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LIGHT RAIL TRANSIT

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FOREWORD

Robert E. Patricelli, Administrator,
Urban Mass Transportation Administration

Late in 1974, the Urban Mass Transportation Administration requested that the Transportation Research Board plan a major national conference on light rail transit. It was felt that a special effort was needed to expose decision makers, planners, engineers, operators, and other interested individuals to the many virtues of the light rail transit mode. It also was believed that the conference proceedings would serve as a comprehensive report documenting the state of light rail transit development.

The papers contained in this Special Report were prepared for and delivered at the National Conference on Light Rail Transit held in Philadelphia, Pennsylvania, June 23-25, 1975. The Urban Mass Transportation Administration was the principal sponsor of this first national meeting. The Transportation Research Board Advisory Committee was responsible for structuring the conference content and reviewing the technical reports. Other cosponsors of the meeting were the American Public Transit Association and the University of Pennsylvania.

About twice the number of people expected attended the Philadelphia conference, which indicates the high interest in light rail transit. Presentations were made by key public officials, transit industry representatives, and members of the consulting and academic professions. To broaden the scope, speakers from several foreign countries also presented papers on light rail transit development in their countries.

There is increasing doubt that a single transport system of any technology can effectively serve the broad range of travel patterns and services that prevail in a large city. There is also no compelling reason why a single type of transportation system must dominate an entire metropolitan area. This trend to move away from a unimodal solution to a system that blends a number of discrete transit elements, each of which is closely tailored to demands and local conditions, should make light rail transit a particularly strong contender for attention by cities that desire some form of fixed guideway system. Light rail transit certainly should not be treated as a panacea for urban mobility problems, but it should be considered as one of various transit options available to cities.

The papers in this Special Report cover a wide range of subjects related to light rail transit. Included are a description of system concepts, such as performance characteristics of light rail transit; comparison with other modes; and applications. The technology and operational aspects of light rail transit are treated in a set of papers that address permanent way requirements, electrification and control systems, and U.S. and foreign vehicle developments. Of major significance are the economic considerations of light rail transit. A number of the papers contained in this Special Report discuss the various costs of construction, operation, and maintenance as well as social costs and benefits.

The sponsors of these proceedings of the National Conference on Light Rail Transit hope that the reader will find much useful information that is readily applicable to his or her special interests. The planned wide dissemination of these proceedings should help to increase the understanding of light rail transit and should help to bring about more rational urban transportation developments.

INTRODUCTION

Stewart F. Taylor, Sanders and Thomas, Incorporated

Growing interest in light rail transit represents a new direction in the search for improved urban mobility. In recent years, alternatives to the private automobile have tended to be expensive and advanced in their technology. Worldwide inflation and frequent deficiencies in development have limited the application of such alternatives. Meanwhile, the problems of congestion, pollution, and energy extravagance have intensified.

For these reasons, approaches, such as light rail transit, which are more evolutionary, have come to the fore. Light rail transit is evolutionary in that its basic technology has seen widespread use for a number of years. At the same time, it has not been locked into a given design framework. Upgrading, expansion, and modernization currently are taking place on more than 80 systems throughout the world. And in the remainder of this decade, a number of totally new systems will begin operations.

Even though worldwide developmental activity is more extensive for light rail transit than it is for any other fixed guideway mode, light rail transit still labors under the burden of being considered by many professionals and lay persons as the streetcar in contemporary dress. Foundations of light rail transit lie in the streetcar mode, but progress from that technology has been so pervasive that a totally new dimension in public transport has been achieved. New vehicles, rights-of-way, fare-collection systems, and service levels are essential elements of a unique mode that demonstrates high potential for attracting riders from the automobile. At the same time, there is no imperative to simultaneously apply all elements over every segment of a particular system. (This characteristic is another evolutionary aspect of light rail transit.)

The objective of the National Conference on Light Rail Transit and this Special Report has been to put forward the basic characteristics of light rail transit and the techniques of applying it to improve transportation and the quality of urban life. Topics were selected to form a program that would serve as a comprehensive introduction for those who participate in any aspect of urban transportation whether it be political, managerial, or technical.

The opening session established the rationale for considering light rail transit from among the several modes demonstrating a potential for improved transportation. The papers in this session also presented a memorable succession of worldwide developments in light rail transit. The papers in the second session, which was on system concept, described specific characteristics that give light rail transit a logical place in the public transportation spectrum. How light rail transit coordinates with other modes was an important aspect of this session.

Physical and operating characteristics were discussed in the third session. Both fixed facilities and vehicles received extensive coverage. The fourth session examined economics, including topics on cost and revenue potential. The beginnings of a method for selecting an optimum urban transport system that uses various modes were formulated.

The fifth and final session placed the potential of light rail transit in the institutional context of contemporary American society. Numerous issues were raised. Some answers were suggested, but the main thrust of the session was that tangible effort must be made in the United States to emulate light rail transit development in Canada and Europe if the true potential of this mode is to be determined.

Throughout the conference there were several recurring themes. One was that no one should suggest light rail transit as a panacea for the urban transportation dilemma. As is the case with all things, light rail transit has limitations, and establishing expectations that cannot be met would create only more waste and delay in the search for workable solutions. Another frequently repeated theme was that extensive research, development, and demonstration are unnecessary for the practical application of light rail transit. Because the need to improve public transportation is so urgent, this makes light rail transit a good candidate for early development.

The dominant characteristic of our urban society is change. In such an environment, the intrinsic features of light rail transit favor its sustained usefulness. Worldwide, it is continually being modified to meet new economic, demographic, and technological conditions. Moreover, in contrast to a number of other transit modes that are confined to a fixed state of the art or program of development, the prerogative for upgrading and expansion remains with the community.

The Conference Committee hopes that this conference will contribute to a wider understanding of light rail transit. If that is achieved, the future course of urban transportation will be determined on a sounder basis.

LIGHT RAIL TRANSIT: A MODERN RENAISSANCE

James R. Mills, Member of the California Senate

Transit development decisions in U. S. cities have as their source the all too familiar litany of ills visited on our cities by the automobile: air pollution, congestion, thoughtless land use patterns, restricted mobility for the handicapped, the elderly, and the poor as well as constrained pedestrian movement and many other conditions affecting the quality of urban life. These have been joined by other frightening specters—a diminishing petroleum resource and an unsettled national economy.

It is now obvious that those in public transit must consider the mobility needs of a population larger than that of the daily commuter. Jitneys, car pools, buses, and light and heavy rail transit are all forms of public transit. Each mode is desirable under specific conditions. Together they can form a transit system that will meet a variety of different service needs.

Defining public transit in broad terms provides the public with numerous transit options; each has its own service characteristics and cost structure. In this regard, the light rail concept is attractive because it expands the available deployment options for rail transit.

Before discussing the attractive features of light rail transit, it would be useful to review its technological evolution in the United States.

Before the development of the electric motor, urban mass transit was provided by horse-drawn streetcars. Horse-drawn rail cars were used first in Baltimore in 1828. The first real system, the New York and Harlem Railroad, was constructed in New York City in 1832. The line was 1.5 miles (2.4 km) long; vehicle capacity was 30 persons; headways were 15 min; and the fare was 12.5 cents. This system did not stagnate. In 1833, it was extended to 4 miles (6.4 km), and cars were added. By 1940, headways on the system were down to 6 min. New Orleans built its system shortly after the New York system. But it was more than 20 years later before Brooklyn, Boston, Cincinnati, Baltimore, Chicago, and Pittsburgh developed horse-drawn rail service. It was 1858 before Philadelphia inaugurated horse-drawn service.

Horses were hardly a satisfactory means of motive power. Five to 10 horses were needed for each car. Each horse cost about $125, which was expensive in those times. Their service life was short (3 to 5 years) because the work was punishing. Average speed was 5 to 6 mph (8 to 9.6 km/h); therefore, the area that they could serve was limited. The horse's susceptibility to disease placed the reliability of horse-powered street railways in a precarious position. This shortcoming became apparent during the Great Epizootic Epidemic in 1872. Thousands of horses died and street railway operations were curtailed or discontinued. In some instances, companies maintained service by hiring gangs of unemployed workers to pull the cars through the streets.

One would expect that the next logical development in transit technology would have been the substitution of the steam engine for horses. Steam engines were used in the London Underground, which began service in the 1860s, and steam was serving well on intercity railroads. However, years before environmental impact statements, the American public knew what it did and did not want in urban transportation. The system should be silent, emit no smoke, and have no exposed parts to endanger pedestrians and horses. Even though Philadelphia, in 1860, had a half dozen steam-propelled streetcars, steam never became an attractive technology for street rail systems.

An interesting technological response to certain topographic conditions was Andrew Halladie's cable car, which incidentally met some of the environmental constraints of the day. Although cable cars had high initial cost, they were less expensive to operate and could carry heavier loads than horse-drawn cars could. Two dozen cities, including Chicago and San Francisco, of course, installed cable cars. Cable car systems, however, were hampered by equipment failure and low speeds.

By 1880, it was obvious that the electric motor was going to be the primary source of traction. During the 1880s, the overhead trolley and the electric collector (the "plow") were invented. The street railway of Montgomery, Alabama, was completely electrified and began service in 1886. It was a 15-mile (24-km) system, but it was plagued with trouble continuously. In 1887, there were 9 electric streetcar systems in Europe and 10 in the United States involving 60 miles (97 km) of track and 100 motors and cars.

Unreliability was nowhere better demonstrated than in San Diego, where an electric line was added to a local system that included cable cars and horse cars. There were 2 trolley wires for positive and negative, and a small 4-wheeled cart ran overhead on wires connected to the car with a trailing wire. This cart often jumped the tracks and landed in passengers' laps or on their heads, which discouraged ridership. Obviously, improvements were needed.

Because of its unreliability, advancement in the adoption of the electric motor had been limited. F. J. Sprague, a U. S. midshipman, changed the situation. Sprague first developed his interest in electricity at the U. S. Naval Academy, and, while serving aboard ship, he produced 60 inventions. In 1881, he built a novel dynamo that led to his selection as secretary of a jury testing dynamos and gas engines at the 1882 British Electrical Exhibition. Sprague's frequent rides on the steam-driven underground in London fostered his idea of an electric railway system. Sprague left the Navy and served as Thomas Edison's assistant for a year before striking out on his own. Richmond, Virginia, let a contract with Sprague for 12 miles (19 km) of track and 80 motors on 40 cars to be completed in 90 days. As Sprague observed later, it was a contract "a prudent businessman would not ordinarily assume." However, Sprague had faith in his ideas and confidence in his ability to carry them out. As is the case with many contracts based on new systems, things did not go well.

He was delayed first by outbreaks of typhoid fever, then by shoddy workmanship and cheap materials, and finally by an "insuperable" combination of grades and curves. Even Sprague's confidence wavered. Could a self-propelled vehicle merely maintain adhesion on grades of up to 10 percent? Late one November evening the car was put to the test. It negotiated curves and grades to arrive finally at the top of the long Franklin Street Hill to the cheers of an enthusiastic after-theater crowd. The crowd did not realize that the motors had overheated and were disabled and that the streetcar that had arrived at the top of the hill so triumphantly would have to be towed home by a team of mules in the dead of night. Sprague now knew his ideas were feasible, and he went back to the drawing board with renewed enthusiasm.

On February 2, 1888, the Richmond system opened for regular service. It is now recognized as the first system in which a large railway was equipped and operated under service conditions by electricity. It was the pioneer of commercial electric traction. More than 1,260 miles (2030 km) of electric streetcar track were installed nationwide by 1890, and 22,000 miles (35 000 km) of electric streetcar track were installed by 1902.

Between 1902 and 1910, streetcar lines expanded and the interurban light rail network developed. The interurban light rail systems were different. They had heavier, faster, and usually more comfortable cars. They were developed in a more sophisticated fashion; they often used reserved rights-of-way in rural areas and continued on city streets in built-up areas. They carried some freight but they predominately were passenger carriers.

Land values soared along the new rail lines and speculators did not overlook their opportunities. Many lines were built not to fill a transportation need but to fill the promoters' pockets. Expansion of track reached its peak in 1916 with 15,580 miles (24 928 km) of interurban railway. From 1910 to 1922, one could have traveled from eastern Wisconsin to central New York [more than 1,000 miles (1600 km)] completely by interurban railway. Southern California's Pacific Electric Railway, centered in Los Angeles, operated nearly 1,000 route miles (1600 route km) and reached 125 cities and communities. However, by 1939, only 2,700 miles (4300 km) of interurban line remained in the United States.

Before World War I, jitneys had penetrated the street railway market, but, by 1917, most of these had been forced out of business. In that year, more than 1,000 street railway companies were carrying about 11 billion passengers/year. Eight thousand electric streetcars covered 45,000 miles (72 000 km) of track, but the companies had problems. The high cost of labor and materials, financial mismanagement, and inadequate fare systems eventually would prove to be their downfall. After World War II, because of lack of maintenance, the street railways became prey to buses and the burgeoning of America's love affair with the private automobile. They did not fall without a struggle. In 1930, leading street railway operators formed the Electric Railway Presidents' Conference Committee to develop a modern vehicle. After 5 years and about $750,000 in research, the PCC car was born. It far surpassed its predecessors in both performance and comfort, and, to this day, it remains the best urban transit vehicle designed and built in this country.

Between the demise of the interurban and electric streetcar systems and the resurgence in urban rail transit best epitomized by the Bay Area Rapid Transit system, the concept of light rail transit was lost. Until very recently, urban mass transit was considered to be buses or heavy rail transit. As a society, we had placed ourselves in a corner. Public officials were faced with an "either-or" situation. This limited rail transit to a very few cities. Buses, in spite of their usefulness, have disadvantages in long-run costs, speed, capacity, and acceptance by the public, but the majority of urban centers in this country were left with no real transit alternative.

Rapidly increasing costs in heavy rail development and uncertainty regarding new transit technology served as an incentive to search for a different rail technology. The search led to Europe and especially West Germany, where the use of intermediate capacity systems variously deployed was widespread. Cologne, Bonn, Bielefeld, and Frankfurt provide a few examples of how light rail transit can be integrated into existing urban environments and multimodal transportation systems. The search led also to Boston, San Francisco, and Philadelphia where the remnants of urban and interurban electric lines continue to provide service and are looked on as useful elements of the transportation system. The search culminated in the renaissance of interest in light rail transit.

The rediscovery of light rail transit was not motivated by sentimentality and nostalgia for a bygone era. It was simply the result of judgments founded on a realistic assessment of growing transit needs and diminishing financial resources. Light rail transit was reborn. The reason for this rebirth is the inherent advantages of the technology. Light rail transit can be run on streets in mixed traffic, in reserved street lanes and highway medians, in activity center malls and rights-of-way shared with other rail transit modes, and in subways. It offers public officials the opportunity to initiate rail transit development at a rather modest cost by using existing rights-of-way. Later, as additional funds become available, the system can be extended or the degree of right-of-way exclusivity improved or both. The flexibility of the technology allows transit service, system capacity, and available resources to be traded off in a variety of ways so that the most ideal transit system for a community can evolve over time.

The benefits of light rail transit are beginning to prove themselves politically. Rochester, New York, and Dayton, Ohio, have committed themselves to light rail technology. Edmonton and Vancouver are 2 Canadian cities that decided light rail was the appropriate rail technology for their fast-developing communities, and Toronto is looking to light rail as the best choice for new interurban service. San Francisco, of course, is well on its way to upgrading new transit technologies. We can be certain many of these technologies will have a role to play in providing transit services.

All of us must examine critically the claims made for light rail transit. The role of light rail transit and its relationship to existing and emerging transit technologies must be defined carefully. This will ensure that light rail will stand the test of technical and public scrutiny.

I am confident that light rail will become a more familiar mode of transportation in the United States. The interest in light rail expressed by the Urban Mass Transportation Administration and the commitment being made to it across the country deserve commendation because urban transit decisions require a degree of pragmatism that has often been lacking in recent years.

LIGHT RAIL TRANSIT: 1975 USAGE AND DEVELOPMENT

Lee H. Rogers, Institute of Public Administration

It is the nature of citizens, as well as planners, to attempt to discover the ultimate truth or ultimate solution to any problem they confront. The problem of urban transport has been one area of community living that has been given high priority for solution. For more than 3 decades, authorities seem to have been convinced that a single technological system would ultimately satisfy all transport problems. In many ways this system, the private automobile, has given more benefit to urban citizens than any previous transportation mode has. During these decades, people have perceived publicly provided passenger transport to be simply an interim necessity until such time as everyone could drive their own automobiles. By the mid-1960s, some planners and officials realized that this expectation might be extravagant. Many officials were shocked to discover districts within their own constituencies where more than 1 out of every 4 persons still could not avail themselves of private automobile transport. Communities then began to reevaluate their weakened and retrenched public transport networks. Because the problem was approached on a total metropolitan area basis, many analysts and designers still perceived that the solution for public transit would be obtained through the use of only 1 technical mode—the city bus. This philosophy was little challenged by the existence of subways or heavy rapid transit being operated in a few cities. In these cities the planner simply shifted the parameters for transit study to address surface-related operations only. If it were found that a community was in need of high-capacity public transport, a non-surface-level subway solution quickly was proposed. During the last 12 years, existing urban transport technology has been continually challenged by new system technologies. The advocates of these new technologies contended that they would best satisfy all existing and future public transport requirements throughout all the portions of the metropolitan area.

Evaluating the many urban transport studies and urban transport operations in cities of the United States and Canada, one is led to believe that no single technology can accommodate all the transit needs of major communities. Transport in all cities becomes quickly established in and around specific corridors. When capacity requirements are analyzed on a corridor-by-corrdior basis, a more economically efficient and socially effective transport system can be developed.

We are reviewing at this conference a proved technology. Light rail transit currently demonstrates its effectiveness as part of the total urban transport system in more than 300 cities of the world. It dominates the transit of some cities and provides important arterial service in other cities. However, it does not establish a modal monopoly in any situation in which it has been constructed. Light rail transit is not being advocated as a replacement for all buses, all private cars, or heavy rapid transit systems. Although advocates promote the mode, they do not envision it as a panacea for all urban transport problems. However, many corridors currently exist in cities of Canada and the United States that could use this means of transport most efficiently to improve public passenger services.

We should review some of the localities and methods of operation. As is true of many transport modes, LRT does not need to be based on 1 policy involving governmental organization, social objectives, or proprietary interests to be used. It should be stressed that light rail transit is one of the few modern transport modes that is available without the holding by 1 group or 1 company of all proprietary rights to the total system. Some people may see this as a fault. Others, particularly operating authorities, may see it as an advantage. In 1975, more than 300 cities are operating light rail systems of various sizes. Of these communities, more than 70 are involved in study, design, or construction of new lines or new equipment for their LRT operations (Table 1).

Unlike heavy rapid transit systems, light rail transit can use the several types of articulated and nonarticulated, electrically propelled vehicles over various types of rights-of-way. Because of the controlled trajectory of the vehicle through the use of steel guide rails, a high-frequency service can be operated with LRT within conditions imposed by narrow and twisting historic streets and land use constraints.

Several European cities have embarked on incremental programs of public transport improvement by using LRT as a major method of reducing central city automobile traffic volumes and penetrating difficult land use areas. In some instances, portions of streets have been converted for exclusive LRT use. At major street intersections, through-trip vehicular traffic has been grade separated from local urban activities, and the surface levels are for light rail and intensive commercial and retail activities. Such methods of traffic separation permit critical junction points and intersections to be designed in a way that permits public transport to operate without conflict with other modes.

Various cities have taken this incremental approach and have adopted urban transport plans that are being implemented over a 10-to-15-year period, thereby gaining early benefits from crucial portions of the system. One of the first low-cost methods of emphasizing public transport and LRT is to separate transit lanes from private vehicle lanes by signing and striping. In some cities, LRT lines have been placed along the curb to provide safer separation of pedestrians and other vehicles. Such application has improved boarding and alighting times for users and limits the use of public streets for private vehicle parking. In totally new rights-of-way, LRT routes do not require the magnitude of capital investment generally associated with heavy rail rapid transit. This is achieved in part from the ability to be flexible in the type of alignment used. The route can provide direct access to major activity centers while being separated physically or visually from highway lanes. In several cities this has been accomplished by a variety of methods. As a result, separate levels and rights-of-way can be developed for LRT along highway routes.

Because of the controlled guide path of this mode, minimal intrusion occurs in sensitive land use areas such as public parks and green spaces. The LRT mode is used to enter such activity areas without encouragement of private vehicular traffic. As a result of this, a more aesthetically pleasing urban area can be maintained and high-capacity transport can still be offered.

Surface level LRT operation can be brought to new suburban areas with new highways, or it can be constructed almost totally independent from other transport investment.

For conurbations envisioning future heavy rail networks, advanced benefits have been obtained from the construction and use of limited sections of underground routes. With the LRT system, minimum difficulty is experienced with transition between surface and subterranean operations. Such transition can be achieved in limited lengths. With the use of these sections, the reduced travel times within the central business district (CBD) encourage greater ridership and more efficient transport operation.

With the support of citizens and officials, Zurich, the largest city in Switzerland, redesigned its traditional primary retail street into a pedestrian walkway and LRT route. Although peak-hour services involve use of more than 60 vehicles, the guided dual-rail control of the vehicle has low noise levels, and the system has conflicted minimally with pedestrians, shoppers, and merchants. The community was behind the project, and the design and construction of this corridor were achieved with minimal negative visual and aesthetic impact.

In other CBD localities the LRT system has been retained within the existing street

Table 1. Cities involved in construction of light rail transit (1).

Location	Stage: Proposed	Planning or Study	Design	Construction	Opening Year	Remarks
Alexandria, Egypt		x				Ext,[a] rehab[b]
Amsterdam, Netherlands	x	x				Ext,[a] rehab[b]
Antwerp, Belgium				x	1974	Sub[c]
Arad, Rumania				x		Rehab[b]
Basel, Switzerland		x	x			Ext[a]
Bastia, France	x					New[e]
Berlin, GDR[d]				x		Rehab[b]
Bern, Switzerland				x		Ext[a]
Bielefeld, FRG[f]				x		Ext,[a] sub[c]
Bochum, FRG[f]			x	x		Ext,[a] rehab[b]
Bonn, FRG[f]				x		Ext,[a] sub[c]
Boston, USA		x		x		Rehab[b]
Bratislava, Czechoslovakia				x		Ext[a]
Braunschweig, FRG[f]				x		Ext[a]
Bremen, FRG[f]				x		Ext,[a] rehab[b]
Brno, Czechoslovakia				x		Ext[a]
Brussels, Belgium				x		Sub,[c] rehab[b]
Bucharest, Rumania				x		Ext[a]
Bydgoszcz, Poland				x		Ext[a]
Cairo, Egypt			x			Ext[a]
Charleroi, Belgium				x		Ext,[a] arl[g]
Cleveland (Teeside), UK	x					New[e]
Cologne, FRG[f]			x	x		Ext,[a] sub[c]
Constantsa, Rumania	x					New[e]
Cottbus, GDR[d]				x		Rehab[b]
Craiova, Rumania	x			x		New[e]
Darmstadt, FRG[f]				x		Ext[a]
Dayton, USA			x			New[e]
Dortmund, FRG[f]				x		Ext,[a] rehab[b]
Dresden, GDR[d]				x		Rehab[b]
Duisburg, FRG[f]				x		Ext,[a] arl[g]
Düsseldorf, FRG[f]			x			Ext,[a] sub[c]
Edinburgh, UK	x					New[e]
Edmonton, Canada			x		1978	New[e]
Erfurt, GDR[d]				x		Ext[a]
Essen, FRG[f]			x			Ext,[a] sub[c]
Frankfurt, FRG[f]				x		Ext,[a] sub[c]
Freiburg, FRG[f]		x				Rehab[b]
Ghent, Belgium			x			Ext,[a] sub[c]
Gorzów, Poland				x		Ext[a]
Göteborg, Sweden				x		Ext,[a] rehab[b]
The Hague, Netherlands			x			Ext[a]
Halle, GDR[d]				x		Ext[a]
Hannover, FRG[f]				x	1975	Ext,[a] rehab[b]
Helsinki, Finland			x			Ext[a]
Helwan, Egypt		x				New[e]
Hiroshima, Japan		x				Ext,[a] sub[c]
Hong Kong		x				Sub[c]
Innsbruck, Austria			x			Ext[a]
Karachi, Pakistan		x			1980	New[e]
Karl-Marx-Stadt, GDR[d]				x		Ext[a]
Karlsruhe, FRG[f]		x				Rehab[b]
Katowice, Poland				x		Ext[a]
Krakow, Poland				x		Ext,[a] rehab[b]
Krefeld, FRG[f]				x		Rehab[b]
Leipzig, GDR[d]	x					Ext,[a] rehab[b]
Liberec, Czechoslovakia		x				Rehab[b]
Lille, France			x			Sub[c]
Linz, Austria				x		Ext[a]
Lódz, Poland				x		Ext[a]
Ludwigshafen, FRG[f]				x		Rehab[b]
Mannheim, FRG[f]				x		Ext[a]
Melbourne, Australia			x	x		Rehab[b]
Milan, Italy			x	x		Ext,[a] rehab[b]
Munich, FRG[f]				x		Ext,[a] rehab[b]
Naples, Italy		x				Rehab[b]
Norrköping, Sweden				x		Ext[a]
Nuremberg, FRG[f]				x		Ext[a]
Olomouc, Czechoslovakia		x				Rehab[b]
Ostrava, Czechoslovakia		x				Sub[c]
Philadelphia, USA			x			Rehab[b]
Pizen, Czechoslovakia				x		Ext[a]
Plauen, GDR[d]				x		Ext[a]
Ploesti, Rumania	x					New[e]
Portland, Oregon, USA	x					New[e]
Prague, Czechoslovakia			x	x		Ext[a]
Riga, USSR				x		Ext,[a] rehab[b]
Rochester, N.Y., USA	x					New[e]
Rome, Italy		x		x		Ext,[a] rehab[b]
Rotterdam, Netherlands		x		x		Ext,[a] rehab[b]
Ruhr region, FRG[f]		x	x			Ext,[a] rehab[b]
Saint-Etienne, France		x				Sub[c]
San Francisco, USA				x		Sub,[c] rehab[b]
Sarajevo, Yugoslavia				x		Rehab[b]
Schwerin, GDR[d]				x		Ext,[a] rehab[b]
Sheffield, UK		x				New[e]
Sofia, Bulgaria		x				Sub,[c] rehab[b]
Stuttgart, FRG[f]				x		Ext,[a] sub[c]
Sydney, Australia		x	x			New[e]
Szczecin, Poland		x				Ext[a]
Turin, Italy		x				Ext,[a] rehab[b]
Toronto, Canada		x	x			Ext,[a] rehab[b]
Torun, Poland				x		Ext[a]
Tyneside, UK			x	x		New[e]
Utrecht, Netherlands			x			New[e]
Vancouver, Canada	x					New[e]
Vienna, Austria				x		Ext[a]
Warsaw, Poland			x			Rehab[b]
Würzburg, FRG[f]		x			1978	Ext[a]
Yerevan, USSR			x			Sub[c]
Zurich, Switzerland		x	x			Ext[a]

[a]Extension of existing system.
[b]Rehabilitation of existing system.
[c]Underground section.
[d]German Democratic Republic (East Germany).
[e]No existing system.
[f]Federal Republic of Germany (West Germany).
[g]Elevated section.

pattern of the community by judicious use of traffic engineering. Part of the Zurich urban policy has been to reemphasize the use of public rights-of-way for the maximum number of users rather than number of vehicles. Three street locations formerly used for general traffic movement have been redeveloped for major junctions and transfer locations in the LRT system.

With the strengthening of specific corridors as primary routes for local urban passenger movement, residential construction is being undertaken, thereby providing an expanded market for the LRT lines. In the suburban residential areas, public and private transport systems frequently have been separated.

In Geneva, Switzerland, a major LRT route provides a surface level spine for overall public transport operation. Even though public street rights-of-way are limited, this mode can use them with a low investment and provide high throughput capacity. In parts of the CBD, the LRT mode has been given priority by use of restricted private-vehicle access. More people are moved within the old street system as a result. The exclusive use of 8 blocks of the primary retail center by LRT has permitted abutting pedestrian walkways to be expanded and cafes and outdoor sales areas to be established. The minor intersecting streets have been converted for civic activities considered to be of higher priority than parking or low-volume private vehicle movement. As a result, festivals, gatherings, and outdoor markets can be provided without sacrificing transport access to the CBD.

In Basel, Switzerland, LRT use is encouraged by new emphasis on the location and design of principal transit stops, and this has improved access to business and retail centers. The original LRT network has been extended and rehabilitated to provide high-quality links between outlying residential areas and the CBD. Light rail routes are able to abut existing land uses while serving the primary goal of urban passenger movement. Along these routes, the authority operates new, lightweight, well-ventilated articulated modern vehicles. The transit shelters and boarding locations have been located away from direct conflict with highway vehicles in residential neighborhoods. The use of LRT has permitted high-capacity passenger access to many tranquil suburban areas without encouraging greater private vehicle intrusion. The rights-of-way have been designed as an integral part of the community. For the investment level incurred, the LRT placement into the urban setting has been accomplished in a more pleasant and positive manner than that normally found with other transport modes.

Munich has retained major use of LRT even though a heavy rapid rail transit system has been established. The LRT vehicles provide surface transport with minimal conflict and intrusion on the CBD for the passenger capacity provided. The mode satisfied the need for short- and medium-distance trips by use of special surface stations for patrons. In addition the LRT connects some of the lower density suburban areas, including high-income residential areas, with the CBD. In 1 case this has been accomplished through the use of a nonhighway alignment that minimally intrudes on the community. This permits residents of such areas to enter the city without having to use private conveyances. This has resulted in more effective use of the limited street space during peak hours. It has been found that the high-capacity routes can be woven into the existing constraints to a degree that is not possible with other modes.

In several German cities near the Rhine River, a 10-year program of incremental improvement has resulted in greater reliance on LRT systems to encourage high public transport usage. The LRT vehicles are designed as a direct result of German public transport marketing philosophy. The vehicle is large enough to permit baseday or nonpeak users to have a seat and retain the floor area necessary to accommodate peak-hour standing loads. Because such vehicles can be operated in single-unit and multiunit sets along private or semiprivate routes, several cities of the Ruhr have provided high-capacity public movement. Part of the benefit from such development has been the retention of strong CBD interest throughout the community.

Attractive segregation of conflicting modes can be made with the various options of design and methods of location employed in LRT technology. Landscaping and shrubbery provide barriers to minimize noise and prevent disruption due to motor-vehicle accidents. Lines have been expanded and upgraded to provide new satellite communities and neighboring medium-sized cities with high-quality public transport access to retail centers of the major cities. The effective blending of this technology within the urban fabric has encouraged the growth of daytime employment and evening civic events within the city. The main commercial areas have been turned over to pedestrian-only activities. The LRT lines link the communities along a corridor in a manner that might be used in the future for heavy rail transit. However, the use of LRT permits low-cost immediate operation and minimum conflict with intersecting streets and abutting structures. Many of the cities have continued to upgrade their passenger-carrying equipment to further reduce travel times and improve travel comfort.

In Brussels, city and state officials have long been aware of the problems of matching the historic city fabric and economic activities with the rising levels of motorization. As a result, they have embarked on a program of improved public transport with major reliance on the use of LRT services to retain the community values and historic buildings and provide greater access to these areas. Originally, many of the LRT routes and passenger stops were located on multiuse streets. As private vehicle congestion increased, some of these LRT routes gradually were changed to private and semiprivate lanes to retain the passenger-carrying capacity available with LRT within street corridors. At selected locations major passenger interchange points were redesigned with an emphasis on the number of people to be served. In 1971, a portion of 6 routes were able to use an early construction segment of the heavy rapid transit system through the center of Brussels. This was accomplished with minimal visual and physical impact within the neighborhoods traversed. The use of these underground sections and the general upgrading of the LRT surface portions have resulted in the reduction of east-west transport travel times during the peak hours from more than 30 min to less than 10 min.

In the older residential neighborhoods the LRT vehicles are operated over conventional street lengths. In one case a new wide boulevard for private automobiles has been provided along the western edge of the community; the existing older arterial through the center of the community is used for LRT exclusively. This has kept high levels of competing private vehicles away from the residential sections while providing the neighborhood with high-quality public transport service. When such options were not available, LRT was placed to 1 side of the arterial road. This offers an additional benefit because bicycle paths can be located along the LRT right-of-way and thus are protected from the busy highway traffic. Public and private residential development for families of all incomes has been encouraged along these LRT routes.

The rapid growth of Brussels' economy has been accomplished without construction of a major system of central city expressways. The use of LRT has relieved pressure for peak-hour volume capacity that would otherwise require major expansion of the CBD street network. The blending of corridor transport methods with LRT has minimized the impact of the urban passenger growth.

The existing high quality of service has not been obtained by reduction of standards for the quality of the surrounding environment. For instance, the LRT overhead electrical distribution system is secured directly to the side of adjacent buildings without severe visual intrusion or structural damage. This placement eliminates the use of poles. The care and consideration used for the placement of such LRT services can be achieved without heavy capital investment. LRT route development impacts minimally on the environment and neighborhood. They are flexible enough in their construction and operation phases to reduce the physical disruption generated within the community. Such effective placement of LRT has provided greater access for citizens in several neighborhoods. New LRT vehicle equipment has been installed on many older lines without major change of the LRT alignment. Because the fixed guideway permits landscaping closer to the operating area of the mode, visual aesthetics are of a higher quality. The overall result of this policy has been that the governmental, institutional, and business employment centers have been located along LRT lines without significantly disrupting existing residential land uses.

Throughout Belgium a growing interest is found for further expansion of existing LRT systems. In Ghent, Belgium, a city of about 200,000 people, a major rehabilitation and expansion program of the LRT system was undertaken. In 1 corridor, expansion of the LRT was made after the local community opposed expansion of a recently completed elevated expressway that was more than 30 m wide. The community perceived that intracity transport could be better served with something other than an expressway. As a result, a new LRT route was extended through the territory originally envisioned for local services of the expressway. The 6-m-wide alignment of the LRT has greater passenger throughput capacity than the parallel expressway would have had.

In Amsterdam and Rotterdam, Netherlands, the LRT system provides both a CBD distributor function and a high-quality link to the suburban areas. With the use of new, articulated vehicles and good management, the LRT mode has provided high movement capacities within the constrained center of the city. Some streets have been converted to a mixture of LRT operation and pedestrian-bicycle ways. The routes have been strengthened by programs of the city highway engineer that reflect the local priorities for transport of people rather than the movement of vehicles. The modern design of major surface intersections and LRT routes provides track layouts built for minimal conflict with other modes. Terminal areas have been placed off the street. The community has developed a program of providing adequate street capacity for non-peak-hour use by private vehicles and employing LRT to accommodate the bulk of the rush-hour needs.

In The Hague, Netherlands, the LRT system provides high-quality public transport. Major junctions and transfer areas have been engineered to reduce modal conflicts and retain patronage. These junction points have been completed without extremely high costs because of the lack of need for multilevel structures. The authorities consider one of the advantages to be the low cost of terminals and stations. The LRT mode has had the ability to keep stations closer to traffic generation points (both work and residential) than is observed with heavy rapid transit.

The extension of LRT lines into new satellite towns helps establish community identity among the new residents without detracting from their desire to maintain their metropolitan or regional orientation. The physical presence of the guideway aids the community to orient itself to the CBD. In new, planned communities, the alignment has been incorporated into the layout of the neighborhood. By various aesthetic methods, the LRT mode operates near recreational areas without creating danger. This has resulted in high access to the station areas and retention of inter-station operation and safety. As a result, the LRT can be perceived without being physically accessible along the nonpassenger areas.

In Canada, Mexico, and the United States, some cities have LRT in their existing urban systems.

In Toronto, the street-oriented LRT system provides an interlinking of CBD employment areas and close-in residential neighborhoods. Well-designed connecting and transfer points are provided at many of the rapid transit stations. There is minimal distance between the subway and the LRT lines. One major line is operated in the median of an expressway. This has provided peak-hour capacities at a capital cost that is lower than would be incurred by providing additional highway lanes.

In Mexico City, the broad park-like medians are used by LRT vehicles with doors on both sides. This permits safe passenger handling even though the vehicles operate in the center of public ways.

Boston has retained a combination subway and surface LRT system providing high-quality movement within the CBD. Its system also radiates lines outward on surface corridors. These corridors have been maintained as transit-priority medians in existing arterial roads. Such routes provide an uncongested means to enter the city's employment district and provide options for nearby park-and-ride. In 1 case, the transit authority was able to purchase an existing abandoned railway alignment and convert it to LRT operation. With minimal investment, an upgrading of the line was made to permit higher speed with frequent schedules to the CBD. This line to Riverside provides dependable access to Boston for some high-income suburbs. Many of the stations and facilities along the route have been designed to blend with the community. As a result, the community has been able to maintain high transit and peak-hour capacities to the city without new major expressways.

In Pittsburgh an LRT system provides communities along a rugged terrain with access to the central employment and retail areas by judicious use of private rights-of-way. The transit authority has rehabilitated the existing equipment and made it an effective marketing tool to encourage ridership. Without resorting to subterranean levels, the LRT system provides a downtown distribution loop for its patrons, partly through the priority use of access ramps that are located within a major, federally aided highway alignment. One of these ramps is connected to an older, low-volume bridge on which the LRT has an exclusive right-of-way. By a tunnel and the penetration of a narrow valley, the LRT route quickly reaches communities on the south. The LRT is operated in hilly, park-like areas. It uses heavy steel bridges for proper elevation to reach the various neighborhoods. To maintain the sylvan character of the valley, officials had the structures painted black. Therefore, the line is not visually dominant. The Library and Castle Shannon lines provide residents with a practical alternative to their private vehicles for access to the CBD. Park-and-ride lots are positioned between the arterial roads and the LRT lines. These locations provide commuters with an effective alternative to central city driving and parking.

The community of Shaker Heights, Ohio, has a municipally operated LRT system that links it to downtown Cleveland, Ohio. This line has operated for more than 55 years within an upper-income community composed of apartments and private dwellings. The passenger transport demand for business and social activities related to the center of the city has been met without expansion of the highway network. Adequate visibility for the operators means that this service can be maintained without physical separation from the residential areas that it serves. As a result of the fixed-guideway operation, the parklands and green spaces of the community are maintained close to the LRT lines. Passenger stop areas are provided away from the heavily used automobile lanes. The community provides parking for workers whose destination is the CBD. This not only reduces the number of peak-hour private vehicles but also encourages retail trade within the suburban community.

Although the community's policy on urban transit or LRT cannot be considered the solution to all urban problems, it is seen by many residents as a barometer for the overall provision of urban amenities. The Transit Bureau of Shaker Heights has found maintenance, reliability, and cleanliness to be of greater importance to the patrons than the actual age of the vehicles.

In an overall view of LRT, it should be remembered that the design and subsystem components for the guideway, as well as the power distribution technology, exist now. And all the elements are proved in daily use. The vehicle necessary to implement this technology is currently in design or being manufacturered in Belgium, Germany, Switzerland, Canada, and the United States. Reemphasizing LRT is not unique to 1 country as can be seen by the data given in Table 1.

REFERENCE

1. 1975 International Statistical Handbook of Urban Public Transport. International Union of Public Transportation, Brussels, 1975.

THE URBAN MASS TRANSPORTATION ADMINISTRATION VIEW OF LIGHT RAIL TRANSIT

C. Kenneth Orski, Urban Mass Transportation Administration

This paper will address the issues of how the Urban Mass Transportation Administration views light rail transit, what future role UMTA sees for it in American cities, and what considerations led UMTA to sponsor this conference.

It should be obvious to anyone who has been following the UMTA program that UMTA has no modal biases. The impassioned debates between the advocates of bus and rail technology have always left those of us in UMTA perplexed, for underlying these debates is the presumption that there is a single "best" solution to urban transportation problems and that the present lack of consensus is merely a reflection of our inability to get at the truth. UMTA's own perception, based on a growing body of analysis, leads to quite a different conclusion. It is becoming increasingly doubtful that a single system of any technology can effectively serve the broad range of travel patterns and service requirements that prevail in a large city. UMTA also cannot find any compelling reason why a single transportation system must dominate an entire metropolitan area. Quite the contrary, the desire for systemwide efficiency may lead us in the opposite direction: away from an emphasis on unimodal solutions and toward a system that blends a number of separate transit elements, each of which is closely tailored to the demands and conditions prevailing within the specific corridors and subregions it serves. This concept, embraced by UMTA's new policy on federal assistance for major mass transportation investments, views each mode as having certain unique attributes that render it particularly effective under specific conditions. The goal of transit planning should be to exploit each mode and each transit technology for the purposes for which it is best suited and then to combine the various elements into a single smoothly functioning and coordinated metropolitan mass transportation system.

To realize the full potential of this approach something more is needed than the express bus and rail rapid transit. These 2 modes operate effectively as line-haul carriers in high-density corridors. But such corridors represent a small and shrinking share of the urban travel market. Increasingly, the need is for more flexible transportation services that can operate efficiently and conveniently in low-density suburban environments where trip patterns are diffused and travel volumes insufficient to justify frequent, high-capacity transit service. Some communities are responding to this need by introducing paratransit, which encompasses flexible transportation systems involving the use of small passenger vehicles that can respond to individual calls for service, deviate from their appointed routes, and provide a more accessible and widespread community transit service. Light rail transit can be the forerunner of a similar trend in the field of fixed guideway transit. Its less obtrusive vehicles and guideways enable the LRT to penetrate residential quarters and provide good coverage in suburban areas. Its ability to operate as a single car or as trains enables it to adjust to fluctuating traffic loads and provide efficient peak as well as off-peak service. In short, light rail transit offers a more versatile alternative to conventional rapid transit.

Although UMTA recognizes the virtues of the light rail concept, it does not see it as a panacea for urban mobility problems. Buses and paratransit always will be needed. Private automobiles alway will have their place in a total urban transportation system. Light rail transit simply represents a valuable addition to the existing array of transit options to widen the range of choices so that cities can select the transit solution that best fits the local needs and budgets.

In UMTA's view, light rail transit should be a particularly strong contender for the attention of the cities that aspire to some form of fixed guideway transit. With construction costs of 40 to 50 million dollars/mile (25 to 32 million dollars/km), conventional rail rapid transit technology is rapidly pricing itself out of the reach of most urban areas. The long lead times required to bring a rapid transit system into operation and the attendant disruption during the construction phase compound the problem of heavy rail transit implementation.

In medium-density areas, UMTA believes that light rail transit can offer an attractive level of service at a significantly lower capital cost than conventional rapid transit. Moreover, a light rail system can be developed on an incremental basis as resources become available. The system is not locked into a given stage of development but can be upgraded to more advanced technology, such as automated operation or off-line stations, without interrupting service. For these reasons, UMTA expects that the cities now considering new fixed guideway systems will give serious thought to the light rail option in their analysis of alternatives. To do otherwise would hardly be consistent with UMTA's new policy that requires prospective applicants for capital assistance to consider a full range of alternatives in planning a major mass transportation investment.

UMTA realizes that, as a result of 30 years of neglect, knowledge of light rail transit—its costs, performance, and service potential—is inadequate. UMTA hopes that this conference will mark the beginning of a concerted effort on the part of the transportation profession to correct this situation. UMTA will do its best to assist in this task. Its support of this conference is a tangible sign of this resolve. Another example is the major state-of-the-art study of light rail transit for which a contract is about to be awarded. UMTA's research and development budget for the next year contains funds for research on light rail items such as improved power collection systems and self-propelled LRT vehicles. Finally, UMTA's foreign bilateral exchange program is oriented toward obtaining the latest technical information and operating experience on LRT from other countries.

UMTA believes that light rail transit may be a major solution in the search for less costly, more efficient, and more environmentally attractive transportation systems that can economically serve the dispersed land use and travel patterns of metropolitan areas.

At the same time, it is UMTA's policy to leave to the local communities the widest possible discretion in deciding how they should meet their transportation needs and what should be the nature and mix of their transportation services. Thus, in the final analysis, the planners, engineers, transit operators, local elected officials, public interest groups, the press, and concerned citizens ultimately will decide whether LRT should become a major force in the transportation systems of American cities.

LIGHT RAIL TRANSIT: AN URBAN TRANSPORTATION ALTERNATIVE

Frank C. Herringer,* Urban Mass Transportation Administration

Had the conference on light rail transit been held 10 or even 5 years ago, those in attendance would have been viewed as little more than eccentrics or nostalgia buffs infatuated with a dying mode of transportation. Much has changed in all of mass transit in recent years, but few events have been as dramatic as the reawakening of interest in LRT.

The conference was most appropriately held in Philadelphia. The first light rail cars to be built in the United States since the 1930s are rolling off the production lines near Philadephia. Philadephia operates the largest remaining light rail and streetcar system in the nation. The system includes several exclusive right-of-way lines, some of which run on subway tracks, and other car lines about 90 percent of which are on exclusive rights-of-way. Most of Philadelphia's light rail lines are feeders to other mass transit modes.

Outside Philadelphia, light rail operations exist only in Boston; San Francisco; Newark, New Jersey; Shaker Heights, Ohio; Pittsburgh; New Orleans; and Fort Worth, Texas. However, at the turn of the century, electric streetcars were the predominant mode of urban transit; 90 percent of all urban trips were made by streetcar. In 1925, nearly 63,000 streetcars ran over 40,570 miles (64 912 km) of track. Today, there are only 1,068 streetcars and 760 miles (1216 km) of track. The average age of streetcars today is 28 years.

The demise of the streetcar came about as urban automobile travel grew. Before cars were widely owned, streetcars had virtually exclusive right-of-way on city streets. As car ownership and dependence on automobile use grew, however, streetcar right-of-way disappeared. And the street car gradually became little more than a nuisance to car owners.

Flexibility then became the issue. Streetcars were fixed on the roadway but buses could weave in and out. Streetcars were slower than the bus and much slower than the automobile. Early infatuation with the automobile made it unthinkable to people in the cities to consider giving some automobile right-of-way to exclusive streetcar use.

