas.

10.5 PROGRESS AND PROBLEMS IN MODE SELECTION

Understanding of technical facts and operational characteristics of transit modes can be very important to

minimize confusion and prevent delays in decision making and to reach an optimum selection, because of the permanent impacts on the quality of transit service and character of city.

10.5.1 Increased Mode Diversification

In 1978 there were only about 15 cities in the United States and 10 cities in Canada that had any transit modes other than buses, and the vast majority of bus services were conventional ones operating on streets in mixed traffic. In 2006, there are dozens of cities operating not only rapid transit and LRT but also many types of these systems differing by their technology, rights-of-way, degrees of automation, and relationship with other traffic. Numerous inventions in transit technology and operational innovations have taken place in many countries around the world.

Consequently, transit planners today have a much greater choice of transit modes and more extensive experience with the operation of different modes under a variety of conditions than several decades ago. The greatly increased diversity of the family of transit modes is also matched by a broader understanding of the planning goals and requirements that define the criteria for mode comparison and selection. Life-cycle cost of the project remains an important but by no means the only criterion in mode selection. Performance and level of service with resulting passenger attraction should be taken into account, as well as impacts on the surroundings and on the city's economic vitality and livability. These aspects have been included in the project evaluation process prescribed by the regulations of the U.S. Federal Transit Administration under the criterion termed "Locally preferred alternative." Several other countries have similar processes as a requirement to receive funding.

10.5.2 Support for and Attacks on Public Transit

Urban transit, as one of the basic utilities and services, has an important role in the functioning of every city. In small cities, its dominant role is to provide social

services, particularly for travel by population groups that cannot or do not want to use private cars. In large cities, transit's vital role for captive transit users is outweighed greatly by the need to serve as many travelers as possible to prevent excessive traffic congestion and reduce the need for construction of the highways and parking garages that otherwise dominate central urban areas and damage city's livability—its economic strength, as well as its social and environmental quality of life.

Civic leaders and planners who realize the vital importance of transit always support development of high-quality transit systems as the basic tool for achieving a balanced intermodal transportation. The policies for upgrading transit usually also enjoy strong support of the population.

Unfortunately, in some countries, particularly the United States, there are not only supporters but also ideologically extreme critics of public transit. Although U.S. Transportation Acts since the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 strongly endorse intermodal transportation systems and the need for coordination among modes, these policies are often criticized and bypassed by powerful highway and oil lobbies, whose origins and activities are well described and documented by Goddard (1996).

The publicity against transit ranges from criticism of individual projects to ideological and extreme rhetoric against planning, public services, environmental protection, energy conservation, reduction of oil consumption and imports, etc. This campaign is particularly noticeable when some national or world developments occur that call for greater investments in transit and intercity rail. A few examples will illustrate this phenomenon.

- During the world energy crises of 1973 and 1979, which logically showed the need for shifting travel from private cars to urban transit systems, several reports were published arguing that construction of transit systems would result in increased energy consumption!
- A report was produced and claims were made in Boston in the early 2000s that replacement of an

electric LRT line by diesel buses would result in reduced air pollution in the region, contradicting the basic physical facts.

- The problem of reduced mobility of senior citizens when their driving abilities decline has been discussed by the U.S. Secretary of Transportation Norman Mineta in 2006 without mentioning transit as a logical replacement for many trips. Moreover, several articles about this problem have used the fact that our transit systems do not serve some cities adequately to argue against investments in it instead of suggesting its expansion and improvement.
- The same illogical argument that an inadequate service is a proof against rather than for its improvement is used in discussions of problems created by the national problem of excessive car dependency—the condition where many persons have no alternative to car travel. The fact that federal laws emphasize the need for intermodal solutions is ignored.

These arguments against transit improvements are based on such obviously flawed logic that their rebuttal is not necessary here. However, when used extensively in public media, such arguments sometimes lead to delays or cancellation of transit projects. The strongest critical publicity is always aimed against rail transit, as discussed next.

10.5.3 Campaigns against Rail Transit

Most persistent among these numerous intermodal debates and criticisms are those aimed against rail transit. Because it is the most permanent and prominent transit mode interacting with urban character and quality of life as well as the mode most capable of competing with the private automobile, rail transit attracts criticism not only by proponents of bus and other transit modes but particularly by highway interests. In the United States, strong attacks by these interests, often joined by the federal government officials encompass also distortions and criticisms of Amtrak the government-owned passenger railroad, and the entire

concept of a national rail passenger transportation system. A brief review of arguments and campaigns against rail transit in the course of recent decades is useful here because it is a persistent phenomenon that sometimes spreads to other countries also and which transit planners should be equipped to dispute effectively.

“Monorails are systems of the future, rail is the past.” Rapid transit planning for a number of cities—such as Frankfurt, Germany, and San Francisco BART during the 1950s and 1960s—included monorails and found the rail mode to be distinctly more advantageous. However, monorail proposals continue to be brought up in many cities with similar claims repeated (see Section 10.1.3).

“We should never again plan an entire metro network to be built at once, as was done in Washington, D.C.; planning should be adjustable to the changing needs in the city.” This statement expresses the anti-planning attitudes that were critical of investments in transit (incidentally, far greater investments in the Interstate Highway System and other highways in the same cities are never questioned). Actually, the planning of the Washington Metro correctly produced a coordinated network rather than a single line-by-line sequence. The plan did not suggest entire construction at one time but rather completion over a 25-year period. The network was opened section by section from 1976 through 2001. The farsighted planning of this network is obvious from the fact that very few changes have had to be made to it over this 25-year period.

“O-Bahn (guided bus) can match rail systems at lower costs and more flexibility.” The invention of the guided bus around 1980 led to proposals by its manufacturers to many cities that “old-fashioned rail systems should be replaced by the flexible buses serving cities with low-density suburbs.” Guided buses have found applications in some corridors of a few cities, but they have not been found superior to rail transit, as explained in Section 5.2.2.8.

In addition to these simplistic comparisons of modes, critical articles and publications constantly appear, giving inaccurate information and distorted facts aimed to prove that rail transit is inefficient and waste-

ful in all applications. Facts from hundreds of rail systems around the world are ignored or distorted.

As usual with biased rhetoric on political and social issues, these extremist arguments about rail transit are often given more publicity than professional and factual publications, and such publicity has caused considerable delays in transit planning and mode selection in a number of North American and other cities.

10.5.4 Discrepancies between Theoretical Analyses and Real-World Systems

Urban transit systems represent a field that is very conducive to theoretical analyses, and comparison of modes is a topic often addressed in academic studies. Interestingly, however, there have been several modes which obtain unrealistically high evaluations in many theoretical studies.

Monorails of different types have very great popular appeal. They are physically fully operational and there are more than 25 monorails in operation. Yet their use is far below popular expectations. Why are they so popular? The main reason is that monorails are always on aerial guideways, which look very futuristic. The attractive pictures of this mode do not show that vehicles traveling on elevated structures through urban streets with buildings and windows in their vicinity are just as objectionable as rail transit on aerial guideways. The slight advantages of monorails, with their lighter guideways and futuristic image, do not outweigh their disadvantages in more complex guideway, switching, and vehicle support. Thus, while fully physically feasible, monorail is inferior to rail systems in the vast majority of applications.

Monorails have been proposed from time to time, and the latest very serious proposal in Seattle was submitted and even approved by two popular referenda in the early 2000s. That proposal created considerable confusion in transit planning before its detailed planning and evaluation led to its collapse and termination in 2005. A monorail system was promoted and built on a line in Moscow; after its opening, however, its ridership was so low that it is operated for only a few

hours every day. Nevertheless, reasonably successful monorails have been built in a number of Japanese cities and in Las Vegas, Nevada, but only as individual lines, not as networks.

Bus transit has repeatedly been found in theoretical studies by academic researchers to be superior to rail in most situations, and such studies have been used to prevent the construction of rail systems. This was the case in Atlanta, Georgia, prior to the adoption of rail rapid transit in 1969. In San Francisco, several academic papers, such as by M. Webber, criticized BART as inferior to buses, although BART had been approved by a referendum in 1962 because bus services were considered by the population to be inadequate. Similar criticisms of rail appeared in Honolulu, Singapore, Houston, and many other cities. Many papers by J. Kain consistently criticized all rail transit, although he admitted that he did not understand light-rail transit. How can theoreticians be so categorically in favor of one and against another mode when real-world development—following engineering and economic studies, political decisions and popular votes—often support not only improvements of buses but also much higher investments in rail systems?

Analyses of a number of extreme pro-bus and anti-rail “studies” show several common characteristics:

- Evaluation of modes based mostly or exclusively on the comparison of monetary costs make a major error in assuming that the two modes attract the same number of passengers. Actually, unit cost curves decreasing with passenger volume for rail systems should be compared with corresponding cost curves for buses, but for a lower passenger volume in the given corridor.
- Much greater economies of scale, or decreasing cost per passenger on rail than on bus system, are seldom taken into account.
- Buses are considered to be so “flexible” that they can serve many routes, provide high frequencies, offer adaptable schedules, etc. Experienced transit professionals know that buses do allow more lines and operational variations but that excessive diversity of services results in irregularities and de-

creased attraction of service. This introduction of real-world experiences in designing BRT systems has led to making this mode more “rail-like” and therefore more attractive to passengers. Thus, greater “flexibility” does not always attract more passengers nor does it have the same positive impacts on the served area and city in general.