The streetcars predictably faded in this country. However, they did not fare quite so badly in Europe. The revitalization of the streetcar industry started in Europe before it started here. Orski and I made a trip last year that focused on the status of LRT in Europe, and it was evident then that the renaissance was well under way. Manufacturers of light rail vehicles had immense backlogs; just a few years ago they were considering going out of the business completely. Some cities were installing new light rail vehicle systems, and others were revitalizing and renovating their old systems with new cars and improved rights-of-way. It was not difficult to predict that a similar reawakening of interest in light rail vehicles would soon take place in the United States.

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*Mr. Herringer is now with the Bay Area Rapid Transit District, San Francisco, California.

UMTA's first major venture into light rail transit was the development of a new standard vehicle to replace the ancient PCC cars now in service on existing systems. When several systems decided in the early 1970s to upgrade their systems rather than abandon them, UMTA proposed that light rail operators work together to develop standard performance specifications for common use that could serve both present and future needs at a minimum cost per vehicle.

Some of the standard specifications for a car are that it should be 70 ft (21 m) long, 8.5 ft (2.6 m) wide, and 11.5 ft (3.5 m) high and it should have three 4.5-ft (1.4-m) doors on each car side. The car is a 2-section articulated vehicle and is double ended. (It can be constructed in a single-end version.) The specification is heavily performance oriented, reflects a synthesis of the requirements of the operating agencies, and preserves latitude for manufacturers to innovate.

Delivery of new cars to Boston and San Francisco in 1976 will mark the first new domestic design for a light rail vehicle since 1935 and the first such vehicles built in the United States since 1952.

The standard light rail vehicle is a good product. I rode it this morning and was impressed by the appearance of the vehicle and by the smoothness of the ride. However, as is the case for other modes of transportation, merely improving the quality of the vehicle is not going to bring people to light rail transit. If we put these sleek, attractive vehicles in mixed traffic, in a short time their fate would be the same as that of the PCC cars. Light rail, like buses, needs exclusive rights-of-way to compete successfully with the automobile. Granting exclusive rights-of-way in many cases requires political courage. Ten years ago such actions would have been doubtful, but increased concern with the environment, energy conservation, and improving the quality of life for those who work and live in cities has made such approaches feasible. This in turn makes the future of LRT much brighter than at any time in the last 50 years.

Light rail on exclusive rights-of-way can be an attractive competitor to the automobile. One of the big problems in introducing light rail to new cities will undoubtedly be concern with the image this form of transportation has. It is much easier to go to the voters for an ultramodern system such as the Bay Area Rapid Transit system than it is to tell citizens that they would be well served by trolleys. Hopefully this conference and other activities will bring trolley cars back into respectability.

One of the objections raised about light rail systems concerns aesthetics. The economies derived are partially a result of being able to put the system at grade rather than underground. However, some object to the overhead wires. I believe that it is important to accelerate research efforts that would make possible the removal of such wires. Early indications are that this research is expensive. Nevertheless, it should continue until a practical system is devised.

Although I believe that we should push ahead with research on improving the aesthetics of light rail vehicles, we should, at the same time, keep the environmental questions in perspective. Perhaps light rail vehicles are environmentally intrusive. But could they be more intrusive than 6 or 8 lanes of highway choked with noisy automobiles emitting pollutants and not moving people as rapidly as they want to be moved? Compared to that, a few overhead wires are not that difficult to endure.

UMTA feels that light rail transit is a workable alternative and a possible supplement to other modes of transportation. It is not UMTA's latest fad as some have characterized it. UMTA does not favor light rail over other modes. UMTA merely says that it should be considered as an alternative when a city is making the choice on what kind of a rapid transit system it should have. It is sometimes necessary to be quite vocal and insistent to get cities to consider light rail; some have misinterpreted this attitude to be advocacy of this mode over others. This is not true. On the other hand, I believe it is essential that light rail and other less costly modes be developed if we are to see many more cities engaged in fixed guideway transportation. The current, incredible costs of new rapid rail systems are about 75 to 100 million dollars/mile (47 to 62 million dollars/km). This is not within the reach of the vast majority of U.S. cities. The economies that are possible with light rail will make fixed guideway transportation a reasonable objective for many cities. But that will not be the case if we cannot keep the costs of light rail within reason. The cars must be made economically and the systems must be constructed at minimum cost. That is going to mean putting a system at grade when a community might prefer putting it underground. But we must recognize and it is our responsibility to inform the public that the resources available are not infinite.

UMTA expects federal policy for investment in major urban transportation projects to lead to a rational allocation of the limited resources. As most of you know, the key elements of these guidelines include a requirement that all pertinent alternatives be considered before a decision is reached on a transit mode, that systems be developed in increments based on operable segments rather than areawide, that full consideration be given to maximizing the use of existing facilities and traffic management approaches as substitutes for and supplements to capital-intensive investments, and that a cost-effective solution to transportation problems as the basis for determining the level of federal investment be emphasized. This is not a radical, new development dictated by the federal government. It is rather a formalization of the way in which sound transportation planning has been proceeding for many years. I expect the adoption of this policy will encourage more cities to consider light rail as an alternative and that it will result ultimately in more light rail systems.

The development and publication of this policy are evidence of an increasing maturity of the federal transit program. Along with the 6-year transit bill passed in 1974 and the practice of making multiyear commitments to major projects, the guidelines will make it possible for both federal and local officials to rationally evaluate commitments to major expansions and new systems.

I believe that the role of transit in our society should, and probably will, expand substantially in the years ahead. I say "probably" only because I am concerned that, if we are not able to show performance for money that will be invested in the next few years, a reaction against more funding for transit will set in. That is why we must encourage cities to look at all alternatives, including light rail transit, as they make the critical investment decisions with which we will be living for decades to come.

PHYSICAL, OPERATIONAL, AND PERFORMANCE CHARACTERISTICS OF THE LIGHT RAIL MODE

J. William Vigrass, Port Authority Transit Corporation of Pennsylvania and New Jersey

An overview of the light rail mode is presented. General characteristics and application of the mode are described, emphasizing the versatility of its guideway, the railway track. Physical characteristics of the right-of-way and ranges of dimensions for right-of-way and vehicles are discussed. Stations are discussed briefly. Basic technical simplicity of the light rail mode is pointed out as a significant virtue. Operating characteristics (both maximum running speeds and typical average operating speeds) are indicated. Acceleration of typical vehicles is noted. Frequency of service is discussed, and ranges for various traffic control systems are given. Riding quality and visual impact are pointed out as being favorable. Capacity of light rail lines is given as a few thousand to 12,000 passengers/h. In special cases, a high of 18,000 passengers/h can be achieved by using multiple-unit trains of 3 or more cars. Choices a designer has to attain maximum capacity are stated. Capital costs of contemporary new light rail systems are given as ranges of costs for various configurations. It is concluded that light rail transit is a medium-cost mode providing a medium level of capacity at medium speeds that can find application in many corridors or areas in medium and larger sized urban areas. It is pointed out that light rail is an existing mode with proved capabilities that needs little or no new research and development.

Light rail transit is an urban electric railway having a largely segregated but not necessarily grade-separated right-of-way. Speeds, capacity, and overall performance are generally lower for light rail transit than they are for fully grade-separated rapid transit, yet LRT is substantially superior in capacity and performance to any form of transit operating on public streets or roadways in mixed traffic. Because it is not fully grade separated and because it is not designed to have as high an overall performance and capacity as rapid transit does, LRT generally costs much less to construct per route mile (route kilometer). This lower cost allows LRT to be economically justified in urban areas or in specific corridors where conventional rail rapid transit is not feasible either because of cost or demand considerations.

Light rail transit is a medium-cost mode that provides a medium-speed service for a medium volume of passengers. It therefore falls into that cost-service region between conventional rail rapid transit and motor bus, yet there is considerable overlap upward into the traditional cost-service domain of rail rapid transit and downward into the domain for which motor buses have been considered most appropriate.

During the past 2 decades, there have been a number of novel modes proposed to fill various medium-speed and capacity needs. It has been evident to planners and researchers, as well as to inventors and promoters, that medium-demand corridors exist in many medium and larger sized metropolitan areas consituting a significant market for these novel modes. However, any new technological innovation needs considerable research and development before it can be used in the marketplace. Highly publicized difficulties of the few operating prototypes of some new modes give cause for caution before such modes are adopted widely. Yet the need to service medium-density corridors is clear to many planners and political leaders.

Light rail transit is suitable to fill this role today. Light rail transit is an evolutionary development of the street railway and full-scale rapid transit and has some features of both. Its subsystems have been fully developed and proved, and there is no need for costly, time-consuming research and development.

Because it is the result of evolutionary development, some say that LRT is an obsolete concept. It must be pointed out to such critics that the 2 major modes of travel today, the automobile and the airplane, had their beginnings at about the same period (1890-1910) as did the electric railway (1, pp. 196-197, 280-299). Today's automobile and its related roads and today's aircraft and related ground support evolved over approximately 70 years of, at times, intermittent and, at other times, very active development and culminated in reliable and widely accepted equipment. It appears that evolution has produced more useful transportation devices for society than revolution has.

Let us therefore look more closely at the physical, operational, and performance characteristics of LRT to see how it can contribute to improving urban and suburban transit.

PHYSICAL CHARACTERISTICS OF LIGHT RAIL TRANSIT

The 2 basic characteristics of the light rail mode are its guidance system (steel wheel on steel rail) and its power source (externally generated electric power). Both have evolved from the predecessors of LRT—the street railway and rapid transit.

The railway track and its related flanged steel wheel provide the simplest, cheapest, most effective, and most thoroughly developed guideway known to engineering. It has been in use for more than 150 years (1, pp. 66-93) on railroads and for 90 years or more in urban railways, yet it is still far superior to any other form of guidance available for implementation today. The railway is the only guideway that is equally adaptable to tunnel, aerial structure, freeway median strips, medians of boulevards, grade on private rights-of-way, and paved streets in mixed traffic. No other guideway, available now or proposed, is this versatile. If the railway had not already been in common use, its invention would be heralded as a great breakthrough! Switches and crossings are fully engineered and can be ordered from a number of suppliers.

The use of externally generated power supplied to vehicles at 600 Vdc provides environmentally clean energy at the use point and permits operating in subways and other enclosed areas with no ventilation problems. It also allows very high installed horsepower (wattage) per vehicle if desired, which is far more difficult to provide in internal combustion engines. The use of direct current with a steel railway track allows a single current collector for the positive side and the use of the track for the negative side. This obviates the need for multiple collectors as required for some of the new modes. The problems of these are just beginning to be appreciated. Simplicity of its guideway and power collection system are the primary virtues of LRT. From these basic items, a complete system has been developed.

The right-of-way, including track, wayside power, communication, and signal systems, is the physical foundation for this fixed guideway system. Rails used are somewhat lighter than those generally used for main-line railroads or rail rapid transit. The rails are about 100 lb/yd (50 kg/m) or somewhat less for present day installations compared with 115 lb/yd (55 kg/m) to 135 lb/yd (60 kg/m) for main-line railroad. This weight differential can result in a significant difference in cost for a complete system.

Width required for a double-track light rail right-of-way, including adequate platforms, is approximately 40 ft (12.2 m). Between stations, 24 to 35 ft (7.5 to 10.5 m) often suffices.

Light rail transit is especially versatile for both vertical and horizontal curvature; the new Boeing light rail vehicle (LRV) is designed to take a curve with a 42-ft (12.8-m) inside radius (2); traditional street railway equipment, exemplified by the PCC car still in use in most U.S. light rail systems, could negotiate a 36-ft (11-m) radius (3). Such curves can be negotiated only at very low speeds [10 to 15 mph (16 to 24 km/h)]; therefore, their use generally is not recommended; however, such curves can be used where civil engineering needs make it necessary or expedient. The Boeing LRV can accept a vertical curvature radius of 310 ft (95 m) on a crest of a hill and 460 ft (140 m) in a sag (2). Nonarticulated cars can accept even more severe vertical curvature. While it is usually desirable to employ the largest possible radius to allow maximum operating speed, it is a strong advantage, especially in urban areas, to have highly versatile geometric characteristics when laying out a given line or system. It is therefore possible to install LRT in places where other guided modes cannot fit.

For types of right-of-way, LRT is the most versatile of any guided system. Its track may be on a private right-of-way, at grade, or grade separated. If it is below grade, surface streets pass over the light rail line. The track also may be on an aerial structure or in a median strip of a freeway; both provide grade separation. More commonly, the median of a boulevard or arterial road has been used with infrequent grade crossings with other streets. Often such crossings are protected with signal lights, railroad gates, or traffic signals with preemptive control to give LRVs priority. In congested city centers, subway sections have been used for short distances. In some places, particularly in western Europe, segregated paved track is used in the city center, sometimes on thoroughfares on which automobiles are excluded entirely (5). In streets that already have street railway track or have traffic flow light enough to permit it, light rail track can be installed in the street pavement and LRVs can be operated in mixed traffic. Each of these right-of-way variations can readily be employed within 1 given system, or if required, on 1 route. The same vehicle can be used throughout.

Grades of 4 to 6 percent are common in light rail practice and pose no particular difficulty other than a moderate reduction of speed on an upgrade and an increase of required braking distance on a downgrade. There are a number of examples of substantially steeper grades that, although their occurrence is infrequent, indicate clearly the alignment versatility of the light rail mode. For example, the portal on the San Francisco Municipal Railway system (Muni) has a grade of 8.9 percent. Muni has a grade of 8.6 percent leading to a curve of 42.5-ft (12.7-m) radius on the L line. The new Boeing LRV is designed to operate over this grade and curve combination (2).

Light rail stations can range from a stop sign painted on paved streets to simple trackside platforms on private rights-of-way. These platforms often have a small shelter, or controlled access stations such as those used on rail rapid transit subways or aerial structures could be provided. Where traffic is heavy and prepaid fare collection is desired, as it is on conventional rapid transit, light rail station design is nearly identical to that of conventional rapid transit. There is a strong tendency toward simple, inexpensive stations on nearly all existing light rail installations.

The size and weight of the LRV are usually less than that of rapid transit vehicles. The Boeing Vertol-UMTA standard LRV currently being built for Boston and San Francisco is 72 ft (22 m) long and 8.5 ft (2.55 m) wide; it rests on 3 trucks; the center unpowered truck is under an articulated joint (2). The distance between truck centers is about the same as it is on the existing single-unit PCC streetcars being used on the same routes. These measure 46 ft (14 m) long and 8.33 ft (2.5 m) wide; there is 22.75 ft (6.8 m) between truck centers (3). This results in a rather long overhang on the front and rear of the car, the effect of which is minimized by some tapering of the car ends. Height is typically about 10 ft (3 m) over the roof, plus 1 or 2 ft (0.3 to 0.6 m) more for whatever current collecting device is installed (trolley pole or pantograph). Some PCC cars were built to lengths of 50 ft (15 m) and widths of 9 ft (2.7 m). In Europe, cars are usually narrower and shorter than they are in North America. The spaciousness of LRVs permits a wide variety of interior arrangements. They can be equipped with spartan seating allowing extensive standing room for high-density, short-haul travel, or they can emphasize comfortable seating for long-haul suburban traffic.

Nearly all new transit equipment is air-conditioned. Light rail vehicles can be air-conditioned if desired. Because of the climate of San Francisco, the LRVs for that city are well ventilated, not air-conditioned. An important aspect of the air-conditioned LRV is that its performance is not impaired by the addition of air-conditioning equipment. Air conditioning is powered separately by externally supplied electrical energy and is in no way connected with the vehicle propulsion system. In diesel motor buses this is not the case. The bus engine generally powers the air-conditioning compressor and blowers. This degrades bus performance whenever the air-conditioning system is operating. In some situations, a driver can have the engine propel the bus or air-condition it but not both at the same time!

An important and often overlooked characteristic of LRVs and the entire light rail concept is the relative simplicity of this mode compared with contemporary rail rapid transit systems and particularly compared with fully automated new modes. The more equipment or subsystems there are in a complex system, the more there is to go wrong. A reliability engineer can calculate this readily. Most contemporary light rail installations demonstrate a high degree of technical reliability and operate a high percentage of their vehicle fleets during each rush hour. The percentage of vehicle down time is low, and maintenance needs are moderate.

TRAFFIC CONTROL FOR LIGHT RAIL SYSTEMS

The simplest traffic control for light rail systems is on-sight control, which means that the operator of a train or car merely operates the vehicle an estimated safe braking distance behind the preceding vehicle. This type of control will be retained on the street portions of both Boston and Muni routes, and is also commonly used on street or surface sections of European light rail lines.

A higher type of traffic control is provided by block signals that provide a visual indication to the train operator of the condition of the block ahead or speed at which to run or both. Block signals are commonly used on private rights-of-way (including elevated and subway sections) of many present light rail lines. These depend on the operator's observing and responding to visual indications on wayside signals. It is uncommon to employ rapid-transit-type trip stops on LRV, particularly those that may operate in street traffic on a portion of their route because an unwanted obstruction can too easily inadvertently trip a car and cause an emergency stop. (Shaker Heights, Ohio, Rapid Transit trains do use mechanical trip stops on the joint section of track shared with Cleveland Transit System trains. This use of trip stops by light rail transit is unique to the United States.)

Several European light rail lines using wayside signals have an intermittent inductive train stop that triggers an emergency brake application if a train attempts to pass a red signal (5). This type of stop enforcement is unaffected by encounters with other vehicles or debris in the street.

Cab signals may be readily adapted to the light rail mode; in fact, this is being done for the Market Street Subway portion of Muni. The cab-signal concept has been used for many years by certain railroads and has been applied to a number of rapid transit lines during the last decade. Normally a cab-signal system will indicate visually to the train operator the speed at which to operate. The system also will apply the brake to slow or stop the train if it is operated in excess of the indicated allowable speed. The cab-signal concept provides all-weather capability because the train operator does not need to see wayside signals. This allows full-speed operation in snow, rain, or fog.

The primary virtue of cab signals is that they improve performance. A train (or vehicle) need not proceed at restricted speed from, say, a yellow signal to the next signal if the signal should clear to green. With a cab signal, the operator immediately knows the condition of the block ahead and can accelerate or decelerate accordingly. In addition, where visibility is impaired, as in a subway section with curves, cab signals provide the operator with a continuous indication of the block or blocks ahead. Cab-signal systems therefore provide somewhat higher capacity and safety over wayside-signal systems.

It is natural in a cab-signal system to progress to fully automatic train operation. This would add the capability of automatic station stops in which deceleration to a stop and positioning at a platform would be programmed as has been done on several recently implemented rail rapid transit lines. No light rail system yet implemented or proposed has opted for a fully automatic train operation.

OPERATING CHARACTERISTICS

Light rail maximum speeds are in the range of 40 to 60 mph (65 to 95 km/h). The obsolescent but still used PCC streetcar has a maximum speed of 42 mph (66 km/h); the top speed of the new standard light rail vehicle (SLRV) is 55 mph (88 km/h). Certain suburban light rail equipment can attain speeds in excess of 70 mph (110 km/h), but this is unusual.

Overall schedule speeds for light rail lines on fully segregated rights-of-way generally fall in the 15 to 35-mph (24 to 56-km/h) range depending on station spacing and degree of segregation. If the track is in the street, schedule speeds will be much lower; they will range generally from 10 to 15 mph (16 to 24 km/h), and maximum speeds will be limited to whatever the allowable speed is for traffic in the street. In most places, the speed limit is 25 to 35 mph (40 to 56 km/h).

Acceleration of 3 mph/s (1.33 m/s^2) is a generally accepted industry standard based on what a typical standing passenger can tolerate. The PCC streetcar was designed and built to attain a rate of 4.75 mph/s (2.11 m/s^2) in the lower speed ranges; some operating properties reduced this somewhat, however. For instance, San Francisco's PCC cars are set for 4.25 mph/s (1.89 m/s^2).

Acceleration of the Boeing LRV has been found to be 2.6 mph/s (1.16 m/s^2), but it holds this rate to a higher speed. Therefore, its overall performance is expected to be quite attractive when station spacing allows the vehicle to attain its 55-mph (88-km/h) running speed.

Past accomplishments indicate that it is technically possible to attain whatever rate of acceleration is desired within the limitations of adhesion. The tolerance of standing passengers and the various costs related to installing the desired horsepower (wattage) (or torque) are the controlling factors.

Headways between vehicles on light rail lines vary widely. Minimum headways traditionally have been achieved on unsignaled routes at relatively low speeds operating with on-sight control under visual rules. Under such conditions, 1-min headways commonly have been attained; in some cases, 30-s headways were used for relatively short periods such as 15 to 30 min. Such frequent service requires effective dispatching to prevent irregularities in operation.

Minimum achievable headways depend on many factors. The major ones are vehicle speed, braking rates, degree of safety, system response time, train length, station dwell time (which is influenced by number, design, and arrangement of door openings, doors, and steps, and number of passengers boarding and alighting at stations), and the effect of random influences on the line. Random influence on the line is determined primarily by the degree to which the right-of-way is exclusive.

With wayside signals, speeds can be increased safely, but then this forces an increase in required braking distance. As a result, headways become longer, so that headways of about 60 s are about the best that are achieved on signaled lines having moderate speeds in the 30 to 40-mph (48 to 64-km/h) range. In certain special situations, closer headways are attained by using permissive signals that allow a vehicle to pass a red signal at restricted speed, which is typically 15 mph (24 km/h). Strictly speaking, a train that has passed such a red signal is operating under visual rules rather than signal protection.

Higher speeds, such as 60 to 70 mph (84 to 110 km/h), have been attained on a few suburban light rail lines. These systems typically use wayside signals sited to permit headways of 3 to 5 min because that is all that traffic requires. Fixed wayside signals (with mechanical or inductive trip to enforce a stop signal) generally allow headways of 2 min with speeds in the 45 to 60-mph (75 to 95-km/h) range.

At present, no light rail line in the United States or Canada is using a cab signal or automated mode of operation. However, Muni is installing cab signals in its Market Street subway, and these will offer several operating speeds with a maximum of 55 mph (88 km/h). Headways of 60 s are expected.

Equally important to capacity operation is that light rail systems can operate economical off-peak headways of 10, 12, 15, or even 20 min by using 1-person vehicles with fare collection on board. Although such headways are not difficult, that they have been popular with many riders, particularly when they repeat every hour, has been an important characteristic of existing light rail systems.

A few light rail routes have single track with passing sidings for opposing vehicles or trains to pass. In some cases, single track has been used simply for economy as it has on outlying suburban lines requiring infrequent (15- to 30-min) headways. In other cases a short, single-track section can provide an inexpensive means of coping with a physical or geographic constraint. Bridges and tunnels are typical places where single track has been employed successfully.

Riding quality of LRVs can be described as good to excellent. This depends greatly, however, on the maintenance of both vehicle and roadbed. Ride is superior to that of buses because the body of a rail vehicle is carried on 2 or more trucks that smooth out irregularities in the track (guideway). Noise levels of LRVs are low. Most cases are considerably less noisy than diesel engine buses. Most contemporary LRVs are equipped with resilient or rubber-cushioned wheels that lower or nearly eliminate wheel squeal on curves.

Visual aspects of LRVs are pleasing. Large picture windows provide the passenger with a clear view of the station or stop or scenery. The total effect of a light rail line is usually unobtrusive, although some object to the visual effect of overhead wire components.

The combination of a pleasant ride at attractive speeds is one reason many motorists willingly park their cars to ride an electric-rail-transit vehicle.

CAPACITY

A light rail route can be designed to economically handle up to 12,000 or 18,000 passengers/track/h. Higher numbers are attained by using multiple-unit trains. For instance, the 72-ft-long (21.6-m-long) Boeing LRV would have a rush-hour capacity of about 150 to 180 passengers, depending on seating arrangements and assumed space per standee. A 3-vehicle train thus would accommodate easily 450 passengers. At a 2-min headway, 30 such trains could pass a given point in 1 h. This results in an offered capacity of 13,500 passenger spaces/h. A 4-vehicle train would handle 18,000 passengers/h although, at this level of traffic, fully grade-separated rail rapid transit may be a better choice.

Several existing light rail systems carry 10,000 to 15,000 passengers/day on a given route. Such volumes require that only 2,000 to 4,000 passengers be carried during a rush hour, which is attained easily with 1- and 2-car trains on 3- to 5-min headways. Yet these passengers enjoy a speedy ride not attainable by transit vehicles in mixed traffic. This is what generates higher per capita LRT ridership in a given corridor.

A light rail system can be designed for modest traffic and can be upgraded from time to time as demand increases. It is not necessary to invest large amounts of money in an initial system at 1 time. Investment can be distributed over a long period of time and grow in increments as the need arises. Several options in vehicle and station characteristics give a designer numerous investment choices and combinations.

A system can be designed for moderate headways of, say, 5 min. As traffic increases, train length can be increased from 1 to 2 or even 3 or more vehicles. Concurrently, stations must be lengthened (which may require substantial investment) and substation capacity increased to provide power for longer trains. On the other hand, it is sometimes easier to decrease headways from, say, 5 min to 2 min with 1- or 2-vehicle trains before additional capital is invested in lengthening stations and increasing substation capacity. It also might be necessary to alter significantly a signal system when changing from a 5- to 2-min headway. This could be costly. Short trains on short headways and longer trains on longer headways have their place. Both may be needed.

COSTS

The basic attribute of light rail transit is that the costs of installing a light rail system are significantly less than they are for fully grade-separated rail rapid transit or for fully automated novel modes requiring full grade separation. Yet, light rail can provide a fast, frequent, attractive service that can attract a significant number of riders who would not (and do not) use conventional surface transit.

Light rail vehicles cost from 450,000 to 600,000 dollars for a 6-axle articulated vehicle (Boeing Vertol-UMTA SLRV being built for Boston and San Francisco). A single-unit, 2-truck car that is 50 ft (16 m) long and 8.5 ft (2.45 m) wide is expected to cost about 250,000 dollars in Canada (4). Although the unit price of a vehicle appears high, it should be borne in mind that its service life is about 30 years; its schedule speed will be in the region of 20 to 25 mph (32 to 40 km/h); and its capacity ranges from 75 passengers (for a single car seating 50 to 60) to more than 200 for the articulated LRV. This is 2 to 3 times the life of a bus, 2 to 3 times the average operating speed of a bus, and from one 1.5 to 3 times the passenger capacity of a bus.

Construction of a double-track light rail route should cost from 4 to 8 million dollars/route mile (2.5 to 5 million dollars/route km). This includes track, power distribution facilities, signals, and communications. It does not include land. Aerial structure costs 10 to 20 million dollars/mile (6 to 13 million dollars/km). Subways cost 30 to 50 million dollars/mile (18 to 30 million dollars/km). A yard and maintenance shop might cost 3 to 5 million dollars for a car fleet of 50 to 100 vehicles.

A light rail line needing 50 to 100 cars and 10 to 15 miles (16 to 24 km) in length that is constructed on surface might cost between 50 and 100 million dollars. If an abandoned or underused railroad line is available, costs might be significantly lower, possibly as low as half that amount, because new civil engineering work would be minimized.

CONCLUSIONS

Light rail transit is a medium-cost mode that will fit many corridors or urban areas requiring a medium-capacity and medium-speed mode. Light rail transit is versatile in where its guideway (railway track) can be installed. It can be completely grade separated; it can be segregated horizontally from other traffic; it can be within a mixed traffic stream. The conventional rail track is the only guideway that is so versatile.

Light rail vehicles are attractive to passengers and are environmentally clean because they are propelled electrically. Noise and visual effects levels are low.

The performance of LRT is superior to any surface mode and is nearly as good as that of some rail rapid transit or novel modes. Yet it can cost much less.

Light rail transit may be an attractive transit mode for some locations that have not been candidates for any form of rapid transit. It is a mode that exists now and can be implemented now with little research and development. It is a mode with proved capabilities.

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ROUTE LAYOUT PHILOSOPHY AND SERVICE COORDINATION PARTICULARLY FOR LIGHT RAIL TRANSIT

Brian E. Sullivan, Bureau of Transit Services,
British Columbia Department of Municipal Affairs

Peak-period and all-day service in public transportation are discussed with emphasis on light rail transit. Peak-period service treats each line as a separate entity operating from residential neighborhoods directly to the central business district. This type of service is typified by the American metro-mode motor-bus concept. Each route in an all-day service interacts with every other route enabling regionwide mobility. This integrated approach is found throughout Europe and is also well developed in a few U.S. and Canadian cities. Traditional network arrangements, such as radial and grid setups, and more recent concepts, such as the timed transfer focal point, are considered. Detailed aspects of service integration including schedules, passenger facilities, information, and fares are reviewed. That a widespread disinclination in North America to implement integrated systems exists because of limited funds and management disinterest is noted. The organizational structure successfully adopted in Europe to bring about service integration is described.

In North America today, 2 different schools of thought exist concerning the layout and function of a transit system in a metropolitan area. One approach, the single-line approach, perceives the ideal transit system as a set of individual, unrelated routes covering an urban area with each route offering the user direct, no-transfer service between some point of origin to 1 or more on-line destinations, which, in most cases, involves the central business district (CBD). Although this approach can be applied to any mode, recently it has been widely featured as a central element in a commercial scheme using motor buses (metro mode).

The alternative to treating routes separately is to view each as part of an overall system with interaction between them taking place at numerous transfer points. In this network approach, 1 or more modes are knit together into a unified whole, which permits the user to travel to a wide variety of destinations throughout the urban area in exchange for the minimum (if the design is correct) inconvenience of a transfer.

This paper discusses these 2 approaches as applied to metropolitan transit, particularly light rail transit, and describes aspects of coordination that are either common to any coordinated system or are peculiar to light rail transit.

ROUTING AND SERVICE PHILOSOPHY

Single-Line Approach

Transferring has been identified in a number of consumer preference surveys as a factor that is strongly disliked by many users. Frequently mentioned complaints include long wait times between transit vehicles, unreliability of connections, and poor or nonexistent station facilities. These unsatisfactory experiences have led to this negative consumer attitude. The response of some transit systems has been to design services that do not require a physical transfer. In the minds of planners of these systems, and in the way the systems are operated, there is no interaction of transit lines. Each is a unique element; there are no feeder routes, no crosstown connecting routes, and there is no mode-to-mode transfer.

Although it is an advantage for the consumer to avoid the various discomforts of transferring and although a no-transfer system is easier to operate, the single-route, no-transfer approach has a serious drawback in that there are very few origin-destination pairs in metropolitan areas that warrant their own direct linkage. Typically, only those links between a residential area and the CBD can be justified. As a consequence, many important lines are not served by transit services, which leads to a high level of dissatisfaction on the part of those whose intended journey is to some place other than downtown. From the standpoint of transit system revenues, this approach typically leads to rather high peak-to-base ratios and low ridership outside the peak hour. Exceptions to the latter occur on routes that serve important corridors that have a variety of origins and destinations of all kinds along them. Many central city lines and development strips in the older streetcar suburbs are of this nature.

If the objective of the transit system is seen solely or primarily as carrying rush-hour commuters to downtown office buildings, this design concept can be appropriate. It is easy to implement and simple to run. Buses are routed through residential neighborhoods and then head for the nearest freeway, arterial street, or exclusive busway for a nonstop trip to the CBD. There are no connections to make, no short turns to make, no stations to build, no fare systems to coordinate, and no inspectors on the street to ensure reliability. In fact, there is no integration to worry about because the essence of this approach is the independence of each line. Numerous examples of this kind of route design can be found in U.S. cities and particularly in suburbs.

Less common, but equally workable where passenger volumes warrant the necessary capital expenditure, is the operation of light rail vehicles on local streets where routes converge and trunk into the downtown on a high-speed light rapid transit corridor. San Francisco provides the most commonly referred to case, but Boston, Philadelphia, and Pittsburgh also feature this design element. The reader should note that, for these light rail cases, some passengers transfer from nearby bus routes, which makes these examples somewhat less than pure. Indeed, the transfer and the wide range of travel possibilities that it offers are central to the network approach.

Network Approach

The alternative to thinking of transit services as individual lines is to think of them as a network. In the network a passenger can travel anywhere in the metropolitan area by means of transfers between lines. On a system designed this way, important origin-destination pairs will have high-quality service, but desired trips that are not possible with the single-line approach can be accommodated by piecing together sections of routes with a transfer. This systems approach means that the user is offered a wide variety of destinations. In gestalt fashion, it also means that the transit system receives a level of ridership on its route that is greater than if these same routes were operating independently (1).

As might be expected, there is a relationship between transit ridership and the degree to which the transit system adopts a network approach. As a public transport system develops, the orientation of its network passes through several stages (20). The simplest stage in this hierarchy of transit services offers a system that provides service only to the CBD, generally only during the rush hours. The second level includes systems that still basically display a radial, CBD-oriented pattern but offer frequent service at all hours of the day. The third, or highest level, exhibits a grid pattern, in which routes not only provide good access to downtown but also cut across radials to link one suburban area to another. Each of these 3 levels is shown in Figure 1. Generally speaking, 25 or fewer annual rides per person are associated with level 1; 50 or more annual rides per person are associated with level 3.

Grid Layout Approach

Instituting a route pattern that will allow for a high degree of mobility about an urban area is possible. If one organizes one's routes into a citywide grid with 0.5-mile (0.8-km) spacing, which means that no user has more than a 0.25-mile (0.4-km) walk to the nearest route, a person can travel from any place to any other place on no more than 1 transfer. If the frequency of the services operated on the grid is high, say, between 5 and 10 min, waiting time at the transfer point is minimal. To produce such a grid system for an entire metropolitan area (city and suburbs) would consume a considerable amount of resources. Financial losses would be particularly high in the suburban areas where the density of development, and consequently the trip generation, is rather low. As a result, grids are usually found within the central city. Nevertheless, in these situations, the level of transit ridership is high, and the transit operation functions as an integrated system, regardless of the particular mode used on an individual route.

The best example of an integrated grid in North America is that operated by the Toronto Transit System in Canada. There, both city and suburbs are covered by a grid in which even the outer reaches of the built-up area have 20-min headways. The routes in this grid include conventional rapid transit, light rail transit, trolleybus, and motor-bus lines (3). So carefully is the integration worked out that 96 out of 109 surface bus and light rail lines make 131 connections with the 2 grid lines operated by heavy rapid transit (4). Transfers from bus to bus, bus to light rail transit, bus to heavy rapid transit, and light rail transit to heavy rapid transit are expedited by careful station design that minimizes confusion and walking time and at the same time offers pleasant surroundings.

Grid route layouts are usually found only in central cities in North America. In a recent scheme for the well-developed suburb of Berkeley, California, a grid system of surface routes was proposed. Most of the system would be bus routes except for the heaviest route, which would be a new streetcar line (5).

Timed-Transfer, Focal-Point Approach

A grid system of transit routes will work well in the city, but only in exceptional cases (such as Toronto) can it function satisfactorily in low-density suburbs. Planners who have attempted to add simple crosstown routes to a radial system to provide a metropolitan-area-wide grid have had difficulty arranging connections between the low-frequency crosstown route and the many radial routes that it intercepts. As a consequence, waiting times are long and happy customers are few. The solution to this problem is to reduce the number of interception points so that connections become feasible. By establishing a limited number of nodes or focal points at which all routes serving that portion of the urban area can meet and by careful control of route length, one can arrange schedules so that all services arrive at 1 of these nodes or focal points at the same time (6).

This timed connection at a focal point on the network of transit routes enables a person to make a journey to any place in the urbanized area without long waits while transferring. The overall attractiveness of the service can be further enhanced if the focal points in the transit network coincide with the focal points of activity for the community in which it operates. In this way, transit routes that are put in place to provide regionwide mobility can also be used by local residents to make short trips to the closest supermarkets, department stores, or recreation centers. The resulting network of routes generally resembles that of a cobweb, as shown in level 3 of Figure 1.

Figure 1. Three-part transit network hierarchy (20).

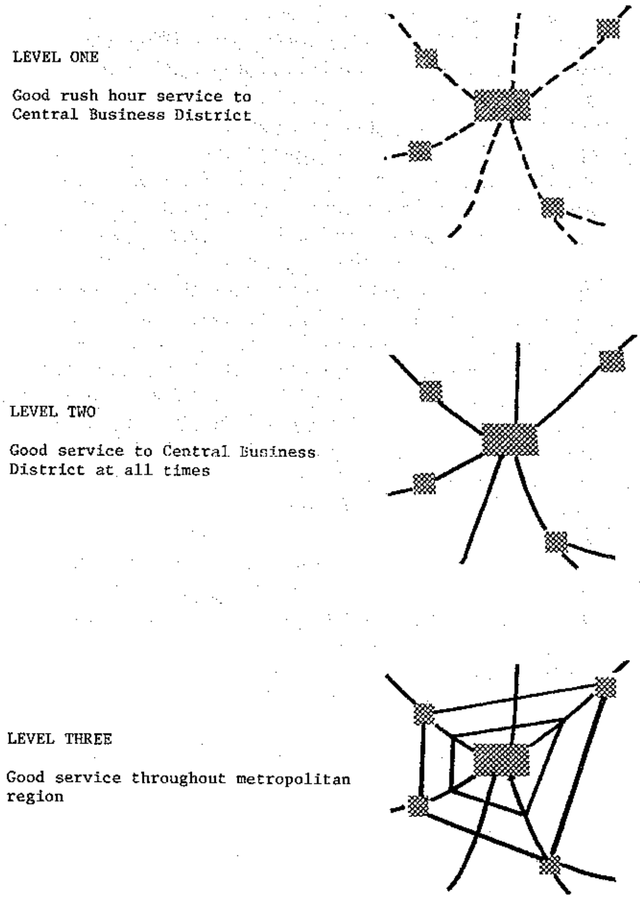

Table 1. Types of transfer point stations in use with metropolitan railways (12, p. 31).

Metropolitan Area	Total Stations	Stations Connecting With Surface Routes	Type A Points	Type B Points: Existing	Type B Points: Proposed	Type B Points: Avg Number of Surface Routes Serving Each Point	Type C Points: Existing	Type C Points: Proposed	Type C Points: Avg Number of Surface Routes Serving Each Point
Barcelona, Spain	46	—[a]	—[a]	—	—	—	—	—	—
West Berlin, FRG[b]	—[a]	—[a]	—[a]	—	—	—	8	1	—[a]
Badapest, Hungary	7	7	1	5	3	15	1	1	21
Glasgow, Scotland	11	11	—	11	—	—[a]	—	—	—
Hamburg, FRG[b]	75	46	34	4	—	3	8	—	7
Copenhagen, Denmark	24	21	5	15	3	3	1	—	3
Lisbon, Portugal	20	11	—	9[c]	—	—	2	—	2
London, England	276	268	126	130	—	—[a]	12	—	10
Milan, Italy	43	32	25	7	—	—[a]	—	2	—
New York (LIRR), N.Y., USA	—[a]	—[a]	—[a]	17	—	—[a]	2	—	9
Nuremberg, FRG[b]	—[a]	—[a]	—[a]	1	1	4	1	1	1
Paris, France	309	254	133	98	—	6	23	—	9
Philadelphia (PATCO), Pa., USA	—[a]	—[a]	—[a]	—	—	—	2	—	7
Rome, Italy	—[a]	—[a]	9	—	—	—	2	—	1
Rotterdam, Netherlands	8	—[a]	—[a]	1	—	—[a]	1	1	39
San Francisco, Calif., USA	34	34	11	23	4	8	—	—	—
Sydney, Australia	157	69	54	15	—	5	—	—	—
Stockholm, Sweden	76	76	—	74[c]	—	—[a]	2	—	6
Stuttgart, FRG[b]	—[a]	—[a]	—[a]	4	—	5	—	—	—
Vienna, Austria	27	21	18	1	—	4	2	—	6

[a]Not available. [b]Federal Republic of Germany (West Germany). [c]Figure includes type A points.

Edmonton was the first city in Canada to introduce the timed-transfer, focal-point concept (7, 8). Routes serving residential suburbs in this metropolitan area of 450,000 people focus on a local shopping center or other activity node. From there, radial routes proceed to the CBD, and cross-radial routes proceed to 17 other nodes. The heaviest trunk routes have frequent trolleybus and express bus service during local work hours. As passenger volumes build up on these corridors, the present service on the links will be replaced by light rail transit. This is now happening on the northeast corridor from downtown Edmonton, where a subway and surface light rail line is under construction and will be operational by 1977.

The results of this approach to transit service design have been most rewarding. At a time when many other transit systems were experiencing patronage decline, or, at best, were maintaining the status quo, the Edmonton Transit System was consistently posting a 5 or 6 percent annual growth rate to keep pace with and sometimes surpass the total population growth rate in the urbanized area. The 1962 patronage level of 26 million grew to 44 million in 1974. During the same time period, the Calgary Transit System, which uses a traditional routing structure (including nonstop express service to downtown), grew from 26 million to 28 million annual riders.

The timed-transfer, focal-point approach also has been used in British Columbia (9). This form of network design is being implemented in both the Greater Vancouver and Greater Victoria areas, and, as with Edmonton, higher quality forms of transit are to be substituted for buses on important links as patronage on these links grows. Thus a rapid transit ferry is being constructed between Vancouver and North Vancouver to replace an important express bus link; a suburban commuter rail service between Vancouver and the Coquitlam area is planned to provide rush-hour relief to the express bus service between eastern Burrard Peninsula points and Vancouver; and light rail routes are planned in both Vancouver and in Victoria for operation as soon as bus volumes become too high to be practical. The resulting system in Greater Vancouver will be an interconnected, interregional-level network. The links of the network will have a mix of rapid transit ferry, commuter rail, light rail, and express bus, all of which will be fed by local bus routes.

COORDINATION

The purpose of coordination of services is to enable the public, by means of connections, to travel between 2 points that lack sufficient interaction potential to justify their own no-change, direct link. Because transferring involves some inconvenience, the transit manager should try to make the journey as close as possible to a no-change trip.

Schedules

Frequent Service

The connection problem is simple when transfer movements involve only frequent lines. Buses, trains, and other modes arrive and leave at random, but, because the average wait time is short, timed (guaranteed) connections on the operating schedule of each vehicle are unnecessary.

Untimed connections with close headways are the most common form of schedule coordination with light rail in North America today and are widely found in Europe also. They are found with all physical modes. In North America, random connections from light rail to full rapid transit are found in San Francisco, Chicago, Philadelphia, Boston, Cleveland, Toronto, and Mexico City. Random connections from light rail to commuter rail (regional rail or S-bahn) links are found in Philadelphia, Boston, Newark, and Toronto. Random, frequent connections from light rail to trolleybus links are found in San Francisco, Toronto, and Mexico City. Random, frequent connections from light rail to motor bus are found everywhere.

Infrequent Service

Convenient connections between busy routes may be easy to accomplish, but convenient connections between infrequently serviced routes not only are difficult but also are rarely found in North America. Anyone who has traveled often on transit services has experienced the feeling of dismay and frustration that comes when a connecting service pulls away just as the vehicle he or she is on pulls up. To this annoyance, add the passenger environment that is all too typical of even good systems (no shelter, poor lighting, minimal security, no information about alternatives), and it is little wonder that the act of transferring is given a negative rating on consumer surveys.

The obvious answer to the problem is to schedule connections and to enforce adherence to them. What is not so obvious is the host of operating difficulties that this poses to the average North American transit company, which finds it enough of a challenge to merely get its vehicles out each morning. These difficulties include accurate timekeeping (which, in turn, demands good supervision), proper timetable building, and freedom from random delays en route caused by traffic (12). Timed connections also usually include a requirement for regular-interval scheduling (clock headways) at least where the services run more often than 3 or 4 times per day.

There are no examples of connections between long-headway light rail and other services except late at night, when normally frequent LRT lines are cut back. There are, however, numerous examples of an important variant—connections from infrequent to frequent lines.

Infrequent-to-Frequent Service

In those cases in which a frequent light rail line connects with an infrequent bus or other service, standard practice is to operate with random connections. Although this is easy on the carrier, it is hard on the user transferring from a frequent to an infrequent service. Fortunately, this difficulty is not experienced in the opposite situation because average waiting times are minimal. Because of longer waiting times in the frequent-to-infrequent direction, it is not too difficult for the transit company to select a connection and to guarantee it.

Passenger Facilities

Proper attention to passenger facilities is essential to the successful operation of an integrated system.

Types of Stations and Functional Considerations

A striking difference between the public transport systems in western Europe and those in North America is the attention paid by the former to facilities for passengers. In the United States and Canada, the patron usually finds either no facility or one that is old and has minimal facilities and maintenance. Passengers transferring between routes or modes in established downtown areas often find that the terminal point for suburban bus routes is not at the same point as the terminal point or major transfer point for urban routes and that neither of these bears any relationship to numerous rail and intercity-rural bus stations. In newer suburbs, the lucky passenger may find a simple glass or wood shelter; the not-so-lucky passenger has nothing more than a street corner and a sign. There are, however, exceptions to this rule. New rapid transit lines and a certain number of bus services have attractive station facilities. Light rail lines in Philadelphia, Boston, and San Francisco are renovating their old stations. And, in a number of cities in the United States and Canada, intercity railway passenger stations are being redeveloped as joint urban transit-intercity railway stations (10, 11).

Passenger facilities can be anything from a shelter or island platform in the street to a major rapid transit or intercity terminal. Some experimentation has been done with the development of passenger facilities that are a compromise between a simple shelter and a full station. These ministations can be found on Ontario's GO Transit commuter bus lines and at the terminus of the San Francisco Hyde Street cable-car line. With a ministation, a transit system may use an off-street platform area for buses and pedestrians, or it may use the street and sidewalk.

Cirenei (12) has identified 3 types of transfer stations in his analysis of integration of metropolitan railway services with other services.

1. Type A has interchange points with no special facilities.
2. Type B has interchange points with shelters or other simple structures to facilitate passenger waiting.
3. Type C has interchange points with integrated infrastructures designed to facilitate transfer between metropolitan railway lines and other modes of transport.

Data on twenty such systems are given in Table 1. As can be seen, nearly half the transfer points, even with full rapid transit, have minimal facilities. Note too that most places that have type B stations also have some of the more advanced type C facilities. Cirenei (12) points out:

> When surface transport is restructured and the different modes of transport allotted specialised functions, so that large numbers of passengers change at particular transfer points, it becomes necessary to equip these points with a minimum of protection (type B points) and at the same time to provide more complex facilities (type C points) where the volume of transferring passenger movements is greatest.

Careful attention to both vehicle flows and pedestrian flows is essential if a station is to work safely and smoothly. Although this does not necessarily mean that pedestrian flows and vehicle flows must be grade separated, it does mean that the pedestrian environment must be considered carefully and that long devious walks, a feature of even some of the newer stations, are avoided. One common failing of North American design that is evident in stations built by 1 carrier for the use of many carriers is that pedestrian flow between the various modes and the various carriers is not well worked out. Put differently, the station designers were thinking of their own management needs and generally have executed these properly but were not motivated to give the same level of consideration to users of other carriers at the same station. This kind of problem is less likely to occur where an independent agency or terminal authority is responsible for a station design (13, 14).

Because light rail transit is essentially a child of heavy rapid transit and the streetcar (much as the trolleybus is related to the streetcar and the motor bus), designers of stations have considerable flexibility in how they handle light rail transit. (For example, light rail cars can operate into the same stations, often by using the same tracks as commuter trains or heavy rapid transit.) An example of the former is contained in the Toronto Technical Transportation Plan Review proposals for an urban light rail system to share tracks with GO Transit commuter trains. An example of the latter can be found in Chicago where the North Shore Interurban (and its successor, the Skokie Swift) shares facilities with Chicago Transit Authority Rapid Transit. In Cleveland, the Shaker Heights Rapid Transit shares facilities and track with commuter rail and the heavy rail of the Cleveland Transit System.

The street running capabilities of LRT also enable it to be treated in the same fashion as buses at an interchange station. The simplest example of this is the familiar loop and shelter at which streetcars and buses exchange passengers. Other examples exist that are somewhat more sophisticated; at many of the exchange points for light rail and bus to heavy rapid transit in Toronto, bus and streetcars share common facilities or are treated similarly; at the Sixty-ninth Street station in Philadelphia, the Media and Sharon Hill light rail lines operate into and out of a facility also used by buses. In the latter case, a high-speed light rail line also terminates at the same place but receives a treatment more like that of a heavy rapid transit service (15, 16).

Site and Setting Considerations

The preferred location for a transit station, whether it is a full-fledged facility or a ministation, depends on the nature of the service offered. Park-and-ride stations, for example, are best located away from built-up urban areas where land is cheaper and where the flow of automobiles does not congest developed areas. On the other hand, stations at which access is to be made by local transit routes should be located at activity centers or planned activity centers in the communities they serve. This arrangement has 3 benefits: (a) many passengers on the trunk service will find that their destination is within walking distance of the transit line; (b) passengers wishing to make a journey from a local residential area near the community activity center can do so by using a local bus; and (c) the tremendous impact that a transit station can have on development can be channeled by land use planners to serve the community's best overall interest.

Giving the Transfer a Purpose

Imagine an automobile commuter wishing to pick up some groceries or other convenience goods on the way home from work. He or she must get into the car, drive to the desired store, leave the car, make the purchase, return to the car, and then drive to a final destination. He or she has broken a journey to accomplish some task in addition to simply getting home. If the transit authority encourages the development of small shopping centers at major stations or locates stations at shopping areas, then the passenger who has to transfer from one mode to another or from one service to another can buy groceries or other convenience goods while in the act of transferring. Thus the transfer has been given some additional purpose, other than being part of the journey home.

This kind of treatment has reached its zenith in Toronto, where a number of stations, such as Islington and Warden, contain a small shopping mall as an integral part of the station facility. Customers of the mall are in a fare-paid area and, as a result, shopkeepers receive 100 percent of their custom from transit users. The physical possibility already exists at or near some stations for passengers to disembark, shop, and board the next transit vehicle, but the fare system may prevent them from doing so. A relaxation of transfer conditions, such as those found with stop-and-shop provisions, is necessary to allow this to take place.

Information

Visitors to Switzerland can purchase a pocket book that lists schedules and other details for every public transport service (except frequent central city lines) operating in that country. This enables them to plan and make a trip and use any number of modes and carriers. A visitor to Hamburg, Munich, or Frankfurt can obtain a large timetable book showing all services within the region served by the transit community. This book, which is about the size of a small telephone directory, is kept in the home and is used like a telephone book. When someone wants to make an other than usual journey, he or she merely looks up the information in the transit book. What a different situation in North America! In some cities, one can obtain a map showing services of 1 carrier. In Boston and San Francisco, one can obtain a map showing the lines of all carriers serving the area. Only in very small cities where there are only a handful of routes is an all-service timetable generally made available.

If an integrated system is to function properly, it is necessary for the user to have quick and easy access to the information necessary to complete the journey. This kind of information can be conveyed in the form of timetables, maps, or telephone information services. With the renewed interest in public transport, some very encouraging experiments are being tried with information conveyance. But, again, it is necessary for the people designing these information aids to be responsive to the needs of patrons wishing to make multiroute or multicarrier journeys.

Simplicity

Children are taught in school how to use traffic lights and public libraries. In some high schools, they are taught how to drive. Rare, however, is the school that teaches its students how to use a timetable. The transit manager of today is confronted with a consuming public to whom even the easiest of timetables or other information can be a mystery. With this unfortunate state of affairs, a key element in information dissemination is simplicity, and one of the most basic aids to simplicity is a simple system design. A simple, logical route layout permits easy comprehension and may generate more patronage than might a complicated one that has better performance on another service variable. This rule is particularly important for managers and planners of integrated systems to follow because connections in and of themselves are complicated.

Fares

Price

Integrated service implies an integrated pricing system. Whether a zone fare or a flat fare is adopted, the passenger on a journey involving a transfer between routes or between carriers should not be penalized financially. Most systems offer free transfers between routes of the same carrier. A few, such as the Greater Vancouver Transit System, make them available between carriers.

Fare Collection System

The standard method of fare collection and fare checking in North America is a 1-person-operated collection in which a driver collects the revenue and, if necessary, issues and checks zone coupons. In rapid transit systems, fares are almost uniformly collected at turnstiles. (Cleveland, in the off-peak period, offers an interesting example of 1-person-operated, pay-as-you-enter fare collection on a rapid transit line.)

Special care must be taken with fare-collection procedures at transfer stations to avoid delaying transferring patrons. The Toronto Transit Commission uses the technique of the fare-paid platform. With this technique, passengers transferring from one vehicle to another need not use a piece of paper to indicate that they have paid their fare. Because access to the platform is limited to those who have already paid (fare collection for passengers entering the system at this point takes place through a turnstile at the station entrance), people can board and alight through any of the doors on any of the buses or streetcars.

Toronto's fare-paid platform system works well where volumes of passengers justify a major station facility; fare collection is by turnstile for new passengers. Unfortunately, many of the situations where people must transfer from bus to bus or bus to light rail transit do not warrant such extensive treatment. In these cases and with the present fare scheme used in North America, all boarding passengers must file past the driver for transfer inspection. A number of European systems, including Frankfurt, Munich, Hamburg, Amsterdam, and Vienna, use a self-service fare system that overcomes this problem. With self-service fare collection, the passenger does not have to pass by the driver to have the fare collected or the transfer verified. The passenger may board or alight at any door and, if he or she does not possess a monthly pass or a valid transfer, he or she purchases it from a ticket machine that is mounted either at curbside or on the transit vehicle itself. Passengers on board transit vehicles are inspected at random by ticket inspectors who levy a tariff surcharge (usually amounting to several times the fare) to those passengers who are traveling without valid tickets. These self-service fares are time based or a combination of time and distance based. The time-based fare is, in effect, a 1-h transit pass similar to the monthly pass used by some North American systems.

The ability to board and alight through any door offered by self-service fare means not only that interchange between various routes and modes can be made easily but also that boarding on the street can take place rapidly and shorten present times by one-half or two-thirds. Because transit vehicles in downtown areas spend about half their time stopped and about half that is taken up with boarding and alighting, some significant economies in the overall transit system are possible with the self-service fare.

How to Achieve Service Integration

In a large metropolitan area, usually more than 1 carrier is involved in providing public transport service. How can one achieve service integration in circumstances such as this? How does one encourage a bus carrier to route buses into the appropriate rapid transit, light rail transit, or commuter train station when the carrier might prefer to run these buses directly into the CBD? These problems are real. They are sometimes handled by a cooperative effort among carriers. But, in recent years, a new organizational form has emerged to promote this type of integration. This organizational form, referred to as a transport community or a public marketing agency, first appeared in its full modern version in Hamburg in 1966 (17, 18). An agency was set up as a creature of both government and the carriers; it has the responsibility for planning and marketing all transit services. Thus the integration of transit services and collecting and redistributing revenues are ensured. This organizational format has been formed in a number of other European cities, and variants of it can be found in Toronto (GO Transit), Vancouver (Greater Vancouver Transit System), and San Francisco (the emerging Metropolitan Transportation Commission). These public marketing agencies can be carrier associations, creatures of senior government, or a combination of agencies (19). Whatever they are and however they are structured, they offer a means of ensuring the integration of public transport services in what can otherwise be very trying circumstances.

SUMMARY

As with any other form of public transit, light rail services can be arranged to operate as single entities, or they can be organized into an interacting system. The latter approach results in a system more useful to the community and in more riders and revenue for the transit company. It does require greater management effort if the necessary service integration is to take place. With time and effort, the integration elements described in this paper will be available and will offer North Americans a truly attractive alternative to the automobile for a substantial portion of urban travel.

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LIGHT RAIL AND RAPID TRANSIT

Friedrich Lehner, Hannover, Federal Republic of Germany

Light rail transit can be considered as an advanced form of the conventional streetcar. Its tracks lie primarily on separated rights-of-way. In areas where there is heavy congestion, they are often in tunnels. Like rapid transit, which is independent from surface traffic on its entire length, light rail transit with modern vehicles can undertake the role of the primary transit carrier in medium and large urban areas, supplemented by and coordinated with a secondary feeder system. The most common application of light rail is in medium-sized cities. Rapid transit serves large cities. With respect to its service quality, capacity, productivity, and efficiency, rapid transit is superior to light rail transit in various degrees. However, a particularly important advantage of light rail transit is that its network can be constructed with lower investment costs and in a shorter period of time than can a rapid transit network. Moreover, individual sections can be used immediately after completion. When light rail transit has underground sections in central urban areas, it can be a transitional system to later rapid transit as long as adequate alignment standards are applied in construction. The requirement for an integration of transportation and urban design is particularly important for light rail and rapid transit. Their radial lines from the central cities should form the axes of residential corridors. Thus they perform 2 roles: To the corridor residents and commuters from the region, through park-and-ride, they represent an attractive alternative to the private automobile; at the same time, they reduce traffic loads on urban arterials and streets.

This paper starts with some basic remarks about public transportation in Germany because the paper, which is a comparison of light rail and rapid transit, will include mostly experiences and knowledge obtained in that country.

The understanding of the importance of public transportation in urban development was reached in Germany more than 10 years ago. The change was brought about by the report of the Committee of Experts that was published in 1964. Based on a legislative requirement, this report studied measures for improving transportation in urban areas. The impetus for the study was the continuously worsening traffic conditions in cities caused by increasing automobile ownership. In addition, experiences from the United States showed that transportation problems in a city cannot be solved by simply adding more and wider highways, multilevel interchanges, and parking structures and continuously increasing financial outlays. Results of the policies that were doing everything for the automobile while neglecting high-capacity transit were too alarming. Urban environments were being created with their transportation-related facilities that hardly allowed areas one would consider acceptable for human living; this is in addition to the loss of the functional value of urban areas, which in many cities became quite obvious.

The Committee of Experts reached the conclusion that uncontrolled development of transportation should no longer be allowed; it was necessary to establish powers to evaluate alternatives and set preferences. Only in that way can we preserve the numerous features that distinguish the character of our cities; preserve their historic values, the urbanity of their inner areas, the diversity of their functions and cultures;

and protect them from destruction.

The results of the committee's study, which took several years, were summarized in 4 statements.

1. Travel to work, which is vital for the functioning of metropolitan areas, must be shifted predominantly to high-capacity public transportation.
2. To offer an acceptable alternative to the automobile driver, the improvement of transit operation to increase service quality must be an integral part of every policy for the solution of transportation problems in urban areas.
3. In building transportation systems, priority should be given to public transportation.
4. Larger cities and metropolitan areas cannot solve their problems without rail transit.

Under the influence of the report of the Committee of Experts, the federal government and the states accepted their shares of responsibility in solving the transportation problems of urban areas and introduced in 1967 federal and state financial aid. In 1974, the federal government gave more than 1 billion deutsche marks (DM) (400 million dollars) for construction of public transportation facilities; the states contributed an additional 30 to 35 percent of this amount. Local governments also have continually increased financial contributions toward transit. There are cities that already give more for public transportation than for highways.

Facilities eligible for federal and state assistance are rights-of-way and stations for rapid transit and light rail transit, including track, signal and power supply systems, depots, and maintenance shops.

This government assistance made it possible for West Berlin and Hamburg to expand their rapid transit networks, for Munich and Nuremberg to open new rapid transit systems, and for 12 other cities to construct grade-separated facilities for light rail transit mostly in central urban areas.

CHARACTERISTIC FEATURES OF LIGHT RAIL AND RAPID TRANSIT

Light rail transit can be considered as an advanced development of the conventional streetcar. In Germany, we usually call this mode Stadtbahn. With modern, high-capacity vehicles, which operate mostly on exclusive rights-of-way, it represents a mode of transportation between bus and streetcar and rapid transit.

Common Features of Light Rail and Rapid Transit

Light rail and rapid transit have a number of common features. Each one can represent the backbone of transit in larger cities. Both modes usually require a secondary mode for collection and distribution service. Both lend themselves to grade separation, which allows fitting them to traffic, urban design, and topography conditions. Both are capable of operating in connected networks. With respect to passengers, rail vehicles are highly space efficient and have a high degree of technical reliability. Moreover, with respect to the current energy crisis and the attempts to improve the environment, it is particularly important that both have very low energy consumption per seat kilometer and produce no pollution in cities. Inherent in the modes are, however, several differences of various degrees.

Differences in Service Quality

Safety and Operation Reliability

Rapid transit, as a mode that must be fully independent of surface traffic, has a grade-separated right-of-way over its entire length. The right-of-way can be in tunnels, in open cut, elevated, or at grade. Control of the operation is achieved through train safety and track control devices. Thus rapid transit has a high degree of safety, reliability, and punctuality.

With LRT, an attempt is made to achieve extensive independence from surface traffic. Its tracks lie (although not entirely) on exclusive rights-of-way that may be placed in the middle or on the side of the street, elevated, in open cut, or at grade. Grade crossings of sections with cross streets and pedestrian crossings do not have to be eliminated. In congested areas, which is typical of city centers, tracks can be placed in tunnels. Driving on sight without signals is possible, but the system also can be controlled through electric signal-control systems. Safety, regularity, and punctuality are not at the same high level as with rapid transit, but they are considerably higher than they are for conventional streetcars.

Operating Speed

Generally the operating speed of LRT is lower than it is for rapid transit. Among the reasons for this can be shorter station spacings for LRT; lower maximum speed; lower track alignment standards, such as shorter radii; and the remaining disturbances from surface traffic.

Several examples of travel speeds for different systems in various cities are given in Table 1. Average operating speeds are approximately in the following ranges (in some cases they may be higher):

System	Speed (km/h)
Light rail transit	20 to 25
Rapid transit	25 to 45
Regional rail transit	40 to 70

On older rapid transit systems, travel speed is often not higher than that on modern light rail systems. Thus, for example, travel speed of the Paris Metro, which has an average station spacing of only 521 m, lies between 21.1 and 25.8 km/h, and the old small-profile lines in Berlin operate at only 27.1 km/h.

Riding Comfort

With respect to dynamic and ride characteristics, modern light rail vehicles lag only slightly behind rapid transit. Good suspension of car bodies, low noise level, smooth acceleration and braking, stable ride on straight sections, and quiet negotiation of curves are already attributes of both systems. Automatic acceleration and braking connected with antiskid and spin-prevention devices, common for rapid transit vehicles, also have been applied to some light rail systems, such as those in Hannover, Frankfurt, Cologne, and Düsseldorf.

The excellent riding characteristics of modern light rail vehicles, however, can be found only on well-aligned and well-constructed tracks. Technology of tracks and related equipment therefore is given particular attention. Efforts have been made to improve the maintenance of track, to reduce shocks, body vibration, and noise production

Table 1. Travel speeds for different systems.

System	City	Speed (km/h)
Light rail transit	Bremen	26
	Frankfurt	26, 32, 35
	The Hague	25
	Hannover	22.3
	Cologne	25,31, 35
	Mannheim	30
	Stuttgart	25.8
	Brussels (Pre-Metro)	20
Rapid transit	Berlin (new lines)	34 to 35.6
	Hamburg	31.5
	Munich	35
	London (Victoria Line)	40.3
	London (old lines)	32.3
	Oslo	31.2
	Stockholm	31, 35, 39
	Rotterdam	43
Regional rail transit	Paris (R.E.R.)	More than 50
	Hamburg (S-Bahn)[a]	40.4
	Munich (urban areas)	30
	Munich (outlying areas)	60

[a]S-Bahn are regional rail systems that are operated by German Federal Railways and carry a substantial portion of intraurban passenger traffic in both Hamburg and Munich.

through the use of welded rails, movable frogs, and elastic rail supports. Track without ballast, including application of composition ties in Vienna, also is being tested (to ensure good current pickup, constant tension overhead wires are used).

Differences between rapid transit and LRT with respect to lighting, heating, and ventilation of vehicles are also minor. Greater differences exist in sitting comfort. Because of the greater body width of rapid transit vehicles (73 percent of rapid transit vehicles in the world are between 2.80 and 3.30 m wide; light rail vehicles range from 2.30 to 2.65 m wide), more space per seat with greater knee space and adequate aisle width are possible. Seats generally are more comfortable on rapid transit than on light rail because the seats are upholstered. The S-Bahn in Hamburg offers first-class cars with even greater comfort.

There is a general trend to increase the seat-to-capacity ratio as well as comfort for standing passengers. In Germany, scheduled capacities are therefore computed now only on the basis of 4 standees/m^2. An overloading of vehicles by 30 to 60 percent is physically possible under such conditions. Rapid transit in Berlin, Hamburg, Munich, and Vienna has a seat-to-capacity ratio of 35 percent; Victoria Line in London has 27 percent; in Barcelona, it is 10 to 15 percent. On German light rail systems, this ratio is between 35 and 40 percent.

Whether it is possible to completely eliminate standing is a question of capacity and economics. This possibility comes under consideration only on systems with long trip lengths (Bay Area Rapid Transit in San Francisco). Experience also has taught us that standing spaces are required for short trips.

For protection of standing passengers, the acceleration rate of both modes in the speed range from 0 to 40 or 50 km/h is limited to 1.0 to 1.2 m/s^2, deceleration in braking to 1.2 to 1.6 m/s^2.

To ensure fast passenger boarding and alighting at stations and thus contribute to increased travel speed, the vehicles of rapid transit as well as those of modern light rail have several (5 to 10 on each side) wide doors. Rapid transit, with its high-level platform, allows fast and comfortable boarding. Light rail transit must use steps at stations with platforms, such as where street medians are used for rights-of-way.

In summary, it can be said that LRT provides high riding comfort although it does not quite match rapid transit.

Advantages of Rapid Transit

Capacity

Capacity is the maximum number of spaces that can be offered per hour and direction. Capacity depends on vehicle capacity and the number of trains that can pass a point per hour.

Light rail transit consists of one to three 4-axle, 6-axle, or 8-axle articulated cars. The capacity of 1 car is between 80 and 270 spaces. Car length ranges between 16 and 29 m.

Rapid transit uses 4-axle cars of varying lengths (14 to 23 m) that are usually semi-permanently coupled into 2- or 3-car units. The capacity of a single car lies between 100 and 250 spaces. A train can consist of up to 10 cars.

The maximum throughput of a line depends, among other factors, on the signal-control system, length of trains, station spacing, speed, dwell times at stations, and block lengths, and it can amount to between 28 and 40 trains/h and direction. For small train units of LRT this number can be somewhat higher. Experience has shown, however, that headways under 2 min result in a decrease of speed and regularity of service. With visual control in surface running it is possible to operate 60 to 70 trains/h and direction, although this will cost some loss of speed and regularity.

On the basis of these facts the capacities of the 2 modes are as follows:

System	Range (persons/h)
LRT	5,000 to 20,000
Rapid transit	10,000 to 40,000

With respect to capacity, rapid transit is clearly superior to LRT. Regional rail system capacity may be even higher.

In practice, except for some special cases, maximum capacity is usually only partly used. Table 2 gives peak-hour capacities for different systems.

Vehicle Productivity

Expressed in space kilometers/h and direction, vehicle productivity is computed as the product of car capacity and operating speed. Because maximum capacity of light rail and rapid transit averages approximately 1:2, their vehicle productivity has a ratio of 1:2.5 to 1:3.

Table 2. Peak-hour capacities for different systems.

System	City	Capacity
Light rail transit	Cologne	9,000
	Stuttgart	8,600
	Brussels (Pre-Metro)	6,300
Rapid transit	Hamburg	14,000
	Munich[a]	17,200
	London (Victoria Line)	33,000
	Barcelona	18,000 to 24,000
	Oslo	13,000
	Rotterdam	10,000
	Stockholm	27,000
Regional rail transit	Paris	24,000

[a]In transporting stadium visitors during the 1972 Olympics, rapid transit in Munich carried a maximum of 30,500 in 1 h.

Because vehicle productivity incorporates operating speed, which is an important element of service quality, this ratio indicates the superiority of rapid transit even more clearly than does the capacity ratio of the 2 modes.

Labor Efficiency

Efficiency of labor is the annual unit product (space kilometer produced per 1 operating employee). Labor efficiency depends on the number of operating persons per train, spaces per train, commercial speed, and labor contract agreements.

In Germany, trains of streetcars, light rail, and rapid transit are now operated by the driver alone. To make this possible, there must be a central operating control and radio communication with trains. Because of the greater capacity of a rapid transit train and its higher commercial speed, its labor efficiency is considerably higher than that of light rail. The labor efficiencies of the 2 modes are in a similar relation to those of their vehicle productivities. In 1972, the labor efficiency of rapid transit in Hamburg was 24.4 million space km/operating employee; in Munich, it was 20.5 million space km/operating employee. In the same year, the labor efficiency of LRT in Hannover was 8.5 million space km/operating employee; the labor efficiency of streetcars was 3.5 to 5 million space km/operating employee; the labor efficiency of buses (on urban lines) was 1.7 to 2 million space km/operating employee. However, if light rail trains are operated by 1 employee and rapid transit trains are operated by 2 or more employees, the labor efficiency of LRT may become higher than that of rapid transit.

With rapid transit it is possible to optimize the punctuality and reliability of operation, increase labor efficiency, and minimize energy consumption through full automation of driving. Equipment of this kind already is in operation or is being tested. Full automation makes possible transition to operation without train crews. However, it is questionable whether trains with 100 or more passengers can be allowed to run without a single attendant. This function could be given to the driver. He could intervene in case of disturbance or accident, and, as in the Munich rapid transit, he could be in charge of train departure control when stations that are supervised by closed-circuit television have no personnel.

Advantages of Light Rail Transit

Although it can be stated that rapid transit, with respect to its service quality, capacity, vehicle productivity, and labor efficiency, is superior to light rail, light rail transit has a series of advantages.

Investment Costs

An important advantage of LRT is its lower investment cost, an advantage that, with the present scarcity of investment funds, is considerably significant.

Let us consider right-of-way costs classified by construction methods. These are average values that should indicate only the order of magnitude. With construction of tunnels these numbers may vary greatly depending on construction methods, depth of tunnels, underground water level, alignment, station spacings, relocation of utilities, and required traffic detours. Table 3 gives the total cost of construction of right-of-way, track, and electrification for 1 km of double-track line.

Construction costs for LRT stops in street medians are very low. The proportion of different types of construction along a line may cause a great variation in average costs per kilometer. In this respect, the investment cost of LRT, excluding, of course, exceptional cases, is substantially under that of rapid transit. This is also the case when LRT must be placed in tunnels in downtown areas. If we assume that 30 percent of a light rail network is in tunnels, then the average construction cost per kilometer of such a network would amount to only 20 to 40 percent of a rapid transit network,

Table 3. Construction costs.

Facility	Cost: Deutsche Marks (millions)	Cost: Dollars (millions)
Tunnel and 1 station with partial mezzanine[a]	25 to 40	10 to 17
Tunnel[b]		
Without station	50 to 60	21 to 25
With station	50 to 75	21 to 31
Station for crossing lines with several levels	70 to 80	29 to 33
Elevated structure with 1 station	15 to 20	6.3 to 8.3
Embankment alignment with 1 station	10 to 15	4.2 to 6.3
Open-cut line with 1 station	8 to 10	3.3 to 4.2
At-grade line with 1 station	8 to 10	2.9 to 4.2
Reserved right-of-way in street median	1.3 to 1.5	0.5 to 0.6

[a]Cut-and-cover method. [b]Boring method.

which is constructed entirely in tunnels. For example, the cost per kilometer of the Munich U-Bahn, 68 percent of which is tunnel, has cost 46 million DM (19 million dollars); 1 km of LRT in Cologne, 54 percent of which is tunnel, cost an average of only 26 million DM (11 million dollars).

The purchase prices of modern light rail and rapid transit vehicles do not differ very much today because LRT vehicles are equipped with many technical innovations. In both cases, vehicles are large, of lightweight construction, and have a long life. The married pair of the Munich U-Bahn, which is 37 m long, cost 1.6 million DM (670 thousand dollars); the Berlin large profile, a 32-m-long pair, cost 1.3 million DM (540 thousand dollars); the 3-axle articulated light rail car for Hannover, which is 27 m long and is equipped with thyristor chopper control and energy regeneration, cost 1.3 million DM (540 thousand dollars).

As a consequence of the considerably lower investment cost of light rail, a larger, denser network with more branches can be built for light rail than for rapid transit at a given investment level. This leads to 4 important advantages.

1. Central urban areas can be served better. Experience in Germany has shown that the core of the city should have 3 to 4 km of line/km^2.
2. Feeder lines can be less extensive.
3. Because of the larger area coverage and somewhat shorter station spacing, more people are directly served by the network.
4. The percentage of passengers who must transfer is lower because interconnection of routes is greater. The disadvantage of lower operating speed for LRT thus is partially compensated. Experience shows that passengers prefer, for example, 5 min longer travel time over a transfer between vehicles.

The more extensive network of light rail is an important component of service quality.

Time of Construction

A further advantage of LRT is that it can be constructed in a considerably shorter time than a rapid transit system can, particularly if the latter requires extensive tunneling. Duration of tunnel construction depends considerably on previously mentioned factors. It also is influenced strongly by the availability of funds. In Germany, construction speed in central urban areas is less than 1 km/year. In Cologne, Hannover, and Dortmund, for example, it is 0.7 km/year. Outside the central business district one can count on 2 to 2.5 km/year. With all other types of rights-of-way, speed of construction is greater. By simultaneously building a line at 2 locations, one can proceed at 7 to 8 km/year.

TYPES OF APPLICATION

Because of its higher capacity, productivity, efficiency, and higher operating speed, rapid transit is undoubtedly the most appropriate basic mode of transit for large cities. Light rail transit can have the same function in medium-sized cities where its lower capacity is fully adequate, particularly when constructing a reasonably extensive network is possible. An exact delineation between the 2 modes is not possible because not only the population of the cities but also density, urban form, topographic conditions, and characteristics of outlying areas exert an influence. Generally, cities with populations of more than 1 million need rapid transit; cities with populations from 300,000 to 800,000 are served adequately by LRT. In the larger cities of this group, this is particularly true when light rail is placed in tunnels in central city areas. For cities with populations of 800,000 to 1.2 million, applications of the 2 modes overlap.

Rapid Transit

Rapid transit networks remain limited to the corridors with large spatial and temporal concentrations of traffic. The routes predominantly are laid out radially and they can have branches. With some exceptions, such as those in Oslo, London, and San Francisco, where several routes converge to the central section, rapid transit generally is operated with independent routes because of the operational and capacity problems where routes are interconnected. City centers often are served inadequately. Yet, in Europe, rapid transit systems exist that offer both good area coverage of a large central area and good service for short- and medium-length trips.

Station spacings in central cities are between 350 and 800 m; on outlying sections they increase to between 800 and 3,000 m. Table 4 gives some examples of average station spacing in various European cities.

Factors for planning stations include not only area coverage and achievement of high operating speed but also the large investment cost of stations and costs related to their construction and maintenance (lighting, escalators, and the like) which, depending on station size, amount to 100,000 to 200,000 DM (40,000 to 80,000 dollars)/year.

The maximum technical speed for which vehicles and lines are designed lies between 80 and 130 km/h. Table 5 gives some examples of maximum speed for systems in various European cities. Higher speeds than those given have importance only for longer station spacings. On the S-Bahn in Munich, which has a maximum speed of

Table 4. Average rapid transit station spacings.

City	Spacing (m)
Berlin	776
Hamburg	1065
Munich	830
London (Victoria Line)	1400
Barcelona	500 to 720
Oslo	765
Rotterdam	1400
Stockholm	1000

Table 5. Maximum speeds for rapid transit systems in various cities.

City	Speed (km/h)
Hamburg	80
Munich	80
Nuremberg	80
Vienna	80
Stockholm	80 and 90
Rotterdam	80 and 90
London (Victoria Line)	88
Oslo	70
Berlin[a]	50, 60, and 70

[a]Oldest German U-Bahn.

120 km/h, the average station spacing on outlying sections is 3.5 km. Today, more than ever, it is necessary to select the maximum speed not only for operation but also for energy consumption.

Light Rail Networks

Light rail networks are not limited to the directions of high volumes of passenger travel; they can have higher density and more interconnections. Light rail transit also generally proceeds in radial directions with branches toward outlying areas, but LRT also can follow heavier flows in a cirumferential direction. Interconnections and convergence of routes are possible within capacity limits. The central area generally is served better by light rail than by rapid transit. Station spacings in city centers lie between 300 and 600 m; in outlying sections they are between 600 and 1500 m. The following table gives some examples of average station spacing in various European cities:

City	Spacing (m)
Cologne, city center	660
Cologne, outlying area	1040
Frankfurt, city center	600
Hannover, city center	580
Bremen, outlying area	870
Brussels, city center	700

The maximum speed of most German systems lies between 50 and 80 km/h. The following table gives some examples of maximum speed for systems in various European cities:

City	Speed (km/h)
Stuttgart	50
Cologne, city center	50
Cologne, outlying area	80
Hannover	70
Bremen	70
Düsseldorf	70
Frankfurt	80

It should be mentioned here that when maximum speeds higher than 80 km/h are used German law requires vehicle speed control and signal-control barriers at grade crossings.

An effort is always made to separate light rail from surface traffic as much as possible. For this purpose, all forms of separate rights-of-way are applied, although embankments are seldom used because of aesthetic reasons. German cities have benefited from the fact that, for many years, special efforts have been made to provide separate rights-of-way for light rail transit. There are cities in which such sections amount to 70 percent of the network length. In upgrading rights-of-way for light rail systems, modifications are needed for higher speeds and usually for wider vehicles. When the tracks are in street medians, the number of crossings by automobile traffic should be substantially reduced, and at the remaining crossings, the light rail system should be given priority through special signals. Intersections with heavy cross-street traffic and major squares that cause long delays and disturbances should be modified by grade separation of light rail.

It should be pointed out here that reserved rights-of-way in street medians represent a useful element that also increases safety and smooth flow of automobile traffic.

In central areas, particularly those in older cities, where traffic impedances most frequently occur that reduce regularity and punctuality of operation on the whole network and often reduce operating speeds to walking speeds, the light rail system is placed in tunnels because insufficient street widths exclude the possibility of placing a right-of-way on or above the surface.

An example that show the great significance of this vertical separation of modes in the areas of the greatest disturbances is the Pre-Metro in Brussels, which can be considered as a light rail system in its present stage of development. In its first year (1969), the 3.6-km-long tunnel section between Parc du Cinquantenaire and Place Sainte Catherine on which 4 streetcar lines converge had a total passenger increase of 40 percent; in the period between noon and 2 p.m. it was even 85 percent. The operating speed, which had been between 10 and 11 km/h on the surface in normal periods and 4 to 5 km/h during the peaks, increased to 24.2 km/h for the entire day. In 1972, the 6-km-long Pre-Metro tunnel representing less than 2 percent of the total network length served 17 percent of all trips. Grade separation of modes thus leads to a substantial increase in both speed and regularity of service on the lines crossing the center, and, because of that, to savings on vehicles and personnel particularly during the peaks. Separation is an excellent method of increasing the attractiveness of service. Undoubtedly, the increase of ridership can be traced to the automobile drivers who have switched to faster transit.

If the light rail network is developed from a streetcar network, as it was in Germany, construction can be undertaken step by step. Because the continuity of the network is not disturbed, the constructed sections can be placed into operation immediately after completion and be served by streetcar or light rail vehicles. This is a major advantage. The gradual construction allows not only better fitting to available finances, but also allows sections that had to be renovated in any case to be upgraded ahead of schedule. Extensions in new settlements can be constructed to light rail standards from the beginning.

One operational difficulty exists when a tunnel section is connected with private right-of-way in street medians or without full separation from street traffic. Because of the possibilities of minor or major delays on the surface sections one must expect somewhat irregular arrivals of trains to tunnel sections, which reduce its capacity. To alleviate this problem, a system for the computer control of operations is currently being developed in Hannover.

LIGHT RAIL AS PREDECESSOR OF RAPID TRANSIT

Light rail operated in tunnels in city centers can be a transitional form for rapid transit. However, the planning concept of rapid transit must be established from the beginning to prevent changes, especially in the alignment. The design must have elements such as large curve radii, no grade crossing, and no converging points on open sections adequate for rapid transit. Tunnel widths and platform lengths must be designed for the later introduction of wider cars and longer trains. If rapid transit should have third-rail current pickup (light rail has it from an overhead wire), its later addition must be possible. If single-directional light rail cars operate in tunnels, only side platforms are possible. Cars with doors on both sides, such as those in Boston, and left-hand operation, such as that in Cleveland-Shaker Heights, would be exceptions.

Difficulties exist for both systems when there are different platform heights and car widths. For platform heights, certain solutions have been used.

1. When platforms in tunnels have the height needed for rapid transit, 2 methods have been used. In Hannover and Frankfurt (line B), the light rail cars have adjustable

steps that are in high position in the tunnel and allow boarding and alighting without steps; at stops in surface running the steps are in low position, and boarding and alighting is made by means of 3 steps. In Düsseldorf, during light rail operation, the tracks lie 61 cm higher than they do in rapid transit operation; for transition the tracks are lowered. Structural changes of the tunnel are not required for transition to rapid transit in either of these cases.

2. In Brussels, tunnel platforms are built to rapid transit elevation, but, in an area approximately 30 m long and 2.15 m wide, they are lowered to 0.27 m above rail. Access to this depressed area is by means of lateral steps. In transition these depressions are filled up and covered.

3. In Stuttgart, Essen, and Cologne, tunnel platforms have the same elevation as do platforms on the outlying sections. In conversion to rapid transit they must be elevated. This measure requires other adjustments in the tunnel.

With respect to the different car widths, it is recommended that platforms be designed for the narrower light rail cars and cut back as necessary to accommodate wider cars in converting to rapid transit.

The conversion, naturally, brings operational difficulties. They are smallest when platforms are already constructed in their final form; they are the greatest when, as in Stuttgart, they must be raised in the whole station. Also, lowering the tracks, as in Düsseldorf, is not easy. Some difficulties also exist in adding the third rail or changing the signal system. However, all these difficulties can be overcome.

Construction of a rapid transit network by means of construction of a light rail network is probably more expensive in the long run than its direct construction would be, but one should not overlook its advantages. Although opening a rapid transit line is possible only when its length has a certain magnitude causing completed tunnel sections to remain unused for a long time, tunnels for light rail can be opened for operation as soon as they are completed. The underground light rail lines in city centers, therefore, in many cases, can have a higher value for transit and for reducing congestion of streets and intersections than can a single rapid transit line that would require the same investment cost. Moreover, many cities, particularly smaller ones, that want to have rapid transit may find that its introduction is easier to foster by way of light rail transit than it would be through immediate construction of rapid transit. From the central underground network, further construction of tunnels can follow until the length of lines permits conversion to rapid transit.

PLANNING

In planning light rail and rapid transit systems, one must always be aware of the fact that transportation is one of the basic determinants for the total spatial interrelationships between habitation and economy and that, through this, it influences the interactions that characterize an urban cluster in its totality as a socioeconomic spatial unit. Transportation is one of the most important components of spatial organization. Therefore, transportation planning must be performed from the beginning hand in hand with land use policies and city planning concepts that determine land use. City planners should understand that transportation and buildings are not different things, but are 2 sides of the same problem (2).

Requirements for the integration of transportation and urban planning apply strongly to public transportation for city centers and even more so for their surrounding areas. To ensure an economical and acceptable transportation service, radial lines from the central city served by rapid transit or light rail transit should become the axes of regional development corridors on which residential concentrations are placed in a linear pattern. Through a concentration of buildings along rail axes, the demand is created that justifies the provision of a rapid, high-capacity transportation mode with sufficient service frequencies. This planning principle already has been applied in many metropolitan areas such as Hamburg, Munich, Hannover, Copenhagen, and Stockholm.

Through provision of park-and-ride and kiss-and-ride facilities and feeder buses, areas served by stations can be increased greatly; thus rapid transit and light rail can serve areas with lower densities that previously could not be served economically.

Rapid transit and light rail transit offer commuters from a region an attractive alternative to the automobile and contribute to the reduction of peak-hour highway congestion. This is an important condition for securing access to the city center for the necessary commercial truck traffic and for preventing the threatened functional devaluation of the city. Germany considers maintaining the life of cities one of the most important problems of today; as the German city planner Hillebrecht (4) expressed it, "The most important life element of the city is its center, its visible, comprehendible center, which attracts and radiates."

In this connection it is of interest to mention the service distances of both rail systems and their trip lengths. In Germany, we claim that travel times from different points in a region to the city center should not exceed 45 min. This yields a radius between 20 and 25 km for light rail, between 25 and 35 km for rapid transit, and between 35 and 45 km for regional rail systems.

Average trip length for light rail and rapid transit usually lies between 4.5 and 8 km. Compared with the usually great trip length on regional rail systems, these trips may be described as short to medium.

A balanced system of transit service is based on the principle that the intersecting points between different modes should be designed so that transferring can be performed comfortably and safely. A number of such successful examples exist; they include, for example, transfer stations in Hamburg between U-Bahn and bus at Wandsbeker Platz, in Rotterdam between rapid transit and light rail, and in Frankfurt-Nordweststadt between light rail and bus. Particularly convenient are the facilities that provide for cross-platform passenger interchange.

CONCLUSIONS: STATUS OF LIGHT RAIL PLANNING IN GERMANY

I believe that to maintain the vitality of an urban area public transportation is tremendously important. This does not imply that the private automobile should be condemned. The modern socioeconomic spatial unit, particularly the city, needs both modes, but it needs rationally allocated roles and cooperation between them. In this multimodal system, LRT has an important task. Although it is, as I have shown, inferior to rapid transit in some aspects, it has a number of advantages that show it should be the primary mode in medium-sized areas. With respect to the average operating cost per passenger kilometer, the difference between the 2 modes is not critical.

In Germany, construction of light rail facilities is given great attention. Thus the streetcars that operate as rapid streetcars or suburban rail systems on private rights-of-way are being upgraded for light rail operation and are being equipped with modern vehicles so that later a major light rail system may be formed such as the one in the area of Mannheim, Ludwigshafen, and Heidelberg. In many cities, such as Bremen, Frankfurt, Mannheim, and Cologne, large outlying residential settlements are being connected by light rail transit with the city center. In the large development complex of Frankfurt-Nordweststadt, the rail system is placed centrally and underground.

The largest project already under construction is the light rail system for the Rhein-Ruhr region. This system should serve the cluster of cities in this region in the north-south direction and complement the Federal Railway S-Bahn, which mostly meets the demand for travel in the east-west direction. In the first stage, 124 km should be constructed. Parts of the urban light rail systems that already have been constructed in tunnels or elevated alignments in the cities of Cologne, Düsseldorf, Duisburg, Essen, and Dortmund will be incorporated in this regional network.

As already mentioned, 12 cities have started to relocate their streetcars (primarily those in city centers) into grade-separated alignments. Frankfurt and Cologne also have constructed outlying elevated sections, and each already operates a grade-separated light rail system with 20-km-long lines and modern light rail vehicles. Hannover started light rail operation in September 1975. Other cities, such as Essen, Stuttgart, and Ludwigshafen, operate tunnels in combination with surface lines and streetcars. When the surface network is operated predominantly on private rights-of-way, this subway-surface system can be classified as light rail.

Six of these cities later plan a transition to rapid transit. There is no doubt that, after the federal government and states made financial means for construction of transit facilities available, there was a certain enthusiasm for rapid transit. There have been experts who considered light rail as an inferior solution and have propagated rapid transit. Recently, however, a change has taken place. Not only the financial position of the federal government and cities but also decreasing city populations make reevaluation of growth and rapid transit concepts necessary. Criticisms of rapid transit planning in cities the size of Nuremberg and smaller are increasing. I am convinced that, under the pressure of changing conditions, several cities will give up planned upgrading to rapid transit and remain with light rail as a permanent solution to their transportation problems as Hannover has recently done.

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COMPARISON OF BUSWAY AND LIGHT RAIL MODES

William H. Morris, Jr., Rochester-Genesee Regional Transportation Authority

Much has been offered to convince decision makers that busways are the least costly of fixed-guideway services in medium-density urban corridors. Until recently, these claims could be questioned but not refuted because a thorough analysis of comparable busway and light rail transit (LRT) systems did not exist. However, such a work was completed in late 1974. The Rochester, New York, Charlotte-Henrietta corridor studies are a detailed busway-versus-LRT mode comparison for a specific corridor. The studies show that, although LRT and busway investment costs are similar for equal facilities, LRT exhibits substantial operating cost, operation, and service advantages.

Proposed new applications of busway and light rail transit (LRT) technology in U.S. cities have focused mainly on radially oriented, city-suburb corridors. In medium-sized cities, busway and LRT proposals are similar in their patronage handling, line-haul characteristics, private right-of-way (ROW), high speed, multiple stations and central business district (CBD) distribution.

In 1970, Rochester, New York, began an analysis of busway engineering and economic feasibility for the 19.4-mile (31.2-km) Charlotte to Henrietta (C-H) urban transit corridor. For a number of reasons, the busway analysis soon became a series of detailed busway-versus-LRT mode comparisons. The study output is a landmark in that the several volumes of final report represent the most comprehensive comparison of LRT and busway costs yet performed in the United States for a specific corridor. The findings of the Rochester studies may provide useful guidance to others choosing between a busway and light rail transit.

CHARLOTTE-HENRIETTA CORRIDOR

The 1969 Metropolitan Transportation Plan, which was adopted by the local Rochester government, recommended construction of a high-speed busway running north and south from city center. The corridor location was carefully established by the plan to be on or parallel to existing, active freight railroad rights-of-way (ROWs). The old Rochester City Subway ROW was to be used under the CBD.

From the beginning, Rochester area policymakers determined that the C-H busway must exhibit high degrees of comfort, safety, and speed. The urban transit facility was to be totally grade separated from highways and streets at intersections and designed to enable travel speeds as high as 60 mph (96.6 km/h) and automobile-competitive average scheduled speeds exceeding 30 mph (48.3 km/h). Use of comfortable air-conditioned buses and pleasant, high-quality stations also were provided for. To minimize acquisition of private property and the relocation of persons and businesses, every reasonable effort was to be made to construct the new busway entirely within the confines of existing railroad ROWs.

COMPARISON OF BUSWAY AND LIGHT RAIL CONCEPTS

Recently, exclusive busways have been promoted as the best option for low capital investment in the intermediate patronage range between the extremes of rail rapid transit and buses in mixed traffic. Light rail transit, however, also is well suited for intermediate patronage corridors.

Busways

A busway is a roadway limited to exclusive use by buses. The nation's largest bus manufacturer has promoted bus rapid transit, bus platooning, and Metro-Mode use of busways. Bus rapid transit involves use of a high-speed, grade-separated roadway along which stations are spaced at various distances; buses operate in local, limited, skip-stop, and express service.

Metro Mode is a variation on bus rapid transit. Theoretically, the bus provides its own feeder service; that is, it exits the busway and picks up and discharges passengers on local streets. The ability to operate on streets as well as on the high-speed busway eliminates some requirements for passenger transfers. Two types of Metro Mode service were examined for the C-H corridor. One, which involved the use of small buses in local feeder, express busway, distributor service, was not considered because of its large rolling stock and high operating costs. The other, which involved substituting main-line vehicles (using busway on and off ramps) for feeder buses on local streets, was eliminated because it increased total fleet requirements, capital costs, and operating costs.

Bus platooning involves groups of buses operated together in closely spaced, minimum-headway, trainlike fashion. In other words, trains of buses provide rapid transit service. (Bus platooning at speed has never been tested and proved in actual passenger service, nor is it likely that it will be because flow stability and safety standards are seriously affected when the stopping time of independently operated vehicles approaches the headway between those vehicles.)

Light Rail Transit

Although many light rail vehicles (LRVs) are manufactured throughout the world, only the basic U.S. standard Boeing Vertol LRV was considered for Rochester.

Because LRVs are guided by rails, cars may be coupled together and operated as a train. If the vehicles contain proper equipment, only 1 operator is required to handle a train of several cars.