- Computer-based theoretical models, used for many hypothetical studies comparing modes, can easily be manipulated through selection of assumptions to make results look more favorable to any one of the compared modes.
- Externalities of electric rail systems as compared to ICE buses are generally omitted in theoretical studies. Thus, the advantages of electric traction, enhancement of pedestrian and other livable areas in a city when LRT lines serve these areas directly on streets, the ability to use tunnels where this is desirable or necessary, the strong impact of permanent rail infrastructure, and the advantages of these for the character of a city—as compared to buses which are inferior in these respects—are not considered.

Thus, excessive orientation to economic aspects, overlooking passenger preferences among modes and neglecting to consider the long-term impacts of rail versus bus modes, explain this considerable bias of theoretical comparisons of modes favoring buses.

Personal rapid transit (PRT), described in Section 7.3.3, has been subject of numerous theoretical studies and international symposia. Many designs of PRT vehicles—with great details of their mechanical and electrical design, control systems, vehicle flow through a network, etc.—have been advanced. However, the detailed studies of PRT components were not matched by a systems analysis of physically feasible PRT networks and their imagined real-world operations. Therefore the incompatibility of low-capacity vehicles with very complicated infrastructure has been overlooked by promoters of this mode.

As a result of this gap between theoretical analysis and real-world conditions, PRT has been proposed and has attracted the attention of many laypersons, but its

plans were never adopted for implementation (note that the AGT system in Morgantown is technically not a PRT).

10.5.5 Systems Approach in Mode Selection and Intermodal Relationships

Greater availability of different transit modes and the need to provide convenient travel throughout metropolitan areas has increased the need to achieve efficient intermodal integration and easy intra- and intermodal transfers. In recent decades, many cities have developed new design concepts for networks and transfer stations as well as methods of coordinating schedules of interconnected lines that facilitate transferring and allow optimal use of modes and vehicle types on different lines.

However, some transit systems are not using these state-of-the-art methods in selecting modes and integrating them. For example, there are cities with excellent rail networks that are operated with little integration with buses, resulting in the underutilization of both modes. Examples are several cities in Japan and in the United States. Thus, despite the great progress in planning and operating balanced intermodal systems, there are many transit systems that fail to utilize real-world experience with such integration.

Using a systems approach to analyze complex interactions between livable cities and their transportation systems tends to produce interesting results. Cities operating a single-mode network of many independent bus lines can be very efficient and require low investments. Cities that operate several well-integrated modes and allow easy transfers require higher investments and have more complicated operations, but they offer more attractive and efficient services and tend to have much higher per capita ridership. Examples of cities with up to eight mutually integrated transit modes are Boston, Munich, San Francisco, Toronto and Vancouver. Different modes tend to provide better integration with various urban activities and land uses. Most importantly, it can be shown that large cities cannot be livable if they are heavily auto-dominated and

have unsatisfactory transit services. And large cities can have high-quality transit services only if they have several integrated modes.

Therefore failure to carefully select modes that meet local requirements and integrate them is a serious obstacle to achievement of efficient transportation systems as well as economically viable cities with high quality of life (Vuchic 1999).

The importance of integrated transit services has been demonstrated when coordinated rail-bus systems were converted into unregulated minibuses and buses, which provide lower service quality than coordinated systems (examples are many British cities, Lima, and Mexico City). The opposite change, when rail and BRT systems replaced uncoordinated minibuses, which took place in some other cities of developing countries (São Paulo RRT, Mexico City's Insurgentes BRT line, Manila LRT, and others) resulted in major improvements.

Another issue that has a great significance for the choice and design of transit modes and types of operation is automation, specifically the introduction of driverless vehicles and trains. The technology of automated train travel was developed and proven feasible during the 1960s. The next step was solving operational issues in driverless operation, such as door control and dispatching, information systems, security, handling of emergencies and unexpected events, etc. These problems were first solved and tested on APM systems during the 1970s (see Section 7.3.1), i.e., on systems operating in controlled environments, such as airports, university and medical campuses, amusement parks, etc. Finally, fully automated driverless regular transit systems began to be used when the VAL system was opened in Lille and SkyTrain in Vancouver; these demonstrated the fact that driverless vehicles and trains can be operated on regular urban transit lines.

During the development of fully automated systems, the transit industry was very cautious, creating the impression that only systems with rubber-tired guided technology and small vehicles or short trains could be fully automated but that regular rail transit systems must have drivers. Both of these views were challenged (Vuchic 1973): whether a transit system has rail or guided rubber-tired support has no relationship with manual or automated train control. Moreover,

many rail rapid transit systems—such as those in Hamburg, San Francisco, (BART) and Washington—had operated successfully with most elements of fully automated operation and station train dispatching control.

Train automation is not a goal in itself: it is a means to achieve better and more economically efficient service. Automation can contribute significantly to such improvements under certain conditions but not in all cases, as discussed in Section 6.6.1. By far the most significant aspect of transit service that automation can bring is economic feasibility of running high-frequency service with either long or short train consists at all hours of the day and on all days of the week. Another major advantage is that train consists can be changed very quickly, even in response to unexpected passenger variations. However, these most significant factors do not seem to be understood and utilized by many transit designers and operators. Most of the rubber-tired AGT systems in Japanese cities—such as Kobe, Osaka and Yokohama—always operate the same train consists of six, four, and eight cars, respectively. The Northeast Line in Singapore, which has driverless trains, also has fixed consists. The Vancouver SkyTrain is one of very few automated systems that use these capabilities of driverless systems.

The trend toward fully automated transit systems is rather strong, but it is still limited to new systems only. The U-Bahn system in Nürnberg, Germany, is likely to become the first metro system that has been converted from manual into driverless operation. With respect to system technology, rubber-tired systems dominate APM applications, but there are indications that transit systems with driverless operation will increasingly be conventional rail systems, rapid transit or LRRT, which is a form of minirapid transit.

The systems approach combined with real-world experience is also very important in evaluating proposed and unconventional transit modes. A great number of modes were developed in the category of rubber-tired AGT systems. They have now been tested and evaluated, and several have been successfully introduced in cities, while others have not found adoption. These initiatives for innovations represent a healthy phenomenon, but their products must be evaluated against two criteria, as discussed in Chapter 7.



Photo 10.9 Intermodal integration (Freiburg, courtesy of NeiTech)

First, a new system must be physically feasible (some proposed systems do not meet this criterion); if it is, it must have a comparable or superior “performance/cost package” (PCP) as compared with those of conventional systems in the same category.

10.5.6 Importance of Rational Choice of Transit Modes

The central decision in long-range transit planning, evaluation, and selection of modes should be based as much as possible on technical, functional, and impact considerations. Local conditions and preferences must be considered, with special emphasis on the three interested groups: present and potential transit passengers, the transit operating agency, and the served community or city. Pressures by special interest groups and simplistic economic evaluations, particularly those focusing on minimum short-term direct costs, should be resisted, because they often create long-term losses in the form of lower service quality,

a decreased role of transit system, and decreased livability of the city.

To achieve these goals, the city must have a clearly defined set of goals and transportation policies that incorporate specific definitions of the desired roles of private and public transportation as well as the role and treatment of pedestrians.

For implementation of transportation policies, the city must have a competent transit planning organization that cooperates with other transportation authorities and groups (departments for city planning, streets and traffic, parking, business and community organizations, and others).

With respect to transit modes, their optimal selection must be followed by implementation of specific measures for physical, operational, and service integration (Photo 10.9). Different modes must be seen not as adversary competitors, but as constructive components of the city’s intermodal transportation system. Ultimately, transit should be seen not only as a system providing personal mobility, but also as an active supporter of the city’s activities and quality of life, as the example in Photo 10.10 illustrates.



Photo 10.10 Portland streetcar has become a symbol of city's liability; it is integrated with buses, LRT, and traffic management (Courtesy of James Aslaksen)

EXERCISES

- 10.1. How does the need to implement an intermodal transportation system that has a desirable balance between private and public transportation affect the selection of transit modes?
- 10.2. Which transit system element has the greatest influence on its performance/cost package (PCP)? Explain why.
- 10.3. Why are transit systems using ROW category C adequate for services in small cities while they cannot satisfy the requirements of large cities?
- 10.4. Define the advantages and disadvantages of transit modes operating on ROW category B as compared to those on category C.
- 10.5. Explain the correlation between ROW categories and transit systems technology. Specifically, are the modes with steered rubber-tired vehicles usually more efficient than rail modes on ROW C or A? Why?