The ROWs, tracks, and structures of freight railroads may be used by LRVs with modified wheels. Scheduling provisions can enable this facility-sharing if either service can be given exclusive track occupancy during individual periods of the day or night. Safety rules forbid mixing freight-train and LRT services on a common track at the same time of day.

Given the availability of tracks and catenary, LRT systems can perform all busway operations: rapid transit, Metro Mode, and platooning. The ability of LRT to be operated in these ways has been tested and proved.

VEHICLE CHARACTERISTICS

Both the physical and performance characteristics of LRVs and buses influence the mode-selection process. A review of existing and planned foreign and domestic equipment clearly indicates that no high-capacity, double-deck, or articulated bus of adequate horsepower (wattage) would be available to render high-speed, start-stop corridor service. Conversely, high-seating-capacity LRVs, offering a wide range of desirable physical and performance characteristics, are being produced.

Physical Characteristics

The transit vehicles selected for LRT and busway comparison in Rochester's C-H corridor were the standard 49 to 53 passenger diesel transit bus and a modified LRV manufactured by the Boeing Company. The basic physical dimensions of both vehicles are well known. The 75-ft-long (22.9-m-long), 6-door, articulated LRV seats a nominal 80 passengers and has 4 in. (10 cm) more aisle space than the bus has. The bus, with its rear door widened to 54 in. (137 cm), seats only 49 passengers. Both vehicles use 36-in. (91-cm), transverse, semisuburban seats. Passenger boarding on the LRV is by high platform; passenger boarding on the bus is by steps.

Performance

Speed

A check with Boeing Company representatives indicated that minor variations in their production-line vehicle (changes in gear ratio and wheel diameter) would permit safe LRV speeds of 60 mph (96.6 km/h).

The acceleration and speed characteristics of LRT are clearly superior to those of the bus. The bus attains 60 mph (96.6 km/h) in 33 s while traveling 1,560 ft (476 m); its initial rate of acceleration is 2 mph/s (0.9 m/s^2. [Improvements in bus acceleration (gearing modifications or wheel diameter reductions) are obtained at the sacrifice of top speed.] Accelerating initially at 3 mph/s (1.35 m/s^2), the LRV requires only 22 s and a distance of 1,020 ft (311 m) to reach 60 mph (96.6 km/h). Taking other factors into account, C-H corridor, peak-hour average speeds were estimated to be 34.3 mph (55.2 km/h) for LRT and only 30.8 mph (49.6 km/h) for buses.

Braking

The normal braking characteristics of LRVs and buses are satisfactory for corridor rapid transit service. However, on a wet or frozen surface, the bus operator could easily lose control of the vehicle while braking. LRVs, because they are physically guided, are not subject to this hazard.

Dwell Times

Because of the basic physical characteristics of the vehicles, bus and LRV dwell times differ significantly. The limited number and narrowness of door openings [30 in. (76 cm) at the front and 54 in. (1.37 m) at the rear] and necessity of stairs in buses cause high dwell times compared with those of the modified LRV, which has wide doors and high-platform loading at all entrances.

Calculations of C-H corridor dwell times assumed prepaid fares at all stations. The formula used a constant of 10-s minimum reaction time for both vehicles and 0.4-s/passenger boarding time for LRT and 1.3-s/passenger boarding time for bus. Use of this formula for calculating peak-hour dwell times at all 20 C-H corridor stations resulted in averages of only 322 s for LRT and 452 s for buses. A requirement for on-board fare collection would increase station dwell times for both modes. The disparity between bus and LRV dwell times would remain great, however, because LRVs have more and wider doors and no steps.

CORRIDOR CHARACTERISTICS

The physical characteristics (types of stations, ROW widths, and the like) of the C-H corridor were shown to have little effect on mode selection. Far more important in influencing decisions were factors related to passenger volumes and perceived quality of service.

Passenger Volume

Busway and LRT systems are capable of handling wide ranges of corridor patronage. In Table 1, the Boeing LRV modified to Rochester specifications and seating a nominal 80 passengers is compared with a standard 50-passenger bus over a range of peak-period patronage estimates. The comparison assumes only that a given number of passengers must be moved to, from, or past a certain point on the transit line during a 15-min time period. (On the C-H corridor, the peak 15-min patronage in 1 direction equals approximately ⅓ of peak-hour boardings.) Note that, as patronage increases, headways for the busway become extremely short. The ability of LRT to maintain 2- or 4-min standard headways by using trains of various lengths (1 to 4 cars) enables operation of a safe, near-constant headway at rush hour; this permits reliable service without delays.

Qualitative Factors

Several of the physical and operational characteristics of bus and rail vehicles influence the design, operating cost, and use of the corridor, and most affect the quality of service that can be offered. A comparison of selected corridor characteristics, many of which are qualitative in nature, is given in Table 2.

Two qualitative characteristics purportedly favoring the busway are: (a) the ability of buses to overtake each other at stations and (b) the ability of buses to provide through services to and from neighborhoods. But both are possible, at substantial additional cost, for either the LRT or busway modes. These options were examined for the C-H corridor and discounted for their cost or service implications or both. The ability of the transit operator to use vehicles for charters and school trips was proposed as a busway advantage. However, Rochester's existing fleet of buses is available for such uses during base periods.

RIGHTS-OF-WAY AND COSTS

Both modes can be accommodated on any reasonable horizontal or vertical alignment. Either mode also can be constructed entirely or partially on private ROW and be grade separated at some or all street intersections. Decisions on the type of ROW to be used and whether grade crossings are to be permitted have a substantial effect on the construction cost and safety of both systems.

Grade Separations

Grade crossings are safety hazards and easy transitway access points. If fare controls are station located rather than vehicle borne, at-grade crossings close to stations cannot be easily tolerated. Under such circumstances, limiting platform access to fare-paid passengers is nearly impossible.

Safety

Above a minimum patronage level, the frequency of service on a busway must be greater than on an LRT system. The greater the frequency of transit vehicles intersecting cross streets at grade is, the greater the risk of accidents involving automobiles and transit vehicles is.

A nomogram developed for railroad operations showed the high probability for grade-crossing accidents to occur even on corridor outer ends. After further analysis, it was concluded that the 1990 rush-hour headways of LRV trains (averaging 3.25 min for both directions of travel) would permit the installation and safe observance of railroad-type grade-crossing control devices or LRV-actuated traffic signals.

For the busway, conclusions were different. Average rush-hour headways for buses on the C-H corridor outer ends in 1990 were as low as 42 s. To prevent a total disruption of street traffic at busway intersections, regular pretimed traffic signals would have to be used. These would reduce the average scheduled speeds of the busway, and extra buses would have to be added to the fleet to cover headway and capacity gaps.

If we do not consider other factors, the required high frequency of buses during rush hours compared with the much lower frequency of LRV trains makes exposure to any C-H corridor grade-crossing accident a minimum of 2.5 times greater for the busway than for LRT.

Investment

Three main factors affect the construction costs of busway and LRT grade-crossing-elimination projects: gradients, clearances, and the relocation or sharing of freight tracks. Typical unit costs in 1974 dollars for transit-highway grade-separation structures on the C-H corridor are as follows:

	Cost		
Facility	Busway	Simple LRT	LRT and Freight
Transitway underpass	2,550,000	2,830,000	4,135,000
Transitway overpass	1,040,000	860,000	1,380,000

Each LRT and freight separation is designed to accommodate rail freight traffic. Busway and simple LRT structures do not reflect any rail-freight-related costs. One may quickly conclude that the cost of a transitway underpass (retained cut) ranges from about 2.5 to more than 3 times the cost of a comparable overpass. Such costs do not include cost of land or charges for any related highway work. Among all the alternatives except a subway, the simple LRT overpass is the least costly of all grade-crossing-elimination structures.

The requirement for a greater vertical clearance makes a simple LRT underpass more costly than its busway equivalent. A busway requires a vertical clearance of only 14.5 ft (4.4 m); LRT requires 17 ft (5.2 m).

Freight grades should not exceed 2 percent; LRT or busways can easily tolerate 4 percent grades. Thus the LRT line accommodating freight requires grade-separation facilities that are greater in total length and more costly than comparable busway or exclusive LRT structures. The interrelationships of freight service continuance, maximum gradients, and construction costs are given in Table 3.

Economy can be maximized if a simple LRT or busway structure can be constructed and, if necessary, separate freight tracks can be relocated horizontally to an existing vertical alignment. However, before a final decision on freight-track sharing versus relocation can be made for LRT, other factors should be considered, including (a) public policy, traffic improvements, and social and environmental benefits derived if the at-grade freight crossing were eliminated; (b) land costs; and (c) related highway construction costs.

Use of 7 fully protected grade crossings (instead of grade separations) on the C-H corridor outer ends would save an estimated 10.3 million 1974 dollars in construction

Table 1. Travel volumes, vehicle requirements, and headways.

	Light Rail Transit				Busway	
Passenger Demand[a]	Cars Required	Cars per Train	Trains	Headway (min)	Headway (min)	Buses
500	7	1	7	2.14	90	10
500	7	2	4	3.75	90	10
1,000	13	2	7	2.14	45	20
1,500	19	3	7	2.14	30	30
2,000	25	3	9	1.67	23	40
2,500	32	4	8	1.88	18	50

[a]All passengers seated and a 15-min peak period.

Table 2. Corridor characteristics.

Facility	Vertical Clearance (ft)	Maximum Gradient (percent)	Facility Length (ft)	Total Cost[a] (1974 dollars)	Add for Freight Track Relocation[b] (ft)
Highway overpass					
LRT and freight	14.5	2	2,100	1,380,000	Not applicable
Simple LRT	14.5	4	1,325	860,000	0.095
Busway	14.5	4	1,125	1,040,000	0.081
Railroad overpass					
LRT and freight	22.0	2	2,800	2,540,000	Not applicable
Simple LRT	22.0	4	1,700	1,385,000	0.122
Busway	22.0	4	1,600	1,800,000	0.115
Underpass					
LRT and freight	17.0	2	2,300	4,135,000	Not applicable
Simple LRT	17.0	4	1,450	2,830,000	0.105
Busway	14.5	4	1,150	2,550,000	0.083

Note: 1 ft = 0.305 m.

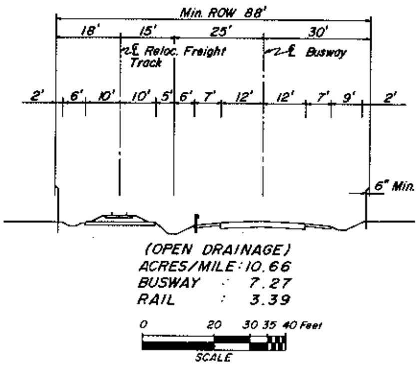
[a]Costs shown are exclusive of any highway-related work. [b]Horizontal relocation to existing vertical alignment (at grade).

Table 3. Adaptability of LRT and busways to typically desired corridor characteristics.

	Mode	
Corridor Characteristic	LRT	Bus
Passenger accessibility		
High platform loading potential	Yes	No
Curb height loading only (steps)[a]	Yes	Yes
Combination high platform and curb height loading potential	Yes	No
Passenger safety		
Simple deadman control	Yes	No
Fail-safe signalization	Yes	No
Aesthetics and environment		
No overhead wires	Yes[b]	Yes
Low vehicle emissions	Yes	No
Low vehicle noise emission	Yes	No
Low noise incidence[c]	Yes	No
Engineering and economics		
Share common freight track	Yes	No
Low labor intensity	Yes	No
Upgrade to rapid transit	Yes	No
Potential for total automation	Yes[d]	No

[a]Significant disadvantage for the physically handicapped.
[b]Where LRT is located on private right-of-way, power can be transmitted by a third rail (though at higher cost than for catenary operation). Conduit-encased, underground third-rail power transmission systems have been used successfully in Washington and New York.
[c]The frequency of occurrence is lower for an LRT system compared with that of a busway at a given patronage level (Table 1).
[d]If fully grade separated.

Figure 1. Relocated freight track for simple, at-grade busway.



Note: 1 ft = 0.305 m. 1 in. = 2.54 cm. 1 acre/mile = 0.25 hm^2/km.

costs for LRT and 12.7 million 1974 dollars for a busway. LRT 1990 operating cost would be unaffected; busway operating costs, however, would increase by 90,000 1974 dollars as a result of adding vehicles to compensate for increased running times.

Private Right-of-Way

The private ROW, high-speed aspect of busway and LRT operation makes both attractive alternatives to private automobile usage. Free of interfering traffic, busway and LRT top speeds of 60 mph (96.6 km/h) and average scheduled speeds exceeding 30 mph (48.3 km/h) can be obtained easily. The use of private ROW implies safety, high speed, schedule adherence, and transit dependability and reliability.

Busways and LRT lines can be built and safely operated on relatively narrow private ROWs. LRT, at a desirable and safe dimension, generally requires less ROW width [45 ft (13.7 m)] than does a busway [60 ft (18.3 m)]. Because rail vehicles are physically guided, their lateral motion is restricted; this is not so for bus. In addition, a rail vehicle that breaks down can be pushed; a stalled bus must be bypassed.

Ideally, a private ROW should be entirely fenced. At minimum, fencing should be included along all high-speed segments, at stations, and wherever else pedestrians or pets might trespass. Other safety features, such as guardrails on busways, standing-room clearance between busway lanes or rail tracks, and adequate grade-crossing protection, are desirable. Comparisons of LRT and busway ROW requirements and costs are without merit when reasonable safety features have been omitted or unjustifiably reduced.

Light rail transit and busway ROW requirements and construction costs for the C-H corridor are given in Table 4. These costs include engineering and contingency costs but not land costs. The busway with closed drainage categories are for urban situations in which ROW width is restricted or land value is high or both.

At-Grade Private Right-of-Way

A review of Table 4 indicates that only in the typical at-grade open drainage situation does the busway exhibit a construction cost advantage. If land values were high, the marginal cost advantage for the busway would not exist because its ROW requirement is $1/3$ greater than that of LRT.

It is proposed frequently that busways be constructed on railroad ROWs parallel to active freight tracks. However, Rochester-area railroad ROWs are typically only 66 ft (20.1 m) wide with 8 acres/mile (2 hm^2/km). Even with the freight track relocated to 1 side of the rail ROW (Figure 1), the busway cannot be accommodated without the purchase of additional land. This is not the case with LRT because LRT can share freight railroad tracks.

Other Construction

Embankment, viaduct, and retained cut are construction forms widely encountered in highway and rail transportation. Generally, on a cost-per-mile (kilometer) basis, these construction forms are less costly for LRT than they are for busway because LRT has a narrower ROW requirement. Caution is exercised against oversimplification, however. Construction standards, land values, and environmental or site-specific factors can alter such general situations.

Subway

Dedicated ROWs, modern traffic control devices, and good traffic engineering practice can enable busways or LRT to achieve satisfactory speed characteristics on the street surface in many urban core areas. This is a major attribute of busways and LRT; such low-cost solutions to speed and capacity problems may minimize or obviate the need for tunneling in CBDs.

Rochester's C-H corridor will require only 3,750 ft (1144 m) of new cut-and-cover subway if street operation is to be avoided entirely. No station structure is planned in the subway, and busway speeds would be high. Therefore, the ventilation of diesel bus exhausts is a minor item of busway cost. No ventilation is required for the LRT system. LRT vertical clearances [a minimum of 17 ft (5.2 m) for catenary] will permit freight operations to be conducted if necessary. The comparative costs for this new subway segment are as follows in 1974 dollars:

	Cost		
Mode	Construction	Ventilation	Total
Busway	11,344,000	2,025,000	13,369,000
LRT and freight	12,263,000	Not required	12,263,000

A comparison of the C-H corridor busway and LRT and freight profiles is shown in Figure 2. The comparison indicates that almost twice as much at-grade construction may be used for LRT compared with that for busways. Also significant is the fact that additional private property abutting the freight ROW must be purchased along 6.2 route miles (9.9 route km) of the busway. However, on the LRT system, only slightly more than 1 mile (1.6 km) of ROW must be widened beyond existing railroad ROW boundaries.

STATIONS

Light rail transit and busway stations may range from controlled-access, grade-separated, rapid-transit-type structures to unsheltered curbsides. The ability to select from or adapt to such a wide range of station possibilities is one of the most significant attributes of LRT and, to a lesser degree, busways.

To encourage high transit ridership on the C-H corridor, Rochester planned for complex busway or LRT stations. Each is to have heating, ventilating, and air conditioning; controlled and TV-monitored passenger access (for security); fare collection facilities; and, where appropriate, elevators and escalators. High platforms at LRT stations will speed passenger travel, minimize boarding and alighting mishaps, and enable the physically handicapped to have access to transportation. Because the use of high platforms is not possible on the busway, the same benefits could not be enjoyed by patrons of that mode.

The efficiency, design, and cost of a busway station can be radically affected by high patronage. Determinants affecting busway station design are bus headways, average dwell times per vehicle, and peak boarding and alighting volumes. When the station dwell time of a bus exceeds vehicle headways, buses will back up waiting for others to clear the station platform. Under such conditions, vehicle flows, service schedules, and station efficiency will suffer. One proposed but unproved solution to this problem is to platoon the buses. However, more practical methods of speeding the movement of large peak-hour bus movements through stations would be to provide additional passenger platforms, lengthen existing platform areas, and construct bus bays.

The cost, in 1974 dollars, of 20 complex stations in the C-H corridor was estimated to be 16,165,000 dollars for a busway and only 13,278,000 dollars for LRT. A minimum of slightly more than 2 million dollars extra would be required to add elevators to the LRT single-platform stations. A much greater expense would be incurred to equip double-platform busway stations with elevators.

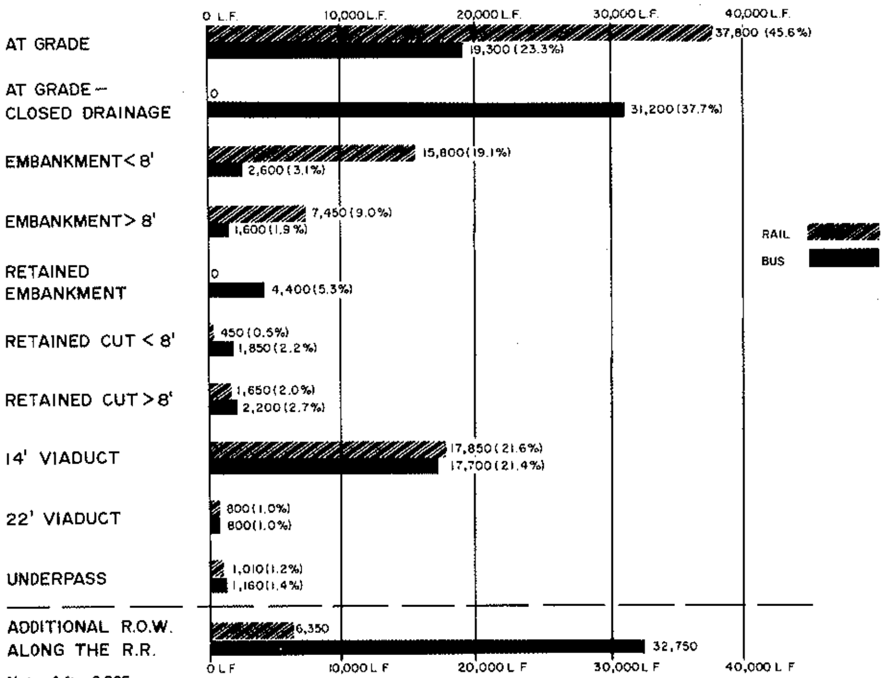
Table 4. Right-of-way requirements and construction costs.

Location	Mode	Right-of-Way Width (ft) Minimum	Add for Freight Track Relocation[a]	Total	Acres/Mile Minimum	Add for Freight Track Relocation[a]	Total	Construction Cost (1974 dollars) Cost per Mile	Add for Freight Track Relocation[a]	Total
At grade	LRT and freight									
	Open drainage	45	—[b]	45	5.45	—[b]	5.45	665,000	—[b]	665,000
	Closed drainage	—[b]	—[b]	—[b]	—[b]	—[b]	—[b]	—[b]	—[b]	—[b]
	Busway									
	Open drainage	60	28	88	7.27	3.39	10.66	605,000	380,000	985,000
	Closed drainage	50	21	71	6.06	2.54	8.60	921,000	380,000	1,301,000
Embankment[c]	LRT and freight									
	Open drainage	87	—[b]	87	10.54	—[b]	10.54	855,000	—[b]	855,000
	Closed drainage	—[b]	—[b]	—[b]	—[b]	—[b]	—[b]	—[b]	—[b]	—[b]
	Busway									
	Open drainage	98	28	126	11.88	3.39	15.27	890,000	380,000	1,270,000
	Closed drainage	90	20	110	10.91	2.42	13.33	1,365,000	380,000	1,745,000
Retained cut[d]	LRT and freight	50	—[b]	50	6.06	—[b]	6.06	13,622,000	—[b]	13,622,000
	Busway	53	24	77	6.42	2.91	9.33	15,056,000	380,000	15,436,000
Viaduct[e]	LRT and freight	27	—[b]	27	3.27	—[b]	3.27	6,716,000	—[b]	6,716,000
	Busway	35	27	62	4.24	3.27	7.51	6,909,000	380,000	7,289,000
Subway[f]	LRT and freight	49	—[b]	49	5.94	—[b]	5.94	17,266,000	—[b]	17,266,000
	Busway	52	—[b]	52	6.30	—[b]	6.30	18,818,000	—[b]	18,818,000

Note: 1 ft = 0.305 m; 1 acre/mile = 0.25 hm^2/km.

[a]Horizontal relocation to existing vertical alignment (at grade).
[b]Not applicable.
[c]Maximum height: 19 ft (5.8 m).
[d]Vertical clearance for LRT: 17 ft (5.2 m); vertical clearance for busway: 14.5 ft (4.4 m).
[e]Vertical clearance: 14.5 ft (4.4 m).
[f]Simple, unimpeded cut-and-cover construction including ventilation cost. Vertical clearance for LRT: 17 ft (5.2 m); vertical clearance for busway: 14.5 ft (4.4 m).

Figure 2. Rail and bus profiles.



Note: 1 ft = 0.305 m.

CAPITAL INVESTMENT

Basic, all-inclusive construction costs of the 1990 LRT and freight and busway systems in the 19.4-route-mile (31-route-km) C-H corridor [20 complete stations, 3,750 ft (1144 m) of new cut-and-cover subway, land acquisition, and total grade separation] are estimated (in 1974 dollars) to be 130,032,000 dollars for LRT and 137,540,000 dollars for a busway. The lower LRT construction cost is partially explained by its lesser ROW acquisition requirements because of its ability to share freight track and lower station costs.

The construction cost advantage of LRT for equal facilities in the C-H corridor is relatively insignificant. Rather than indicating a clear advantage for either mode, the analysis should indicate to the observer that for comparable facilities neither mode exhibits a significant construction cost advantage over the other. System capital costs over 60 years are slightly higher for LRT than they are for busway primarily because of the disparity in vehicle investment. For the C-H corridor, LRT and busway total system capital costs, in 1974 dollars, are as follows:

	Cost	
Item	Busway	LRT
Construction	137,540,000	130,032,000
Rolling stock		
Main line	27,378,000	36,400,000
Feeder	5,520,000	5,520,000
Total capital costs	170,438,000	171,952,000

Rolling stock includes initial orders and replacement vehicles over an assumed system life of 60 years (1977 to 2027).

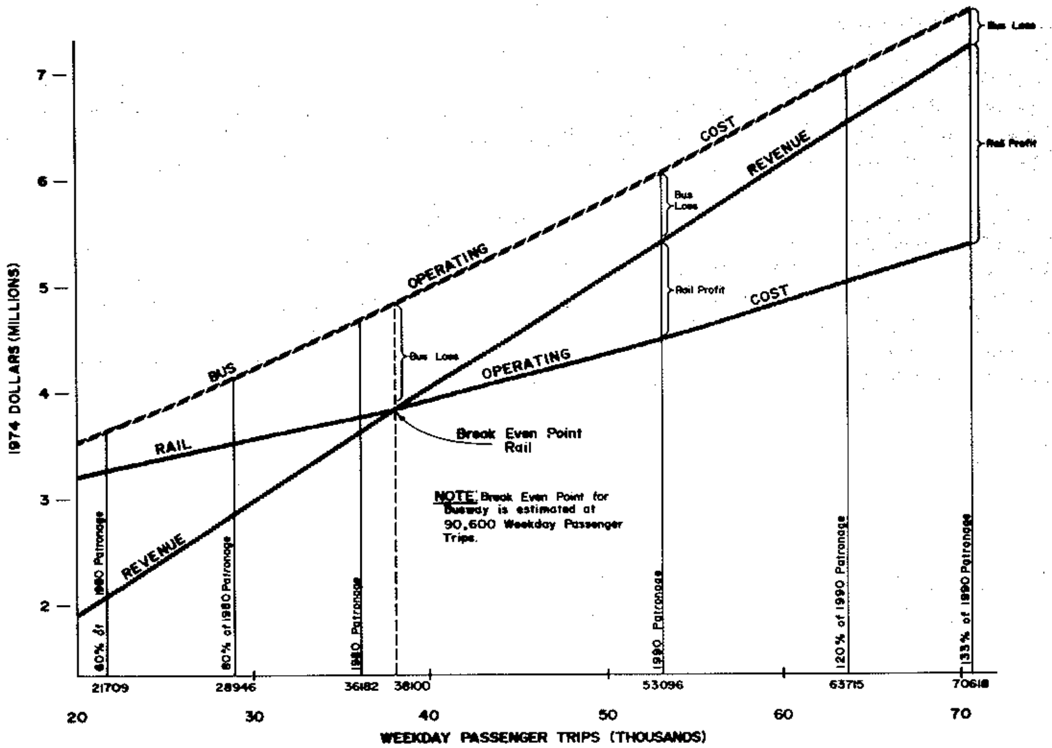
OPERATING COSTS

It is in the specific area of operating cost that LRT demonstrates a clear superiority over busways. The comparative 1990 total system operating costs, in 1974 dollars, for the C-H corridor systems are 4,986,000 dollars for the busway and only 3,351,000 dollars for LRT. LRT evidences a direct operating cost advantage of more than 1.6 million dollars at the projected 1990 level of service. Feeder bus operating expenses are estimated to be an additional 1,053,000 dollars for either the busway or LRT systems.

Figure 3 shows a comparison of busway and LRT operating costs throughout a range of patronage levels. Even at the maximum patronage level shown, revenue has failed to cover busway operating expenses. As patronage increases above the 38,000 weekday trips, the potential for the earning of a revenue surplus by LRT appears to be excellent.

Differences in personnel requirements resulting mainly from the ability of LRT to be operated in trains of LRVs controlled by only 1 operator and the higher per-unit passenger capacity of LRVs compared with that of buses are responsible for superior cost performance of LRT. Total personnel requirements for the year 1990 are 134 busway vehicle operators versus 38 LRT vehicle operators. One hundred twenty-one other personnel would be needed for each system.

Figure 3. Operating cost and revenue versus weekday passenger trips.



CONCLUSIONS

As a proposed solution to transportation problems in Rochester's C-H corridor, LRT exhibits a number of qualitative and quantitative advantages over the busway. Because of its characteristics of labor intensity and passenger capacity, the grade-separated, line-haul busway mode exceeds LRT operating costs. This operating cost advantage of LRT, which is evident at patronage estimates as low as 20,000 per average weekday, increases markedly with C-H corridor ridership growth.

Busway implementation costs in the corridor are slightly lower than those for LRT primarily because of the disparity in vehicle investment. Neither mode exhibits a significant construction cost advantage over the other. In terms of qualitative factors (passenger accessibility, safety, and environment), LRT was judged to be clearly superior to a busway in the Charlotte-Henrietta corridor.

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PLACE OF LIGHT RAIL TRANSIT IN THE FAMILY OF TRANSIT MODES

Vukan R. Vuchic, University of Pennsylvania

The paper attempts to clarify concepts and terminology of urban transit systems. Modes are defined by type of right-of-way, system technology, and type of service and operation. Right-of-way is shown to be the most important single feature determining mode performance and cost. Advantages of partial or full separation of transit from surface traffic are defined. The basic features of system technology are analyzed. Guided systems are compared with driver-steered systems; rail systems are compared with rubber-tire guided systems; and manually driven systems are compared with automated systems. With respect to operations, it is pointed out that commuter transit should be a supplement to, not a substitute for, regular transit. An analysis of optimal vehicle size shows that, for guided systems that are in use or may be operational in the near future, minimum vehicle capacity should be 40 to 50 spaces. Based on this analysis of mode components, it appears that potential light rail applications are in medium-sized cities as carriers serving major routes and in large cities as a supplement to rapid transit. In large cities with low densities, light rail transit or light rapid transit (fully grade-separated light rail transit) also has potential for application. Small cities and special services may sometimes also use this mode. The following rights-of-way are best suited for light rail: street and highway medians, railroad rights-of-way, aerial structures, and, in downtown areas, short tunnel sections.

Transit planning requires a thorough understanding of characteristics of different modes. However, because modes have different characteristics, many of which are difficult to quantify, relationships among them are complicated and often they are not clearly understood. The lack of a complete theoretical basis for comparing modes combined with emotional tendencies toward unimodalism or a belief in a single mode represents serious obstacles to a rational choice of transit modes.

The purpose of this paper is to define the relationships of light rail transit (LRT) with other modes and describe the most typical applications of this mode. First, we should define the modes and analyze their basic characteristics.

DEFINITION AND CLASSIFICATION OF TRANSIT MODES

A transit mode is defined by the following 3 types of characteristics:

1. Right-of-way (ROW) category,
2. System technology, and
3. Type of service and operation.

This shows that the frequent tendency to equate mode with technology is incorrect. An express bus line is a different mode than a shopper shuttle service because it differs in its type of operation even though the vehicle technology for the 2 systems is the same. Similarly, there is a tendency to equate LRT with streetcars because of the similarity of their technologies. It will be shown that, on the basis of this broader definition of modes, LRT is a distinct, well-defined mode.

The comparisons of features cannot be extensively documented here because of space limitations, but certain basics are assumed.

1. Each characteristic is analyzed by itself, other things being equal. For example, different technologies are compared assuming the same ROW and type of operation insofar as these are not a direct function of technology.
2. The latest development and comparable condition of all modes are assumed (state-of-the-art technology, efficient operation and maintenance, and the like).

Comparisons are made for the most typical, realistic situations. It is conceivable that unusual conditions may change and even reverse results of some comparisons.

Right-of-Way Categories

Transit rights-of-way vary greatly from regular urban streets to fully controlled rapid transit tunnels, viaducts, and the like. They can be classified into 3 major categories that have distinctly different features.

1. Category C includes surface streets with mixed traffic. A vast majority of bus lines in cities represent systems in this category.
2. Category B includes partially controlled ROW. For most of its length, this ROW is separated from other traffic, but some grade crossings and street running also exist. This category is broad. It encompasses modes with reserved bus lanes and curbed light rail street medians to modes with only a few grade crossings, such as the Shaker Heights, Ohio, Light Rail System and the Media Line in Philadelphia.
3. Category A is a fully controlled (also referred to as exclusive, private, or separated) ROW, that is, one without street running, vehicular or pedestrian crossings at grade, and the like. Rapid transit systems are in category A exclusively.

The dominant belief is that technology is the basic feature of transit modes. On the contrary, the ROW category is usually the most important factor determining transit system performance and its ability to attract passengers. In category C, transit vehicles on streets cannot travel faster than other traffic. In Figure 1 the standard traffic volume/travel time curve is plotted for automobile travel. Because surface transit vehicles are mixed with automobiles but also must stop at passenger stops, its travel time curve is higher. Thus, transit service in category C ROW can never be competitive with the private automobile either in speed or in overall service quality. Separated transit on the other hand is not influenced by automobile traffic; its travel time decreases as travel increases because of shorter headways. This fact is valid regardless of the technology used although, as will be shown, the ROW category does influence the choice of the most appropriate technology.

Because category B encompasses a great variety of facilities, there is no sharp distinction between categories B and C. However, the differences between typical B and C category facilities are nevertheless highly significant. They are presented here in a condensed form.

The advantages of category B over category C are as follows:

1. Higher speed, capacity, reliability, comfort, and other service quality elements;
2. Stronger system image and identification;
3. Higher passenger attraction, which is a consequence of item 2;
4. Lower unit operating cost; and
5. Stronger impact on urban form and land use (more permanence).

The disadvantages of category B when compared with category C are that systems in category B require more land and higher investments.

Category A is, on the other hand, distinctly different from category B, because of its full grade separation and control of ROW, which allows many operating efficiencies. Among these efficiencies are operation of longer trains, full signal control, high-level platforms, and enclosed stations with fare collection. These differences give category A the following advantages over categories B and C:

1. Highest capacity, speed, and productivity;
2. Highest comfort and other service quality elements;
3. Highest safety (fail-safe operation);
4. Strongest image and identification;
5. Highest passenger attraction, which results from items 1 through 4;
6. Lowest operating cost per unit capacity;
7. Strongest impact on urban form and land use; and
8. Most fully automated operation possible.

The disadvantages of category A are as follows:

1. It requires land and grade separation for the entire line;
2. It requires the highest investment; and
3. It is the least extensive network, which is a result of items 1 and 2.

This analysis shows that ROW categories largely determine overall mode performance and investment cost. The 3 categories represent 3 distinctly different performance and investment cost combinations, as shown schematically in Figure 2. Consequently, in planning transit systems, the basic decision is choosing the ROW category for the system, that is, choosing the degree of separation and control, because that choice influences most directly the overall quality of transit system performance and the approximate investment level the system will require. This decision, which should be made by political bodies with the advice of transportation planners, is followed by selecting the technology and type of operation. This should be done mostly by transportation engineers with expertise in various modes.

System Technologies

The basic technological difference among modes is method of vehicle guidance. Many physical, operational, and cost characteristics of systems depend on whether the vehicles are steered by the driver or are physically guided externally. Transit systems can again be classified in the following 3 general technological categories:

1. Driver-steered vehicles operating on highways (all types of buses),
2. Guided steel-wheel-on-steel-rail systems,
3. Systems that are a combination of items 1 and 2 (trolleybuses, rubber-tire guided systems, and dual-mode transportation). Dual-mode transportation is not currently operational. Table 1 gives a classification of modes by ROW category and technology.

Major differences caused by different technological characteristics exist among modes. Guided systems have the following advantages over driver-steered systems:

1. Narrower ROWs;
2. Superior performance;
3. No air pollution;
4. Lower noise levels;
5. Greater cleanliness;
6. Easier maintenance;
7. More durable vehicles;
8. Higher capacity and productivity because vehicles can be coupled;

Figure 1. Average travel time by surface transit, automobile, and separated transit as functions of passenger volume.

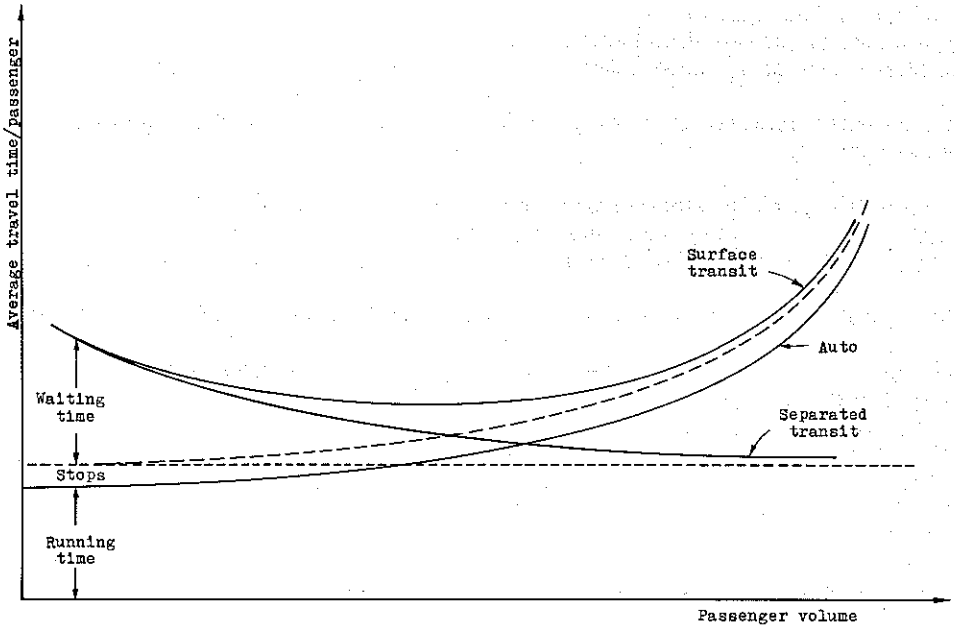


Figure 2. Relation of service quality and investment cost for transit systems in different right-of-way categories.

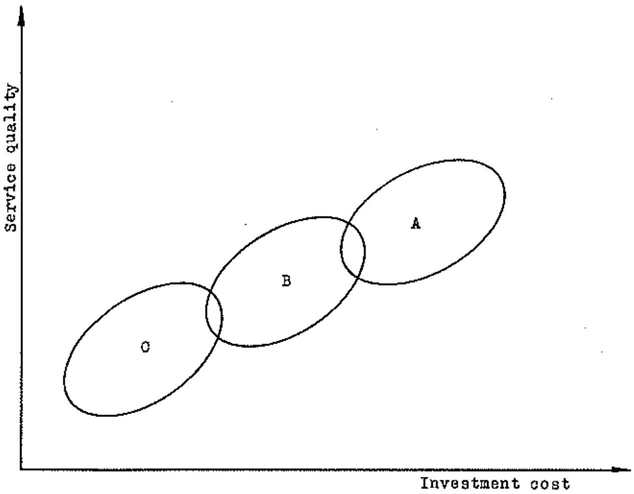


Table 1. Classification of modes by right-of-way category and form of guidance.

ROW Category	Guided: Rail	Guided: Other	Driver Steered
A	Rapid transit Regional rail Light rapid transit	Rubber-tire rapid transit Monorail People movers Personal rapid transit	Bus on busway only
B	Light rail transit	Dual mode	Bus partially on busway
C	Streetcar	Trolleybus	Surface bus

9. Greater safety and reliability;
10. Lower operating cost per unit of offered capacity;
11. Lower energy consumption because steel wheel on steel rail has much lower rolling resistance than does rubber tire on roadway (only true for rail-guided systems); and
12. Can be better operated in tunnels, viaducts, or park areas without significant environmental damage.

Fixed alignment that permits electric traction allows the advantages of items 2, 3, and 4 and the operational advantages of items 5, 6, and 7.

Guided systems have some disadvantages when compared with steered systems.

1. They are less compatible with other traffic, which creates problems in street operation.
2. They are limited to guideway networks only, which is uneconomical for extensive routing in low-density areas.
3. They have lower operational flexibility (rerouting, charter service).
4. They require a slightly higher investment cost (the higher cost of the guideway usually is not fully offset by the savings from the narrower ROW).
5. They offer less frequent opportunities for modernization because of the longer life of their vehicles.

These listings show that, for systems in category C, deficiencies of guided systems are significant and usually outweigh the advantages. For category A, however, the disadvantages of guided systems practically disappear, and the bus is strongly dominated by rail systems. For category B, advantages of rail outweigh disadvantages under most, but not all, conditions.

Some of the listed advantages are either decreased or changed into disadvantages for rubber-tire guided systems. Thus, energy consumption becomes higher than that for buses. This becomes clear when rail and rubber-tire guided systems are compared. Rubber-tire systems have the following advantages over rail systems:

1. Slightly better traction under normal weather [on rapid transit, the maximum gradient for rubber-tire systems is 7 percent, and the maximum gradient for rail systems is 5.5 percent (1)] and
2. Easier control of noise in curves.

The following are the disadvantages of rubber-tire systems when compared with rail systems:

1. Higher energy consumption (sometimes substantial),
2. Poor traction in wet conditions (rain, snow, and ice) that may require expensive guideway heating,
3. Much more complicated switches with slower operations,
4. More expensive and bulkier guideways, and
5. Cannot be used in categories B and C.

This comparison shows that rubber-tire guided systems are inferior to rail systems under all conditions except for some special circumstances. For example, a rubber-tire system would be less noisy on the old steel viaduct in Paris, which could not be replaced by a modern concrete structure. Actually, it should be pointed out that, if the latest developments in each technology are compared, rail remains the best technology by far for guided systems. Although magnetic levitation conceivably may become competitive with rail in the future, it currently is not developed to the stage of technological feasibility.

An interesting recently published study of rubber-tire rapid transit (5) reaches conclusions considerably different from these and much more favorable to rubber-tire systems. The study finds, for example, that rubber-tire systems use less energy than steel-wheel systems because of an estimated 15 percent lower weight/passenger of rubber-tire vehicles. However, this weight advantage is not corroborated by actual data. As a matter of fact, weight per unit of vehicle floor area of rubber-tire rapid transit vehicles is higher than the corresponding weight of many steel-wheel rapid transit vehicles. The assumption of weight advantage therefore is incorrect. The study also finds that rubber-tire vehicles have a speed advantage assuming that adhesion limits acceleration rate at higher speed; however, because, for most systems, motor power rather than adhesion is the constraint, this argument is not valid for real systems.

To complete the analysis of type of guidance, we should consider fully automated operation of transit vehicles. This potentially highly significant feature that is not yet operational requires that the ROW be fully controlled (category A) and that the vehicles be physically guided. Full automation is not, as sometimes believed, related to such features as vehicle size, off-line stations, or any other unconventional technological solutions (8). Actually, rail technology can be better adapted to full automation than can any proposed technology because it has the greatest simplicity and has no untested elements. The advantages of fully automated systems over manually operated systems are as follows:

1. Much higher frequency of service for the same operating cost,
2. Reduced energy consumption and vehicle wear through preprogrammed driving,
3. Easier recovery from service disturbances,
4. Higher capacity for a given level of safety, and
5. Lower operating cost (if labor savings outweigh cost of increased system complexity).

The disadvantages of fully automated systems when compared with manually operated systems are as follows:

1. Considerably higher investment,
2. Serious reliability problems often created by the much greater technical complexity, and
3. Guideway control equivalent to that drivers perform and a system for communicating with passengers in emergencies.

The advantage in item 1 is by far the most important advantage because it would permit high-quality transit to be used economically for lower passenger volumes, such as in cities that currently cannot justify rapid transit. It therefore would be sufficiently significant in many cases to outweigh all the disadvantages of automation.

Types of Service and Operation

Several basic elements of transit system operation needed for modal analysis will be presented in this paper. Two of these elements—frequency of service and vehicle capacity—are closely related to technologies. The other 2 elements—trunk and branch lines and regular and commuter transit—concern the transit network and the role given to transit in urban transportation.

Frequency of Service and Vehicle Capacity

The relationship of frequency of service and vehicle capacity strongly affects both system cost and passenger cost. If the operator operates large units at long headways, cost is always reduced but passenger waiting time is increased. Because full automation permits high frequency of service with short trains and no extra cost, frequency can be increased as a direct function of passenger volume theoretically to the level of line capacity. With most transit systems, this frequency would be 30 to 120 operating units/h depending on station operations, speed, safety requirements, and the like. In practice, as this frequency is approached, service reliability and efficiency begin to decrease, progressively increasing operating cost.

Figure 3 shows that, if increasing passenger volume is served by increasing frequency of operating units with fixed capacity, unit cost of the system remains constant and average passenger cost (time) decreases. When maximum possible vehicle frequency on the line is approached, operating cost begins to increase rapidly. From that point, instead of further increasing frequency, one can increase line capacity by using higher capacity operating units without any effect on unit cost. This can be done by coupling vehicles into trains.

Vehicle capacity for medium-capacity automated transit (MCAT) systems is often a subject of different opinions. Many suggestions are that small vehicles with 12 to 25 seats and some with 20 to 30 standing spaces should be used for a more personalized service. The diagram in Figure 4 clarifies some aspects of this. Figure 4 shows the physical relationship of frequency, operating unit capacity, and capacity offered on a line. The region of relevant values is delineated by rather liberal assumptions. The minimum peak-hour volume that would justify an automated system is assumed to be 3,000 persons. On the upper end is the volume of 10,000 persons/h. Beyond this light rail transit and rapid transit are clearly dominant. The lowest acceptable frequency for an automated system is considered to be 10 vehicles/h; the highest, with currently available technology, is 40 vehicles/h; with technological improvements, this would be 60 vehicles/h. These improvements may be expected in the foreseeable future. The diagram shows that for all conceivable applications of MCAT systems, which are delineated by dash lines, the absolute minimum capacity of operating units should be 50, but, in most cases, it should be 100 to 300 persons. Because modern transit systems must be designed mostly for sitting, these capacity requirements are substantial; and, because providing a given capacity by a small number of large vehicles is more efficient, it is concluded that the minimum capacity of vehicles for automated systems should be about 40 to 50 spaces, most of which should be seats.

Trunk and Branch Lines

Trunk and branch lines affect network configuration and type of operation. Ability to service branch lines without significant degradation of trunk line operation (reduced capacity and reliability) is a major asset of any transit technology. However, because operation on branches may be quite different from operation on the trunk line, compatibility of trunk and branch sections can be achieved if certain conditions are met.

1. If the trunk line has a high ROW (category A or B), branches should also be free from frequent delays to prevent service degradation on the trunk.
2. Branches should have at least moderate passenger volumes so that the same vehicles can effectively serve both the trunk and branches.
3. Because services with very low volumes require smaller vehicles (and sometimes a different type of operation, such as dial-a-ride) than do high-capacity lines, lightly traveled routes should be operated as feeders with transfers to major lines.
4. The number of branches should be limited by the requirement that the sum of frequencies on individual branches must be somewhat lower than the maximum frequency that the trunk line can handle to minimize the impact on the trunk line of deviations from schedule on branches. The only way to handle the cases in which sum of branch frequencies exceeds trunk line capacity is to couple vehicles at converging points. This operation has had limited applications in some cities (LRT in Göteborg, Sweden). Eliminating all stations from the trunk is, of course, another solution to this problem, but it has serious disadvantages, as further discussion will show.