- 10.6. Many theoretical studies conclude that buses are superior to rail modes even on heavily traveled lines, contrary to experiences with application of these modes in real-world situations. Which errors in the theoretical analyses of these modes often lead to such biases?
- 10.7. Discuss the problem of car dependency: how does the situation where people depend only on cars for traveling in cities affect lifestyle and standard of living and what social problems does it cause?
- 10.8. How is car dependency related to energy consumption? How does that relation affect the economies and political stability of countries that do not have sufficient internal energy sources?
- 10.9. Why do applications of monorail systems usually fail to fulfill the high expectations this mode is often described as having? Explain the problems that often occur in their planning and construction.
- 10.10. List, briefly describe, and compare the main features of the three most widely used medium-performance transit modes.
- 10.11. Define the major differences between typical streetcar/tramway and LRT modes. Give two examples of each of these modes.
- 10.12. Select and describe three of the nine described types of applications of the LRT mode. Find examples of each of these three types.
- 10.13. List and discuss the features of LRT that result in its much greater passenger attraction as compared to regular buses.
- 10.14. Define each one of the three bus modes—regular bus, bus transit system, and bus rapid transit—and list major differences among them.
- 10.15. List and describe three main advantages and three disadvantages of bus compared to rail systems.
- 10.16. Which elements of BRT are most important in their greater attraction of passengers than that of regular buses? Which are the main obstacles to their introduction (effort and investment that must be made)?
- 10.17. How does the level of labor wages influence the relative feasibility of BRT and LRT in a specific country?
- 10.18. Why are automated transit modes more advantageous than manually driven ones on medium-capacity lines?
- 10.19. What are the two most important advantages of fully automated modes (AGT) as compared to driver-driven ones?
- 10.20. Many automated transit systems, AGT and metros, operate fixed consists (constant train lengths at all times). Explain why is this not an optimal design and operation.
- 10.21. Compare the advantages and disadvantages of AGT compared to LRT for applications on main lines in medium-sized cities.
- 10.22. List and explain the features that give rail rapid transit much higher performance than any other transit mode can have.

- 10.23. Metro/rail rapid transit systems require heavy investment and involve considerable disturbance of the areas along their lines. List and explain the positive features of these systems in performance and impacts that outweigh the high investments and disturbances and justify construction of metros in many cities. (Hint: discuss the life of the system, its impact on city development, reconstruction of the surrounding areas which is usually triggered by metro construction).
- 10.24. Compare traditional commuter railroads with contemporary regional rail systems—their network forms, types of services, roles they play in the region, and relationship with other transit modes and private cars. Give two examples of each of these modes.
- 10.25. Describe why systems like BART and Washington Metro are classified as systems spanning RRT and regional rail.
- 10.26. Select and discuss three major developments of regional rail systems that have been intensified in recent years and give examples of them from three cities.

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- <http://www.lightrailnow.org/> LRT advocacy
- <http://www.lrta.org/> LRT advocacy
- <http://www.railfaneurope.net/> European rail information
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- <http://world.nycsubway.org/> Rapid transit information UITP
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- <http://www.trb.org/> Transportation Research Board— <http://www.vdv.de/> German Transit Association—
TRB VDV

APPENDIX I

SI AND ENGLISH UNITS AND CONVERSION FACTORS

The International System of Units (Système International d'Unités, or SI) recognizes seven basic units from which all others are derived. They are:

<i>No.</i>	<i>Quantity</i>	<i>Name of Unit</i>	<i>Symbol</i>
1	length	meter	m
2	mass	kilogram	kg
3	time	second	s
4	electric current	ampere	A
5	temperature	kelvin	K
6	luminous intensity	candela	cd
7	amount of substance	mole	mol

Multiples of units are designated by the following names:

<i>Amount</i>	<i>Prefix</i>	<i>Symbol</i>	<i>Amount</i>	<i>Prefix</i>	<i>Symbol</i>
10^1	deca	da	10^{-1}	deci	d
10^2	hecto	h	10^{-2}	centi	c
10^3	kilo	k	10^{-3}	milli	m
10^6	mega	M	10^{-6}	micro	μ
10^9	giga	G	10^{-9}	nano	n

This appendix presents the SI and English (imperial) units, which are used in various areas of transportation engineering, and their conversion factors. Some metric units and factors that are not listed in the SI but are commonly used and remain internationally recognized are also included. Examples are the units of centimeter (10^{-2} m), hour (3.6×10^3 s) and kilowatt-hour (3.6 MJ) and multiples of 10, 10^2 , 10^{-1} , and 10^{-2} .

For more extensive coverage of units, the following book is suggested:
Cardarelli, Francois. *Scientific Unit Conversion*. New York: Springer-Verlag, 2003.

Units and conversion factors within and between the two systems of measures are presented here for each dimension in a separate box. The format followed for each dimension is shown in the first box:

DIMENSION	
<i>SI unit (symbol)</i>	<i>English unit (symbol)</i>
<i>Conversion factors</i> (for conversion in the direction of the arrow, multiply by the number provided)	

LENGTH	
millimeter (mm)	inch (in. ")
centimeter (cm)	foot (ft. ')
meter (m)	yard (yd)
kilometer (km)	mile (mi)
$10^3 \text{ mm} = 10^2 \text{ cm} = 1 \text{ m}$	$36 \text{ in.} = 3 \text{ ft} = 1 \text{ yd}$
$10^3 \text{ m} = 1 \text{ km}$	$5280 \text{ ft} = 1760 \text{ yd} = 1 \text{ mi}$
mm	in.
m	ft
m	yd
km	mi

AREA

square millimeter (mm^2)square centimeter (cm^2)square meter (m^2)

hectare (ha)

square kilometer (km^2)square inch (in^2)square foot (ft^2)square yard (yd^2)

acre

square mile (mi^2) $1296 \text{ in.}^2 = 9 \text{ ft}^2 = 1 \text{ yd}^2$ $3,097,600 \text{ yd}^2 = 640$ acres = 1 mi^2 $10^6 \text{ mm}^2 = 10^4 \text{ cm}^2 = 1 \text{ m}^2$ $10^6 \text{ m}^2 = 10^2 \text{ ha} = 1 \text{ km}^2$
 $\begin{array}{ccc} & 6.452 & \\ \swarrow & & \searrow \\ \text{cm}^2 & & \text{in.}^2 \\ & 0.1550 & \end{array}$
 $\begin{array}{ccc} & 0.0929 & \\ \swarrow & & \searrow \\ \text{m}^2 & & \text{ft}^2 \\ & 10.76 & \end{array}$
 $\begin{array}{ccc} & 0.8361 & \\ \swarrow & & \searrow \\ \text{m}^2 & & \text{yd}^2 \\ & 1.196 & \end{array}$
 $\begin{array}{ccc} & 0.4047 & \\ \swarrow & & \searrow \\ \text{ha} & & \text{acre} \\ & 2.471 & \end{array}$
 $\begin{array}{ccc} & 2.590 & \\ \swarrow & & \searrow \\ \text{km}^2 & & \text{mi}^2 \\ & 0.3861 & \end{array}$

VOLUME

cubic millimeter (mm^3)cubic centimeter (cm^3 or cc)

liter (L)

cubic meter (m^3)cubic inch (in.^3)

quart (qt)

gallon* (g)

cubic foot (ft^3)cubic yard (yd^3) $10^6 \text{ mm}^3 = 10^3 \text{ cm}^3 = 1 \text{ L}$ $10^6 \text{ cm}^3 = 10^3 \text{ L} = 1 \text{ m}^3$ $46,656 \text{ in.}^3 = 27 \text{ ft}^3 = 1 \text{ yd}^3$ $4 \text{ qt} = 1 \text{ gal} = 231 \text{ in.}^3$ $1 \text{ qt} = 57.75 \text{ in.}^3$
 $\begin{array}{ccc} & 16.39 & \\ \swarrow & & \searrow \\ \text{cm}^3 & & \text{in.}^3 \\ & 0.0610 & \end{array}$
 $\begin{array}{ccc} & 3.785 & \\ \swarrow & & \searrow \\ \text{L} & & \text{gal} \\ & 0.2642 & \end{array}$
 $\begin{array}{ccc} & 0.0283 & \\ \swarrow & & \searrow \\ \text{m}^3 & & \text{ft}^3 \\ & 35.32 & \end{array}$
 $\begin{array}{ccc} & 0.7646 & \\ \swarrow & & \searrow \\ \text{m}^3 & & \text{yd}^3 \\ & 1.308 & \end{array}$

MASS		
gram (g)		ounce (oz)
kilogram (kg)		pound (lb), pounds mass (lbm)
(metric) tone or tonne (t)		(short) ton (tn ⁺ or stn), long ton (ltn)
	$\begin{array}{ccc} & 28.35 & \\ g \swarrow & & \searrow \text{oz} \\ & 0.0353 & \end{array}$	
$10^3 \text{ g} = 1 \text{ kg}$	$\begin{array}{ccc} & 0.4536 & \\ kg \swarrow & & \searrow \text{lb} \\ & 2.205 & \end{array}$	$16 \text{ oz} = 1 \text{ lb}$
$10^3 \text{ kg} = 1 \text{ t}$	$\begin{array}{ccc} & 0.9072 & \\ t \swarrow & & \searrow \text{tn} \\ & 1.102 & \end{array}$	$2000 \text{ lb} = 1 \text{ tn}$
	$\begin{array}{ccc} & 1.016 & \\ t \swarrow & & \searrow \text{ltn} \\ & 0.9842 & \end{array}$	$2240 \text{ lb} = 1.12 \text{ tn} = 1 \text{ ltn}$

DENSITY		
grams/cubic centimeter (g/cm ³)		ounces/cubic inch (oz/in. ³)
grams/liter (g/L)		pounds/cubic inch (lb/in. ³)
kilograms/cubic meter (kg/m ³)		pounds/cubic foot (lb/ft ³)
		$16 \text{ oz/in.}^3 = 1 \text{ lb/in.}^3 = 1728 \text{ lb/ft}^3$
$10^3 \text{ kg/m}^3 = 10^3 \text{ g/L} = 1 \text{ g/cm}^3$	$\begin{array}{ccc} & 1.743 & \\ \text{cm}^3 \swarrow & & \searrow \text{in.}^3 \\ & 0.5737 & \end{array}$	
	$\begin{array}{ccc} & 16.02 & \\ \text{L} \swarrow & & \searrow \text{gal} \\ & 0.0624 & \end{array}$	
	$\begin{array}{ccc} & 0.5933 & \\ \text{m}^3 \swarrow & & \searrow \text{ft}^3 \\ & 1.686 & \end{array}$	

SPEED		
meters/second (m/s)		feet/second (ft/s)
kilometers/hour (km/h)		miles/hour (mph)
$10 \text{ m/s} = 3.6 \text{ km/h}$	$\begin{array}{ccc} & 0.3048 & \\ \text{m/s} \swarrow & & \searrow \text{ft/s} \\ & 3.281 & \end{array}$	$88 \text{ ft/s} = 60 \text{ mph (exact)}$
	$\begin{array}{ccc} & 1.609 & \\ \text{km/h} \swarrow & & \searrow \text{mph} \\ & 0.6214 & \end{array}$	$(1.1467 \text{ ft/s} = 1 \text{ mph})$

ACCELERATION

meters per second squared
(m/s²)

(km/h/s is not used)

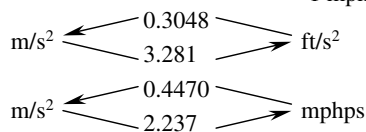
$$g = 9.807 \text{ m/s}^2$$

feet per second squared (ft/s²)

miles per hour per second
(mph/s)

$$g = 32.18 \text{ ft/s}^2$$

$$1 \text{ mph/s} = 1.467 \text{ ft/s}^2$$

**JERK**

meters per second cubed
(m/s³)

feet per second cubed (ft/s³)

Factors are the same as the corresponding ones for acceleration.

FORCE, WEIGHT

dyne (dyn)

newton (N)

kilonewton (kN)

(metric) ton or tonne (t) (not in SI)

$$10^8 \text{ dynes} = 10 \text{ N} = 1 \text{ kN}$$

$$\text{Force} = \text{mass} \times \text{acceleration}$$

$$1 \text{ N} = 1 \text{ kg m/s}^2$$

ounce (oz)

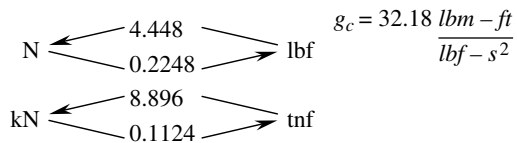
pound force (lbf)

10³ pounds (kip)

(short) ton force (tnf or s.tnf)

$$3200 \text{ oz} = 2000 \text{ lbf} = 1 \text{ tnf}$$

$$\text{Force} = \frac{\text{weight} \times \text{acceleration}}{\text{gravity const. } (g_c)}$$



LINEAL MASS*

kilograms per meter (kg/m)

pounds per yard (lb/yd)

kg/m

0.4960

2.016

lb/yd

*Common use in transportation: mass of rails.

PRESSURE*

pascal (Pa)
kilogram force per square
meter (kgf/m²)
1 kgf/m² = 9.807 Pa

pounds force per square
inch (lbf/in.²) (psi)
pounds force per square
foot (lbf/ft²)

Pa

6,894.76

1.45 × 10⁻⁴

psi

Pa

47.88

0.02089

lbf/ft²

*Often used for area weight of vehicles.

FUEL CONSUMPTION (C)
AND EFFICIENCY (E)*

(C) liters per 100 kilometers
(L/100 km)
(C) joules per kilometer
(J/km)
(E) kilometers per liter (km/L)

(C) gallons per mile
(gpm, gal/mi)
(C) British thermal units
per mile (Btu/mi)
(E) miles per gallon
(mpg, mi/gal)

m/s

0.4251

2.352

ft/s

km/h

235.2

0.00425

mph

km/h

0.6557 × 10³

1.525 × 10⁻³

mph

ENERGY

erg
joule (J)

British thermal unit (BTU)
foot-pound force (ft-lbf)

10^7 ergs = 1 J

J $\begin{matrix} \swarrow 1055 \\ \searrow 9.482 \times 10^{-4} \end{matrix}$ Btu $\begin{matrix} 1 \text{ Btu} = 779.2 \text{ ft-lbf} = \\ 118.98 \text{ hp-h} \end{matrix}$

J $\begin{matrix} \swarrow 1.356 \\ \searrow 0.7376 \end{matrix}$ ft-lbf

Joint units:

watt-hours (Wh)

kilowatt-hours (kWh)

10^3 Wh = 1 kWh

J $\begin{matrix} \swarrow 3.6 \times 10^6 \\ \searrow 0.2778 \times 10^{-6} \end{matrix}$ kWh $\begin{matrix} \swarrow 0.3776 \times 10^{-6} \\ \searrow 2.665 \times 10^6 \end{matrix}$ ft-lbf

POWER

ergs per second
horsepower (metric) (HP)

foot-pounds force per
second (ft-lbf/s)
horsepower (British) (hp)

1 HP (metric) = 75 kg-m/s

1 hp (British) = 550 ft-lbf/s

Joint units:

watt (W) [1 W = 1 J / s 10^7 ergs/s]

kilowatt (kW)

HP (metric) $\begin{matrix} \swarrow 1.360 \\ \searrow 0.7355 \end{matrix}$ kW $\begin{matrix} \swarrow 0.7457 \\ \searrow 1.341 \end{matrix}$ hp (British)

TORQUE

dyne-centimeter (dyn-cm)
newton-meter (N-m)

inch-pounds force (in.-lbf)
foot-pounds force (ft-lbf)

10^7 dyn-cm = 1 N-m

12 in. lbf = 1 ft-lbf

N-m $\begin{matrix} \swarrow 1.356 \\ \searrow 0.7376 \end{matrix}$ ft-lbf

APPENDIX II

LIST OF ABBREVIATIONS

<i>Abbreviation^a</i>	<i>Stands for:</i>	<i>Introduced or Defined in Section</i>
AGT*	Automated guided transit	7.3.1
AB*	Articulated bus	5.2.2.5
AC	Alternating current	3.4.1
ADA	Americans with Disabilities Act	9.4.4
AERA	American Electric Railway Association	1.4.1
ALRT	Advanced (or automated) light rail transit	7.3.1
APM*	Automated people mover	7.3.1
APTA	American Public Transportation Association	1.3.1
ATB*	Articulated trolleybus	5.2.2.5
ATO*	Automatic train operation	3.4.5
ATP*	Automatic train protection	6.6.1
ATS*	Automatic train supervision	6.6.1.4
AVL	Automatic vehicle location	5.4.5
BRT*	Bus rapid transit	2.1.2.4
BST	Bus semirapid transit	10.2.1
BTS*	Bus transit system	5.1.3
CAD	Computer aided despatching	5.6.1
CBD	Central business district	2.1.2.3
CBL*	Contraflow bus lane	5.3.4
CNG	Compressed natural gas	5.2.1.1
DAR*	Dial-a-ride	9.4.4
DC	Direct current	3.4.1
DD	Double-decker (bus)	5.2.2.7
DPM	Downtown people mover	2.3.3
DAR	Dial-a-ride	2.3.1
EBL*	Exclusive bus lane	5.3.4
FS	Far-side (stop location)	5.5.1.2
FT	Following train	6.6.1.2
FTU	Following transit unit	4.3.1.1
GIS	Geographic information system	9.4.4
GLT	Guided light tramway	5.2.2.8
GPS	Global positioning system	5.6.1
GRT*	Group rapid transit	7.3.1
GTO	Gate turn off thyristor	3.4.2.1
HOV*	High-occupancy vehicle	2.1.2.1
HVAC	Heating/ventilation/air conditioning	5.2.3
ICE	Internal Combustion Engine	2.1.2.2
IEB	Inertial energy bus	5.2.1.5

<i>Abbreviation^a</i>	<i>Stands for:</i>	<i>Introduced or Defined in Section</i>
IGBT	Insulated gate bi-polar transistor	3.4.4
ISTEA	Intermodal Surface Transportation Efficiency Act	1.6
ITS*	Intelligent transportation system	2.1.3
K+R*	Kiss-and-ride	6.5.4
LIM	Linear induction motor	2.1.2.2
LNG	Liquid natural gas	10.2.2.3
LPG	Liquefied petroleum gas	5.2.1.5
LRRT*	Light rail rapid transit	6.1.2.2
LRT*	Light rail transit	2.1.2.1
LRV	Light rail vehicle	3.4.6.2
LOS*	Level of service	2.1.4
LT	Leading train	6.6.1.2
LTU	Leading transit unit	4.3.1.1
MAC	Major activity center	8.1
MagLev	Magnetic Levitation (transportation system)	7.2
MB	Midblock (stop location)	5.5.1.2
MB	Minibus	5.2.2.2
MLS	Maximum load section	4.4.1
MP*	Married pair (rail vehicles)	6.2.1
MU	Multiple unit (train)	6.2.1
NEXTEA	National Economic Crossroads Transportation Efficiency Act	1.6
NS	Near-side (stop location)	5.5.1.2
OMS	Optimal metro service	6.6.1.3
PCC	Presidents' Conference Committee (streetcar model)	1.4.1
PCP	Performance cost package	10.1.5
PMS*	People-mover system	7.3.1
PRT*	Personal rapid transit	4.3.5
P+R*	Park-and-ride	6.5.4
RB*	Regular bus (service)	2.3.2
RBL*	Regular bus lane	5.3.3.3
RGR*	Regional rail	2.3.4
RRT*	Rail rapid transit	2.3.4
RT*	Rapid transit	2.3.4
RTRT*	Rubber-tired rapid transit	2.3.4
RTS	ROW-technology-service/operation	10.2.4
ROW*	Right-of-way	2.1.2
SAE	Society of Automotive Engineers	3.2.1.1
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users	1.6
SB	Standard bus (vehicle)	5.2.2.3
SCREC	Silicon controlled rectifier	3.4.2.1
SCR*	Streetcar (tramway, trolley)	2.3.2
SES	Surface effect ship	8.3.1.3
SOV	Single occupancy vehicle	3.7.5
SQ*	Service quality	2.1.4
SU*	Single unit (rail vehicle)	6.2.1
SWATH	Small waterplane area twin hull (boat)	8.3
TB*	Trolleybus (vehicle or service)	2.3.2
TOR	Top of rail	6.2.1.1