The mode least adaptable to branching is rapid transit because it must have controlled ROW, the cost of which makes extensive branching economically infeasible. Operationally, more than 3 branches are not recommended, although there are cases

Figure 3. Unit transit costs for single-vehicle and train operation as functions of passenger volume.

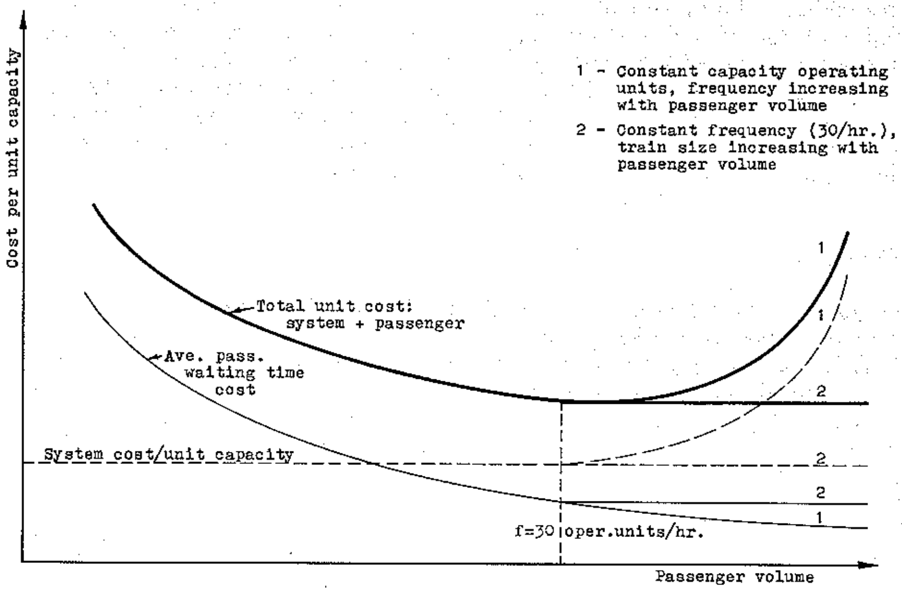
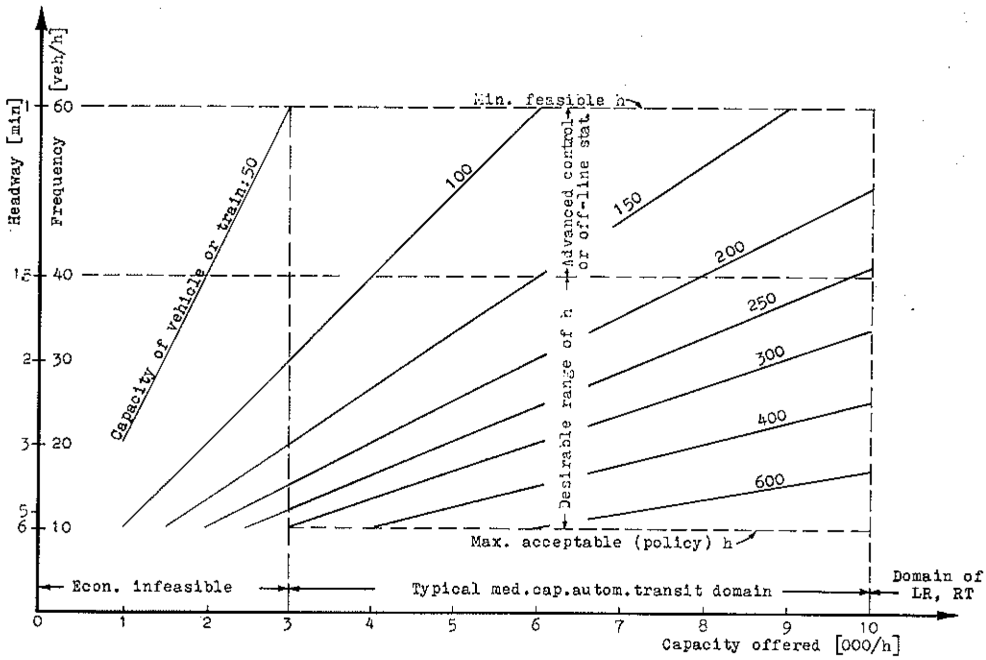


Figure 4. Relation of required frequency and operating unit capacity for medium-capacity automated transit.



where 5 to 6 branches are operated (London, Munich S-Bahn).

Because it does not require special fixed facilities, the bus mode is the mode most adaptable to branching. This physical ability often influences the operator to use it to such an extreme that the system has far more than the optimum number of branches, since it violates some or all of the conditions for merging given above.

Light rail transit is between these 2 modes. Operationally and economically, it can serve branches much more easily than rapid transit can, but much less so than buses can. In most cases, LRT is capable of serving as many branches as physical conditions, investment requirements, and operational efficiency permit.

Regular and Commuter Transit

Regular and commuter transit as shown by Sullivan (6) and Vuchic and Stanger (10) are 2 distinctly different types of service. Regular transit consists of a network of lines with stations and transfers between them; it operates during all daily hours. All vehicles usually stop at all stations although skip-stop, express, and other accelerated operations are possible. Commuter transit consists of bus collection routes in suburbs, nonstop operation into the city, and distribution on 1 or several routings through the central business district (CBD).

Consisting of many branch routes in suburbs and several routes in the CBD, commuter transit provides very low frequency of service on most origin-destination pairs. The reason for this is that, even for a very high frequency of operation, F, on the trunk line, the average frequency on any 1 route between m suburban feeders and n CBD distribution routes is equal to $F/(m \cdot n)$. Because this type of operation usually does not allow off-peak service, commuter transit is actually similar to car pools. It provides direct (no-transfer) fast service to a great number of people traveling to the CBD, but it does this very few times per day. It usually does not provide for non-CBD trips, even for those between different points along its corridor.

A schematic presentation of regular and commuter transit is shown in Figure 5. Commuter transit has some advantages over regular transit.

1. It provides a more direct (no-transfer), higher speed service for CBD-oriented commuters.
2. It requires much less dependence on the automobile for access to transit.

Commuter transit also has some disadvantages when compared to regular transit.

1. It can serve few non-CBD-oriented trips.
2. It offers much lower quality off-peak service.
3. It has a much lower frequency of service even during peak hours.
4. Its extremely high peak-to-base ratio and high labor intensity make it less economical.

This comparison clearly shows that commuter transit, exemplified by express bus lines in many U.S. cities (Shirley Busway in the Washington, D.C., metropolitan area and many lines in New York, Boston, and other cities), represents a convenient service for regular, peak-hour, CBD-oriented commuters, but it does not provide the complete service required from transit, which is mobility throughout the urban area at all times. Transit networks consisting of each of these 2 types of services are shown in Figure 6. Commuter transit is therefore a supplement but by no means a substitute for regular transit. This conclusion is not necessarily related to the ROW category or guidance technology of modes although commuter service usually is operated by buses.

Incidentally, it can be shown that many commuter bus systems could be improved by separating operating branches into independent feeders to trunk line as well as by introducing some stations on the trunk sections.

Figure 5. Corridor service by regular and commuter transit.

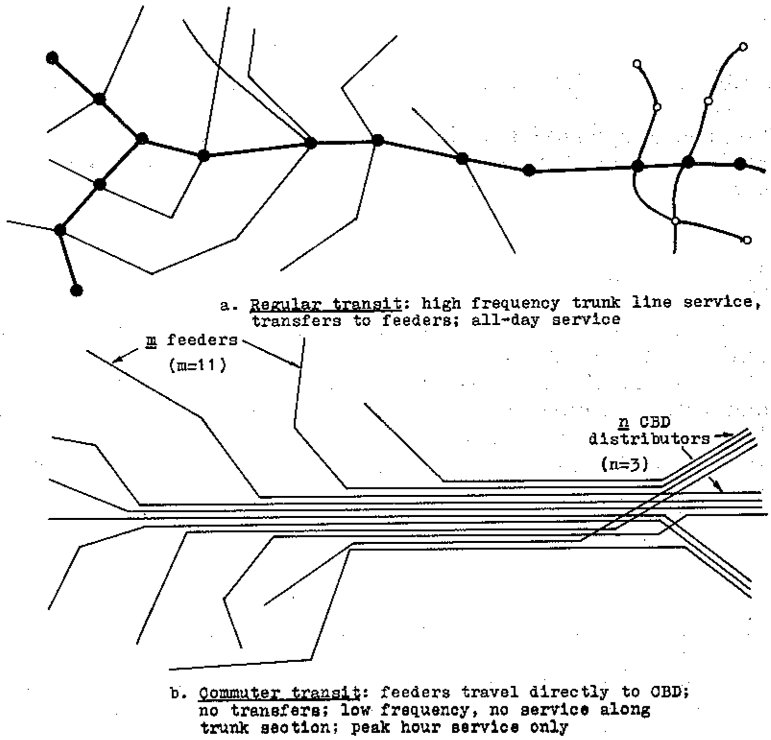
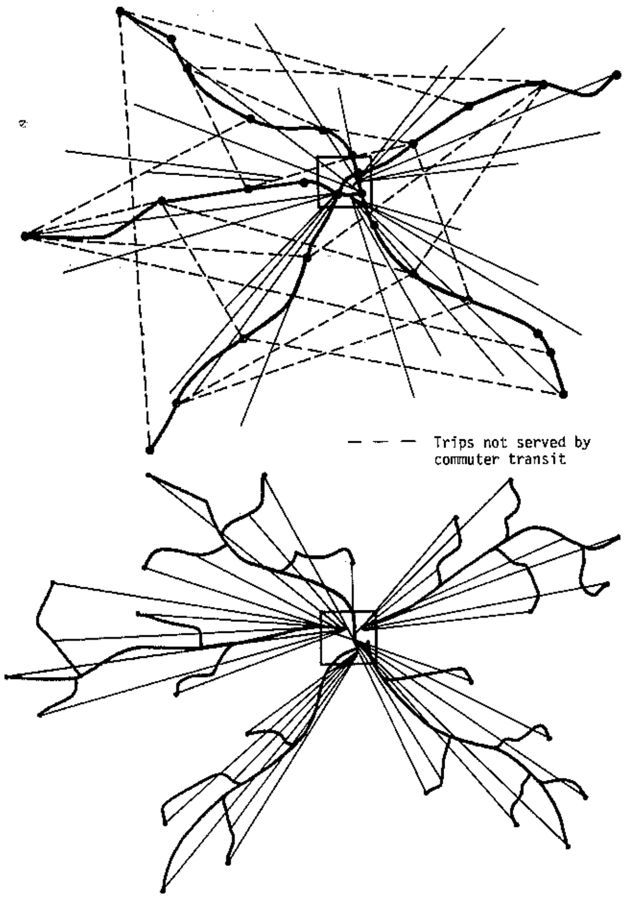


Figure 6. Urban networks of regular and commuter transit.



A BRIEF REVIEW OF DEFINITIONS AND TERMINOLOGY

The preceding analysis of the major components and characteristics establishes the groundwork for precise definitions of the concepts and terminology related to light rail systems.

Light Rail Transit

Light rail transit is more than a technology; it is a mode that combines technology similar to that of streetcars (tramways) but operated on a category B ROW. This puts LRT into a functional category of semirapid transit. Its definition therefore must include not only information on vehicles but also information on ROW and operation. Light rail transit is a mode consisting of electrically powered, modern rail vehicles operating in 1-, 2- or 3-car trains predominantly on exclusive rights-of-way. Modern implies quiet, spacious, aesthetically pleasing vehicles that provide high-quality ride.

Pre-Metro

Pre-Metro is a light rail mode that is a transitional system, such as those found in Brussels and Düsseldorf, for rapid transit.

The boundary between LRT and streetcars is not clear because many streetcar systems are gradually upgraded into light rail systems. The "boundary" between LRT and rapid transit (RT) is, on the other hand, quite clear: RT has fully controlled ROW (category A). The 2 modes, however, can be fully compatible in operation as they are in Frankfurt.

Light Rapid Transit

Light rapid transit is a mode that has LRT vehicles and stations (platforms for up to 3 cars only) but has fully controlled ROW. This mode usually has a third-rail power supply and high-level platforms (Norristown Line in Philadelphia), which makes it a hybrid of LRT and RT. Although there are only a few of these modes in operation, this "small-scale RT" may gain wide application if full automation of transit operation is developed to an operational stage. The intermediate capacity system (ICS) planned for Toronto most probably will be this mode.

Rapid Transit

Rapid transit systems are systems operating exclusively on controlled ROW. They are capable of providing high line-haul capacity, high operating speed, and a high degree of safety (fail-safe operation). The great majority of rapid transit systems use rail technology; most other guided systems also belong in this category. Examples of these are the rubber-tire rapid transit systems in Paris, Montreal, Mexico City, and Sapporo, Japan; monorails such as the airport line in Tokyo; and medium-capacity automated transit represented by the Westinghouse Transit Expressway and Airtrans systems. Unguided technologies, such as buses and trolleybuses, have never been used for rapid transit. Buses on busways also operate on surface streets; therefore, they belong, as light rail does, in the category of semirapid transit.

COMPARISON OF LIGHT RAIL WITH OTHER MODES

Local conditions have a significant influence on the efficiency of different modes.

Comparison of modes therefore can be made only in general terms, and nontypical conditions may change some of the relationships.

Regular Bus and Streetcar Systems

Regular bus and streetcar systems belong to a different ROW category than LRT does and represent distinctly lower service quality and investment cost packages than LRT does. In areas where category C ROW is not a serious handicap, such as on suburban, lightly traveled streets where required capacity is low, the advantages of LRT are far smaller than the advantages of buses. Thus the latter mode is superior. When, on the contrary, high passenger volumes or requirements for a high-quality system justify provision of category B ROW, then LRT is superior.

Busway Systems

The busway mode is more similar to LRT than the regular bus is. Yet comparison of these 2 modes can be complicated if the busway is operated as a commuter service only. In that case, a 2-step comparison is appropriate. The first step is to compare commuter bus transit with regular bus transit (stations on the trunk section and all-day service). As pointed out, regular transit usually should be the basic system and be supplemented by commuter transit when demand justifies it. The second step is to compare regular bus transit using the busway mode with LRT mode, both of which have bus feeders in the suburbs. Preceding analyses and other studies (10) show that the bus has the advantage of easier branching and, therefore, requires fewer transfers, but it is inferior in performance (comfort, speed, capacity, and safety) on the trunk section. In the CBD, LRT usually requires higher investment facilities than buses do, but it also provides a much higher quality of service. Actually, CBD distribution represents a serious bottleneck for most busway systems, and, in most cities, this problem cannot be solved because of the inability of buses to operate in tunnels without major problems. Consequently, for a corridor with a long trunk line and when the possibility of providing partially or fully separated ROW in the CBD exists, LRT is the superior mode. If a large number of feeders converge onto a rather short common route and CBD streets are not seriously congested, the busway tends to be the favored mode.

An important point is that transit routes regardless of mode preferably should follow alignments on major avenues rather than freeways to provide better accessibility for the population in the area.

Another important difference between LRT and the busway mode is in their approach to ROW upgrading. Light rail transit is first provided high-quality ROW in the CBD, where congestion is most serious and benefits from less congested streets are the greatest. Outlying sections can have more crossings because the lower traffic density does not cause major interference. The busway mode, on the contrary, has high-quality ROW in the outlying areas but degrades to street running in CBD. This is the most serious single drawback of the busway mode.

Rapid Transit

Rapid transit, as clearly shown by Lehner (2), represents a higher quality and higher investment mode than LRT does. The superiority of LRT with respect to lower investment, greater physical compatibility with urban environment, and adaptability to staged development are important advantages, and they make LRT a more rational choice in many cities. However, transit planners should not believe that LRT can offer the same performance as RT can for a lower investment. The advantages of RT in terms of higher speed, safety, capacity, labor efficiency, and passenger attraction are significant, and, in many cities, they are more important than the lower investment and other advantages of LRT.

New Modes

New modes, mostly MCAT, which are often given the nondescriptive name "people movers," represent a promising concept because they allow higher quality transit in smaller cities than is currently feasible. This also is the primary role for many LRT applications. Actually, the following will show that the 2 concepts are fully compatible.

Various MCAT systems, such as Transit Expressway, Airtrans, the Morgantown, West Virginia, system, ATC, VAL (France), and Krauss-Maffei (Germany), incorporate various permutations of positive and negative unconventional features in their guidance technology, switching, vehicle capacity, and type of operation. Advantages of the positive innovations thus are, in most cases, either obscured or outweighed by the disadvantages of unsound features in the concept of each mode (3, 11).

A systematic approach based on analyzing each feature separately and combining them into a mode afterward is recommended as more promising for development of a successful system than the approaches used by most developers in the past. If the comparisons of individual system features previously presented are analyzed and the best features required for applications of MCAT modes are selected, one can see that the preferred features would be the following:

1. Operating unit capacity of 50 to 200 persons (the latter obviously requires coupling of cars into trains),
2. Category A ROW,
3. Rail technology, and
4. Automatic operation.

This actually defines an automated light rapid transit mode. It is thus clear that LRT systems can be designed so that they can be upgraded into an MCAT system. This compatibility of LRT with new mode concepts may prove to be highly significant in the future, provided full automation becomes operational.

POTENTIAL ROLES OF LIGHT RAIL TRANSIT

Most large cities use RT as the basic transit mode and supplement it with extensive bus networks. Small cities obtain adequate service from buses only. The medium-sized cities, however, face a dilemma if only these 2 modes are available; they need better service than buses can provide, but they cannot afford the high investment required for RT. This is the reason that only those medium-sized cities that use LRT (Zurich, Göteborg, The Hague, Hannover, and others) have adequate transit service today. Mobility in them is vastly superior to that in similar medium-sized cities in countries that have generally abandoned rail transit, such as Great Britain, France, and the United States.

Some lay observers have posed this question: Why are we returning to LRT after abandoning streetcars as inefficient? The fact is that, if the LRT concept is understood properly, it is clear that introduction of this mode is not a step backward but a major step forward in upgrading the existing surface transit systems. The potential for introduction of LRT into our cities lies in the fact that LRT is better adapted to separation and preferential treatment than are streetcars and buses, that it offers a higher service quality (speed, reliability, and riding comfort) and that it has a better image. Most important, LRT can, because of these features, attract passengers that surface transit cannot. Moreover, LRT is environmentally superior because of its lower noise and because it does not pollute the air. Many cities may find these features worth the higher investment.

The most popular question on the "volume threshold" for LRT cannot be given a simple answer. Many existing LRT lines operate successfully with peak-hour volumes that are as low as 2,000 persons; new lines with such volumes can be justified, however, only when low-cost ROW is available. At about 4,000 to 5,000 persons/h, LRT becomes operationally and economically superior to buses. At 10,000 to 12,000 persons/h RT may be superior if the ROW for it is not excessively costly. Where RT would require an extremely high investment, LRT can be a more economical solution even for 8,000 to 20,000 persons/h although service quality will be lower. It should be pointed out, however, that 2 different modes never attract the same number of passengers. Changing from bus to LRT or from LRT to RT always increases patronage.

Light rail transit can serve several roles in different cities. In medium-sized and some large, but low-density cities (Göteborg, Düsseldorf, Bremen, Amsterdam, Vancouver, possibly even Los Angeles), it can be the basic mode. In many cities with RT, complementary or feeder service can be provided by LRT (Boston, San Francisco, Milan, and Moscow). Many special services (individual corridors in small cities or resorts, shuttles, and the like) also can be operated by LRT.

CLOSING REMARKS

There are indications that LRT has potential for introduction in dozens of U.S. cities. The definitions of its place in the family of transit modes, given here, can serve for general orientation, but they must be supplemented by studies of conditions and comparisons of alternatives for each potential application. Each one of the major modes is superior to others under certain sets of conditions.

Major progress in improving technology and modernizing operations of LRT systems that has taken place during the last couple of decades in West European countries is largely unknown in the United States. Modern LRT systems can be introduced into U.S. cities with only minor modifications to local conditions. However, there are several directions in which this mode is likely to be further developed. The analyses presented here lead to certain observations with respect to the future of LRT and related modes.

Developments of LRT as well as other concepts would be greatly stimulated if research and development efforts were redirected from examination of various new systems to a systematic examination of individual mode components, such as:

1. Fully automated transit system operation (the one absolute essential of all new, guided concepts that should be developed on rail systems first to eliminate technical problems unrelated to automation from which all new systems suffer),
2. Optimal vehicle size,
3. Different guideway technologies,
4. Value and practicality of off-line stations, and
5. Acceptability of aerial structures for transit.

The federal government through the Urban Mass Transportation Administration should be the logical leader in this research and development effort. Light rail transit is the best technology for testing most of these components and concepts although applicability of their results would greatly exceed this specific mode.

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LIGHT RAIL PERMANENT-WAY REQUIREMENTS AND SOURCES

Robert J. Landgraf, Shaker Heights, Ohio,
Department of Transportation

This paper sets forth the technical requirements for the permanent way needed in construction of light rail transit facilities and then develops sources for assembling rights-of-way. Described first are the physical capabilities of light rail transit for grade, curves, and clearances. Requirements for the guideway are established with the development of standards for track work suited to light rail transit. Latest techniques in track component design are evaluated. Pitfalls to be avoided in light rail facility design are pointed out. General requirements for stations are set forth with particular emphasis on space needs. Types of platforms, shelters, and security enclosures are described. Station needs for light rail transit are contrasted with the needs of full-scale rapid transit. Sources that can be considered for light rail rights-of-way are treated in a way intended to stimulate the imagination of the engineer and planner in locating potential routes. Dealt with are surplus railroad tracks, boulevard and freeway center strips, canal beds, stream channelization, electric transmission lines, parkways, street running, reservation of streets, and the selective application of elevated lines, bridges, and subways to light rail transit. Advantages and limitations of each type of right-of-way are explained.

This paper will discuss the technical requirements for the permanent way needed in constructing light rail transit (LRT) facilities. It also will develop sources for assembling rights-of-way.

CONFIGURATION LIMITS

Grades

An outstanding feature of LRT lines compared with most other forms of fixed-route transit, whether they have a fixed guideway or do not, is its physical flexibility. Light rail transit can do things that a heavy-duty rail line or a busway cannot approach.

Grades of 6 percent or more both ascending and descending are common with light rail vehicles. Short grades of up to 14 percent are the extreme limit. Some light rail grades such as those in Pittsburgh were simply too steep for bus replacements; other routes had to be developed.

Because of low vehicle weight and high power-to-weight ratio, LRT can handle grades at a faster speed than the usually heavy trains can. The desire to operate long trains in conventional rapid transit work precludes doing some of the things that have been done with LRT. The controlling factor is braking capacity, a feature that easily can be made higher than standard on light rail vehicles.

Curves

Vertical curvature can be rather extreme on LRT compared with that on conventional rapid transit. Having no requirement for riders to pass between vehicles, light rail vehicle design can provide great freedom in vertical curve limits, both sag and crest. Single vehicles made to the rather short Presidents' Conference Committee (PCC) truck centers can do amazing things in this respect. When light rail vehicles (LRVs) are operated in multiple units, the couplers with their drawgear and radial carriage requirements can tend to restrict the vertical curves that can be taken. However, this limit is not reached on any active North American operations.

Articulation can place fairly restrictive limits on vertical curves, though the new standard light rail vehicle seems rahter liberal in that respect with a limit of 310 ft (94.5 m) radius crest and 460 ft (140.3 m) radius sag (1, pp. 2-4, paragraph 2.1.7). Passenger apprehension of the change in curvature might be greater with articulation. Just about anything reasonable can be done. The decision involves how much seating capacity to sacrifice to make the connecting drum larger.

Horizontal curve capability is what sets LRT apart from conventional rapid transit. Light rail transit was originally conceived to have a track that could accommodate the right-angle intersections on city streets.

Light rail cars usually have been designed with rounded ends. This has been done not so much for aerodynamic design as for clearance on turning, particularly when they are run in multiple units. Couplers are radial; they swing in a semicircle rather than ride in a striker box as they do on a railroad car. When knuckle couplers are used, the capability of going around curves becomes very high.

Today's light rail vehicles are designed to negotiate curves of 42-ft (12.8-m) inside rail radius (1). Anything tighter than that would place limits on features other than the coupling or articulation. Car width, location of trucks, and wheelbase might have to be restricted unduly.

Usually, the most extreme horizontal curves in a light rail system are in the non-revenue tracks required for reversing single-end vehicles at the end of a route. The single-end design is highly desired in markets that demand maximum seating, and the relative inflexibility and need for turning trackage of the single-end car can be a favorable trade-off for its lower first cost and greater number of seats than double-end cars. Loops and Ys can be placed in a relatively small space because of the 42-ft (12.8-m) radius.

Clearances

Clearances can be very close in any fixed-guideway system when compared with those needed to allow for steering variations. Indeed, only the sway of the vehicle and a small allowance for air movement and any door folding need be considered for clearance in tunnels. Recesses for maintenance personnel to stand clear are needed at regular intervals. However, the low first cost of very tight tunnels for a light rail system may result in a later generation being unhappy with what was done originally. The Boston Central Subway testifies to this problem; later add-ons were built less restrictive than the original construction. The possibility of eventual conversion to full-scale rapid transit ought to be considered at the beginning.

An important factor not to overlook when one establishes controlling clearances is whether railroad interchange will ever be needed. Many things can be done on vertical and horizontal curves with railroad cars handled 1 at a time, but no side or top clearance means that no car can pass. Of course, not all parts of a light rail system may be candidates for interchange traffic, and designers can take this into account. As in all engineering work, a cardinal rule is to plan ahead. Many of the light rail systems built on standard-gauge track in the early years of this century provided full railroad clearances for the freight cars of their day.

The maximum clearance desired also can be important. There is no gain in taking on responsibility for more land than a light rail operation can use to any advantage. This situation has arisen at Shaker Heights, Ohio, where a light rail line may be absorbed into the Regional Transit Authority (RTA). Boulevard center strips of 60 ft (18.3 m) and 90 ft (27.4 m) were originally provided, and title to these has been held by the transit system. However, when the system goes from the city to the RTA, a perpetual easement for 42 ft (12.8 m) may be granted; the city would retain the land and maintain the landscaping (2). Existing paved platforms, which are adequate, fall within these dimensions.

It is possible to provide a double-track light railway line having cars 9 ft (2.74 m) wide and ample, 40-ft-wide (12.2-m-wide) side platforms directly across from each other. This leaves plenty of room for landscape screening except at the platforms. Any width beyond 45 ft (13.7 m) saddles the light rail operator with more land than can be used. Someone is going to compel the operator to keep that land free of weeds or mow it. By offsetting platforms and using reverse curves in the track, widths as narrow as 32 ft (9.8 m) could be used. For single track without stations, or for each additional track, a horizontal allowance of 14 ft (4.3 m) is adequate.

Vertical clearances must leave enough room for overhead wire and not cause insulating problems or difficulty with current collectors. Twenty ft (6.1 m) from top of rail to ceiling should be enough for any light rail application and still allow later conversion to any other rail use. A minimum of 14 ft (4.3 m) should be observed if there are severe restrictions because a potential bottleneck has been built in.

GUIDEWAY REQUIREMENTS

Rail Weights and Types

Light rail lines in the early days used just what the name says: light rail. It would be difficult to find any 60-lb/yd (29.8-kg/m) rail remaining, but at one time it was very common. Many interurban lines were built with 75-lb/yd (37.2-kg/m) rail. The minimum-weight T-rail now in common use on light rail lines is 80 lb/yd (39.7 kg/m).

A desirable standard for light rail operations is 100-lb/yd (49.6-kg/m) rail. A fairly heavy rail, because it is more rigid, can help to overcome a poor roadbed. The 80-lb/yd (39.7-kg/m) rail in wide use is just too light, and 90-lb/yd (44.6-kg/m) rail is becoming difficult to obtain. One-hundred-pound-per-yard (49.6-kg/m) rail, particularly in the ARA-A cross section, will probably remain common for many years.

Some rebuilding of existing light rail lines has been done with much heavier rail. Anything larger than the popular 115-lb/yd (57.0 kg/m) AREA rail may be a waste of money, unless a larger section is wanted for greater electrical return and it proves more economical than supplementary negative cable. The trade-off must take into consideration that the rail will have to be replaced eventually and that the cable should last indefinitely.

The use of grooved rail originated with street railways. It still finds wide application even in open running on curves because it provides the safety feature of a separate restraining rail at a low cost. The underground portions of the Rotterdam Subway in the Netherlands are built with grooved rail; they probably want very much to avoid any derailment (3).

Grooved rail was originally meant for pavement on which the paving material was likely to fill up the flangeway inside T-rail and cause cars to climb and wander off the rails especially on curves. It is recommended for the portions of the line that are in pavement. However, interchange railroad cars and their larger wheel flanges will be difficult to handle unless the very large rail sizes designed especially for full-size railroad car wheels in pavement are used. New light rail projects should consider adopting Association of American Railroads standards on wheel contour to ensure easy availability of track components.

Rail Gauges

Rail gauges for light rail applications have ranged from meter gauge common in Europe to as wide as 5 ft 4½ in. (1.64 m) in the Baltimore street railway system (4). The narrower gauges [meter and 3 ft 6 in. (1.07 m)] originally were adopted for economy; ties could be shorter, and the ballast cross section was narrower. These gauges generally are inadequate for U.S. practice. To avoid poor riding of cars, narrow-gauge rail lines must have better maintenance than standard-gauge lines, particularly for cross level. The meter-gauge light rail lines of Europe usually are maintained superbly.

The nonstandard wide gauges [4 ft 10⅞ in. (1.50 m)] once fairly common in the United States and still surviving in Toronto were imposed by city councils who wished to prohibit physically the operation of interchange railroad cars in city streets. So-called wagon gauge, which is about 5 ft 2½ in. (1.59 m), survives in Pennsylvania, in both Philadelphia and Pittsburgh.

Although the wide gauges are better than narrow gauges for controlling sway, they have no particular riding merit and have cost disadvantages in light railways, for which 4 ft 8 in. (1.44 m) is just about right for the usual light rail car. Wide gauges of 5 ft 6 in. (1.68 m), which are used in Spain and on Bay Area Rapid Transit in San Francisco, are better than standard gauge for today's giant railroad operations that have very high cars and fast unit trains, but a general change probably will never be economically justified.

Any new light rail system should be built to the common gauge of the country in which it will be located. Extensions to existing nonstandard systems, such as might take place in Pittsburgh, Philadelphia, or Toronto, should follow existing gauge. There are 3 advantages to standard gauge or the country's common gauge. First is the availability of standard components. Second is the possibility for railroad interchange on parts of the line where other conditions permit. Third and perhaps most important is the capability to transport materials for extensions and maintenance projects in 1 rail vehicle from supplier to installation site. A substantial unnecessary cost for transferring materials from one car to another thus can be avoided. Any new light rail line ought to have, at absolute minimum, the ability to handle the interchange of 50-ft (15.2-m) flatcars except at turning loops and Ys and other problem locations where no full-clearance solution is practical. Each stretch of the line blocked from the others by such a clearance restriction ideally ought to have its own access to the general rail network.

Special Work

For ease of availability, special work (frogs, switches, crossings) ought to be standard railroad or heavy rapid transit types except when tracks are in pavement. When using the street types of special work intended for paved surfaces, one must take care that the rail contour and flangeways will accommodate the wheels of any equipment to be used on that part of the line. Deep flanges can readily smash street railway switches; again, any new project should use full-depth railroad types of paved-area special work.

Special elastic switch points and improved frogs have been developed in Europe and are used widely in light railways. In the United States, use of the spring frog, which required conscientious maintenance, has declined. One special work item that should be considered more often is expansion points. Expansion points minimize problems with continuous welded rail (CWR), especially on sharp curves. If CWR with all its advantages is not installed correctly and is not maintained to the best standards, it can be terrible for a light rail line whose cars are sensitive to misalignment. At the speeds proposed for most new light rail projects, this alignment matter can be very important. In other words, CWR must be done right or be avoided. Field welding is not as suitable as shop welding because the latter generally gives better accuracy of alignment.

Track Structure

The time-proved support for all types of railroad still is treated hardwood ties on crushed-rock ballast. For light rail, the ties can be smaller than standard railroad practice. Cross section of 6 by 8 in. (15 by 20 cm) is adequate. Length of 8 ft (2.4 m) is suitable, but 8 ft 6 in. (2.59 m) is more common. Tie centers can be 24 in. (60 cm); this requires 2,640 ties/mile (1650 ties/km) versus 3,000 ties/mile (1875 ties/km) or more for heavy-duty railroads. In a light rail application in which properly selected hardwood ties are used on a well-drained and adequate ballast and in which tie plates are used and good maintenance practices are observed, the ties should last an average of 40 years.

Concrete ties are becoming more established in the U.S. market even though their problems seem to continue year after year. Failure by cracking is still too high; special fasteners are required; and insulation is always a problem where rail-actuated signal systems are involved. It is awkward to replace a few concrete ties; the problems of gradually converting existing track to concrete are formidable.

Metal ties have been used in rail applications where speeds are low and cushioning demands are light, such as in yards and spur tracks. However, in an electric railway with return current in the track, they promote electrolysis. They probably would generate considerable noise except at very low speeds.

Slab track, on which the ties or a substitute method of support and gauge holding are completely enclosed in 1 or more concrete pours, has proved satisfactory in preserving excellent alignment and minimizing maintenance costs. Pittsburgh has several examples, some of which have been in use a long time. Indeed, joint use of private right-of-way by buses requires this method and pavement up to top of the rail. The line thus becomes a restricted-use street for public transit vehicles only. A law enforcement problem is created in keeping automobiles out. Disadvantages of slab track include a far higher installation cost than ballasted track and the difficulty of using track-actuated signal systems, which require special rail-to-rail electrical insulation. Noise transfer ought to be studied carefully before a decision is made to install slab track at a particular location. Major railroads are studying the entire question of track structure because it is believed that the present standard practices are inadequate for heavy loads at high speeds. Open types of slab track with rail and fasteners fully exposed show promise, and considerable advanced testing is going on in both Europe and Japan (5). However, the conventional standards even when applied at the minimums suggested in this paper have served light rail very well. Moreover, it must be emphasized that there is no substitute for proper track maintenance.

STATIONS FOR LIGHT RAIL TRANSIT

Limits of Range

Stations for light rail facilities can vary all the way from a mere patch of cleared ground to elaborate enclosed facilities in a subway or terminal building. The type of station to be provided is a function of several variables: passenger volume, train frequency, climate conditions, method of fare collection, immediate surroundings, and civic requirements.

One thing to keep foremost in mind when one plans stations for a light rail facility is that most sites should be able to be upgraded later if conditions warrant. When possible, it is important to obtain control over enough land at the station locations at the beginning to allow for later elaboration. Space for parking requirements ought to be a major consideration in locating some of the stations.

Platforms

Most LRVs have the first step at a considerably greater height from rail head than the intervals between steps including the car floor. This extra height is to give better clearance from snow or foreign objects near the track. It is therefore helpful to provide a platform somewhat above rail height as is done in commuter railroad practice. The PCC car first-step height was selected to work very well from a "safety island" with foldout doors, and it is quite difficult to board from pavement (rail-head) level (6).

The practice on some U.S. light rail lines of paving up to the running rail on open track to give a no-cost edge to the platform should be avoided. Not only is the platform too low, but an ideal environment for electrolysis is created. The seam between the paving (usually asphalt) and the rail quickly opens up, and moisture, salt, and dirt go in.

Where it is desired to run railroad interchange traffic, the standard gauge light rail lines should avoid platforms that are so high and close to the running rail that they interfere with railroad clearances. Of course, if other factors, such as tight tunnels, preclude interchange, platforms do not matter. With this limitation in mind, it is a good feature of light rail lines that floor-height platforms can be constructed at selected high-volume stations not on interchange territory simply by equipping some or all vehicle doors with automatic high-low steps. This is being done on the center doors of new LRVs for San Francisco. The downtown subway will have floor-height platforms to speed passenger flow.

Platforms on light rail systems usually are on the outside of double tracks, but center platforms often are used at locations accessible only by stairway or escalator to avoid the need for 2 platforms at each station. Double-end cars or left-side doors make platform location choice flexible; in some instances, left-hand running has been used with single-end cars having doors on 1 side only to allow use of center platforms. Note that light rail systems can be adapted to any need in this respect.

Station Enclosures and Security

When on-board fare collection is used, light rail operations need not have fenced stations. It is desirable to have fencing in the center strip between tracks at busy stations to prevent passengers from stepping across in the way of oncoming trains. Reverse-flow, off-train fare collection concentrated primarily at 1 or a few points also can eliminate need for fencing at all but these points. With a prepaid fare collection, the security needs for LRT can become as great as for standard rapid transit systems, which eliminates one of the low-cost advantages of LRT. European-style self-validating fare systems avoid this problem. Certainly fencing should be minimized to help light rail stations blend into the environment.

Shelters or buildings for LRT can be minimal where frequency of service is good. The main purpose of a light rail shelter is to protect the passenger from the weather. Monumental facilities are to be avoided unless the light rail boarding point is only an auxiliary use of the building.

Any shelter should provide good visibility on the inside as well as the outside. Passengers feel safer when they are not hidden. The new designs of shelters that use metals and clear plastics are especially suited to light rail. These designs give the impression of permanence without seeming overbearing.

Unless frequency is very high, little amenities such as interior lighting and radiant heat are desirable. Every shelter ought to have a good bench that is large enough for the patron to wait in comfort. Making transit benches narrow enough to keep vagrants from sleeping on them is typical of negative thought in the industry.

An attractive idea for downtown portions of light rail lines is to run the tracks on tangents or gradual curves adjacent to the sidewalk on a lane reserved exclusively for transit vehicles, taxis, and emergency automobiles. This method makes the sidewalk the continuous platform and helps to solve problems of mixing buses and light rail cars on the same street. No shelters are needed because there are usually plenty of stores and building lobbies to provide shelter in bad weather. The concept of combining this layout with transit malls could be very attractive. Allowance must be made for unusual geometry when turning from one street to another.

SOURCES FOR LIGHT RAIL RIGHTS-OF-WAY

Surplus Railroad Tracks

Today, a great deal of attention is being given to lightly used railroad tracks in and around urban areas as the most obvious opportunities for establishing LRT service (7). Freight-only branches that go radially from downtown, such as those in the Dayton, Ohio, proposal, are good candidates. Freight operations can be continued on a twice-daily basis, and a short train can run during a midday lull. Any fairly long trains and most switching would be confined to night hours after the transit operation is closed. Institutional problems on work rules, crew sizes, and jurisdiction among unions are encountered, but these obstacles are of a political rather than a physical character. They should be overcome by agreement in advance.

Second main or third main track no longer needed on a full-time basis offers a chance to establish LRT economically. Indeed, such multiple-track facilities often have grade separations and plenty of room for stairways and platforms already provided. Although the extra tracks may be gone, restoration is fairly easy. The 2 tracks for light rail need not be adjacent, though they might best be in the innermost tracks of such a facility to minimize the need to cross the light rail tracks for industrial switching. Here again, the light rail tracks could be relinquished at night for freight movement. Some proposals involve the use of 3 tracks for both freight and LRT; one commonly is used for both services in the middle of the day.

A few cities, particularly in the East, have obsolescent radial rail routes that primarily were for passenger service; freight service was merely incidental. These commuter facilities can make fine light rail routes and often carry more passengers at a lower unit cost after conversion as shown by the Riverside operation in Boston. Proposals to convert such lines to full-scale rapid transit are often needlessly expensive and not justified by volumes to be realized; LRT then becomes a lower cost alternative. In some cases, the underused or abandoned downtown passenger station can be included advantageously in the light rail plan.

Belt or bypass rail routes in the major cities are looked on now as candidates for LRT as feeders to radial routes. Freight sharing is essential; heavy-duty rapid transit possibly is not justified; so-called railbus did not work out. It is light rail or nothing for such a line.

Boulevard and Freeway Medians

The center strips or "parkways" of boulevards are favorite targets for planners of LRT. After all, that is what many of them were in the heyday of the trolley era. Why not restore them? We must be careful here not to pick such a boulevard while overlooking a better but less obvious right-of-way possibility in the same corridor. Many of these older boulevards have so many cross streets that a light rail line would run too slowly unless some crossings could be eliminated. In general, it is undesirable to encounter grade crossings in boulevards more frequently than station stops, and it helps safety to have both at the same locations unless the light rail car can preempt the traffic signals (7).

A narrow boulevard strip can be used for one track in a light rail line if another linear way nearby can be used for the return. In fact, the 2 tracks of a light rail line could be a city block apart if that is what works out best. Again, light rail is flexible.

Some streets and highways are lightly used because they have been made somewhat superfluous by construction of parallel roads such as freeways. A new median strip could be created for light rail in such older roads without having to take extra land; the new use would interfere little with vehicular traffic. Indeed, the paving could remain as an excellent foundation for ballasted track. Cities with fully developed freeway networks may have several such opportunities.

Older freeways with all ramps at the outside lanes may be suited to light rail construction in the center median, especially if at least one lane for vehicular traffic can be given over to mass transit (8). Such a conversion will become more feasible if the economics of private automobiles and electric mass transit continue in the direction they have been going. Such a light rail line would have the virtue of being as fully grade separated as the freeway it supplements. The practice of placing light rail lines in freeways is common in Europe. The smaller, less obtrusive rail vehicles have somewhat less of a visual impact on motorists than do full-scale rapid transit lines with high-platform stations, such as those in Chicago and Oakland.

Other Linear Ways

Abandoned rail rights-of-way are the ground on which planner and historian meet in today's renewed interest in light rail. There are many stretches of former street railway, interurban, or steam railroad rights-of-way still intact; every one of these in an urbanized area seems at first glance to be a target for LRT. Caution must prevail; perhaps the very reasons why the line did not become a street or highway after the tracks were taken up are valid reasons today for not selecting that route for restoration. The temptation to put LRT back merely because it is cheaper to build there must be resisted; LRT has to go where the customers are.

Old canal beds have made good light rail lines; the existing Newark line and a possible Rochester facility are examples. A high degree of grade separation is built in. A somewhat related possibility for LRT can be found in the channeling or culverting of existing streams. Slopes can be built up with gabions or crib walls to provide a horizontal surface adequate for light rail, especially if a track is located on each side of the stream. Culverting of waterways has been used for making streets; it should be as easy to use for LRT.

Many metropolitan regions are crisscrossed by electric transmission lines. Combining these with light rail facilities is an old idea that had outstanding application in a famous and unwisely abandoned line. This type of routing is being considered for a light rail line in the northeast Toronto area. When the rail-transmission project is planned as a unit, the electric towers can carry the rail overhead contact wire along with commercial power and rail power feeders.

Parks are often linear especially in cities. A light rail line can be blended into the environment of a park better than any other permanent way transportation (9). In Europe, there are several light rail lines with the track intentionally imbedded in sod, as was done on Saint Charles Street in New Orleans. This arrangement makes for quiet running, although track maintenance costs will be increased somewhat and the rail must be kept free of leaves and grass.

Street Running

Operating light rail lines with mixed traffic in the style of a streetcar is a last resort. It should be confined in future installations to those critical locations where no other practical alternative is available. Certainly the major portion of any light rail line should not require the trains to compete with mixed traffic. Some LRT in general-use paving is tolerable in areas where automotive traffic is light.

Light rail operation in streets or portions of streets that have been reserved for the exclusive use of transit vehicles is a completely different proposition. It should be highly desirable especially as a low-cost yet extremely convenient method of downtown distribution. It has found a wide and growing application in the older city centers of Europe. The rebuilt line in the Pittsburgh Mount Washington tunnel combines LRT and a busway. There are various ways to set off the reserved area, from temporary striping to permanent curb-type barriers that still allow passage for emergency vehicles (9).

As mentioned earlier in the discussion of slab track, signaling results in higher costs. Advanced technology involving use of electric eye, radar, or some other unproved sophisticated method could provide the equivalent of signals.

Elevated Systems, Subways, and Bridges

Because of cost, elevated systems, subways, and bridges must be limited to the highest density locations or key bottlenecks. Light rail transit is meant to be a lower cost alternative, and an excess of fully grade separated structures or tunnels can quickly eliminate most of that cost advantage. However, there is no other practical way to cross a freeway or a railroad of major importance.

The subway, as a method of downtown distribution for LRT, has wide application in Europe and in 3 cities on this continent. Aside from costs, it is a mixed blessing. The facility is removed from the customary habitat of the rider, and the subways are difficult to keep attractive. When the light rail line has several branches, there may be no politically realizable downtown solution other than a subway because too many surface streets would have to be sacrificed otherwise.

A general rule to be followed in designing any light rail elevated structures, bridges, or subways is that physical capabilities for heavy rail transit operations must be built in unless no possibility exists that later conversion will be desired. Bridge design should allow excess capacity in any event. As mentioned earlier, LRT tunnel clearances that proved inadequate for rapid transit have been the bane of several underground transit operations. It is better to err somewhat on the side of generosity and leave enough for future generations to work with.

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ELECTRIFICATION AND CONTROL SYSTEMS FOR LIGHT RAIL SYSTEMS

R. D. Touton, Jr., Louis T. Klauder and Associates

This paper provides a broad overview of available electrification and control system technologies for new light rail systems. It is intended for groups with widely diverse backgrounds ranging from city planners to economists and consequently does not deal with detailed, specific, technical design parameters. The portion on electrification is subdivided into sections on power generation, distribution, and collection on the light rail vehicle. The portion on control systems is broader and is divided first into propulsion control on the vehicle and then into systemwide operational control features that are further subdivided into sections on control on the vehicle, control among a number of vehicles, control at a central status reporting area, and automation. The paper concludes with general recommendations for a typical light rail system but recognizes that conditions might require additional or fewer optional features. This is done to emphasize the flexibility and adaptability of light rail systems.

The principles of electrification and control are equally applicable to all modes of rail transport from main-line railroad commuter service to full-scale rapid transit to light rail transit (LRT). Fortunately, as these principles are scaled down to LRT requirements, the cost and complexity also can be scaled down without any serious degradation of the ability to transport passengers effectively and comfortably.