		<i>Introduced or Defined in Section</i>
<i>Abbreviation^a</i>	<i>Stands for:</i>	
TU*	Transit unit	2.1.2.3
TW*	Tramway	6.1.2
UITP	International Association of Public Transport	1.3.1

^aAsterisks (*) indicate terms which are defined in the Appendix III.

APPENDIX III

DEFINITIONS OF TRANSIT SYSTEMS TERMS

This appendix presents definitions of new and refined concepts and terms as well as definitions of basic concepts of transit systems and technology but not including technical components and hardware. The listing is not intended to be either comprehensive or exhaustive for the entire transit field.

ACCELERATED SERVICE—Transit line operation in which successive TUs travel without stopping through alternate sets of stations on a predetermined schedule. Examples: skip-stop and zonal service.

AERIAL TRAMWAY—Passenger transportation mode consisting of cabins suspended on a stationary cable and towed by a moving, usually closed-loop cable, used to overcome steep gradients, deep valleys, or bodies of water.

ARTICULATED BUS (AB) or ARTICULATED TROLLEYBUS (ATB)—A 16 to 18-m long three axle bus or trolleybus with the rear body section connected to the main body by a joint mechanism that allows the vehicle to bend in curves and yet have a continuous interior.

ARTICULATED RAIL VEHICLE—(1) An extra-long (17- to 50-m) rail vehicle with 2, 3, 5, or 7 bodies connected by joint mechanisms that allow bending in curves yet with a continuous interior. Very common on LRT and streetcar systems but also found on several recently built RRT systems. (2) Rapid transit cars with separate bodies sharing a common truck.

AUTOMATED GUIDED TRANSIT (AGT)—Any guided transit mode (with rubber tires or rails) with fully automated (driverless) operation; the term usually refers, however, only to guided modes with medium-sized vehicles, sometimes referred to as modes. Operates on regular transit lines or as a shuttle system in airports and other activity centers. Also referred to as automated people mover (APM) or people mover system (PMS).

AUTOMATED PEOPLE MOVER (APM)—See **AUTOMATED GUIDED TRANSIT**.

AUTOMATIC TRAIN OPERATION (ATO)—A control system that performs all functions of train travel along a transit line.

AUTOMATIC TRAIN PROTECTION (ATP)—A control system that prevents trains from following each other at less than a safe stopping distance.

AUTOMATIC TRAIN SUPERVISION (ATS)—A system that controls movements of all trains on a transit line or a network.

BASIC OPERATING UNIT (IN RAPID TRANSIT)—The smallest number of RT vehicles that can operate independently: usually 1 to 3, exceptionally 4 to 5 cars. Most common types are:

MARRIED PAIR (MP)—Two semipermanently coupled cars sharing some mechanical/electrical equipment

- SINGLE UNIT (SU)**—A car that can operate by itself
- THREE-CAR UNIT**—Three semipermanently coupled cars sharing some mechanical/electrical equipment
- BUS (SERVICE)**—Transit services provided by buses; they include:
- BUS RAPID TRANSIT (BRT)**—Bus transit designed as an integrated system of distinct bus vehicles, mostly separate ROW (category B or A), preferential treatments at intersections, ITS, and other elements for greater efficiency. Its better performance and stronger image result in greater passenger attraction than regular bus.
 - BUS TRANSIT SYSTEM (BTS)**—A bus service developed as a coordinated system with improvements in ROW separation, stops, vehicles, operations, passenger information, etc., for higher speed, reliability, and efficiency.
 - EXPRESS**—Express transit service operated by buses.
 - REGULAR (RB) OR LOCAL**—Common urban bus routes serving all stops, as distinguished from short-haul and express services.
 - SUBSCRIPTION**—Bus service provided exclusively for persons who subscribe for a time period (week, month, year) to travel every working day at the same time on the same route (commuting). Also used for special groups, such as the disabled.
- BUS GATE**—A bus priority signal control for intersection approaches. Signals located 30 to 40 m upstream from the intersection stop traffic in regular lanes while the bus lane remains open, allowing buses to proceed to any lane at the intersection signal ahead of other traffic.
- BUS LANE**—Traffic lane for dominant or exclusive use by buses. It may be:
- CONTRAFLOW (CBL)**—The same as a regular bus lane but with buses operating in the opposite direction from other traffic.
 - EXCLUSIVE (EBL)**—Bus lanes (usually two) for bus use only, physically separated (by curbs or barriers) from other traffic.
 - REGULAR (RBL)**—A lane on urban streets or freeways reserved for bus use only, separated from other lanes by pavement markings, signs, or rubber cones but not by fixed physical barriers.
- BUS RAPID TRANSIT**—See BUS SERVICES, BUS RAPID TRANSIT.
- BUS TRANSIT SYSTEM**—See BUS SERVICES, BUS TRANSIT SYSTEM
- BUSWAY**—A roadway reserved for buses only (ROW category A).
- CABLE CAR**—Rail transit mode with single cars (without motors) propelled by a continuously moving cable located in an underground slot between rails.
- CAPACITY (TRANSIT)**—(1) Static: total number of spaces or persons a vehicle can accommodate. (2) Dynamic: the maximum number of TUs, vehicles, spaces, or persons that can be transported on a transit line past a fixed point in one direction per unit of time (usually 1 hour). Major concepts of both static and dynamic capacities are:
- FLEET (or ROLLING STOCK)**—The total number of passenger spaces in all vehicles of a transit fleet.
 - LINE (C)**—The maximum number of spaces which transit vehicles on a line can transport past a fixed point in one direction per unit of time (usually 1 hour).

- LINEAR VEHICLE (π)—The number of spaces per unit of vehicle length (meter).
- OFFERED—The line capacity in sps/h, or theoretical maximum ability of a line to carry persons, as distinguished from utilized, practically achievable capacity in prs/h.
- POINT—The maximum number of vehicles or spaces that can cross a point in any direction per hour.
- SCHEDULED LINE—The number of spaces transported on a line per direction per hour with a given line operating schedule.
- STATION (C_s)—The maximum number of spaces transported in vehicles stopping at a station per direction per hour.
- TU LINE ($f_{\max}$)—The maximum number of TUs that can pass a fixed point per direction per hour, or maximum frequency of service.
- UTILIZED (C_p)—The maximum number of persons transit vehicles on a line can transport past a fixed point per direction per hour.
- VEHICLE (C_v)—The total number of passenger spaces in a vehicle. In some cases this may refer to the number of seats only.
- VEHICLE LINE (c)—The maximum number of vehicles that can pass a fixed point per direction per hour (as single vehicles or in trains).
- WAY (C_w)—The maximum number of spaces which can be transported in vehicles past a point per direction per hour without stopping.
- CAR SHARING—System of cars parked at many locations in the city at which subscribed members can take them for use during a period of time, paying by the amount of use.
- CITY TRANSIT—Transit lines serving urban area, as distinguished from short-haul and regional transit lines.
- COG RAILWAY—A rail transportation mode with auxiliary or full traction via a geared wheel in the middle of a powered axle, which is engaged with a linear vertical gear (rack) installed along the track center, providing traction on very steep grades.
- COMMUTER RAILROAD, see REGIONAL RAIL
- COMMUTER TRANSIT—Transit services operated during peak hours only, primarily serving work trips.
- CONCURRENT FLOW BUS LANE, see BUS LANE, REGULAR
- CONSIST (TRAIN)—A composition of rail cars coupled in a train.
- CONSUMPTION RATE—The ratio of the quantity of a certain resource utilized in a process (e.g. of transporting) to the quantity of a specific output of the process, such as kWh/veh-km.
- CONTRAFLOW BUS LANE, see BUS LANE, CONTRAFLOW
- DEMAND RESPONSIVE TRANSIT—Paratransit services with routes and schedules partially or fully determined by travel desires of individual passengers. Examples: dial-a-ride, taxi.
- DOUBLE-ARTICULATED BUS—An 18–24 m long bus with three articulated body sections and four axles.
- DIAL-A-RIDE (DAR)—A paratransit service consisting of minibuses or vans directed from a central dispatching office to pick up and drop off individual passengers according to their desires expressed via telephone.

DUAL-MODE OPERATION—A transit operation that involves two different travel modes, such as steered and guided (dual-mode vehicles), with ICE and electric traction (dual-mode bus or rail vehicle), on ROW category C and A (LRT on street and in tunnel), manual and automatic driving (recent RRT systems), and others.

EXCLUSIVE BUS LANE, see **BUS LANE, EXCLUSIVE**

EXPRESS SERVICE—A transit line with long spacings between stations that has high operating speed and serves primarily long trips. It usually operates on the same street or parallel tracks as a local line with more frequent stopping, which serves short trips and acts as collector/distributor for the express.

FUNICULAR—A passenger transportation mode consisting of a pair of rail vehicles (or short trains) permanently attached to two ends of the same cable, counterbalancing each other. May have a single track with a turnout or a double track. Used to overcome steep gradients.

GUIDED TRANSIT—Transit modes with vehicles physically guided by guideway; includes rail, monorail, AGT, and several other technologies.

GUIDEWAY—A travel way (rail track, guide beam, riding and guiding surfaces, and others) that physically guides vehicles specially designed to travel on it. Guideways always require ROW category A except rail, which can be placed in any category (A, B, or C).

HEAVY RAIL—see **RAIL RAPID TRANSIT**

HIGH OCCUPANCY VEHICLE (HOV)—Vehicle of any type (automobile, van, bus or others) that carry at least a certain prescribed number of passengers (usually four). Concept used for reserved “HOV lanes.”

HIGHWAY TRANSIT—Transit modes with highway (rubber-tired, steered) vehicles; includes all bus modes, trolleybuses, and paratransit.

HYBRID:

SERVICE—Bus services “between” conventional fixed-route transit bus and paratransit, including route-deviation, DAR and others.

VEHICLE—bus or rail transit vehicle with propulsion combining two different motors, such as ICE and electric, which operate in optimal combination for each regime, such as acceleration, low or high speed, etc.

HYDROFOIL—Boat with two foil supports on which the boat rises to reduce water drag and travel at much higher speed than conventional boats.

INTELLIGENT TRANSPORTATION SYSTEM (ITS)—Transportation or transit system which utilizes computers, scanners, communications and other electronic devices to enhance safety, short headways, priority signals, passenger information, etc.

INTERURBAN—Electric rail transit service between cities and towns in close proximity to each other, with lengths of 15 to 80 km. This mode usually has ROW category B, high speed, and comfort.

JITNEY (SERVICE)—Paratransit service provided in passenger cars, vans, or minibuses along fixed routes, sometimes with minor deviations. Vehicle ownership, scheduling and organization of service vary among cities. Used extensively in cities of developing countries that have inadequate transit service.

KISS-AND-RIDE (K+R)—A mode of travel by transit when the passenger is driven to or from a transit station by another person.

- LEVEL OF SERVICE (LOS)—An overall measure of all service characteristics that affect users.
- LIGHT RAIL RAPID TRANSIT (LRRT)—Light rail transit with ROW category A on its entire length. It may have low- or high-level platforms and visual or signal control. Mode “between” LRT and RRT.
- LIGHT RAIL TRANSIT (LRT)—A transit mode utilizing predominantly ROW category B, sometimes A or C, on different network sections. Its electrically powered rail vehicles operate in one- to four-car TUs. The mode has a wide range of LOS and performance characteristics.
- LOAD FACTOR (α)—The ratio of passengers carried to offered passenger spaces in a TU or on a line during certain period of time.
- LOCAL SERVICE—(1) Transit line operation in which all TUs stop at all stations or (2) Transit service in a city or its immediate vicinity as distinguished from regional transit or interurban lines.
- LOW-FLOOR VEHICLE—Bus or rail vehicle with floor not higher than 0.35 m above the travel way or TOR which allows fast and easy boarding/alighting, accommodates the disabled and eliminates the need for high platforms. Used for buses, LRT and RGR modes.
- METRO—A popular name for rail rapid transit systems.
- MODE, TRANSIT—A transit system category characterized by specific ROW, technological, and operational features. Examples: trolleybus, express bus, rail rapid transit.
- MODULAR (VEHICLE) CONSTRUCTION—Vehicle design consisting of components (modules) which can be replaced, simplifying repairs, or exchanged, increasing utilization of vehicle fleet.
- MONORAIL—A guided transit mode riding on or suspended from a single rail, beam or tube; vehicles usually operate in trains.
- OPERATING REGIME—Any state of vehicle motion with a specific physical characteristic, such as acceleration, constant speed, or deceleration (coasting and braking).
- PARATRANSIT—Modes of passenger transportation consisting of small or medium capacity high-way vehicles offering service adjustable in various degrees to individual users’ desires. Its categories are:
- PUBLIC—Paratransit services available to any user who pays a predetermined fare. Main modes: taxi, jitney, dial-a-ride.
- SEMPUBUC—Paratransit services available only to persons of a certain group, such as a company, neighborhood, etc. Examples: vanpools, subscription buses, car sharing.
- PARK-AND-RIDE (P+R)—A mode of travel by transit when passengers drive to a transit station and park their automobiles in the station’s P+R lot. Possible with any transit mode but most commonly used with rail modes, particularly RT and RGR.
- PEOPLE MOVER SYSTEM (PMS), see AUTOMATED GUIDED TRANSIT
- PERFORMANCE (TRANSIT SYSTEM)—A composite measure of transit system operating characteristics, mostly quantitative, such as service frequency, speed, reliability, safety, capacity, and productivity.
- PERSONAL RAPID TRANSIT (PRT)—An imaginary transit mode consisting of small-capacity (two to six spaces) cabin-type vehicles traveling automatically over an elaborate system of guideways; individuals or small acquainted groups would use a cabin to travel between origin and

destination stations without stopping. The concept is hypothetical and not feasible in the real world.

PREMETRO—An LRT system designed with provisions for easy conversion into RRT (metro).

PRODUCTIVE CAPACITY (P_c)—The product of line (or vehicle) capacity and its operating (or technical) speed. Dimension: sps-km/h^2 . A good composite representative of transit system performance.

PRODUCTIVITY—The quantity of (transportation) output per unit of consumed resource. For example, $\text{veh-km/driver/hour}$, or $\text{prs-km/unit cost of operation}$.

RAIL RAPID TRANSIT (RRT)—Electrically powered rail vehicles usually operating in 4- to 10-car trains on ROW category A. In many performance features—such as speed, capacity, reliability, safety, and operating efficiency—superior to all other transit modes. Also called **HEAVY RAIL** and **METRO**.

RAIL TRANSIT—A family of transit modes with rail technology. Major ones, generally in ascending order of performance, are streetcars, light rail transit, rail rapid transit, and regional rail.

RAPID TRANSIT (RT)—A generic class of electrically powered guided transit modes that operate exclusively on ROW category A and have high speed, capacity, reliability, and safety. Includes RRT, RTRT, LRRT, and most RGR systems.*

REGIONAL RAIL (RGR)—A regional passenger service, usually provided by railroad agencies, that consists of electric or diesel-powered trains on grade-separated railroad lines (sometimes with protected grade crossings). Characterized by very high performance and service quality.

REGIONAL TRANSIT—Long bus or rail transit lines with few stations and high operating speeds that primarily serve long trips within metropolitan regions, as distinguished from city transit and short-haul transit.

REGULAR BUS LANE, see **BUS LANE**, **REGULAR**

REGULAR BUS (SERVICE), see **BUS (SERVICE)**, **REGULAR**

REGULAR or ALL-DAY TRANSIT SERVICES—Transit lines operated during most hours, typically 16 to 18 hours per day.

RIGHT-OF-WAY (TRANSIT), (ROW)—(1) Strictly defined, a legally and physically separated strip of land for exclusive use by transit vehicles; crossings may be allowed, (2) Broadly defined, any path or way on which transit vehicles travel. Based on the latter definition, transit ROW are classified in three categories:

CATEGORY A—Fully controlled ROW without (or with fully protected) grade crossings or any legal access by other vehicles or persons; also called “grade-separated,” “private,” or “exclusive” ROW. It can be a tunnel, aerial, or at grade level.

CATEGORY B—ROW types that are longitudinally physically separated (by curbs, barriers, grade separation, etc.) from other traffic, but with grade crossings for vehicles and pedestrians, including regular street intersections.

* Since rapid transit is well known by its high performance, various modes are often called “rapid transit,” although they technically do not belong in that class of modes. Examples: BRT and PRT. The first is actually bus transit system, since no bus line has ROW category A only. As for the second, no PRT has achieved high speed, capacity, and safety in actual applications.

CATEGORY C—Surface streets with mixed traffic. Transit may have preferential treatment, such as reserved but not physically separated lanes, or it may travel in general traffic lanes.

ROLLING STOCK—A collective term for a fleet of rail (transit) vehicles.

RUBBER-TIRED RAPID TRANSIT (RTRT)—The same as rail rapid transit except that the vehicles ride on and are guided by rubber tires on a specially designed guideway with concrete or steel running surfaces. Switching and vehicle support in cases of tire failure may be provided by additional steel wheels and conventional rail track or by other mechanisms.

SEMIRAPID BUS, see **BUS RAPID TRANSIT**.

SEMIRAPID TRANSIT—A generic class of modes utilizing mostly ROW category B, but C or A may also be used on some sections. By performance, it is between street transit and rapid transit. Examples: BRT and LRT.