We will concern ourselves first with the basic means by which electrical power is generated, distributed over the system, and finally collected on the vehicles under the term electrification. The term control systems then will be used first to cover propulsion control on the vehicle and then systemwide operational control on the vehicle, control among a number of vehicles, control at a central status reporting area, and automation relationships.

It is important to recognize that LRT is a "here-and-now" technology. It is evolutionary and not revolutionary. Worthwhile designs and even apparatus developed in the past can and should be used where the technology is either still appropriate or has room for growth. On the other hand, dramatic improvements also can be achieved by using current technologies or even by making provisions for using advanced technologies. The key here is selection: selection of the proper design or equipment to do the job. "Old" is not necessarily best but neither is "new" necessarily better. A careful appraisal of the goals and the risks must be made. Technology for the sake of technology must not be part of that appraisal.

Electrification begins at the substation or powerhouse where the appropriate type of electricity is converted or generated for use on the vehicle. Direct current is provided for distribution to the vehicles on line even though, in most cases, alternating current has first been generated and subsequently rectified. Perhaps some of you are aware that a few personal rapid transit (PRT) systems are using alternating-current power. However, in these cases the 3-phase alternating current is collected by 3 power collectors and rectified on board each vehicle for use by the direct-current traction motors.

Direct current was chosen because it was the most easily generated at the turn of the century, but it was soon determined that direct current had another major advantage; that is, it is easily controlled so that motors can be operated at various speeds quite readily. This, of course, is what all electric transit vehicles must do and is especially true of light rail vehicles (LRVs), which must start and stop more frequently than full-scale rapid transit systems or main-line railroads.

However, the use of low, 600 Vdc suffers from high transmission losses over long distances and, unlike high-voltage alternating current, transformers cannot be used to step voltages back up to usable values. These losses stem from the resistance in the distribution lines, and consequently either substations must be provided at very frequent intervals or many additional distribution lines called feeders must be provided. Traditionally these feeders have been heavy insulated wires supported in the air by lineside poles and often have appeared unsightly.

Developments have occurred in recent years that can reduce both the losses and the unpleasant visual impact. For example, new solid-state substations are so small that they can be unobtrusively and economically placed in small underground vaults in city areas or inside small attractively landscaped enclosures in outlying areas. The substations may use convenient local sources of high-voltage alternating-current power, and in many cities these alternating-current sources already have been placed underground.

Now let us consider exactly what type of electrical energy is being carried by the distribution system. For example, in mining operations, 250-Vdc systems are used because of the close proximity of open wires to personnel and structures, but, to reduce losses, extremely large overhead wires are used. At the other end of the scale, older electric interurban systems used 1,200- or even 1,500-Vdc systems because of their need for improved transmission characteristics over long distances. The new Bay Area Rapid Transit (BART) system has selected 1,000 Vdc as being optimum, but the vast majority of existing and proposed rapid transit systems still remain in the 600- to 750-Vdc range. The streetcar predecessors of LRVs also operated at the 600-Vdc level, and this still appears to be a good level in terms of safety, current-carrying capacity, and minimum installation cost. In any case, a great deal can be gained by picking a single standard for future development to maximize interchangeability of parts and reduce production costs as well as use an existing technology based on the extremely modern mining substation designs without significant developmental risks.

Entirely adequate 600-V light rail substations with typical capacities of 2,000 to 4,000 kW are available and can be placed at 2-mile (3.2-km) intervals on the outer portions of any light rail line. Each will operate unattended, turn itself on and off as needed, and, in the event of an overload or failure, will even bypass itself so that adjacent similar substations on either side can temporarily carry the loads. They also are virtually maintenance free, have an almost infinite service life potential, are extremely efficient, and are environmentally sound.

These same self-contained substations can be used on the inner portions of light rail lines, but, if 2 or more lines converge, it may be even more efficient to use larger size units. For example, the San Francisco Muni-Metro will have the capacity to run up to four 4-car trains simultaneously in each power block with an 8000-kW capacity in the downtown subway sections. Fortunately, these, too, are available off the shelf from other industrial applications and have all of the virtues of their smaller brothers.

However, it must be clearly understood that light rail systems do not necessarily guarantee the use of smaller substations than are used with full-scale rapid transit. The required capacity is tied to the number of vehicles that will be in operation, not only the type of vehicle.

There is 1 additional source of power that must not be overlooked and that is the vehicle itself. Of course, the vehicle uses power as it accelerates, but it also can generate power as it decelerates. This characteristic has been known for years, but, in the cheap energy era, it was never developed on any significant scale for transit applications after an initial flurry in the early trolley car days. Luckily, the necessary technology is available, and it is only a matter of developing a business climate to justify going into production of the necessary hardware. One point deserves clarification. Estimates on energy savings by use of vehicle generation of power range from

0 to 50 percent or more but only 20 to 30 percent savings have been demonstrated to date. This saving is a worthwhile goal, though.

With the appropriate source of direct-current power available at suitable intervals along the line, we may now consider how these fixed sources are best delivered to moving LRVs. In the current state of the art, an overhead wire system is used for main-line electrified railroad operations and city streetcars, and a third-rail system is used on full-scale rapid transit systems. A few cities including Paris, London, New York, and Washington, D. C., previously used a plow-and-conduit system in which an arm reached down from under the car into a slot in the surface of the street. Beneath the slot, a pair of conductors were arranged to make contact with the arm as the car moved. Although visually better because no overhead wires were used, the conduit system was incredibly complex and costly to maintain, particularly in later years when streets were salted in the winter and severe corrosion was caused.

The third-rail system can carry high currents effectively as required by trains of relatively high-powered transit cars, but the structure and on-car collection devices are such that speeds must be limited to about 85 mph (136 km/h) for new systems. The Long Island Railroad will eventually operate at speeds around 100 mph (160 km/h) by modifying their present third-rail system, but this exception is based on a cost-benefit analysis that showed that installing a wholly new overhead system was better than long-term maintenance of the third rail.

Although the third rail is covered by insulating material, primarily to safeguard the operating and maintenance staff, the casual unauthorized intruder can receive a lethal shock if any part of his or her body comes in contact with the third rail. Thus virtually all modern rapid transit systems are totally grade separated and often are completely fenced in to protect against this intrusion. Because light rail systems may operate on some sections of city streets and very likely will not be fully grade separated or fenced on their outer extremities, it is not usually appropriate to consider third-rail power distribution.

An overhead system, usually of catenary design, is used on main-line railroads because of its capability to collect power at speeds up to 200 mph (320 km/h). The catenary is the free hanging curve of a line or cable suspended between 2 points. A contact wire is hung from this catenary in precise vertical and horizontal alignment over the track. This arrangement serves 2 purposes. The 2 wires add to the current-carrying capability (a form of feeder), and the precise alignment allows the collector on the vehicle to attain the desired high speeds.

In light rail applications, the overhead contact wire is the best choice in the interest of safety of persons on the ground, but, contrary to a popular misconception, an elaborate catenary system is not always required. This is true because precise alignment is not essential at lower speeds that seldom exceed 65 mph (104 km/h) and because current capacities of main-line railroad character are not needed. Instead, a simple single wire suspended at 100- to 125-ft (30- to 38-m) intervals usually will suffice. This suspension can be a supporting cross-span wire between 2 poles or buildings in city areas or a bracket arm mounted on a single pole adjacent to the track in outlying areas. Those of you who remember streetcars may recall that some people considered this single wire and the related poles to be ugly. However, since those days, myriad other poles, some towering, have sprouted up to carry complex automotive traffic signals and high-intensity street lighting. Very often, installation of a light rail system can provide the impetus to bring order out of this chaos. A single attractively designed pole can be arranged to carry the street lights, traffic signals, and the light rail overhead wire in an aesthetically pleasing and effective manner.

Two successful types of vehicle current collectors remain in use today. The first and oldest is the trolley pole in which a U-shaped shoe slides along the wire to collect power. With carbon as a shoe material, currents of 400 to 500 amperes (399.92 to 499.9 A) (typical of a PCC car) can be collected. With bronze, the current can be increased to 700 or 800 amperes (699.86 to 799.84 A); with steel, it can be increased to 1,000 to 1,200 amperes (999.8 to 1199.76 A), but then the wire must be lubricated. None of these is adequate for the new LRVs because they will require 1,000 amperes (999.8 A) per car and the cost and complexity of wire lubrication would be excessive.

Fortunately, suppliers are working on the problem and new copper-carbon shoes capable of 1,200 amperes (1199.76 A) are being tested in Boston and San Francisco. The trolley pole is inexpensive ($750), simple, and lightweight, and is free to track any wire irregularity in any combinations of horizontal and vertical deflections. However, if the LRV is of bidirectional design, then 2 poles are needed, 1 for each direction.

The second collector is the pantograph in which a long, flat, bar-shaped carbon shoe that is affixed to the top of the wire also slides along under the wire. Contact shoes are available for current capacities ranging up to several thousand amperes. The pantograph is costlier ($2,500), more complex, and heavier than a trolley pole and is free to move only up and down. Horizontal wire misalignment is accommodated by having the longest dimension of the shoe arranged transverse to the wire so that the shoe and wire can slide from side to side. Several forms of this device exist, but the functions are the same. At LRV speeds only 1 pantograph per car is required, and it will work equally well in either direction. However, at main-line railroad speeds, most railroads require separate pantographs for each direction.

Current European practice almost universally uses pantographs. In certain applications, however, the trolley pole should not be discounted. It is interesting to note that the first 20 new LRVs for Boston and San Francisco will carry both poles and pantographs and the proposed Canadian standard light rail vehicle will offer either option without degradation of performance.

Now that we have considered the methods by which electrical power is generated, distributed over the system, and collected on the vehicle, we can proceed to investigate the equally important area of control systems. It should be noted that control criteria for LRVs are no different from those for a full-scale rapid transit vehicle. The only basic variable is the degree of automation that is desired.

The control system must permit the car to remain at rest, accelerate smoothly, run at speed, decelerate smoothly, and stop safely. A way must be provided to vary the energy to the motors and this takes the form of a variable resistor (or its more modern equivalents) that varies the voltage from 0 to maximum while limiting the current to reasonable values so that the system is not overloaded.

As the car is started a high resistance is inserted into the propulsion system and this is gradually reduced to allow the car to accelerate. At full speed this resistance is cut out entirely. Further speed increases can be achieved by altering the electrical characteristics of the motors themselves, such as field weakening.

In the past, the operator of the first electric vehicles varied resistors manually by turning a handle connected to a moveable contact running over the surface of the resistor in the 600-Vdc circuit. This was not an optimum electrical arrangement. Also the early wooden cars tended to short circuit in wet weather and the operator often became the variable resistor. Low-voltage control devices became almost universally used by the 1920s, and this circumvented the problem. In this situation, the operator moved a controller through a series of switch contacts that connected various combinations of safer 32-V circuits, and these, in turn, activated relays that selected appropriate portions of the 600-V resistors.

Quite logically, it was obvious that these relays could be operated automatically in a more effective predetermined pattern (now we would call it programmed) than that provided by the operator's judgment. In moving the controller handle, the operator, with this system, could select a suitable rate of acceleration or desired running speed (depending on the type of control installed on the car). Then, a series of interlocked electrical relays or pneumatic contactors opened or closed automatically as needed, or a mechanical motor-driven cam advanced automatically and opened or closed appropriate switches. In another form, this latter device was called accelerator control. It has been used on over 6,000 Presidents' Conference Committee streetcars built in the United States and is still used on many new LRV cars in Europe.

At the current state of development the cam and accelerator control still have considerable merit because they are relatively simple, rugged, and easy to maintain by current shop forces. However, a new form of all-electronic solid-state control called the chopper has arrived as a result of developments in the past 5 years. The chopper control holds promise for reduction of energy losses and improved reliability because some mechanical devices are eliminated. The same function as that performed by resistors is obtained electronically by "chopping" the 600-Vdc propulsion current into small energy blocks of various sizes through use of solid-state devices called thyristors.

The existing BART full-scale rapid transit cars and the forthcoming San Francisco and Boston LRVs are chopper equipped and will be watched with great interest by the rail transit community.

Choppers, however, are not the final answer. All devices have some inherent limitation, and something will probably come along in 5 to 10 years to replace the chopper. The chopper system retains direct-current traction motors, which, although rugged and reliable, require frequent routine maintenance. Thus, the next step likely will be a fully integrated system making use of other chopper-like concepts such as pulse-width-modulation propulsion, which incorporates a more forgiving and maintenance-free alternating-current traction motor yet retains the desirable direct-current performance characteristics.

Finally, it is also important to note that virtually any propulsion-control system, from electromechanical cams to solid-state choppers, can be designed or retrofitted to provide the energy-saving regeneration features previously mentioned, and any of them can provide the same acceleration capabilities with adequate smoothness.

Short of coasting down a hill, using the motors is the only way to accelerate the car. Deceleration or stopping, on the other hand, can be accomplished in 2 ways. First are various friction braking combinations in which a pad or shoe is caused to rub against the wheels, against disks attached to the wheels, or directly against the rail head itself. Second are the unique characteristics of motors that permit them to be used as generators. The kinetic energy of the moving vehicle is used to turn the motors, which then apply a retarding force by virtue of having to do work to generate power. But, unlike an internal combustion engine, which spews out useless exhaust gases, some of the power generated can be put back into the overhead line for use by other LRVs on the system. If this energy is reused, the system is called regenerative braking; if the energy is not put back in the line and is dissipated on the car, the system is called dynamic or rheostatic braking. To achieve higher braking rates and added reliability through redundancy, the friction braking and the dynamic/regenerative braking can be combined to supplement each other; this arrangement is called blended braking. These systems must simultaneously move the car safely and simply, must be economical in usage of power, must operate smoothly, and must be reliable and capable of easy maintenance.

So far we have considered only 1 LRV operating by itself, but, if full advantage is to be taken of the light rail scheme, vehicles should be capable of being coupled together in trains and operated from a single control point. Thus, the control system is called on to relay commands to all cars. This concept is called multiple-unit or, simply, MU operation.

Automatic control allows the operator to select an appropriate value of acceleration or running speed or both; the desired performance will be achieved without further intervention by the operator. However, he or she still must bear the responsibility for determining whether the way ahead is clear of other cars, whether the speed selected is appropriate to conditions of curves or grades, and whether the desired headway is maintained with respect to other cars on the line. As service speeds and traffic densities have increased over the years, the operator may not be able to make the best choices to control all of the variables. Consequently, it is often desirable to introduce additional automation concepts to relieve him of some or all of these burdens, but these installations must be based on sound economic, passenger-capacity, and safety judgments.

Many techniques described by many different names have evolved over the years, but in the simplest terms they are all forms of signaling systems in that they "signal" the operator to do something or "signal" the control equipment to take automatic action. This information can be provided visually by wayside signal lights (or even just wayside signs) or by coded energy fed through the running rails. These can be used singly or in combination if the traffic density warrants.

Wayside signals require that the operator (or a wayside device called a "track trip") initiate a desired action but this can be done only when the car arrives at the next signal location.

Coded energy rail systems are in the general category of cab signals; they can be arranged to alert the operator to take action, or they can directly trigger the control system on the car. In either case, they give an instantaneous picture of conditions ahead as they change. Thus the operator (or the car itself) can immediately increase speed to take advantage of improved conditions rather than plod along until the car gets to a wayside signal with a higher speed aspect. This feature alone maximizes capacity of the rail line and reduces minimum headways.

In addition to their basic function, either the wayside or the cab-signal system can be arranged to determine track, curve, and grade conditions without operator intervention for safety, maximum speed, and minimum headways, or they can be arranged to operate automatically from a central reporting area to maximize operation of all cars on all parts of the system.

Any combination of automation devices can be considered under the broad term automatic train operation (ATO). These may include automatic speed control (ASC), automatic train protection (ATP), and automatic train control (ATC).

Automatic speed control quickly brings the vehicle to a stop if it exceeds any of a predetermined series of speed commands appropriate to the curves and grades. The operator can prevent such emergency stops only by keeping car speed within the prescribed limits and properly acknowledging any reduction in speed commands. In other words, automation enforces the speed limits, but the operator still runs the train.

Automatic train protection establishes signal blocks of appropriate length to provide adequate stopping distance for cars entering each of these blocks at maximum speed. Car occupancies of all blocks also are compared continuously. This results in an arrangement in which a car will be stopped before it gets too close to the car ahead. In this case, automation enforces train separation, and the operator limits the speed and runs the train.

Automatic train control establishes a local operational pattern on a given line so that all cars are accelerated, run at speed, braked, and stopped automatically in accordance with curve and grade conditions, block occupancy, required station stops, and desired headways. This can be expanded to an operational pattern for all lines in a system under the manual direction of a single person at a central reporting area or under automatic direction of a computer system. If desired, even the opening and closing of a car's doors at station stops can be included. This means that automation performs all functions, and the operator may have so little to do that he or she might become bored and inattentive.

All of these features can be provided on an LRV system, but full automation usually is not needed (at least not initially). If full automation seems necessary, then full-scale rapid transit would probably be a better choice than a light rail system. Nevertheless, the fact must not be overlooked that a light rail system can be started economically with minimal automation, and various features can be added without obsolescence to all or part of it as traffic increases over a period of years.

The new San Francisco Muni Metro includes 6 miles (9.6 km) of dense, close headway tunnel and subway operation into which 5 light rail lines will operate with trains of up to 4 cars. This section will be equipped with a wayside signal system at junctions (interlockings). It also will be equipped with a 100-Hz, continuously coded, cab-signal system permitting speeds of 10, 27, and 50 mph (16, 43, and 80 km/h) as an ASC function and providing block occupancy protection as an ATP function. Full ATC is not provided. However, on the surface portions, where each route runs on its own separate track, no signaling is provided and cars will be operated on a manual, line-of-sight control basis. The system is further designed so that failure of 1 or more functions still allows safe operation with relatively little service degradation. If the cab-signal system (ASC/ATP) fails, the cars still can be run manually by observing the wayside interlocking signals. If the wayside signals fail, the cars can be manually dispatched by radio from central control. Under no circumstances should any light rail system be designed to rely on 1 automation control system whose partial failure will stop all service.

So far, we have considered only how propulsion and signal-control systems directly affect normal movement of car. But there are other system interfaces. The control system must be arranged so that a car cannot start if any of its doors is still open, that the doors cannot be opened while the car is moving, that the wheels do not slip and spin if the rail conditions are slippery, and that a car does not proceed into an area where a rail has broken. These and many other functions can be achieved at little additional cost or complexity.

Fortunately, the selection of the proper ingredients is not as difficult as it might seem, and we can close with a brief summary and a recommendation for an initial starting point for a light rail system.

Commercial high-voltage alternating current could be purchased and delivered at key property owned substations where the voltage would be reduced and rectified to 600 Vdc by small solid-state units. This power could be fed to a single overhead wire every 1,000 ft (305 m) and collected by a trolley pole or pantograph on the vehicle as appropriate. The arrangement could be bidirectional so that power could be delivered to the car in acceleration or back to the substation from the car in deceleration for reuse by other cars under the regeneration option. The LRV would have either an electromechanical or an electronic solid-state propulsion-control system selected on the basis of local conditions and cost considerations. Finally, ATO signal-control options would be installed on the vehicle and the wayside to the extent necessary as established by readily identifiable passenger-capacity, policy-headway, and safety criteria.

In short, the light rail concept makes use of vehicles that are constructed by using proved, but modern, technologies that will be appropriate for at least the design life of the vehicle. The system can be built now and will be fully operational now on a reasonable, cost-effective basis.

With the support of the properties in accepting standardized hardware, the support of industry in taking normal business risks to provide this hardware, and the continued generous support of government in providing funds and research facilities, light rail transit will become an even more valuable addition to the catalog of available and appropriate transit vehicles of all kinds.

NORTH AMERICAN LIGHT RAIL VEHICLES

Joseph S. Silien and Jeffrey G. Mora,
Urban Mass Transportation Administration

This paper presents the evolution of North American light rail vehicles from the 1920s to the present. Emphasis is placed on conditions of the electric street railway industry in the 1920s, attempts at car standardization, and movement toward a radically new, high-performance car as background to the development of the Presidents' Conference Committee car of the 1930s. Events leading to the new standard light rail vehicle are presented along with its significant dimensional specifications and performance characteristics. The proposed Canadian light rail vehicle is described.

The development of a new generation of light rail vehicles (LRVs) is both a timely reflection of and a stimulus for widespread interest in light rail transit for North American cities. Recent vehicle developments have a close relationship to the process by which the predecessor of today's LRV, the Presidents' Conference Committee (PCC) car, was developed. In fact, today's LRV is part of the continuing and long evolution of transit vehicles.

In the early 1920s, the electric urban and interurban railway industry reached its zenith in profitability and ridership. However, automobile ownership began to increase dramatically at that time. The automobile proved to be a strong competitor for public transit and negatively affected the transit service that existed because it worsened traffic congestion. Along with these competitive factors, the street railway industry was burdened with obsolescent equipment that became increasingly expensive to replace as the depression neared. It was pointed out at the 1926 American Electric Railway Association (AERA) annual convention that more than 28,000 electric railway cars over 20 years old were in operation causing not only higher operating costs but also an increasingly poor public image. Although car design and performance had not changed dramatically during the 1920s, car prices escalated rapidly. The street railway companies were in financial difficulties because franchise restrictions frequently mandated a low flat fare that companies were unable to change in spite of higher capital and operating costs.

Two AERA subcommittees, the Committee on Unification of Car Design (1924) and the Committee on Essential Features of Modern Cars (1926), were formed to deal with the car replacement problem. The latter group developed what we would consider a set of standard specifications for street and interurban railway cars to overcome the problem of a proliferating number of car designs that were among the most important factors in dramatically increased car prices, and, of course, to stimulate ridership by providing modern equipment.

However, in spite of the importance of these committees in standardizing streetcar design and components, there was increasing discussion within the industry of even more radical improvements in car design and performance. For example, Charles Gordon, editor of the influential Electric Railway Journal, presented a paper in 1928 that discussed future rolling stock requirements and emphasized the difficulty in getting key technical personnel (master mechanics, in those days) to accept progress and innovation.

Of greater significance was a little known report prepared by an AERA Committee on Research in 1929. This committee conducted a survey of many electric railway companies to determine what research efforts were under way throughout the industry, and, more important, to make recommendations on what action AERA should take to coordinate or encourage these efforts. Prominent among the findings was the need for "a study to develop the type of street car needed for the future including its general design, control equipment, method of drive, and the like" (1). W. A. Keller of Pittsburgh Railways continued the discussion on a better car at the 1929 American Electric Railway Engineering Association meeting (2).

The movement toward a research program that culminated with the PCC car coalesced in a paper delivered in 1930 by Thomas Conway (3 pp. 137-148), president of the Philadelphia and Western Railway Company [Conway's legacy survives as the high-speed Norristown Line, which is operated by the Red Arrow Division of the Southeastern Pennsylvania Transportation Authority (SEPTA)].

Conway reviewed the serious problems then besetting the street and interurban railway industry. He focused his discussion on the car as the key to the problem. He complimented efforts at standardization but noted the lack of coordination of research projects being conducted by various companies. Conway pointed out that, of 74,000 electric railway cars operating in the United States in 1930, almost 40,000 were more than 20 years old and were ready for retirement. He stated that the 1930 automobile was far superior to its predecessors and that its cost was rapidly decreasing compared with the increasing cost of electric railway cars. He also stated that "so long as improvements are made in the private automobile, the electric railway car must keep pace. We cannot anchor while our rivals continue to sail ahead" (3). Conway then compared performance characteristics of the latest automobiles and streetcars and concluded that the automobile far outperformed the newest streetcar. The ideal performance characteristics of the streetcar had never been determined. Conway also was keenly aware of how important image was, even to streetcars of the 1920s, when he said: "There is . . . a brief and fleeting period of public attention when new equipment is placed in service on a line, but the fact is that . . . no one has yet evolved a railway car which possesses that elusive quality sometimes called 'it' which has been such a tremendous factor in the phenomenal success of certain makes of automobiles" (3, p. 143).

The 2 factors Conway cited as helping the industry decline were (a) individualistic master mechanics and (b) the fact that the streetcar was assembled and the joint product of many manufacturers (3, pp. 144-145). The systems integration problem was recognized even then.

At Conway's suggestion, a committee of presidents of street railway companies was established to direct a major research effort leading to the production of a new streetcar. The research and development program was funded by the street railway industry, suppliers, and manufacturers.

The committee chose C. F. Hirshfeld, director of research for Detroit Edison, as chief engineer. Hirshfeld was chosen because the committee wanted an engineering executive from outside the electric railway industry who could manage a large research and development project and who could win the confidence of key persons both inside and outside the industry. Hirshfeld approached the problem by using the concepts of systems analysis long before that term came into existence. Some of Hirshfeld's research is available elsewhere (4). In 1935, the research and development program was completed and the first production order for the PCC car had been placed. About 5,000 PCC cars were built in the United States and Canada, and nearly 1,200 are still in daily operation.

The streetcar systems in operation in the 1970s are far different from those of the 1920s. The systems in use now are few in number; they are for the most part publicly owned, and, except for New Orleans, they are served by PCC cars. The last U.S.

PCC cars were built in 1952. The PCC cars remaining in service are physically and economically obsolete.

Several large PCC fleet operators, notably the San Francisco Municipal Railway (Muni), the Massachusetts Bay Transportation Authority (MBTA) in Boston, and the Southeastern Pennsylvania Transportation Authority (SEPTA) in Philadelphia, were faced with the problem of what to do with their streetcar systems. Should they upgrade them or should they eliminate them? San Francisco was the first to make a decision and opted to upgrade in conjunction with a new high-platform subway being built below Market Street for the Municipal Railway streetcars. In the fall of 1971, Muni requested bids on 78 new cars designed by L. T. Klauder and Associates. The cars were 2-section, 6-axle, articulated, double-ended units featuring a powered center truck [for 65 mph (104.6 km/h) top speed], air conditioning, and a new fare collection and transfer issuing device and were capable of multiple-unit operation. In November 1971, 2 bids of approximately 500,000 dollars per car were received. After consultation with the Urban Mass Transportation Administration (UMTA), the bids were rejected as excessively high. The rejection of the Muni bids coincided with a decision by the transit authorities in Boston and Philadelphia to preserve and upgrade their light rail systems. A primary element of the upgrading naturally was to be a new vehicle.

The recent Muni bidding experience, the urgent requirement that 20- to 30-year-old cars be replaced quickly, and the previous experience of the transit industry in developing the PCC car prompted UMTA to call together the light rail system operators and urge that they work together toward a standard performance specification for common use. The proposed industry design effort was to be geared toward meeting current and future needs with a minimum cost vehicle. The market for replacement vehicles on existing systems is limited to perhaps fewer than 800 cars. If this market is diluted by purchases of 80 to 100 cars with no insurance of following orders, car builders have no choice but to charge all engineering, development, and tooling costs to the initial order. This fact was borne out by the Muni experience on the 78-car bid in 1971.

The rationale for a new standard vehicle seemed obvious. Rebuilding the PCC cars was not considered a satisfactory alternative principally because of the lack of readily available parts, the overall age and condition of the fleets, and the requirement for doors on both sides of a double-ended vehicle.

Transit property staff and UMTA had been reviewing the situation in Europe where the trend had been for many years to expand and improve light rail systems and where new equipment was operational. The review of European rolling stock led the MBTA to propose importing and demonstrating a modern European car not only in Boston but also in the other U.S. cities operating streetcars.

The proposal progressed to the point where, after an on-site inspection and negotiation, the so-called Hannover car built by Duwag as a prototype for a new generation of equipment was to be modified and imported. The program as envisioned might have shortened the specification development process by enabling the cities to test the equipment firsthand and to specify only required modifications.

Because the United States found itself in an adverse balance of payments position, the European vehicle demonstration was never implemented. Instead, the project was restructured as a specification development effort with the MBTA designated as the lead agency and UMTA grant recipient (5). Ground rules were few and rather rigidly enforced. The already developed Muni car specification was to be the basis for the new design. Variations among the properties were to be minimal and dictated by system requirements rather than preference. Advanced technology propulsion similar to that developed on the state-of-the-art car (SOAC) was to be an allowable bid item.

In a fashion not unlike that of the Presidents' Conference Committee, a Project Technical Committee was formed. Consulting assistance was obtained from Parsons, Brinckerhoff-Tudor-Bechtel, which used the UMTA Guideline Specification format in developing the new car specification.

The process of designing the car involved compromise on many points. As a basis for proceeding, it was decided to determine the largest possible car size that would satisfy the 3 principal users' needs (MBTA, Muni, and SEPTA). (SEPTA's clearances remain somewhat questionable because of a less than successful attempt to operate the

MBTA clearance car on the SEPTA system.)

Nevertheless, agreed on dimensions reflect the envelope of Muni and MBTA and are probably suitable for SEPTA as well. The new car, as specified, measures 71.5 ft (21.6 m) over anticlimbers, 8 ft 8 in. (2.64 m) wide, 11 ft 6 in. (3.5 m) high with locked down pantograph, has 23-ft (7.0-m) truck centers, and three 4.5-ft (1.3-m) doors per car side (6). The car is a 2-section, articulated vehicle. It is double ended but can be constructed in a single-ended version. The specification is heavily performance oriented and reflects a synthesis of the requirements of the operating agencies while preserving latitude for the manufacturers to innovate.

MBTA requested air conditioning, and Muni did not. Muni requested convertible high-low steps for the Market Street subway where platforms are at car floor height. The October 1972 specification bidding resulted in a low bid from Boeing Vertol Company of \$316,616 each for 80 Muni cars and \$293,422 each for 150 MBTA cars. That compares with the low bid price of \$473,000 per unit in response to the 1971 Muni solicitation.

In a technical sense, the new LRV will be a success. Although it is somewhat less of a "hot rod" than either the PCC car when it was new or the earlier Muni design, the new vehicle incorporates all of the performance considered useful and practical based on the duty cycle requirements of the properties involved.

Removal of the requirement for a powered center truck resulted in a reduction in top speed from 65 mph (104.6 km/h) to 50 mph (80.5 km/h). Although the car can incorporate different rates of acceleration, the Standard Light Rail Vehicle Specification requires a maximum acceleration rate of 3.1 mph/s (1.4 m/s^2), a nominal rate of 2.8 mph/s (1.2 m/s^2), and a minimum rate of 2.5 mph/s (1.1 m/s^2). (Deviation from the nominal shall not exceed 10 percent.) The original PCC specified maximum acceleration rate was 4.75 mph/s (2.1 m/s^2).

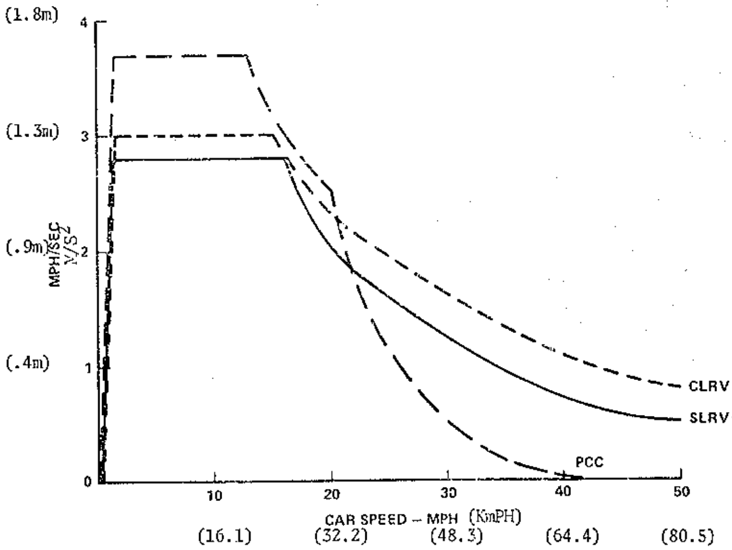
Let us compare the effect of the higher initial rate of the PCC car with the capability of the LRV to sustain acceleration for a longer period. The LRV is required to reach 50 mph (80.5 km/h) from a standing start in 37 s; the PCC could reach only 36 mph (58 km/h) in the same time period (Figure 1). The result is the ability of the LRV to travel between stations more quickly and comfortably than its predecessor could. The new light rail cars have several other innovations worthy of mention. These include an energy-absorbing coupler designed to sustain a 72,000-lb (320 000-N) compression while deflecting 14 in. (35.6 cm); a 2-position movable step (for Muni); a smooth-sealed articulation unit; a monomotor truck with both motor and gear box mounted to the truck frame, which reduces the unsprung weight and thus improves ride quality; a unitized car body that uses equipment bays as structural-load-bearing members to redistribute loads around the large 54-in.-wide (1.37-m-wide) door openings; and biparting plug doors (7).

The car body is constructed primarily of low-alloy, high-tensile (LAHT) steel except for the central roof skin, which is fabricated from stainless steel. The articulated section permits a rotation of 16 deg in a horizontal plane. In the vertical plane, the inclusive angles of 3 deg in a sag condition and 4.26 deg in a crest condition are the limiting values.

The LRV has a solid-state propulsion and a thyristor chopper-control system similar to that used on SOAC cars. The system uses a monomotor truck with a separately excited direct-current traction motor rated for 210 hp (157 kW) continuous. The armature voltage is controlled by a single 600 Vdc to direct-current force-commutated chopper with fixed frequency and variable pulse width. The field voltage is controlled by a separate, single 600 Vdc to direct-current chopper with variable frequency and fixed pulse width. The trucks are constructed of welded steel and have an inboard frame design. Twenty-six-in.-diameter (66-cm-diameter) resilient wheels are used. The truck frame has a rubber-chevron primary suspension system at each journal bearing, and a secondary air-suspension system that provides vertical and lateral cushioning.

The first new LRV became operational on a 0.5-mile (0.8-km) track at the Boeing plant late in 1974. Late in 1975, several pilot cars will be tested on the UMTA rail transit test track at Pueblo, Colorado. In 1976, the first new light rail vehicles built

Figure 1. Light rail vehicle acceleration curves for average passenger load.



CAR	PCC	SLRV	CLRV
PASS. LOAD (CRUSH)	75	219	93
LOADED WT (LB)	43,800	82,500	62,400
GEAR RATIO	7.17	5.57	5.57
WHEEL DIA	25 IN.	25 IN.	25 IN.
MOTORS (NO.)	4	2-DA214.3	–
MFG (MOTORS)	GE/WE	GARRETT	–

LEGEND

— — — — PRESIDENTS' CONFERENCE COMMITTEE CAR (PCC)
———— STANDARD LIGHT RAIL VEHICLE (SLRV)
– – – – CANADIAN LIGHT RAIL VEHICLE (CLRV)

in the United States since 1952 should enter service in San Francisco and Boston.

A second significant LRV development program is under way in North America. The Canadian Urban Transit Development Corporation has developed a specification for a single-unit (nonarticulated) replacement vehicle for PCC cars operated by the Toronto Transit Commission.

The Canadian LRV will include a chopper-regenerative propulsion system, resilient wheels, a new suspension system, and low-level step entry for passenger convenience. The car will be 51 ft (15.5 m) long, 8 ft, 4 in. (2.54 m) wide, and 11 ft (3.35 m) high and will have a seating capacity of 45 to 51, depending on interior configuration.

The car is designed to be 10 dBA quieter than PCC streetcars. Exterior noise level specification is 75 dBA measured at 15 ft (4.57 m) at 40 mph (64.4 km/h). Interior noise is reduced by acoustical treatment of the car structure. A 3-level brake system is specified: electrodynamic, friction disc, and magnetic track brakes. The acceleration rate is specified at 3.0 mph/s (1.35 m/s^2), and the car is designed to go from 0 to 30 mph (0 to 48.3 km/h) in 12 s and from 0 to 50 mph (0 to 80.5 km/h) in 30 s. Maximum speed in a streetcar version is 50 mph (80.5 km/h) and 70 mph (112.7 km/h) in a light rapid transit configuration. The maximum service braking rate is 3.5 mph/s (1.6 m/s^2). The car also features energy-absorbing front and rear bumpers. Design life is specified at 25 years.

In summary, the new U.S. and Canadian LRVs represent a new generation of urban rail cars for medium-capacity light rail service. Although the heritage of these new vehicles can be traced from the first electrified streetcars of the 1880s and the PCC development of the 1930s, the LRVs represent a unique blend of contemporary performance requirements and industry criteria that will result in a vehicle of the 1970s that will satisfy its share of today's urban transportation needs.

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FOREIGN LIGHT RAIL VEHICLE DEVELOPMENT

Joachim von Rohr, Rheinische Bahngesellschaft AG,
Düsseldorf, Federal Republic of Germany

This paper begins with a brief description of how the light rail mode has been developed in several West European countries, especially in the Federal Republic of Germany. The basic features of the light rail vehicle and how the vehicle was derived from the streetcar and the subway or heavy rapid transit car are explained. Finally, the various attempts at standardization of light rail vehicles in West Germany after World War II are discussed. Several modern light rail vehicles are described, and it is explained why standardization could only be partially achieved.

This paper discusses the light rail mode in western Europe and especially West Germany. The light rail vehicles that are being used also are covered.

EVOLUTION OF THE LIGHT RAIL MODE

Outside the United States, the light rail mode has shown an interesting development in recent years, especially in some West European countries. The reasons for this are well known. Some cities are too small to justify a full-size heavy rapid transit (HRT) system, and, in both large and small cities, there is a desire to operate tunnel sections with existing streetcars as soon as they are completed. In the latter case, European countries avoid letting the large amount of money spent for the civil engineering works lie idle for a long time.

Before the first tunnel sections were actually built, many existing street running routes were transferred to private rights-of-way, and, in West Germany at least, considerable financial help was received from the federal and state governments. These sections were situated mostly in the suburbs and outside the central business district and formed the basis for the subway network in the downtown areas.

In the 1960s, some cities such as Stuttgart, Frankfurt, Cologne, Ludwigshafen, Essen, Federal Republic of Germany; Brussels, Belgium; and Vienna, Austria, started tunnel construction along their most heavily trafficked routes or on those where existing operating conditions made tunneling appear advantageous.

Of these systems, only the one in Frankfurt planned for and implemented the use of new cars considerably wider than their existing ones because the tunnel section was to be connected with 2 suburban routes on private rights-of-way with generous clearances and a new route partially in tunnel into a new satellite town (1). The other systems also built their tunnels and rights-of-way for wider cars with greater capacity but used and still use existing conventional streetcars on these routes with low platforms the edges of which extend toward the tracks. Of these cars, only the Cologne 8-axle, articulated, single-end cars that are 30 m long and 2.5 m wide are of adequate size for long-term light rail operation. The Stuttgart 4-axle, articulated cars have a rather small capacity even with multiple-unit (MU) operation, and the Belgian

Presidents' Conference Committee (PCC) cars used in Brussels and Antwerp, Belgium, are seriously handicapped by their narrow doors and car bodies. Ludwigshafen uses medium-capacity, conventional, 6-axle, articulated single-end cars that are 20 m long and 2.2 m wide, and Essen still has not yet opened its subways for local reasons (2, 3, 4).

Frankfurt decided to have its first genuine light rail route from the downtown area (railway station) to the new satellite town operated by new light rail vehicles (LRVs) of a 6-axle, articulated design, 23 m long and 2.65 m wide instead of the 2.3-m-wide, conventional, 4-, 6-, and 8-axle surface cars. The 2 connecting suburban routes could not be converted immediately to such wide car clearances because of limited financial resources and physical difficulties (freight interchange with the German Federal Railway) and are still partially operated with modified conventional cars with movable steps and a fiberglass structure along the right side of the body to bridge the gap between the platform and the narrow body of the car. As soon as both suburban lines are converted for operation of wide cars, the modified cars may be rebuilt to their original appearance or scrapped.

Further evolutionary developments have taken place almost exclusively in West Germany since 1968, and most of this paper therefore deals with cars of that country. Several types of cars have been designed that truly can be classified as LRVs. One reason for this boom in LRVs is that more West German cities (Bonn, Düsseldorf, Bielefeld, Hannover, and several cities in the Ruhr) had started subway construction about that time, but lack of money and limited construction capacity for civil and electrical engineering works as well as the impossibility of closing several major streets at 1 time for construction work had slowed down considerably the upgrading of existing streetcar routes and the construction of the new HRT lines.

DEFINITION OF THE LIGHT RAIL VEHICLE

The LRV is defined as a vehicle not as heavy as a conventional rapid transit or subway car and is usually associated with a less substantial right-of-way. Therefore, its construction is less expensive than that of HRT vehicles. The lower weight results because LRVs are less wide than HRT cars. They are less wide because they have to run on existing streetcar tracks with restricted clearances and because the car structures are designed for shorter trains and consequently lower stress levels. The generally lower passenger-carrying capacity can be compensated for in part by MU operation, which is optional with light rail transit (LRT) but mandatory with HRT.

The LRV evolved from the streetcar but has taken features from HRT cars particularly in the area of improved passenger-handling capability. The transition from LRV to HRT vehicle is fluid, and, therefore, it is difficult if not impossible to define precisely whether a certain car is a LRV or a modified HRT car. The presence of common pieces of equipment does not make such a definition easier. However, the LRV is preferred where the number of passengers to be carried in 1 direction does not exceed about 20,000/h. Because of its design, the LRV can run not only on segregated private rights-of-way but also on streets (as a streetcar) and on private rights-of-way with level crossings with other streets. It can run "on sight" without signaling, but the use of signal equipment, and even cab signaling, is desirable, especially in tunnels.

GENERAL DESCRIPTION OF THE WEST GERMAN LIGHT RAIL VEHICLE

Features that the LRV has taken from the streetcar are numerous. Overhead current collection is required because of operation on unprotected rights-of-way and third-rail clearance problems on sharp curves. A third rail also is impractical when cars have fixed or retractable steps for street loading because the third rail would not clear these steps. Pantographs are used exclusively in European tunnel operation because of their advantages over the trolley pole. That they cannot become dewired (which can be dangerous, especially in tunnels) and that they can take much higher currents from the contact wire are the advantages of pantographs. Also there is no need to change poles when cars are reversed at crossovers, which would be most impractical in tunnels. In fact, the trolley pole was almost completely phased out in most European countries by the time the light rail mode was introduced. Various types of pantographs are used including standard diamonds, semipantographs of the Faiveley type, and a design with 2 lower arms in 1 plane only.

Because of the necessity of loading from the street surface or from safety islands, LRV floor height is kept to the minimum compatible with the power rating of the motors, the gear ratio, and the wheel diameter. (All 3 parameters are interrelated.) Floor heights vary between 880 and 1000 mm; motor power ratings vary from 120 to 235 kW (monomotor trucks); and wheel diameters vary from 660 to 740 mm.

In almost all cases, the floor height is divided into 3 steps; the lowest usually is between 370 and 400 mm above the rail head (with new wheels). The remaining height between the lower step and the floor is divided equally by 1 intermediate step. This arrangement, however, is not particularly well suited for elderly or handicapped passengers. A fourth step, however, intrudes too much on floor surface at the doors, which is especially bad for double-end cars with doors on both sides of the car. A solution to this problem is to make the lowest step retractable and to divide the floor height into 4 almost equal parts (5). This arrangement will be used for the first time in the M-type standard car designed for several Ruhr area systems. The sliding retractable step should not be confused with the movable steps used alternately for low- and high-platform operation and that close the opening in the car floor so that it is flush with the car side leaving only the usual gap between the floor and the platform. Both movable and retractable steps can be used simultaneously, as on the Rhein-Ruhr and Rhein-Sieg Stadtbahn B car, which already is in operation in Bonn and Cologne.

Folding doors are used on most cars for 2 reasons, which are simplicity and suitability for electric operation. Although many LRVs are all-electric cars, even those that have compressed air equipment do not necessarily use it for the doors. Some cars, however, use swing-slide or plug doors that do not occupy space inside the car when opened but are more sensitive to collisions. For such doors, compressed air is more suitable. When closed, these doors are flush with the car sides. When opening, the doors first swing out perpendicular to the side panel of the car and slide parallel to the panel at a distance of about 100 mm until the doorway is fully opened. Because these doors can open under pressure from the inside of the car (by passengers leaning against or pushing on the doors), mechanical locks must provided. This leads to a more complicated design than that for folding doors.

Light rail vehicles often may have to use existing streetcar lines with restricted clearances and where short radius curves are common. Short radius curves can be defined as being below 150 m in normal operation and 70 m for shops and yards. Minimum radius for cars running on tracks designed for streetcar operation is between 15 and 25 m. Overhead current collection is mandatory in these cases because the under-floor equipment of the cars, including steps, would not clear a third rail. The foregoing requires the cars to be articulated to permit shorter truck-center distances and thus reduce overhang in curves. With adequate clearances on tangent tracks, cars wider than nonarticulated cars of practical length may be used. Another reason is for using articulated cars to permit passengers to travel through the whole car regardless of curves and to provide a large 1-operater car that the driver can oversee (6). Articulated cars were built in the United States as early as 1915; they were introduced in Europe, especially in Italy, before and during World War II and were developed significantly and mass produced after 1956 in several European countries, especially in West Germany.

With articulated cars, usually only the 2-end trucks are motored, either with 1 motor per truck (monomotor truck) or 2 as on many Dutch articulated cars. Monomotor trucks make maximum use of adhesion; with their coupled axles, the effects of weight transfer are automatically compensated for. This is most useful when not all trucks are motored. This is the case for trucks under articulations that usually cannot be motored because of the reduced space available, especially if monomotor trucks are used. (With 6-axle cars, the resulting 3 motors would also create problems with series-parallel and dynamic braking control.) When 2-motor trucks are provided, special truck designs may permit motoring axles under articulations. Some 6-axle HRT cars have been built that use 6 × 200 V motors; Brussels 6-axle PCC streetcars use 6 × 300 V motors and 2 complete sets of controls. Any nonmotored axle or truck, of course, reduces performance, especially on 8-axle cars where up to 40 percent of the total weight may rest on these. Accordingly, European cars use all types of drives, depending on the wishes of the operators and the topography of the systems. For example, Freiburg, Germany, has recently acquired 8-axle articulated cars on which all axles are powered. In West Germany, principally monomotor drives are used, however, and they are being used more and more in other countries.