SERVICE (TRANSIT)—A transportation service offered by a transit operating agency to the public; it is classified by:

STOPPING SCHEDULE or **TYPE OF OPERATION**—Local, accelerated, and express services.

TIME OF OPERATION—Regular or all-day, commuter or peak-hour, and special or irregular services.

TYPES OF ROUTES AND TRIPS SERVED—Short-haul, city transit, and regional transit.

SERVICE QUALITY (SQ)—Qualitative elements of service affecting passengers, such as convenience of using the transit system, riding comfort, aesthetics, and cleanliness.

SHORT-HAUL TRANSIT—Low-speed transit services for circulation within small areas, usually with high travel density, such as CBDs, campuses, airports, exhibition grounds, and other major activity centers (MACs).

SINGLE-BODY VEHICLE—A bus or rail vehicle with one rigid (nonarticulated) body.

SPECIAL TRANSIT—Irregular transit services provided on special occasions, such as sport events, exhibitions, and public festivities or for special groups, such as tourists, school students, and the handicapped.

SPECIALIZED TECHNOLOGIES—Transit modes with other than highway or rail technologies, mostly used for short-haul services or for special physical conditions (steep grades, water bodies, etc.). Also called specialized transit modes. Examples: cog railway, funicular, ferryboat.

STATION (TRANSIT)—An off-street at-grade, under-, or above-street-level facility for stopping of transit vehicles to pick up and drop off passengers. Usually has boarding/alighting platforms, waiting area, fare collection, information, and related facilities.

STOP (TRANSIT)—An on-street location where transit vehicles stop to pick up and discharge passengers. It has a sign and basic service information, sometimes also a shelter with benches.

STREETCAR (SCR), TRAMWAY, or TROLLEY—A street transit mode consisting of electrically powered rail vehicles operating in one- to three-car TUs, usually on ROW category C.

STREET TRANSIT—A generic class of transit modes operating on streets with mixed traffic (ROW category C). Examples: regular bus, trolleybus, and streetcar.

SUBSCRIPTION BUS, see **BUS (SERVICE)**, **SUBSCRIPTION**

SUBURBAN RAILROAD, see **REGIONAL RAIL**

SUBWAY—Rapid transit in tunnels. Sometimes used as a popular although incorrect name for any rapid transit.

TAXI—A standard or specially designed passenger automobile operated by a professional driver and hired by one or a group of users for individual trips.

TECHNOLOGY (TRANSIT)—Mechanical features of vehicles and ways, primarily vehicle support, guidance, propulsion, and control.

TERRAIN-SPECIALIZED TECHNOLOGIES—A subcategory of specialized technologies comprising modes for operation on unusual terrain (hills, ravines). Examples: aerial tramway, cable car, cog railway.

TRAM-TRAIN—Popular name for the transit mode combining LRT and RGR: LRT vehicles traveling on railway lines between center city and suburbs.

TRAMWAY—See **STREETCAR**

TRANSFER—Change between vehicles of the same or different modes (intra- and intermodal, respectively) in the course of passenger travel.

TRANSIT—Urban public transportation services with fixed routes and schedules, such as bus, trolleybus and rail services. Also called mass transit, mass transportation, or public transit.

TRANSIT MODE CLASSES—Groups of transit modes classified by their basic characteristics such as:

ROW CATEGORY—Street (C), semirapid (B), and rapid transit (A).

TECHNOLOGY—Highway, rail, and specialized technology transit.

SERVICE OR TYPE OF OPERATION, see **SERVICE (TRANSIT)**

TRANSIT PRIORITY—Physical devices or traffic regulation measures which separate or speed up transit vehicles over general traffic.

TRANSIT UNIT (TU)—One or more transit vehicles traveling together as a physical unit. A joint term for a single vehicle and train.

TROLLEYBUS (TB)—An electrically propelled bus that obtains power via two trolley poles from two overhead wires along its route. It can travel a limited distance on battery power or auxiliary ICE.

URBAN PASSENGER TRANSPORT—All movements of persons in urban areas; this can be classified by:

TYPE OF USAGE:—Private (walking, bicycle, auto); for hire (paratransit); and public (transit);

PASSENGER VOLUME:—Individual (one or a few persons); and group (many persons).

URBAN PUBLIC TRANSPORTATION—Transport systems for intraurban or intraregional travel available for use by any person who pays the established fare. It consists of transit and paratransit. Also **URBAN TRANSIT**.

URBAN TRANSIT—See **URBAN PUBLIC TRANSPORTATION**.

UTILIZATION—Ratio of output to input of the same or similar unit, such as person-km/space-km or vehicles operated/vehicles owned.

VANPOOL (SERVICE)—Privately or publicly provided vans transporting groups of persons to and from work on a regular basis. Drivers are usually selected from each passenger group.

WATERBORNE (TRANSIT) SYSTEMS—Transit services over water bodies. Most common modes are boats and ferries.

APPENDIX IV

ANSWERS TO SELECTED EXERCISE QUESTIONS*

CHAPTER 1

- 1.2 Movement of population from rural to urban areas. Industrialization and shift from primary to secondary and tertiary economic sectors create new jobs that, together with better utilities and living conditions, attract population to cities.
- 1.4 (b) As a mechanized mode, the cable car offered better performance than its predecessors (speed, capacity, hill-climbing ability, safety, etc.) and eliminated the need to keep horses.
- 1.5 Superior to all preceding modes, including cable cars, in performance, simplicity of operation, and costs.
- 1.6 (a) Eliminated constraint on city size through its ability to move very large quantities of supplies; increased densities of all activities around stations.
(b) Decreased residential densities in the center city, intensified developments along their routes.
- 1.8 Four-axle cars; pantograph; soft suspension; elimination of vehicle noise; manual and later indirect motor control providing smooth acceleration/deceleration; magnetic track brakes; high-capacity articulated vehicles; air conditioning; high/low-level platform boarding; thyristor chopper controls with power regeneration.
- 1.10 The same as technical components and design of buses (pneumatic tires, suspension, efficient 4-wheel brakes, larger and more comfortable bodies, etc.) plus improvements of electric motors and their control, overhead power lines and switches and control of trolley poles.
- 1.12 Upgrading of ROW C to B and A, including use of street medians, grade separations at intersections and tunnels; priorities at intersections; development of high-capacity, comfortable, quiet and attractive vehicles; operation of TUs of up to four cars; operation in pedestrian areas; low-floor vehicles; self-service fare collection; integration with buses and rapid transit; improved aesthetics and image.
- 1.13 Some grew into bus companies, others were outlawed because they competed with regular transit services but had no corresponding obligations.
- 1.14 Building physically separated bus lanes or busways; priority treatment, police control and enforcement at intersections; long station spacings; stops with passenger amenities; trunk line with

*Answers given here are for numerical problems and for the cases where they augment the material presented in the body of this book.

- frequent service; distinct vehicles with low floor or high-floor and high platforms; distinct vehicle design; use of ITS elements; integration with other modes and improved passenger information.
- 1.17 Primary domain of interurbans coincided with convenient travel domain of the automobile, which enjoyed extensive public assistance through highway construction. Their public service role unrecognized, the interurbans received no public assistance.
 - 1.19 Increasing requirements for reliable, high-speed, high-capacity, comfortable transit services that can attract auto drivers and thus improve mobility, enhance urban environment, and reduce traffic congestion along with its negative effects on the city.
 - 1.20
 - a. Separate ROW elevates transit into a higher category system due to its independence from congestion, higher productivity, distinct image and permanence.
 - b. Penetration of transit in pedestrian areas gives it excellent convenience and dominant importance in mobility of population. Transit acquires the dominant role in making the city pedestrian- and human-oriented instead of car-dominated.

CHAPTER 2

- 2.1 Availability of service.
- 2.3 Bus and trolleybus differ in technology (propulsion) and operational characteristics caused by that difference; express and shuttle bus have different types of operation and usually, but not necessarily, technology (vehicle characteristics); LRT and RRT differ in ROW category and characteristics caused by that difference.
- 2.4 If a transit line has a fixed ROW, it should use the technology optimal for such operation (i.e., guided). Bus on ROW A only utilizes neither street running of an BTS, nor the advantages of guidance inherent in RRT.
- 2.9 Need for higher level of service, competitiveness with auto; requirement for high capacity, reliability and safety. The high LOS and permanence of guided transit are features that influence land use developments which street transit does not have.
- 2.10 Transit services operated only during peak hours, usually to and from CBD (i.e., many-to-one and one-to-many types of trips). They serve work trips efficiently, but are poorly suited to most other trips. They are a supplement to regular transit.
- 2.11 Use of several different modes, although sometimes involving higher operating costs, allows better “fitting” of service to passenger requirements. Use of only one or two modes in large cities results in “forcing” these to some lines where they cannot provide good service. Passengers and population suffer many losses which are seldom evaluated. Eventually, use of transit decreases, damaging the entire urban environment in the long run.
- 2.14 Guided with electric propulsion and (usually) fail-safe TU control.
- 2.15 Most common type are APM’s—AGT systems serving short shuttle and loop lines in airports, exhibition grounds, campuses, etc. The other type are AGT systems serving regular transit lines, including rubber-tired and, increasingly, ALRT.

CHAPTER 3

- 3.3 Acceleration rates (a) are:
 (a) -0.056 m/s^2 . (b) -0.026 m/s^2 . (c) 0.028 m/s^2 .
- 3.4 (a) on gradient $i = 0\%$, $V_{\max} \approx 85 \text{ km/h}$ (IV gear); $i = 2.5\%$, $V_{\max} \approx 68 \text{ km/h}$ (IV); $i = 5\%$, $V_{\max} \approx 45 \text{ km/h}$ (III).
 (b) $V_{\max} = 99.6 \text{ km/h}$.
 (c) $a_{\max} = 1.40 \text{ m/s}^2$.
- 3.5 Trolleybus would have a 30 to 50% higher acceleration rate.
- 3.6 Explain the functioning of generators their efficiency and limitations.
- 3.7 The same as dynamic braking plus significant reduction of power consumption.
- 3.8 Electronic motor control improves control of motors in different travel regimes; it reduces or eliminates use of rheostats and allows use of regenerative braking which reduces power consumption.
- 3.10 (a) $s_b = 28.22 \text{ m}$; $s_d = 37.12 \text{ m}$.
 (b) $s_{b \min} = 14.40 \text{ m}$; $s_{d \min} = 23.30 \text{ m}$; $b = 2.74 \text{ m/s}^2$.
 (c) $\mu = 0.50$. Hint: adapt Eq. (3.42) for a ; μ applies to tractive axle only.
- 3.11 (a) $a_{\max} = 1.88 \text{ m/s}^2$.
 (b) $b_{\max} = 1.77 \text{ m/s}^2$; $s_b = 35.00 \text{ m}$; braking distance is independent of vehicle weight.
 (c) $\Delta s_b = 11.67 \text{ m}$.
- 3.14 Interstation distance with equal travel times is $S = 1873 \text{ m}$, on which $T_I = T_{II} = 121.5 \text{ s}$.
- 3.15 $\Delta E = 18.25 \text{ kWh}$; $\Delta t = 3.1 \text{ s}$.

CHAPTER 4

- 4.3 (a) $C_o = 21,600 \text{ sps/h}$.
 (b) $\alpha_{\max} = 0.685$.
 (c) $C_w = 97,200 \text{ sps/h}$.
 (d) $c = 204 \text{ veh/h}$.
 (e) $C = 36,720 \text{ sps/h}$. [Eq. (7.11)].
 (f) $\alpha'_{\max} = 0.484$.
- 4.5 $V^* = 39.8 \text{ km/h}$; $C_w^* = 134,300 \text{ sps/h}$.
- 4.7 c_w values are:

n (cars/TU)			
V (km/h)	2	4	6
V_1	641	1056	1347
V_2	552	970	1297

- 4.12 First, peak-hour volume on one section is not the only criterion. Second, present volumes cannot be used as a reliable measure since every upgraded facility generates additional passengers. Third, such statements confuse capacities with warrants for introduction of a mode; the latter are much lower than the former.

CHAPTER 5

- 5.3 Motor noise, exhaust emissions, and limited dynamic performance of diesel buses. IEB is technically too complex.

$$5.5 \text{ (b) } R_b^o = \sqrt{\left[(R_w^{o2} - l_a^2)^{1/2} + \frac{W - w_t}{2} \right]^2 + (l_a + l_f)^2}.$$

$$\text{(c) } R_b^o = 12.56 \text{ m; } R_w^i = 6.20 \text{ m; } W_w = 4.80 \text{ m; } W_b = 6.51 \text{ m.}$$

- 5.7 Rear section leans on the rear overhang of the front section, which has magnified body movements; double tires and rear-mounted motor weight reduce shaking, but fixed wheels increase turning path considerably.
- 5.8 Freeways seldom follow corridors of transit travel; locations convenient for bus stops, in interchanges, are often difficult for pedestrian access.
- 5.12 BTS has longer stop spacings, faster boarding/alighting process, higher speed, fewer but higher LOS lines, stronger image and greater efficiency.
- 5.15 Avoid excessively complicated route networks; use logical and clear route designations; provide the route number, alignment, and stop information at all bus stops, on buses, and on published schedules; paint a line on pavement where bus service goes.
- 5.17 BRT has mostly separated ROW (B and A), fewer lines but with more frequent service; it has stations/stops with fare prepayment, more passenger facilities, information and stronger image; it uses elements of ITS.
- 5.18 Potential for high passenger volume along a corridor in which an exclusive bus roadway or physically protected bus lanes can be installed; effective police control and investment; no possibility for conversion to HOV facility; low or moderate driver wages.
- 5.19 Greater emphasis on passenger comfort and attraction and on superior environmental characteristics of trolleybuses; increased desirability of electric energy instead of oil consumption; improved funding through public support.

CHAPTER 6

- 6.3 (a)

Car Type Lengths	4-Axle	6-Axle	8-Axle
Total length	$l_t + 2l_o$	$2(l_t + l_o)$	$3l_t + 2l_o$
Length/truck	$\frac{l_t}{2} + l_o$	$\frac{2}{3}(l_t + l_o)$	$\frac{3}{4}l_t + \frac{l_o}{2}$

- (b) 7.30, 7.20 and 7.15 m, respectively.
- (c) $l_t/l_o > 2$.
- 6.4 $\Delta R_b^i = 0.20$ m; $\Delta R_b^o = 0.24$ m.
- 6.8 Ability to change train consists and the resulting operating cost reductions; consequences of breakdown on one car on train pullout from service; maintenance procedures on short vs. long TUs; utilization of train length for passenger accommodation; distribution of passengers among cars.
- 6.10 Typically RGR cars are longer and wider, have a higher seat/standee ratio and a lower door/capacity ratio than do RRT cars. They have a higher maximum speed and greater structural strength (railroad standards). RGR stock *sometimes* has the following features which RRT cars do not have: steps for low-level boarding; electric or diesel locomotive with trailer cars; bilevel cars.
- 6.18 *Capacity*: high-capacity cars, long trains, rapid boarding/alighting, high dynamic performance;
Safety: ROW A only; dead-man device on train, fail-safe signalization;
Reliability: ROW A only.
- 6.20 Most of urban growth is taking place in suburban areas served by RGR. Increasing requirements for high speed and SQ which RGR provides.

CHAPTER 7

- 7.4 Two-axle vehicles can be smaller and lighter than 4-axle ones, but they have greater axle loadings and lower riding comfort.
- 7.5 $\Delta R_b^i = 0.23$ m; $\Delta R_b^o = 0.40$ m; $l_t' = 7.04$ m.
- 7.7 Small cabins are ideal for low passenger volumes, complex guideways and sophisticated control for heavy volumes.

CHAPTER 8

- 8.2 Cog railway has no limitations on line length, capacity, and frequency of service; funicular does. Funicular can negotiate steeper gradients and uses less energy.
- 8.3 Line length, land availability, terrain configuration, and specific traction technology used.

CHAPTER 10

- 10.1 To be competitive with car, transit must be independent from street traffic, i.e., it must be semirapid or rapid transit, i.e., it must have ROW B or A.
- 10.2 Right-of-way category/separation because it influences system's capacity, performance, investment and operating costs.
- 10.3 In small cities social service of transit dominates; in large cities transit must be competitive with auto travel.

- 10.5 Buses require low investment (no construction) on ROW C. High investment and exclusive travel way (ROW A) are much better utilized by rail than highway vehicles (electric traction, train operation, higher speed and safety, etc.).
- 10.6 Many theoretical studies overlook the facts that bus service depends on police enforcement, it is subject to regulations which can be changed, high operating labor costs leads to reduction of off-peak services. Most importantly, buses have lower image and passenger attraction than rail modes.
- 10.7 Car-dependent cities provide lower personal mobility than cities with balanced transportation; their non-auto users are second-class citizens; cities are not human-oriented and livable.
- 10.8 Energy consumption is extremely high, the country depends on high oil imports and political vulnerability in international relations.
- 10.9 Aerial guideways and stations of monorails usually have higher investment costs than estimated because their impacts on surroundings are objectionable in high-density areas; their operational complexity and limitations are considerably greater than for rail systems.
- 10.10 BRT, LRT and AGT.
- 10.13 ROW separation, priorities at intersections, more spacious, comfortable, quiet vehicles. Stronger identity, image and permanence.
- 10.16 ROW separation, priorities at intersections, more distinct and widely spaced stops, higher capacity vehicles with distinct design, use of ITS. Require investments in ROW and stations; higher-priced buses; effective police enforcement must be introduced.
- 10.17 BRT is more sensitive to wage levels because of lower labor productivity than LRT has.
- 10.18 Medium-capacity lines may operate at long headways to keep operating costs low unless they are driverless.
- 10.19 Short headways economically feasible at all times; changes in headways and train consists can be done at any time.
- 10.20 One of the main advantages of AGT is foregone.
- 10.22 ROW category A only, rail vehicles in long trains, high platforms, off-board fare collection, electric traction, fail-safe signal control.
- 10.24 Commuter railroads have mostly radial networks with terminals on the periphery of CBD, offering services mainly during peak hours, little or no service at other times. Regional rail has one or more lines through center city and a number of stations. Its services operate through all daily hours with regular headways. Serves all trip types by direction and purpose. It has many transfer points with other transit modes.
- 10.25 Recently built RRT systems in U.S. cities have lines, stations and speeds similar to those of regional rail, but have many RRT features: enclosed stations, high platforms, short headways, one-person crews, etc.

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