Resilient wheels are used on most European LRVs mostly to reduce the noise resulting from wheel squealing in short radius curves and general rolling noise. Noise levels inside modern cars should not exceed 75 dBA, but 70 dBA can be achieved on good tracks with good wheel and track maintenance (grinding). Wear of tires, particularly on the flanges, also is reduced with resilient wheels.

Contrary to HRT practice, where doors are opened and closed by the driver or conductor regardless of whether passengers board or leave the cars, LRVs usually are provided with a door-control system that permits passengers to open the doors inside and outside the cars by pressing buttons after the local door control has been activated by the driver. Electrical interlocking ensures that this is possible only when the car is stopped. Doors close about 4 s after a passenger has left a step treadle or ceased to interrupt a light beam across the door opening. The light beam is sent out by a lamp and reflected by a mirror into a photoelectric cell. This kind of door control usually is combined with a system that permits the passenger to signal the driver to stop the car at the next stop by pressing the same buttons as are used for the doors. (In surface operation, not all stops are compulsory.) The reason for this scheme is to avoid opening all doors of a car or train when only a few passengers board or alight; this reduces wear on the door mechanisms and prevents the escape of heat from the cars during the cold season.

Government regulations usually require any cars operated "on sight" to be fitted with a brake system that is independent of the adhesion between wheels and rails. This brake system is provided by magnetic track brakes that are operated by the driver in emergencies. They also are included in the emergency brake system that can be operated by the passengers.

For safety reasons, cars also have to be provided with sanders placed before the first axle of each motored truck. Double-end cars thus require sanders at both axles of the trucks. The sanders are tubes with gates through which sand can fall on the rails in front of the wheels to increase adhesion and reduce braking distances in emergencies. They also can be used during acceleration to prevent wheels from spinning.

Because of the many junctions found within surface networks, a considerable number of track switches have to be set for each route. It would be uneconomic and inconvenient to operate these switches manually by switch tenders or by the drivers with the usual switch iron (the driver can do so if necessary). Therefore, the track switches are provided with electric drives (motor or solenoid) that can be actuated by the driver by either the conventional power-and-coast method or by inductive control coupled to wayside equipment. The inductive control also can be used for preemption of traffic lights. At junctions, such preemption can be made depending on the position of the track switches so that the proceed signal is given only for that direction for which the switch is set. Preemption of traffic lights can, however, also be achieved when no inductive equipment is available. Overhead contacts touched by the pantograph shoe are used in this case. Where buses use the paved-in rights-of-way of LRVs, they also can preempt traffic signals when inductive equipment is used. This equipment also can be used for the automatic setting of all track switches for a route by means of coded signals transmitted to wayside equipment as well as for setting destination indicators in stations and for transmitting the position of each car to a central control room.

In Europe, all passengers are required to carry tickets or fare receipts that indicate that their fares have been paid. These are inspected at random by roving inspectors who are empowered to levy spot fines against those without prepaid tickets, receipts, or other proof of fare payment. (In West Germany, the fine is currently 8 dollars.) Thus, European streetcar and light rail systems do not require passengers to file by a fare box to deposit their fares as is the custom in the United States. On many European transit systems, especially those in Germany, passengers are permitted to board and leave cars by whatever door they choose. However, when they have no fare receipt or ticket and must purchase one, they must board at the front door close to the driver. Light rail vehicles thus have at least a single door close to the driver's cab. In some cases this door is only on the right (near) side of the car to give more space for the driver's cab. Sometimes it is also on the left. If there are center island platforms (with left-side loading) and if these stations are provided with ticket-selling machines so that the driver does not have to sell any tickets, it is possible to omit the left-side door.

There are features that the LRV has taken from the HRT car. The LRV must be able to reverse in tunnels or on surface crossovers because underground loops are costly and difficult to build. In addition, piece-by-piece construction of LRT lines in tunnels or on the surface, temporary cutting of surface routes due to tunnel construction, and space difficulties in constructing surface turning loops make a double-end car design with doors on both sides advantageous. With a few exceptions, streetcars generally were single ended and thus required turning loops or Ys (track triangles) for reversing the direction of travel. Another reason for doors on both sides is center island platforms, which sometimes are used in subway and even surface stations (7).

Some car designs incorporate movable steps to permit loading from either high-level platforms or from the street surface as is done with streetcars. Such steps, however, are very expensive to manufacture and maintain. They are also extremely sensitive to collisions. If the headway on the LRT lines is not too short, the gain in loading time with movable steps is not important, and fixed steps for loading from low platforms would be preferred. In this case, special precautions must be taken for the day when HRT cars will be introduced. The platform height must be increased to the floor level of HRT within a short time. This is done first for half of the station length (with reduced LRT train length for that time). After the vehicle change, the other half of the platform has to be raised (with reduced HRT train length until the work is finished). This will be done in Brussels and may be done in Düsseldorf. The various step and platform heights show that this problem is complex and highly dependent on local conditions.

Light rail vehicles generally are built for higher maximum speeds and higher acceleration and deceleration values than streetcars are. Maximum speeds of 80 to 100 km/h are usual. Accelerations on level track for empty cars are around 1.2 m/s^2; decelerations are about 1.5 m/s^2. Emergency brake decelerations (with sand and use of track brakes) are about 3.5 to 4 m/s^2. However, there are limits to the normal values because of nonmotored trucks and for the comfort of passengers.

Multiple-unit control is used extensively with modern LRVs especially to increase the number of cars per hour on those sections that are used by more than 1 route. Acceleration and deceleration are controlled semiautomatically, which is similar to that for PCC and HRT cars. Anti-wheel-slip and anti-wheel-spin control as well as maximum deceleration for emergency brake applications also are provided.

Restricted visibility for the drivers in subways does not permit operation "on sight"; therefore, block signals are provided in such sections. Automatic train control (ATC) and automatic train stop (ATS) equipment thus is necessary. These provide an emergency brake application if a stop signal is passed. Wayside equipment consists of electromagnets placed between or alongside the rails to act on the car equipment when required. Under special conditions, a stop signal may be passed at low speed. This equipment may be combined with that used for actuating electric track switches and preempting traffic lights. The deadman control, used more and more on LRVs, is combined with the ATC.

Overhead line voltage is often increased from the usual 600 Vdc to 750 Vdc for 2 reasons: (a) to increase the power output of the traction motors without increasing their size and (b) to reduce voltage drops and power losses in the overhead contact wire system.

Compressed air equipment sometimes is used on LRVs although most streetcars built in Europe after 1945 have been all-electric cars. The amount of such equipment can be quite different. Some cars have as complete an air system as an HRT car does, and others use air merely to operate accessories such as sanders and mirrors. The decision to use compressed air for LRVs is rather arbitrary, but, because of space problems and the increased friction brake performance requirements on larger, faster cars, compressed air sometimes is indispensable. Its availability also permits the use of air springs for secondary (body) suspension.

Streetcars, especially single-end cars, rarely have fully enclosed cabs because there is no need to lock up the control equipment. In double-end cars and for MU operation, rear-end driving positions must be locked to prevent access by passengers and to prevent damage to the equipment. An opening in the door is provided to permit sale of tickets. It is closed by a vertical sliding glass pane. A ticket-issuing machine combined with coin changer and fare box can be fitted in the opening. Tickets or fare receipts also can be issued from a block instead of a machine. In both cases such tickets need not be specially canceled. For multiride tickets, which are common in Germany and are generally sold by machines on the platforms, tobacconists, and the like, several cancelers are provided in each car usually near the doors. In experiments, some cars have been provided with ticket-selling machines to be operated by the passenger, but such machines are still not working satisfactorily.

WEST GERMAN LIGHT RAIL VEHICLES AND STANDARDIZATION

It is not possible to present here a detailed description of the 6 or 7 LRV cars built in West Germany after 1968. Table 1 gives the most important dimensions and technical data of these cars as do Figures 1 through 10. It is interesting to look at standardization, which was so admirably achieved 40 years ago with the PCC car.

The first attempts for standardization were made before, during, and shortly after World War II, but it covered only conventional 2-axle streetcars. About 1956, when modern designs of double truck and articulated cars became available, most West German systems so desperately needed to replace their worn-out cars, which in some cases were built before World War I, that they ordered large numbers of cars without bothering about standardization. Also development of trucks, motors, gears, and electric equipment was still far from a state that would permit standardization. The individual systems, however, generally adhered to 1 design after it had been proved successful. Therefore, cars within 1 system were almost all alike. A certain standardization resulted because 1 manufacturer supplied about 70 percent of the cars at that time and others built their cars totally or partially under license to this 1 manufacturer. This policy continued until about 1970 when most systems had more or less renewed their fleets and the market had shrunk to such a degree that only 5 manufacturers stayed in the business. The major manufacturer covered about 90 percent of the market, and 3 others were building cars under license to that one. Further orders could only be expected from large- and medium-size systems especially because the planned upgrading of their streetcar routes to HRT routes (within the Stadtbahn Rhein-Ruhr and Rhein-Sieg schemes) had slowed down considerably.

In 1966, the Rail Vehicle Committee of the West German Association of Public Transit Properties (VÖV) began to develop recommendations for the standardization of LRVs and HRT cars. At that time, no vehicles existed in West Germany that could be classified as genuine LRVs. When the recommendations of the committee were finally published in 1969, they covered only a single-ended, 6-axle, articulated LRV and 2 types of HRT cars. By this time, however, the first true LRV already had been built for Frankfurt (Figure 1) and had been in operation for more than a year (1, 8). Two other systems, in Cologne and Stuttgart, had opened tunnel sections with conven-

Table 1. Dimensions and technical data for West German light rail vehicles.

Type of Car	Number of Cars	Year Built	Track Gauge	Axles: Total	Axles: Motored	Weight When Empty (Mg): Total	Weight When Empty (Mg): Adhesion	Car Length Over Coupler Faces (m)	Car Width (m)	Truck Center Distances (m)	Truck Wheelbase (m)	Floor Height Above Rail (mm)	Number of Steps: Fixed	Number of Steps: Movable	Number of Steps: Retractable
Frankfurt U2	65	1968 to 1975	Standard	6	4	26.7	20	24.0	2.65	2 × 7.72	1.8	970	1	—	—
P8	100	1972 to 1977	Standard	8	4	34.5	22	28.7	2.35	2 × 6.5 + 7.1	1.8	960	1	1	—
Hannover 6000	100	1974 to 1976	Standard	8	4	38.8	23.4	28.3	2.4	3 × 6.4	1.8	940	1	1	—
Düsseldorf 3000	69	1973 to 1975	Standard	8	4	34	20.5	26.2	2.4	2 × 6.2 + 6.5	1.8	880	2	—	—
Bonn and Cologne B	110	1973 to 1977	Standard	6	4	38	26.5	26.9	2.65	2 × 10.0	2.1	1000	1	1	1
Ruhr and Bielefeld M6	22	1975 to 1977	Meter	6	4	27.8	21.5	20.4	2.3	2 × 6.2	1.8	880	2	—	1
M8	31	1975 to 1977	Meter	8	4	34.5	21.5	26.6	2.3	3 × 6.2	1.8	880	2	—	1
Bremen 500	22	1973	Standard	4	4	21	21	17.4	2.3	8.35	1.8	850	2	—	—

Type of Car	Step Height Above Rail (mm)	Wheel Diameter (mm)	Minimum Curve Radius (m)	Number of Seats	Seat Arrangement	Standing Capacity[a]	Motors: Number	Motors: Power Rating (kW)	Type of Control	Compressed Air Equipment	Doors: Type	Doors: Operation	Maximum Speed (km/h)[b]	Car Builders
Frankfurt U2	680 + 290	710	25	64	2 + 2	100	2	150	Motor-driven camshaft	No	Folding	Electric	80	DÜWAG, Siemens, AEG
P8	400 + 295 + 265	670	18	62	2 + 1	110	2	120	Motor-driven camshaft	No	Folding	Electric	70	DÜWAG, Siemens, AEG
Hannover 6000	390 + 295 + 260	730	17.5	46	2 + 1	105	2	217	Thyristor chopper	Yes	Folding	Electric	80	DÜWAG, Siemens, Kiepe, AEG
Düsseldorf 3000	360 + 260 + 260	670	18	51	2 + 1	90	2	150	Electromagnetic contactor	No	Folding	Electric	80	DÜWAG, Siemens, Kiepe
Bonn and Cologne B	400 + 300 + 300	740	25	72	2 + 2	110	2	235	Motor-driven camshaft	Yes	Plug	Pneumatic	100	DÜWAG, Siemens, Kiepe
Ruhr and Bielefeld M6	280 + 200 + 200 + 200	680	14.5	36	2 + 1	65	2	150	Electromagnetic contactor	Yes	Folding	Electric	80	DÜWAG, Siemens, BBC
M8	280 + 200 + 200 + 200	680	14.5	54	2 + 1	85	2	150	Electromagnetic contactor	Yes	Folding	Electric	80	DÜWAG, Siemens, BBC
Bremen 500	335 + 255 + 250	680	16	44	2 + 1	56	2	120	Hand-operated camshaft	Yes	Plug	Pneumatic	70	Wegmann, Kiepe, AEG

[a] 4 passengers/mile^2. [b] Empty, level truck.

Figure 1. Frankfurt U 2 car, general view.

Figure 2. Frankfurt U 2 car, principal dimensions.

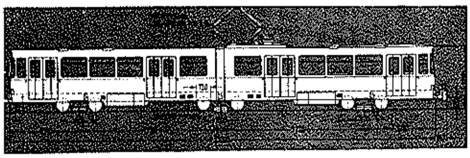


Figure 3. Frankfurt P 8 car, general view.

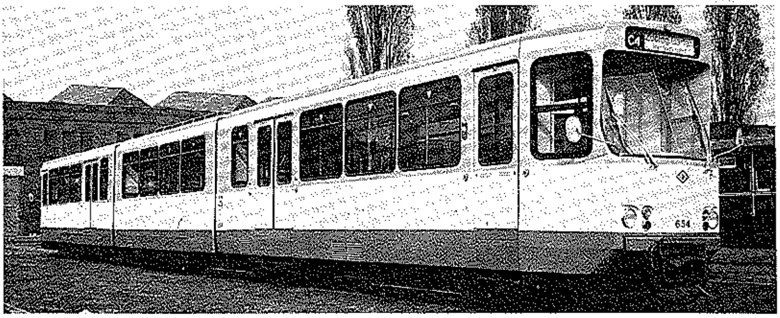


Figure 4. Frankfurt P 8 car, principal dimensions.

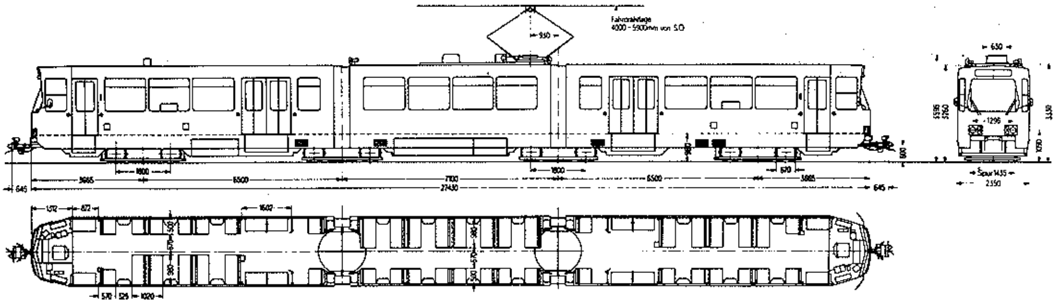


Figure 5. Hannover 6000 car, general view.

Figure 6. Hannover 6000 car, principal dimensions.

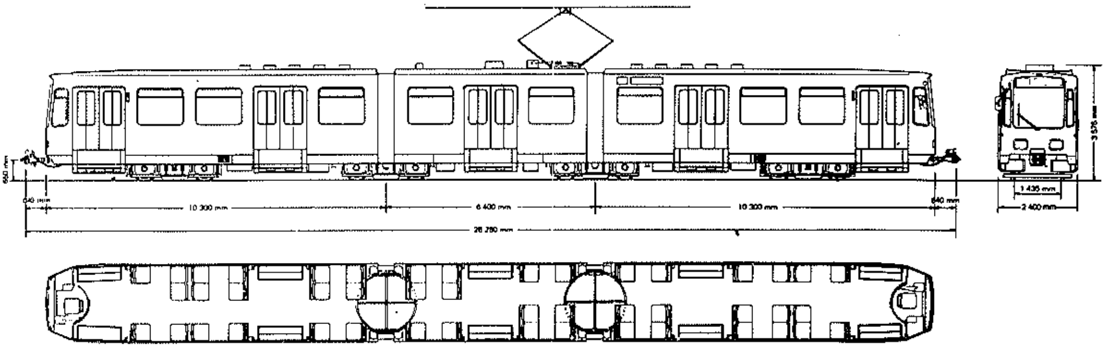


Figure 7. Düsseldorf 3000 two-car train, general view.

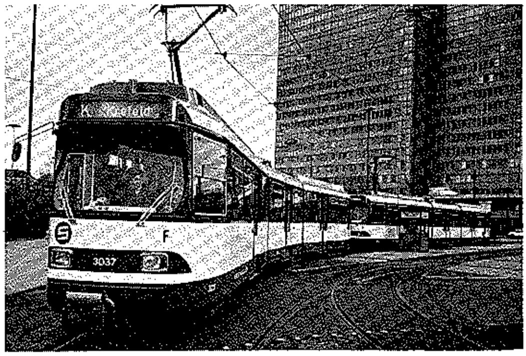


Figure 8. Düsseldorf 3000 car, principal dimensions.

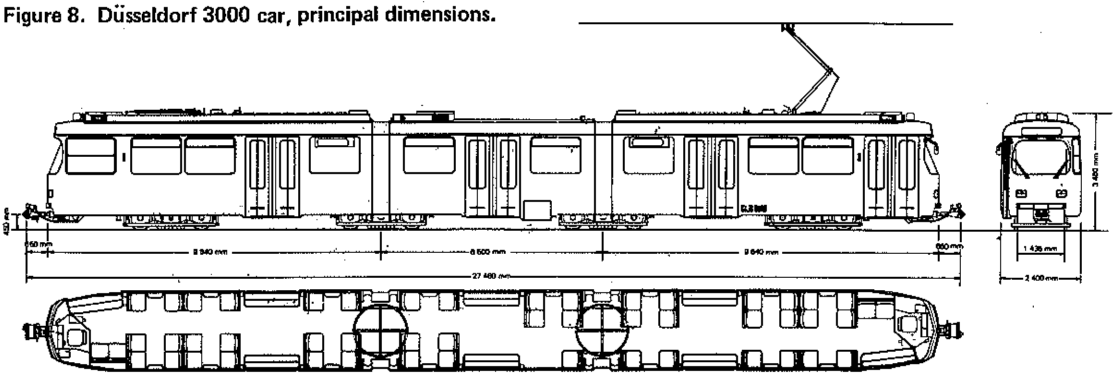
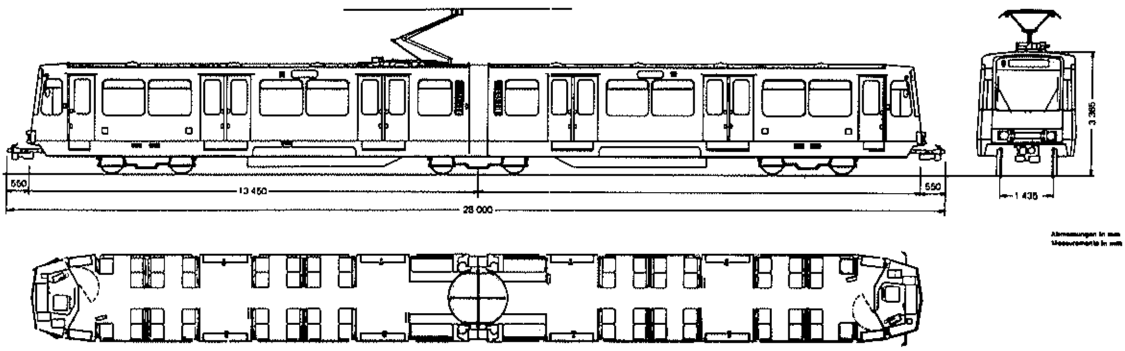


Figure 9. Bonn and Cologne B-car, general view.

Figure 10. Bonn and Cologne B-car, principal dimensions.



tional streetcars modified slightly by the addition of inductive equipment for ATC and operating track switches. Other West German transit systems, such as those in Düsseldorf, Dortmund, Duisburg, and Frankfurt, had plans to replace their remaining 2-axle cars in 1971 or 1972. In some cases, these replacement cars were intended to be used as LRVs in tunnels. When the operators checked the recommendations, they soon found out that they could not easily use the VÖV 6-axle car for 3 reasons.

1. The required car width of 2.4 m could be used only in Düsseldorf without major track relocations. The other systems could use only cars with a maximum width of 2.3 m.
2. The car had to be double ended.
3. The 6-axle car was considered too small for single-car operation. All the systems mentioned wanted an 8-axle car.

The problem of item 3 could be solved easily by adding a center section, but the car width would have to be reduced to 2.3 m. Frankfurt, which needed cars most urgently, had decided to go ahead with its own development, which resulted in the P 8 car, which was 2.3 m wide and incorporated much of the equipment parts previously used in the U 2 car (9, 10). For subway operation on routes that also ran on surface street tracks, about 30 of the cars were built with movable steps. Düsseldorf had begun to develop its 3000-class cars, which at present come closest to the VÖV recommendations both in dimensions and interior and electrical equipment. In 1972, Düsseldorf itself tried to get Duisburg, Dortmund, and Essen fixed on 1 common design based on its 3000-class cars, but, apart from the car width problem, it was impossible for various other reasons to reach an agreement among the 4 systems. The 3000-class cars were already under construction, and it would have been difficult to modify the design at that time to meet the requirements of the other systems (11, 12, 13, 14).

Meanwhile, Cologne and Bonn had started to develop a 6-axle, articulated car suitable for their subway and LRT lines with financial support from the Nordrhein-Westfalen state government because Cologne had started tunnel construction long before the Stadtbahn Rhein-Ruhr scheme was set up in 1969 and could not use the A-car. This A-car consisted of 2 semipermanently coupled, 100-km/h, 4-axle cars that were 2.65 m wide. It was designed for the Rhein-Ruhr scheme including the proposed local subway routes of the Ruhr area cities from Duisburg to Dortmund and for Düsseldorf. Their efforts resulted in the 100-km/h Stadtbahn B-car, 110 units of which are in service or under construction for Cologne, Bonn, and the Essen-Mülheim standard gauge Stadtbahn route (15, 16, 17, 18, 19). This car also will be used on the Cologne-Bonner Eisenbahn system when it is merged into the Stadtbahn Rhein-Sieg scheme (20). It also is intended to be used in Düsseldorf on the intercity routes to Krefeld and Duisburg in about 1982. The B-car thus can be regarded as a standardized car although it is likely that the cars in Düsseldorf will be different in some details because of the technical evolution that probably will have occurred by then. For example, chopper control may be used instead of motor-driven camshaft controllers. The B-car is likely to be included in the VÖV recommendations.

Hannover got two 6-axle prototype cars from 2 manufacturers in 1972. The cars are 2.5 m wide. After they had tested them thoroughly, Hannover ordered 100 cars of the more successful design but with 8 axles. Width was reduced to 2.4 m to permit unlimited use on the entire system, but the VÖV recommendations were respected only partially. These are the first cars with chopper control equipment (18). (The chopper is regenerative.)

The last move in standardization was made in 1973 and 1974 when the 3 central Ruhr area systems of Mülheim, Essen, and Bochum-Gelsenkirchen decided to place a joint order for about 50 cars. The small system of Bielefeld, which is halfway between Hannover and the Ruhr area, later ordered some cars of the same design. Because of the rather small track center distances, the cars could only be 2.3 m wide (the 4 systems had previously used cars 2.2 m wide). All 4 systems use meter gauge; therefore, the cars are called M-cars. Unlike the 8-axle designs for Frankfurt, Düsseldorf, and Hannover, the center section of the 8-axle M-car is neutral; that is, this section has no electric equipment parts necessary for the operation of the car. The M-car therefore can be built as a 6-axle or an 8-axle car. Bochum-Gelsenkirchen ordered only 6-axle cars; the other systems ordered 8-axle cars. The VÖV recommendations were respected as much as possible, but low first and operating costs were emphasized.

The foregoing clearly shows that complete standardization has not and cannot yet be achieved because local conditions are too different and because fixation of a car design for a long time would seriously hamper technical progress and development. The VÖV Rail Vehicle Committee therefore will limit its future work to standardization of equipment parts and groups for such cars and will give recommendations only for basic dimensions.

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OPERATING A LIGHT RAIL SYSTEM

Robert S. Korach, Port Authority Transit Corporation of
Pennsylvania and New Jersey

The most important parts of a transit operation—movement and control of vehicles—are discussed. Scheduling and control of trains in a hypothetical system are described. Examples of movement and control in light rail systems in Boston, Newark, Shaker Heights, and Cleveland are given.

The most important parts of any transit operation are the movement and control of vehicles.

SCHEDULING

All schedules are made up of fundamentals. The physically defined route over which the vehicle operates should be examined carefully, and any problems incurred en route caused by topographical conditions or complications of multiple routing and passenger-carrying difficulties should be noted. The physical route will dictate the running time or the time allowed from one terminal to the other terminal; the time usually is expressed in minutes. This time also is determined, of course, by the capabilities or operating characteristics of the vehicle. It must include the boarding and alighting time of the passengers at each intermediate stop, the combined running times in each direction, and any layover or turn-around time required at the ends of the route. This provides the overall round trip time for a particular vehicle. The size of the train matters little except a longer train generally will move more slowly over a route with physical restrictions such as sharp curves or steep grades. And a multivehicle train will, of course, take longer at terminals if the turning movement is accomplished on tail tracks behind the station or on sharp radius loops.

Having determined the round trip time, one must next decide on the amount of service that is needed to operate on the route. Frequency of service can be determined by the number of passengers to be handled past a maximum load point or by an arbitrary minimum or maximum frequency of service. Most rush-hour service, of course, is based on the numbers of passengers to be carried; off-peak service is based on certain desirable frequencies and economic use of personnel.

One further requirement in a schedule or movement plan for a transit system includes use of personnel on the train. Because peak-hour requirements of on-train personnel far exceed off-peak requirements, the extra rush-hour personnel should be used to increase off-peak frequency, particularly during midday and evening hours; they also can be used to operate an economical all-night service. The secret of good personnel use requires that all on-train personnel work at least 1 peak-hour period. Any personnel not used this way simply add to the operating expenses of the off-peak service without contributing anything to reducing the peak-hour expenses.

In the use of light rail vehicles, an operator or attendant is required on each individual vehicle (whether they are running singly or in trains) if car-borne fare collection is required. Consideration should be given to prepayment of fares over all or certain sections of the light rail route, which would permit 1-person operation. If street operation is required on the outer ends of a light rail line with car-borne fare collection, then individual attendants could be assigned to work only the cars in this area. This type of operation is planned by San Francisco Municipal Railway. Careful study of the optimum use of both on-train operating and off-train station personnel should always be made when planning a new light rail system.

Service levels and capacities can be controlled by using a train with the maximum number of cars in the peak hour and 1- or 2-unit trains in the off-peak hours. A good rule for operation in off-peak hours is to use a 2-unit train in the daytime and a 1-unit train in the evening. A combination of these factors, frequency of service and length of train, will produce the best possible service to the public at the least possible expense to the operating agency.

CONTROL

Control of trains is important to the movement of the trains. New light rail system vehicles can be run manually without a signal system. The operator runs the train and observes the right-of-way while controlling the movement of the train. In the past, this has led to dangerous and undesirable operating practices. Therefore, even the simplest light rail transit systems must use a signal system for rear-end protection and control of trains at interlockings or diverging routes. The signal system also must control operation when physical restrictions require slower speeds. These various types of signals must be obeyed manually by the operator unless inductive or track-trip features are installed that override the operator's control of the vehicle.

A more sophisticated control system consists of a semiautomatic operation in which the signal system itself, by means of track codes or wayside devices, determines the operation of a train between stations; the operator merely presses a button when he or she is ready to leave a particular station or terminal. This feature tends to improve the abilities of even the most marginal operator, but there is no reason to believe that an exceptional operator cannot simulate this semiautomatic feature while running the train under full manual control. The time saved by a semiautomatic operation has proved its worth where it is used. It equalizes the abilities of the train operators and makes them all equal to the best.

The most advanced method of control is an automatic system in which the operator simply monitors the train operation while a central control, presumably with computers, runs the train from terminal to terminal. Unless there is full manual backup for the controllers and operators to use in emergencies, this system can cause many problems in train operation particularly if multiple delays occur on a route. The inability of present computer-control systems to control more than 1 or 2 unusual situations magnifies the problem. In bad weather, many unusual situations occur at the same time, and most require manual control for solution.

A further refinement of the automatic control would be full automation with no employees on the train. This, of course, would be a great advantage because the personnel element would not have to be considered in the process of scheduling trains. Fully automatic control, however, has all the problems of automatic control with an attendant. In emergencies there would be no one on board to handle any of the control functions except the passenger.

EXAMPLES

The simplest type of light rail transit system in the United States is the Mattapan-Ashmont Hi-Speed Line in Boston. Its main function is to provide extension feeder service to a major Boston heavy-duty rapid transit line. It handles about 14,000 rides each weekday on a very short route with about a 20-min round-trip time. Frequencies during rush hour are about every 2 min; only 1-unit vehicles are used. Off-peak service varies from 6 to 24 min; there is no 1:00 a.m. to 5:00 a.m. operation. Control of the vehicles on this line is strictly by the sight of the operator; there is no signal system. Average speeds between stops are about 30 mph (48 km/h). There are few blind spots on the line, and this simple system has proved to be very safe during its many years of operation. The regularly used switches on the line, which are at only 1 terminal, are manually controlled. Simplicity and success describe this small but important light rail operation.

Another excellent example of a simple light rail rapid transit system is the Newark subway. This line is approximately 4 miles (6 km) long and has a running time in each direction of about 12 min. Round trips can easily be made in 30 min; rush-hour operation runs on an even tighter turn-around time. The line runs a single-vehicle operation each day from about 5:00 a.m. to 1:00 a.m. the next morning. On weekdays, headways vary from better than 2 min in the rush hours to 30 min in the late evening. Midday services range from 4 to 7 min. The Newark line runs from one terminal to another without any diverging routes. Operation over most of the route is controlled by a signal system that provides rear-end protection and a few timing devices to control speed. The operator of the vehicle observes these signals when making the round trip. At one end of the line cars are stored in a yard. In this area, during rush hours, switches are controlled from a tower. A simple display board that shows track occupancy is available for the control to use. All other switches on the line, which consist mostly of emergency crossovers, are manually operated.

A slightly more complicated type of operation is the Shaker Heights, Ohio, rapid transit system. This line, which has a 60-min round-trip cycle, has frequent rush-hour service but includes a route diversion in the form of 2 branches. Rush-hour frequencies on the trunk portion of the line are as close as 2 min; there is both single-unit and multiunit train operation. Base service is generally 10 to 30 min. A turnback loop with a 30-min round trip is available at the junction of the 2 branches for certain short-routed schedules. Control of the system is by simple signals that give rear-end protection and must be observed by the operators. The switches at the diverging point and at wayside turning loops are controlled manually by the operator. A further complication in the movement and control of this system is its 2-mile (3-km) joint operation with the Cleveland Transit System (CTS) rapid transit line. Trains of both systems are given preference automatically on this joint section of track in the order in which they entered the section. A manual override of this system is available to a central dispatcher who controls only CTS trackage. The signal system in the joint track area is equipped with track trips to give positive rear-end protection for both Shaker Heights and CTS vehicles. Surprisingly, the Shaker Heights rapid transit downtown terminal has all of its switches manually controlled, which alleviates the need for a control center or dispatcher. The equivalent of a dispatcher is always on Shaker Heights rapid transit property mainly to coordinate the crew assignments and to manually control the train operation by issuing orders.

The most complicated type of light rail operation running today is the Green Line System in Boston. This system currently handles about 175,000 rides each weekday. The trunk portion of this system is an amalgamation of 5 outer-end branches, and there are many forms of short-turn operations on both the trunk and branch lines. Multicar operation is used during the rush hour for most services; and branch-line headways are about 4 min. The trunk headway is therefore better than 1 min and is controlled by a simple rear-end-protection signal system. Because of the density of operation on the trunk portion, there are certain locations where vehicles or trains can close up on each other only by using sight observation. Timing devices also are used when they are needed for further protection. Switches at the diverging points and at most short-turn points are controlled by the power on-power off method. There is no central control over this heaviest of light rail operation.

SUMMARY

In summary, it can be seen that light rail is readily adaptable to the simplest of movement and control systems. If greater sophistication is desired in either of these areas, light rail can be adapted to perform but at greatly added expense and with higher maintenance problems. If the purpose of light rail is simplicity and if it is to be a cost-cutting method of obtaining fixed guideway transit service, simple operating methods and controls should be considered. If used properly, they will ensure a safe, convenient, and popular transit service.

LIGHT RAIL TRANSIT CONSTRUCTION COSTS

George R. Beetle, Louis T. Klauder and Associates

Light rail transit has attractive service characteristics that can be secured in most cities for modest investments. The relatively low construction costs of light rail transit are due primarily to avoiding large civil works by relying instead on reserved rights-of-way at grade. Many options are available for alignments at grade, and costs for way reservation can vary widely. This paper describes the construction costs for modern light rail transit; it takes into consideration way reservation and the more predictable costs for stations, street crossings, track, cars, electrification, signals, communications, and other requirements. The costs presented are estimates, based on the experience of the author in recent evaluations of light rail transit for several U.S. cities. Few new light rail facilities have been built in the United States in recent years; therefore, little opportunity exists for relating estimates of this type to actual construction. Figures discussed here range from high to low where convenient, and single estimates presented are conservative representations of the largest values likely to be experienced in most cities.

Light rail transit does not cost much to build compared with available alternatives. Urban highways now cost between 4 million and 6 million dollars/mile (2.5 million and 3.7 million dollars/km). Underground rapid transit lines require much larger expenditures that range from 30 million to 45 million dollars/mile (18.6 million to 30 million dollars/km).

Light rail transit can be built for between 2.5 million and 5 million dollars/mile (1.6 million and 3.1 million dollars/km), including all costs for way facilities, stations, shops, yards, and cars. Light rail transit service is not as attractive as full-scale rapid transit, but its construction costs are much lower. The low costs of light rail transit are attributable primarily to the avoidance of requirements for major civil works. Light rail transit service can be secured with lines built entirely at grade where appropriate arrangements for reserved rights-of-way can be made.

WAY RESERVATION

There are many alternatives for securing reserved rights-of-way. Light rail lines can be built in the median strips of boulevards and major highways, thus eliminating costs for land acquisition or isolating the line from automotive traffic. Light rail lines also can be built on city streets where curbs or planting can be used to isolate the line from street traffic. These elements can add up to 170,000 dollars/track mile (105,000 dollars/track kilometer) to track construction costs.

Light rail lines can be integrated effectively into pedestrian malls and shopping centers in either downtown or suburban settings. The lines can be built in intimate relationship with the commercial establishments served, and costs for construction and other facilities will be only a small part of the total investment.

Railroad branch lines also can be converted to light rail service. In many cities where little-used freight lines exist, this last alternative can appear very attractive because it frequently allows development of a completely reserved right-of-way for the light rail trains and no significant interference with automotive traffic.

Costs for way reservation for railroad lines can vary widely depending on the extent of track revisions needed to facilitate continued railroad freight service at levels that would be acceptable to shippers. In some cases, the use of railroad rights-of-way may invite consideration of possibilities for the local transit authority to operate local freight service. This could provide an opportunity to preserve railroad freight service that otherwise would be abandoned.

STATIONS

Light rail transit stations need not be elaborate. In most cases, a low-level platform with good lighting and a simple shelter to protect waiting passengers from the elements will suffice. Costs for an arrangement such as this for a station that could handle 4-car trains would be approximately 75,000 dollars/station. In downtown areas, island platforms in streets or at curbside may cost slightly more, but separate lighting often is not necessary in these locations.

High-level platforms may be desirable to reduce dwell times at downtown stations that experience heavy peak volumes, but they often are not necessary even in these circumstances. High-level platforms can be provided for an additional cost of approximately 36,000 dollars/4-car-train station.

Fare collection at stations is an important question involving a requirement to balance investment costs against the continuing costs of operation and maintenance.

One alternative is to use cashier booths. These are easy to provide, but they require that the station area be secured. Fences and turnstile gates at the booths can be used in underground or elevated stations downtown where access to the station platforms can be controlled easily. Suitable arrangements generally cannot be provided in outlying areas where the light rail trains would run at grade. In any case, the need to staff the cashier booths can introduce significant operating costs.

Cashiers can be omitted, and automated fare collection systems can be introduced. Automatic equipment for sale of tickets and ticket-activated turnstiles can be provided for an investment cost of approximately 120,000 dollars for a typical station requiring 2 entrance points. Without the presence of a cashier, security arrangements may need to be tightened, and some means of continuous or periodic surveillance is required. Television surveillance can require an additional investment of 50,000 dollars/station. Automatic equipment introduces a need for continuing maintenance costs. Because most modern equipment relies heavily on electronics, skilled labor, which is expensive, is required for maintenance. Additional staff to provide surveillance and maintain television surveillance systems may be needed also.

A simpler system that has been used effectively in other countries relies on passenger validation of tickets. In this arrangement, automatic vending equipment is installed at stations, allowing passengers to purchase tickets themselves without a cashier. The passengers then validate tickets after boarding the vehicles by using simple marking machines inside the cars. A random patrol force rides the trains and provides periodic checks. This simple system can be installed for an investment cost of approximately 30,000 dollars/station and 1,200 dollars/car. Its advantages are that it does not require any fencing, turnstiles, or surveillance equipment. Also it does not require continuing costs for cashiers or sophisticated maintenance.

Stations, especially those in outlying suburban areas, frequently must incorporate parking and feeder transfer facilities. These items can be provided easily at grade. Costs for parking in suburban territories now are approximately 1,400 dollars/parking space. A loading dock for buses that has a covered waiting area for passengers typically costs approximately 20,000 dollars/bus space.

GRADE CROSSINGS

One of the best advantages of light rail transit is that it usually can be installed without grade separations. Trains are small enough and headways are long enough that operation at grade is acceptable. Cross streets need to be closed to permit the passage of trains, but the crossing movements generally pose no greater interference with automotive traffic than that incurred at ordinary signalized intersections.

In addition, arrangements can be made for light rail trains to preempt signals at street crossings to allow them to negotiate the crossings without stopping. This scheme minimizes delay for the largest number of travelers seeking access to the crossing and has been proved to be very effective in other countries.

Costs for suitable safety protection at crossings are modest. Gates and flashing lights that close streets when trains approach can be installed for approximately 25,000 dollars/crossing. Integrating the crossing protection with the light rail signal system to provide preemptive capability can require an additional cost of approximately 12,000 dollars/intersection.

When overhead electrification is used, pedestrian crossings at grade are safe and completely acceptable.

Although full grade separation of an entire line would never be necessary, the need may exist for individual grade separation structures at particularly difficult crossings. Costs for grade separation improvements will vary greatly depending on local site conditions.

Generally, an investment of approximately 2 million dollars would be needed to carry a 4-lane arterial street over a 2-track light rail line. To carry the light rail line over the same arterial would require approximately 2.5 million dollars. Both of these figures would be higher if railroad freight service were to share use of the light rail transit track. The larger underclearance required for railroad operations would add approximately 500,000 dollars where the rail line would be carried beneath the arterial. If the rail line were carried over the arterial, the heavier railroad axle loads would require an additional 250,000 dollars.

OTHER CIVIL WORKS

Major civil works may be required for light rail lines where negotiation of river crossings or other obstacles imposed by terrain or existing land use is necessary. Often, however, low-cost solutions can be obtained by relying on existing facilities. Reservation of a single traffic lane through an existing tunnel or over an existing bridge often can be satisfactory even where it might require a short stretch of single-track operation for light rail service.

The possibilities and requirements for major civil works depend entirely on local planning and development preferences, however. Many cities find it desirable to place new light rail lines in tunnels or on elevated structure over short distances through the heart of downtown business areas. Where downtown distances are short in relation to total route length, construction costs for the tunnels or elevated structures need not inflate total project costs to unacceptable levels.

Wherever tunnels or elevated structures are used, they should represent the first installment in the development of full rapid transit. Construction of such facilities in downtown business areas represents a relatively painless way to get started in the development of a rapid transit system. It goes without saying that, where tunnels or elevated structures are deemed necessary, they should be designed and built at standards that would be acceptable for full-scale rapid transit.

Costs for tunnels vary widely with respect to prevailing local geology and soils, underground utilities, and urban development in general. Typical costs for tunnels that can be bored without excavation at the street surface are approximately 18 million dollars/route mile (11.2 million dollars/km). Where cut-and-cover techniques must be used, costs would range between 18 million and 35 million dollars/route mile (11.2 million and 22 million dollars/km). Elevated structures would cost between 10 million

...ion ... (6.2 million and 9.3 million dollars/km). Where ...er construction would require that underground stations be built, each station ...uld cost between 5 million and 15 million dollars. Elevated stations would cost approximately 5 million dollars each.

TRACK

Generally, light rail transit lines require the installation of new track structure even where they are being developed on existing railroad rights-of-way. This is necessary to provide acceptable ride quality.

The number of tracks required depends on the passenger volumes expected and the distances to be traveled. The figures presented here relate to construction of single track. The figures can be doubled where 2 tracks are needed; double crossovers between a pair of tracks would add approximately 320,000 dollars each; this would include all track specials, switch machines, and interlocked signaling.

Light rail lines have no special geometric requirements. Existing grades and curves for streets, highways, railroads, or canals would be acceptable for light rail development. New grading of the roadbed is seldom necessary except to dress and shape it for the receipt of new track.

Occasionally the restoration of drainage channels and the installation of improved drainage facilities may be necessary. Revision of existing utilities is seldom needed. Typically an allowance of approximately 40,000 dollars/route mile (25,000 dollars/km) would be sufficient to cover these requirements.

The new track structure should include entirely new ballast, ties, rail, and fittings. Welded rail should be used wherever possible to ensure a high-quality ride. Costs for the new track structure would be approximately 270,000 dollars/mile (169,000 dollars/km) of single track, for nearly all applications.

Where only the light rail trains are to use the track, a rail section of only 100 lb/yd (50 kg/m) would be sufficient. Even lighter sections would work, but they would not generally be available from U.S. rolling mills without extra charges above the base price. Where railroad freight trains are to operate over the light rail line, a heavier section of up to 119 pounds per yard (60 kg/m) would be desirable. Because the running rails are used for the return leg of traction circuits, conductivity requirements may sometimes influence the selection of a rail section, but the electrical requirements are seldom controlling criteria.

The variations of track construction cost with respect to the weight of rail used are relatively small; they are typically less than the variance reflecting local site conditions.

CARS

Cars represent the largest single component of light rail transit system construction costs in most applications. If a light rail system is being developed with all or nearly all of the track at grade, 50 percent or more of the total investment requirement will reflect costs for cars.

The cars are important because of the effect they have on the perceived quality of light rail service. For most passengers, the majority of the time consumed in a trip is spent in the cars. Interior design, seating, lighting, heating, and air conditioning are important elements of comfort that will affect rider choices. The appearance of the exteriors of the cars is also a major influence on public impressions of the attractiveness of light rail transit service. The performance capabilities of the cars can critically affect service speeds for the station spacings most typically encountered in light rail development.

Speed, comfort, and convenience are the service characteristics most needed to attract riders from automobiles in U.S. cities. Therefore, the cars represent a critical factor in the development of a light rail service that can be expected to compete successfully with automobiles.

The actual configuration of the cars is not critical. Articulation sometimes has an advantage for tight turns in city streets or to improve driver productivity where existing work practices will not allow operation of cars in trains with only 1 operator on board. Except for circumstances such as these, however, articulation usually is not necessary.

Car sizes can vary. A typical 50-ft (15.24-m) car can provide space for 55 seats and standing room for approximately 100 additional persons.

Whether the cars are single units or are articulated, they should be capable of operating in trains. This frequently is desirable from an operating standpoint even when work practices do not allow work force savings.

Economies in car design and construction are possible. Modular design of structural components that would allow size variations is practicable and deserves further attention. It would allow wide latitude in tailoring car dimensions to fit local requirements without extra costs (as was possible with the Presidents' Conference Committee car years ago).

Possibilities for standardization of electrical and mechanical components are even more realistic. Standardization can permit substitution of propulsion components, climate control apparatus, and door mechanisms to satisfy local preferences and needs. The important thing is to preserve the capability to respond to local requirements in ways that can provide performance and comfort advantages to allow the light rail service to compete effectively with the automobile.

The full value of standardization of components probably cannot be realized unless all suppliers in the market can share in the engineering cost savings that would follow from it. Without sharing the savings, the current weakness caused by too few builders in the market probably will be perpetuated. Today's small number of active car builders reflects primarily the uncertainty in recent years regarding the prospective size and durability of the market for light rail cars. It also reflects cost inflation risks in car construction contracts, which have been severe in recent experience.

The present cost of a light rail transit car produced in the United States that would be attractive to riders in most urban transport markets would be approximately 450,000 dollars/unit when at least 200 cars are ordered. This cost nearly equals that of a modern rapid transit car, which the contemporary light rail vehicle closely resembles. Future standardization would reduce real costs but to what degree is now uncertain. Certainly broader market participation over the longer term also would reduce real costs.

ELECTRIFICATION

Electrification system requirements depend directly on car characteristics. Supply voltages can vary, but most light rail installations are developed for service with direct-current power supply at 600 V.

High-performance and commercial speeds of approximately 30 mph (48 km/h) are necessary in most U.S. urban areas; cars designed for this level of service will draw large amounts of current. The current requirements together with the train densities on the line needed to carry expected volumes generally will determine the size of substations.

Light rail transit generally requires that substations be durable; they must be capable of sustaining heavy overloads during short intervals when trains are accelerating. A substation for a system requiring 4-car-train operation at 5-min peak headways generally costs 210,000 dollars today.

Although variations can occur, the substations typically are spaced at the same interval as the passenger stations served. An exception to this rule would be in downtown areas where a separate substation for each of a number of closely spaced stops would be neither necessary nor desirable.

Distribution of power along the light rail line should be by overhead trolley wire. Suitable arrangements for overhead supply are easy to design and build. They also pose little danger to the public and obviate fencing the right-of-way.

The required overhead conductor sizes depend on train traffic density and substation spacings. It may be necessary, especially with high-performance cars, to include feeder cables as a supplement to the trolley-wire conductor. These usually can be strung separate from the trolley wire, however, and elaborate catenary structure to support the trolley wire is rarely needed.

The trolley wire can be suspended from simple pole supports that can be spaced at distances of 100 to 200 ft (30.5 to 61 m). A bracket can be used to suspend the wire from the poles, or a transverse span wire between the poles can be employed. Fittings and insulators are available and can be installed without difficulty. Arrangements for constant tension on the trolley wire also are possible.

The return leg of the traction circuits generally is on the running rails, and rail joints therefore must be bonded. Reliance on the running rails can introduce the possibility that electrolytic corrosion would be imposed on nearby utilities or conduits buried in the ground. This is seldom a major problem, however.

The cost for electrification on a typical line with pole supports spaced 120 ft (36.6 m) apart would be approximately 140,000 dollars/mile (86,000 dollars/km) of single track. If substations were spaced at approximately 1-mile (1.6-km) intervals, total costs for the electrification system would be approximately 490,000 dollars/route mile (304,000 dollars/km).

SIGNALS AND COMMUNICATIONS

Simple signal and communications systems are desirable in light rail applications. Requirements and costs for grade-crossing protection already have been discussed. At other points along light rail lines, traffic densities usually are not large enough to require signals, but better speeds and performance usually can be obtained with them. In addition, sight lines can be a problem, and protection for them often is most effectively achieved by providing signals over the entire line.

Either wayside indicators or cab signals can be used. Cab signals are usually easier to install in urban environments and have the advantage of providing a continual indication of conditions ahead for train operators. Typical costs for cab signals are approximately 95,000 dollars/mile (59,000 dollars/km) including all requirements for track circuits, car-borne equipment, signal power supply, and track impedance bonds.

For efficient operations, simple communications systems also are advantageous. Radio contact with train operators from a central control point can be provided for a cost of approximately 5,600 dollars/car. Telephone connections for information and assistance to riders at stations would cost approximately 21,000 dollars/station. With open and well-lighted stations and a simplified fare collection system, television surveillance usually is not necessary.

OTHER COSTS

Yards and shops, land acquisition, and special facilities for physically handicapped riders may add costs for light rail transit development.

Requirements for maintenance and storage of light rail cars are not extraordinary. The design characteristics of shops, shop equipment, and yards have been established by years of experience. In most new systems, costs for these facilities would average approximately 60,000 dollars/vehicle.

Land acquisition requirements arise primarily in relation to car storage yards and parking at stations. Costs vary widely depending on location and existing improvements on the land to be acquired.

Acquisition of land for assembly of a right-of-way generally is not needed. Where light rail lines can be developed in existing streets and highways, there may be no right-of-way costs. Where light rail transit service is to be developed in existing railroad corridors, arrangements for occupancy of the railroad right-of-way may vary, and costs for use of the railroad property would depend on the effect that the light rail service would have on railroad freight operations.

With regard to facilities for physically handicapped riders, the simplicity of light rail stations is advantageous. With a simplified fare collection system and no fencing or gates, movement to and from train boarding areas for handicapped persons would be the same as they currently experience in pedestrian traffic. Simple ramps and platforms for boarding trains can be arranged at minimal cost (approximately 10,000 dollars/station); floor space and entrances on the cars are more than adequate.

CONCLUSIONS

A brief acknowledgment and word of caution may be appropriate in conclusion.

All the figures discussed here represent estimates based on my recent experience in evaluations of light rail transit proposals for several U.S. cities. They have been developed on the assumption that construction of new light rail facilities would be performed by contractors working under competitive bid procurement procedures, and they reflect current price and cost experience in the construction industry.

There is always some risk in an effort such as this in which estimated costs are developed and presented without reference to particular site conditions in some given location. The risk is acknowledged here by emphasizing the major elements required to build a light rail transit line and by providing estimates of costs for each of them. The estimates represent the largest costs that might reasonably be encountered in most cities, except in unusual local circumstances.

The total cost for construction of any given system would depend on how these building blocks would be put together to satisfy local requirements. When the total estimates are assembled, however, total cost for light rail transit construction should fall between 2.5 million and 5 million dollars/mile (1.6 million and 3.1 million dollars/km).

If, during preliminary planning for a line, total estimates begin to exceed this range, it would be wise to stop and reconsider basic objectives. Generally, higher costs would mean that elements representing full-scale rail rapid transit are being mixed in with an outwardly light rail transit solution, and it may be desirable to consider whether full-scale rapid transit development would represent a more effective response to local requirements than would reliance on the light rail alternative.

OPERATING AND MAINTENANCE COSTS OF LIGHT RAIL TRANSIT

Ronald DeGraw, Southeastern Pennsylvania Transportation Authority

This paper explains the costs of operating light rail lines, and it explains how light rail can be more economical than other modes under certain conditions. Using 3 recent studies of proposed light rail lines as examples, the paper shows that new lines can be economically constructed and operated with a potential ridership of as little as 20,000 daily passengers. The self-service fare system used on European light rail lines is explained, and an opinion is given recommending that such a system could be implemented on new light rail lines built in the United States. Relatively fixed maintenance costs, high passenger-to-operator ratios, and multiple-unit capabilities make traffic increases on light rail lines much more economical to accommodate than on bus lines. The paper details how light rail lines have high passenger carrying capabilities (as much as 20,000 passengers/h) yet need relatively low passenger loads (only 20,000 passengers/day) to economically justify implementation and still have sufficient revenue to cover all operating costs. Also discussed are the ease of implementation, the versatility of the mode, and passenger acceptance and preference.

Many cities now are considering the construction of new light rail lines. Some cities, such as Dayton, Ohio, already have undertaken feasibility studies. The Dayton study is interesting. It concludes that a 12-mile (19-km) light rail line constructed partly on an existing railroad freight right-of-way and partly on downtown streets would produce an initial daily ridership of 20,000 passengers. The rail line would be supplemented by a 10-bus feeder system at outlying stations. A flat fare of 40 cents would be charged, and transfers would be free. There would be no complicated zone fares, nor would passengers have to pay extra to transfer to the buses.

It is estimated that the annual operating costs for a fleet of 48 rail cars and 10 feeder buses would be 2.3 million dollars, all of which would be offset by revenues.

By the year 2000, daily ridership would have risen to 48,000 passengers, which would require 99 rail cars and 17 buses. Annual revenue would then amount to 5.4 million dollars; total operating expenses would be only 3.7 million dollars. This would produce a surplus of 1.7 million dollars. This means that, although the number of passengers would more than double, operating expenses would increase by only about 60 percent.

This interesting situation is due to 2 principal factors. Two of the largest expenses in operating a rail line are maintenance of the right-of-way and personnel required to run the service. A doubling of passengers does not require a doubling of maintenance-of-way expenses. Right-of-way expenses are relatively fixed costs, and, although it is true that more traffic results in more wear and tear to the roadbed and stations, the increase is not proportional.

An increase of passengers on a bus line results in a directly proportional increase in the number of people required to operate the buses. But this is not necessarily true with a light rail line. Just as subway and rapid transit lines can operate up to 10-car trains with only 1 or 2 in a crew, so, too, can light rail lines take advantage of longer trains.

It has long been an established practice in some European cities to operate light rail trains of 2 or 3 cars that accommodate as many as 350 passengers with only 1 operator. Five buses would be required to carry the same number of passengers. This is accomplished by use of a self-service system. Persons paying cash fares board the first car where the motorman is stationed. But passengers with tickets may board the following cars by pushing a button on the exterior of the cars that causes the doors to open. Once they are inside, passengers have their tickets validated by a small machine similar to the machines used until recently by the Chicago Transit Authority to validate transfers. A passenger must keep the ticket for the duration of the trip and must show it to roving inspectors. A stiff fine is imposed on any passenger who does not have a validated ticket. This system works well in Germany, and German authorities are convinced that there is little cheating.

Such a system has never been attempted in the United States, and there is certainly some doubt about how well a self-service system would work in large Eastern cities where it is already great sport to try to "beat the system." But it probably would work in many other areas of the country. The Dayton study is predicated on the use of this type of system.

Such a system has a very obvious effect on operating costs. A newly constructed light rail line may operate on a 20-min headway for the midday base period. As the line becomes more popular and attracts more riders, it might be necessary under customary operating conditions to increase the headway to every 10 min and double the number of operators. But, if an automatic fare validating system is used, 2-car trains could be run every 20 min with only 1 operator on board, which would cut personnel costs in half.

The operation of 3-car trains with a single motorman would result in even greater savings per passenger.

Advocates of light rail lines frequently say that a double-track line can carry up to 20,000 passengers/h in 1 direction. These are staggering figures, and they tend to scare smaller cities into thinking that they may not have enough riders to justify constucting light rail lines. The Dayton study, however, predicts initial ridership of only 20,000 per day and claims that construction of a new line for even this small a number of passengers can be economically justified.

It further claims that a new system unfettered with expensive and intricately sophisticated gadgetry can meet all of its operating expenses.

The Media and Sharon Hill lines of the Southeastern Pennsylvania Transportation Authority (SEPTA) carry 15,000 daily passengers. The Norristown High-Speed Line carries about 9,500. The 2 Shaker Heights Rapid Transit lines have a daily volume of 13,500. The line in Newark carries 14,000 daily passengers.

No formula exists that requires a certain number of passengers per hour or per day to justify construction of a light rail line. There are no guidebooks to use to find out whether an area has the potential to build a line. And, unfortunately, there has been no new line constructed in the United States in the last 20 years that could be observed as a model light rail operation. One has to go to Europe for that.

The feasibility of a light rail line depends largely on local conditions. A system that already has light rail lines might encounter union problems if it wished to operate a new line with only a single motorman for a 3-car train. A city in which light rail transit would be new probably would not have that problem.

Operating and maintenance costs on most existing light rail lines in the United States do not tell the whole story. They are higher than those that a new line would incur for a variety of reasons. In many cases, rights-of-way have been permitted to deteriorate, and a transit authority would have an accelerated and costly catch-up program. Cars are old; therefore, their maintenance costs are very high. And, because the cars are old, they are not adaptable to 1-person operation. They are also less reliable and less attractive because of their age.

Most existing light rail lines do not have adequate grade-crossing protection. They lack the crossing gates that would permit faster and, therefore, less expensive operation.

One of the major attractions of light rail transit is its flexibility. It can run in high-speed subways (such as in Philadelphia, Boston, and soon in San Francisco), in the streets, on elevated structures (as in Boston), and on private rights-of-way with no grade crossings (such as Boston's Riverside Line). Its private way can be crossed by many highways (as in Shaker Heights and the SEPTA Red Arrow Division); it can run in the medians of highways (as in Shaker Heights and Boston); it can use abandoned railroad rights-of-way (as in Boston); and it even can run in the bed of an abandoned canal (as in Newark).

The facilities supporting a light rail system can be extremely simple and, therefore, are economical to build and maintain. Stations can be simple blacktop platforms with small 3-sided shelters. Expensive high-level platforms are not necessary, nor are large station buildings, intricate fare collection devices, or cashiers. Routine maintenance costs for such stations are low, particularly in areas where vandalism is not a major problem. Areas that involve street running may simply use curbside loading with no station facilities or special platforms. If operating speeds are not high, wayside signals may be omitted except on curves and at junctions or single-track areas, thereby reducing maintenance costs.

Using single track on lightly trafficked portions of a route can help reduce maintenance costs. However, it also can produce some expensive head-on collisions.

Elaborate terminal facilities are often not necessary. Pittsburgh, for example, has no off-street facilities in its downtown area. Neither do many Philadelphia lines. They simply operate on downtown streets. This can result in a considerable saving in the personnel and maintenance costs required to operate a terminal facility.

Unlike railroads and heavy rapid transit lines, there are usually no yard crews or control tower operators employed on light rail lines. Train operators throw their own switches, manually or automatically, even at major junction points. And they take their own cars to and from storage areas. This creates a large saving in personnel costs.

Existing railroad rights-of-way are the real hope for building new light rail lines in the United States. A recent study for Bergen County, New Jersey, considered the feasibility of converting a Penn Central freight line into light rail service. Passenger service on the 14.5-mile (23.3-km) West Shore Line was abandoned in 1959; now the communities along the line are seeking to reinstitute commuter service into New York City.

The study found that light rail transit, although more expensive to build than conventional railroad commuter service, would have lower operating and maintenance costs. Light rail transit also would operate at higher speeds and offer more frequent headways, thereby providing a more marketable service.

The medium level of ridership contained in the report would result in an operating deficit of about 500,000 dollars/year with conventional rail service and an operating surplus of about 750,000 dollars/year with light rail transit.

A 1971 study of the feasibility of light rail transit for Rochester, New York, concluded that operating costs for light rail transit would be 24 percent lower than bus costs chiefly because the use of light rail transit would require 43 percent fewer operators.

The most expensive item in most transit systems is operators' wages. Light rail transit technology offers the advantage of operating 2-, 3-, or even 4-car trains with a single operator. It now costs approximately 17,000 dollars/year for each operator. Therefore, substantial savings can result from 1-person operation of a train.

There are many costs associated with rail transit that are not necessary in a bus operation, including the maintenance of track, signals, bridges, substations, fencing, and stations. All of these expenses accumulate, and, in many cases, they create a situation in which it is more expensive to operate light rail transit than it is to operate buses.

I am not trying to imply that all buses should be replaced by light rail lines. That would be foolish. There is no question that the bus is an extremely important public transportation vehicle and will remain so. There are many situations in which a bus is the cheaper vehicle and is the most practical mode of transportation. But there are many other situations in which rail lines will perform better and more economically than bus lines, particularly on heavy corridors into a city.

An example of a more economical operation would be where numerous bus routes come from a city in the same general direction on a major highway corridor, then fan out to serve various suburban areas. A light rail line might replace the bus lines on the trunk corridor. The bus lines would then be relegated to short suburban routes feeding into the nearest light rail station. Such a situation probably would reduce the number of operators needed to maintain the total transit service and would provide a speedier, more comfortable, and more economical ride for passengers.

There is considerable evidence that passengers prefer light rail lines to bus routes. According to the American Public Transit Association, passengers per route mile (kilometer) on surface rail lines dropped 11 percent in the 16 years between 1955 and 1971. Passengers per route mile (kilometer) on bus lines throughout the nation dropped 52.5 percent during the same period. Many passengers seem to feel that rail lines are easier to use because there is no question of where they are and where they will stop. Bus routes tend to wander, and there is no visible evidence of where the bus runs. Operators of transit buses tend to create various spurs, alternates, and extensions to their bus routes, many of which confuse passengers. Light rail cars have more comfortable seating and aisle space and a smoother ride than buses.

Perhaps the most important attribute of light rail transit is that its flexibility permits it to grow with the needs of a region. An initial line can be constructed inexpensively, and then can be upgraded gradually to permit higher speeds and greater frequency as money becomes available and as patronage increases.

This flexibility is not inherent in most other forms of transportation. Its presence in light rail transit permits maximum economies in both construction and operation.

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ATTRACTING LIGHT RAIL TRANSIT RIDERSHIP

William A. Jessiman and George A. Kocur, Cambridge Systematics, Inc.

This paper addresses the complex planning considerations for attracting ridership to transit systems, particularly light rail transit systems. Taking the viewpoint of a potential rider, the authors present some observations that lay the foundation for understanding ridership response. Users are not interested in technology per se but in the level of service the system provides. Level of service is a complex combination of many system attributes such as travel time, cost, comfort, and convenience. Different user groups (market segments) make different trade-offs among these attributes. They assign different relative weights or importance to each attribute. To attract maximum ridership, the system should be tailored to the particular needs and constraints of the market segments it is serving. No single system is superior for all market segments. The paper discusses the various level-of-service attributes and their relative importance to different market segments based on empirical evidence and attitude surveys. Although one cannot generalize because different market segments assign different relative weights to level-of-service attributes, the following rank ordering of attributes from most influential to least influential is most typically the case: out-of-vehicle travel time, in-vehicle travel time, cost, comfort, and safety. For work trips, travel time reliability should be added as either the first or second most important attribute. The characteristic convenience is dismissed from this list as being too broad to be specifically and universally defined. The paper goes on to introduce disaggregate, behavioral, travel-demand models as an emerging analytical technique that the transit planner can use to more precisely address the problem of the ridership response of different market segments to different level-of-service packages. Examples of these models are then used to demonstrate how different prototypical households would respond to various technologies under various representative operating policies. Some conclusions are drawn on the situations in which light rail transit would appear to be the most attractive form of public transportation from the rider's point of view, and some suggestions are made on how to improve attraction of light rail transit ridership.

A wide variety of issues must be considered in designing and implementing a light rail transit (LRT) system in an urban area. A partial list of these issues would include the costs and revenues of any potential system, the level of service to be provided to users of the system, and the impacts of the system on the environment of the area. In many cases, there are significant trade-offs among these and other issues, and some difficult design decisions must be made. For example, costs generally rise as service levels are raised. They often rise by more than the increase of revenues associated with new ridership, and a clear trade-off between higher service levels and higher costs (and perhaps deficits) arises.

The role of travel demand modeling (or market assessment) as it applies to evaluating and influencing LRT design lies in making explicit many of the design trade-offs involving service levels, ridership, and revenues. Through modeling of traveler behavior, one can make estimates of responses to service changes that, in turn, yield estimates of revenues, environmental impacts, and profits or deficits.

This paper will address the role of market assessment in LRT systems. It will present some major observations or conclusions to serve as a guide to evaluate markets for public transportation. It will give an overview of the state of the art in modeling travel demand behavior. And it will present some brief analytical looks at LRT and other modes and draw some conclusions on attracting ridership.

FUNDAMENTAL GUIDELINES FOR DETERMINING TRANSIT RIDERSHIP ATTRACTION

Through 11 points, we will attempt to lay a basic foundation for understanding ridership attraction to LRT or any other public transportation system.

1. Transportation is a means rather than an end in itself.
2. Level of service is a complex combination of the factors or attributes of a system that collectively describe the attractiveness or utility of a particular transportation alternative.
3. Different groups of people, depending on their socioeconomic and locational characteristics will make different trade-offs among level-of-service characteristics.
4. Each market segment can be expected to behave differently from other market segments; therefore, characteristics of unique market segments must be identified.
5. With increasing affluence, high automobile ownership rates, and increasing leisure time, travelers have a choice in selecting travel alternatives and are becoming more discriminating.
6. No single service will be sufficiently attractive to all potential travelers.
7. Level of service is not merely a function of transit technology.
8. Improvements in level of service usually add to operating costs.
9. Marketing a service must accompany providing the service.
10. Traditional transportation planning and travel demand forecasting, which are based on zonal averages and aggregate data, are too crude to give a true idea of the different ridership responses of different market segments.
11. The logical hierarchy of a household's travel decision making and the aspects of travel demand that transit service is likely to influence need to be known.

That transportation is a means rather than an end in itself means that the demand for urban transportation is derived from the traveler's desire to accomplish some other objective (go to work, shop, meet a medical appointment, or visit a friend). Because the trip itself is secondary to the primary purpose for which it is being made, travelers want to make the trip as painless as possible. Travelers are not interested in the technology of a particular transportation system; they are interested in the level of service it provides. The nature of the propulsion, control, suspension, and other subsystems (whether the system has steel wheels or rubber tires or whether it is air cushioned or has coil springs) is of secondary importance to users.

The major level-of-service characteristics include (a) in-vehicle travel time (for line-haul vehicles and access vehicles); (b) out-of-vehicle travel time (walk time, wait time, and transfer time, which are sometimes combined and sometimes separated); (c) cost (perhaps related to traveler's income); (d) time reliability and consistency; (e) comfort; and (f) safety. Concerning item 3, different groups of people will assign different relative weights or importances to each of the level-of-service characteristics in evaluating a transportation alternative. These response groups can be called market segments. Unique market segments can be identified by socioeconomic characteristics, particularly income and automobile ownership; trip purpose; life cycle (age, family status); occupation; transportation-affecting handicaps; and access characteristics, such as distance from transit station.

Because travelers are becoming more discriminating, more attractive service than that of the past must be provided to capture riders.

Because no single service will be sufficiently attractive to all potential travelers, different services need to be tailored to different market segments. For example, office or factory workers who punch time clocks must be at work on time, and therefore time reliability is very important to them; senior citizens visiting a friend are far more interested in not having to walk too far to a transit stop than they are in time reliability; suburban, upper-income executives want a high-quality transportation service and would be willing to pay for it; young, married, lower-income workers may be much more cost sensitive.

Item 7 mentioned that level of service is not merely a function of the transit technology. It can be influenced greatly by operating policy as well. (Perhaps the most important point of this paper is that simply to specify a technology as light rail transit or personal rapid transit is not sufficient to provide a basis for distinguishing between them. Within each technology there is a wide variety of different "systems" that can be provided; each has very different levels of service, ridership, costs, and environmental impacts.) Furthermore, it is a matter of how the user, not the operator, perceives operating policy. For example, an LRT system may run vehicles between 2 points at 5-min intervals; this 5-min headway is a system variable. However, users do not perceive the headway; they perceive the wait time for the next vehicle after they arrive at a station. A typical assumption is that average wait time is half the headway; however, this is only the case with uniform vehicle arrivals (headways maintained exactly) and with either uniform or random passenger arrivals. In cases in which passengers know the schedules and the schedules are kept, the wait time can be shorter. In cases in which the schedules are not kept, the wait time can be longer as nonuniformity of headway builds up. A recent example on a heavily used bus line in Boston where vehicle bunching occurred showed wait time equal to the headway itself for headways of less than 10 min (13). This distinction between the system variable, headway, and the user variable, wait time, is important. Better reliability or better information systems could lower user wait times while keeping headways constant. Thus different ridership could be attracted to the same headways merely by maintaining better schedule reliability.

In item 8, we mentioned that improvements in level of service usually add to the costs of operating the service. Generally, ridership response is inelastic; that is, a 1 percent change in a level-of-service attribute will produce less than a 1 percent change in ridership and, therefore, revenue. It is important for a transit planner to consider the economic trade-offs of improved service (net cost increases) because economic efficiency is usually the guiding operating objective. In certain instances, however, overriding social objectives (guaranteed mobility to the poor, elderly, and handicapped, for example) may dictate that service improvements should be offered despite negative economic consequences.

In item 9, we mentioned that marketing service (informing people about it and maintaining a positive image) must accompany providing a good service. Marketing, or creating a positive image, may influence ridership much more than some of the level-of-service variables, and, to a degree, it is much more within the control of an operating transit agency to control.

We have mentioned that zonal averages and aggregate data are too crude to give a transit planner a true idea of the different ridership responses of different market segments. New, more logically structured, analytical techniques are emerging for analyzing travel demand behavior, however. The most promising are disaggregate, behavioral demand models. They are called disaggregate because they deal with the travel decisions and specific influencing circumstances of a sample of individual households rather than zonal aggregates and averages. They are called behavioral because they are causally structured rather than correlatively structured to explain why an individual household member made a particular travel decision. Conceptually, these disaggregate models are far more appealing for explaining travel behavior. Results to date have been extremely encouraging statistically and logically. Because they are behavioral, the models are more readily transferrable from one urban area to another as experience to date in Washington, D.C.; Los Angeles; New Bedford, Massachusetts; Portland, Oregon; and Milwaukee has demonstrated (15). It is much easier to distinguish an individual household's market segment than it is to distinguish the mix of market segments making up an aggregate zone. Each survey observation is for an individual household rather than for many households in a given zone. (Observations for many households involve making a statistically valid, aggregate, zonal observation.) Therefore, these models are much more economical and data efficient to develop and apply. These disaggregate behavioral formulations hold the key to a better understanding of travel demand behavior and to a determination of the proper set of relative weights of level-of-service characteristics for each market segment. It is not difficult to imagine a time when each urban area will maintain and update a random sample of households and their travel patterns and socioeconomic profiles from home interview surveys. Transit planning agencies then will be able to use that data along with disaggregate models to determine the ridership response to some proposed transit improvement or transportation policy change in much the same way the national consumer response to a new product is forecast by market researchers now.

As a final point, we mentioned that the logical hierarchy of a household's travel decision making and the aspects of travel demand that transit service is likely to influence need to be known. The highest level (longest term) decision a household makes involves land use and residential location. This generally begins with the occupation of the head of the household and encompasses residential location and choice of housing. This level of travel decision will be influenced only by such major changes in the transit system as the construction of a new transit line. A medium-term set of travel or mobility decisions for a household concerns the number of automobiles to own and the usual choice of mode to work. These are highly interrelated decisions as research to date has shown (1). In the medium term (say, the next 3 years), a transit service improvement can be expected to cause a shift in mode choice for work trips and a change in the number and type of automobiles a household owns, but it is unlikely to change the frequency or destination choice of work trips. The shortest term travel decisions involve nonwork trips. A household seldom plans these trips far in advance except in abstract or general terms (for example, to plan to go food shopping once a week). Here, the traditional sequential structure of aggregate travel demand models (trip generation, trip distribution, modal choice, time of day choice, and route assignment) done in an independent sequence of steps seems particularly out of place. A potential traveler decides whether to make a nonwork trip, where a trip should be made, and by what mode and route to arrive at the destination in a simultaneous set of decisions. A model of mode choice alone will not be sufficient to accurately reflect nonwork ridership response to a transit system change; changes in total demand (the term latent demand sometimes is used) and destination choice also must be considered.

These 11 points and their explanations leave us with a framework for how market assessment could influence LRT design and operation. This is shown in Figure 1. A much more detailed and explicit discussion of the techniques for assessing the ridership potential of different transit systems can be found elsewhere (14, 15).

A technology such as LRT is defined here as the basic hardware components of the technology (steel wheel on steel rail, manual operation with block signals, on-line stations, and the like). Using this LRT technology, one creates an LRT system by establishing a network and setting routes and schedules. This "system" forms the basis for demand, cost, and other impacts. If these are not as desired, several changes can be effected. Fares can be set to achieve several objectives, such as maximizing system profitability, subsidizing certain socioeconomic groups, and so on. Operating policy also can be altered to meet different objectives. If these shifts are not sufficient to produce a satisfactory system, then changes in the technology may be appropriate. These could include automation and off-line stations.

In the examples that will appear later in the paper, most of the conclusions will relate to how one operates LRT and other systems from a demand analyst's point of view. But, in some cases, changes in the technology that would allow or facilitate some desired operating options also will be pointed out.

LEVEL-OF-SERVICE COMPONENTS

Now that the concepts of level of service, market segments, and disaggregate analysis have been introduced, let us turn to a comparative look at the individual level-of-service components and the relative weights individuals assign to each.

Attitude Surveys

There are 2 basic data sources or procedures for determining relative weights. One is an attitudinal survey in which individuals are asked to

1. Rank a specified set of level-of-service attributes in order of importance,
2. Rate each level-of-service attribute on a scale from bad to good with respect to current choice of transportation mode, or
3. Compare pairs of attributes by deciding which of a pair is more important (preferably each attribute is tangibly defined in a specific scenario rather than left as an abstract, conceptual term).

From these rankings or comparisons, conclusions can be drawn about relative weights. Figure 2 shows the resulting relative rating scale from a sample of 97 individuals in the Chicago area surveyed by use of the comparison of pairs technique. Problems with this technique are

1. Nonindependence of attributes,
2. Vagueness of definitions,
3. Omission of other subjective variables (comfort, privacy, safety),
4. Lack of quantification or specificity of a variable, and
5. Differences between a respondent's professed attitude or rating of an attribute and actual behavior when confronted with the attribute in operation.

This attitude survey technique is in its formative stages, and refinements are being made all the time. Stopher et al. (2) give a good summary of the state of the art of attitude surveys for determining relative importance of transportation level-of-service characteristics in travel demand prediction. Sommers (3) did some earlier work in the same area and found the rank order of attributes to be time, convenience, comfort, safety, weather reliability, cost, noise, and mechanical reliability. Again, this effort suffers from lack of precise attribute definition and lack of quantification. A national survey was conducted for the National Cooperative Highway Research Program in the late 1960s into traveler attitudes toward modes of travel (4). The 7 most important attributes were found to be safety, reliability, independence, transfers, protection from weather, crowding, and comfort.

These early efforts were, in our opinion, noble but too vague and poorly defined to be conclusive. Some good recent work is being done by Golob and others (5, 6) particularly in correcting the major problem of lack of situation-specific, quantitative definitions of attributes and in applying techniques from the psychological and sociological disciplines to travel demand behavior. The Federal Highway Administration currently is undertaking a large attitudinal survey in the Los Angeles Santa Monica Freeway corridor to try to gain further knowledge of the relative importance of different level-of-service attributes. Many others, including professional market research firms, also are rapidly improving on attitude surveying as it is applied to demand for public transportation service; therefore, although the past experience with attitude surveys has been inconclusive, the future could be promising.

Behavioral Data

A much more successful data source than attitude surveys has been the analysis of actual travel behavior decisions of individuals. The basic data source is the traditional home interview survey (or, sometimes, a telephone survey), which establishes the travel decisions that were made and what the socioeconomic characteristics of the household are. From this basic information, specific data on the times, costs, and other level-of-service characteristics of each transportation alternative available to the individual are assembled, and various statistical techniques are employed to determine what the appropriate relative weights must have been (in each market segment)

Figure 1. Framework for light rail transit market assessment.

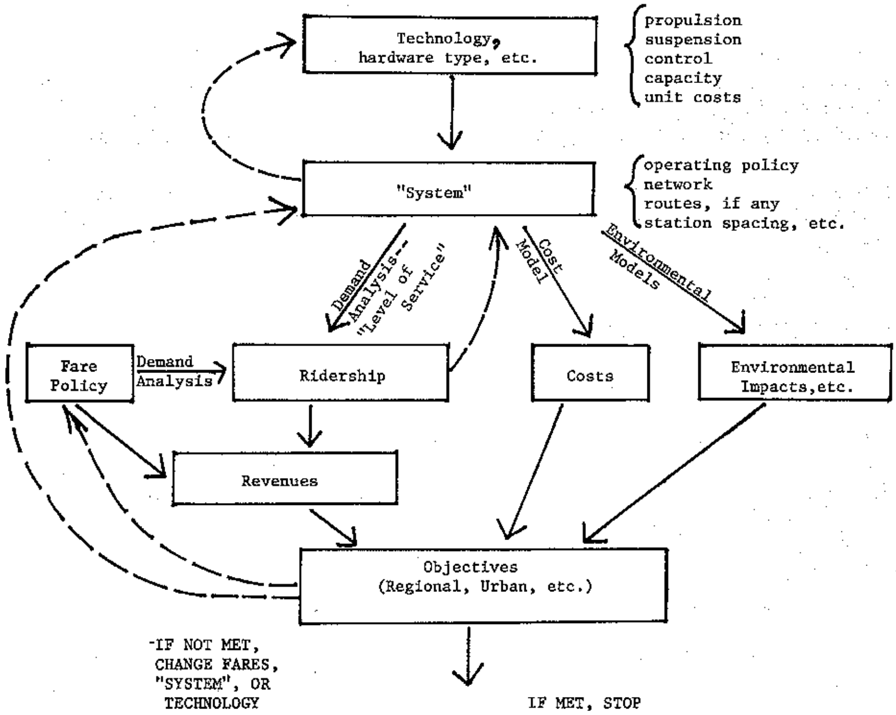
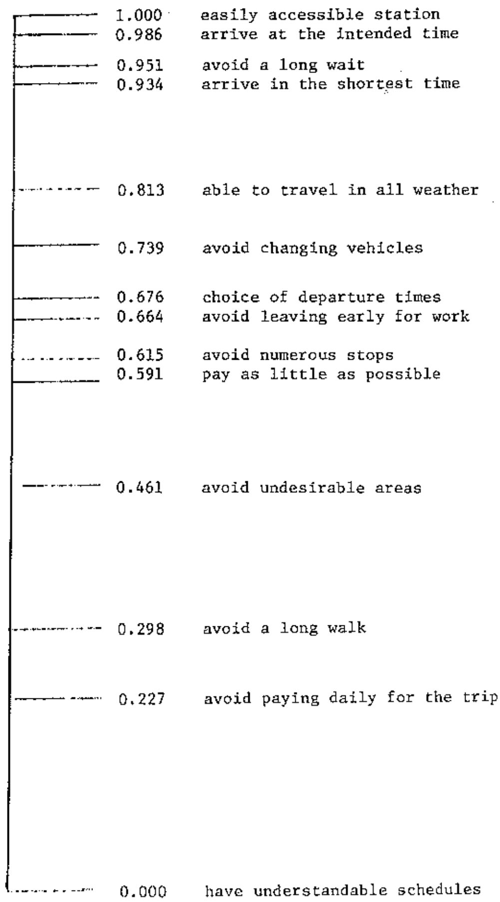


Figure 2. Relative rating of level-of-service attributes from a sample of 97 Chicago-area individuals (2).



to have led to a particular choice. The calibration procedure produces best estimates of what these weights or coefficients are, and it gives some idea of the uncertainty or standard error in estimating each. Conventional, aggregate, modal-split models are calibrated on such data as are the disaggregate, behavioral models referred to previously.

These analyses of actual behavior generally are limited to those level-of-service attributes that are readily quantifiable (most notably various categories of travel time and cost), but the analyses are quite conclusive and consistent in their results. One min of out-of-vehicle travel time (walking, waiting, and transfer time) has anywhere from 1.5 to 10 times the importance of 1 min of in-vehicle travel time depending on the market segment. Disaggregate models estimated on Netherlands data indicate a generally less dramatic ratio of out-of-vehicle time weight to in-vehicle time weight than do models estimated on American data (7). This, perhaps, may be indicative of the American pace of life and desire to make progress.

There is evidence to suggest that, within out-of-vehicle time, certain market segments would distinguish between walking and waiting time. The Netherlands data indicate that walking time is more burdensome than waiting time. Certainly one would expect that this same conclusion would apply to the elderly or for non-time-critical trip purposes. There is some evidence from Boston data, however, that, for work trips, walk time is weighted as less burdensome than wait time (8). This result probably reflects the inclusion of time uncertainty or reliability considerations in the wait time coefficient, however, together with the American desire to make progress.

Although elasticity varies dramatically depending on market segment, the existing split to transit, and the value of the attribute in question, elasticities are generally less than -1.0 for both types of time. (Elasticity of transit ridership to a particular service attribute is defined as the percentage of change in transit riding resulting from a 1 percent change in that service attribute.) The elasticity of transit ridership to out-of-vehicle time would run about twice that for in-vehicle time, based on a few typical calculations, with -1.0 and -0.5 respectively not atypical for a suburb to central business district (CBD) trip. Elasticities for both attributes are greater when the existing market share of transit is small.

Generally, most market segments are not as sensitive to cost as they are to time. Typical elasticities of transit ridership to cost are in the -0.1 to -0.4 range. Elasticities to monthly paid or billed costs are lower than elasticity to out-of-pocket costs. A general conclusion from this fact is that, if fares are increased, ridership will decrease but not by as great a percentage; thus total revenues will increase.

For a work-trip model across all socioeconomic groups, a 1-dollar fare change will have the same effect as a 30-min change in in-vehicle travel time, implying a value for (in-vehicle) time of 2 dollars/h. Again, however, it should be stressed that these relative weights or elasticities cannot be generalized. They will vary significantly depending on market segment. Elasticities will further vary significantly with situation.

Conclusions on Level-of-Service Components

Behavioral data analysis gives one a fairly good grasp of the relative importance of out-of-vehicle time, in-vehicle time, and cost. Attitude survey results would indicate that travel time reliability might be even more important than any of these 3, at least for work trips for certain occupation groups. This, in our opinion, is believable, and offers the transit planner the greatest marketing leverage of any of the level-of-service attributes. If schedules are reliably maintained and the traveling public knows this, then the share of the work trip market captured by transit will be significant. Light rail transit should be better able to maintain schedules relative to buses because of separate right-of-way, limited traffic interaction, and less susceptibility to changes because of weather conditions, but it is probably faced with much more difficulty in maintaining schedules than the grade-separated, exclusive right-of-way service provided by conventional rapid transit.

Safety should be downplayed as an important determinant of travel choice. This is certainly not to say that the ultimate in safety standards should not be strived for, but rather that the importance of safety as suggested by attitude surveys is more an instinctive response than it is a well-calculated distinction of one form of transit's being safer than another. All forms are relatively safe, and few riders choose one mode over another for safety reasons. (An exception perhaps is the concern of individuals with their personal safety from crime in urban areas such as Philadelphia and Chicago. This however, is more the exception than the rule.)

Comfort and convenience are attributes that vary the most from one attitude survey to another. This indicates that they are clearly functions of how carefully and specifically they are defined. Comfort is obviously a consideration in today's transit ridership competition with the automobile and should be strived for and publicized in marketing. Exactly how important a determinant of ridership it is still is subject to some conjecture, but it is probably worth maximum consideration until its importance is determined more decisively. Even though we are guilty of the same abstract definition error that we criticized attitude surveys for making, we rank comfort slightly lower than cost as the fifth greatest determinant of ridership based on the information available.

Convenience has been defined by various sources (1, 5, 9) as including number of transfers, ease of access to stations, crowding conditions, privacy, independence from schedule or choice of departure times, avoidance of walking, shortest travel time, reliable arrival time, safety, mechanical reliability, weather protection amenities, baggage-handling facilities, low cost, avoidance of traveling in undesirable areas, probability of getting a seat, easy-to-understand schedules, avoidance of having to pay daily, ability to obtain information from system representatives, and having refreshments or newspapers on board. As such, it covers a multitude of considerations, some of which are actually encompassed in the other level-of-service variables, some of which are difficult to define, and most of which have never been satisfactorily calibrated. It is suggested that the all-encompassing term convenience be abandoned in favor of more specific consideration of the many individual qualities that make it up.

DISAGGREGATE DEMAND MODELS

To analyze the demand responses to LRT and other transportation systems, one needs to use travel demand models that are sensitive to the transportation system attributes that affect potential travelers.

These models must capture the decision-making process of travelers as they weigh different transportation alternatives and incorporate these factors into the model. As discussed under fundamental guidelines in this paper, traditional aggregate demand models are usually neither policy sensitive nor behavioral. Disaggregate models, however, offer much more promise.

Recall that disaggregate behavioral models are those fitted to the observed travel behavior of a sample of individual households in an urban area and are based on the alternative choices that each household sees.

Let us consider 2 sample households. Household A has an income of 8,000 dollars, has 4 children, owns 1 car, and lives a 1-min walk from an LRT line. The breadwinner works downtown. The observed travel choice for the work trip from this household is transit, and it is easy to see many reasons why. Among them are the relatively easy access to transit, the importance of cost, and the high probability of other demands for the family car. Household B has an income of 15,000 dollars, has no children, and lives 1 mile (1.6 km) from the nearest transit line. The breadwinner works at a suburban office park. The observed travel choice for this household is the automobile, and once again, there are many reasons why this is a rational choice for this household.

There are several points that can be illustrated by this example. The first is the advantage of disaggregate models (which use the data at the household level) over aggregate models (which group together all households in a zone or other geographical area.)

Assume that households A and B are in the same zone, which is a not unreasonable occurrence. This zone would then produce 1 transit trip and 1 automobile trip. The average household characteristics for this zone would be an income of 11,500 dollars, 2 children, and about a 0.5-mile (0.8-km) walk to transit. An aggregate model would predict a 50 percent chance of using transit for this average set of household characteristics (if it was a perfect "fit"), but this is a considerably less strong model than one based on the actual household data. The 50 percent probability seems too high for those average characteristics because of the 0.5-mile (0.8-km) walk, if nothing else. The model also is somewhat unstable, because household A might still choose transit even if its income were 10,000 dollars and household B would still choose the automobile even if its income were, say, 20,000 dollars. The average income then would be 15,000 dollars, but the probability of using transit still would be 50 percent—a very wide variation. The disaggregate model clearly seems to be better in this case.

Another point that this example can demonstrate is the use of market segmenting to improve the power of one's forecasts. Aggregate models in general must assume that all households have exactly the same weights with respect to all the attributes of travel choices (waiting time, walking time, travel time, and the like). This is, of course, not literally true. The elderly certainly weight walking time higher than do other groups, and blue-collar workers who punch a time clock weight time reliability higher than do workers who do not punch a clock. These variations in age, life cycle, socioeconomic status, and the like often are averaged completely out of aggregate models because, even though there may have been considerable variation within the zone, there is often no significant variation in the average of these characteristics from one zone to another and, hence, no way to fit a model to them. Disaggregate models based on individual households can and do incorporate these variables that have long been ignored in travel forecasting even though their importance has been recognized. Thus, in disaggregate models, the different behavior of different market segments can be captured.

A third merit to disaggregate models is transferability. A disaggregate model is based on individual household behavior and is not dependent on any zone system or zone size. Thus it has none of the drawbacks that aggregate models based on zonal averages have when transferred from, say, one urban area to another. If it can be shown that a certain market segment in one urban area will respond to a particular set of level-of-service variables the same way that market segment in another area will respond when faced with the same set of travel choices, then these models can be transferred freely without the expensive and time-consuming calibration required with aggregate models. As alluded to earlier, the experience of Cambridge Systematics in transferring models based on Washington, D.C., to New Bedford, Massachusetts; Portland, Oregon; Milwaukee; and Los Angeles has been positive and has required almost no adjustments in any case. Table 1 gives a comparison of coefficients (relative weights) for the 3 level-of-service variables of particular interest and the same modal-choice model specification (work trips, all socioeconomic groups combined) as calibrated separately on Washington, D.C.; New Bedford; and Los Angeles data. As can be seen, the coefficients are remarkably similar. All but 1 are statistically significant (that is, the t-statistics are larger than 1). A t-statistic is the ratio of the coefficient value to the standard error of estimation of that coefficient. In simple terms, if the standard error is as large as the coefficient, one cannot conclude that the coefficient is statistically significantly different from 0. That is, the inclusion of that variable does not clearly improve the explanation capabilities of the model. It is important to point out that low t-statistics should not necessarily eliminate a variable from a model, however. One must first decide whether a variable is logically a causal variable. If it has a low t-statistic, it may mean that there is a large uncertainty over the predicted value, not necessarily that it should be removed.

Given the arguments in favor of disaggregate behavioral demand models, we now can turn to some example applications that show how these models can be used in evaluating LRT and other transit systems.

THE MULTINOMIAL LOGIT MODEL

Translating some of the earlier arguments into mathematical terms, one can express the utility of a particular travel alternative i to a household in market segment t, U_i^t, as some combination of suitably weighted level-of-service values.

$$U_i^t = \sum_k \theta_k^t X_{ki}$$

where

X_{ki} = value of the k th level of service attribute of alternative i, and
θ_k^t = the relative weight that market segment t would assign to level-of-service attribute k.

In addition to the level-of-service variables, utility of a particular travel alternative also is some function of the socioeconomic characteristics of household t (income and automobile ownership).

$$U_i^t = \sum_k \theta_k^t X_{ki} + \sum_\ell \beta_\ell^t A_\ell^t$$

where

A_ℓ^t = value of ℓ th socioeconomic characteristic of household t, and
β_ℓ^t = weight assigned to ℓ th socioeconomic characteristic.

For notational convenience, let us drop the superscript t and generalize the definitions of level-of-service variables X to include the socioeconomic attributes A.

$$U_i = \sum_m \theta_m X_{im}$$

The probabilities of choosing one alternative from a set of available alternatives, each of whose utilities are known, can be expressed in many different ways, but the mathematical function

$$P(i:A_t) = \frac{e^{U_i}}{\sum_{jA_t} e^{U_j}}$$

known as the multinomial logit model, is by far the most commonly and successfully used disaggregate demand model form. [Rigorous mathematical derivations of this model and other disaggregate demand models can be found elsewhere (7, 10, 11, 12) but are perhaps beyond the level of interest here.] This particular model form exhibits many favorable properties that make its use desirable. First, the probabilities necessarily sum to 1 as they should. Second, the curve of $P(i:A_t)$ versus U_i has the general shape shown in Figure 3. This curve of "diminishing returns" at both ends reflects known travel behavior quite well. That is, no matter how good (or bad) a service is, you will never capture (or lose) all of the ridership, and ridership will be most susceptible to diversion to some other alternative in the highly competitive middle range. Third, the logit model is capable of extension to any number of travel alternatives. Finally, the logit form is mathematically tractable, which leads to simplicity in calibrating, transforming, and applying it.

This model, calibrated on Washington, D.C., data and using maximum likelihood estimation techniques, is that with which we are most familiar and most satisfied and that which we will use in the examples.

SOME CASE EXAMPLES ANALYZED

To make analysis simple, only work trips will be considered, and only the mode-choice decision will be simulated. Although the model system generally used in our studies contains a joint automobile-ownership and mode-choice model for work trips and, simultaneously, a model for trip frequency, destination, and mode choice for nonwork trips with automobile availability conditional on the work-trip choice, this set of case studies will serve as an example of the modeling process and will be kept simple for clarity and brevity.

We will consider only 2 modes—automobile and transit. Only 2 socioeconomic market segments will be considered—blue collar and white collar. They are defined as follows:

Segment	Income (1968 dollars)	Automobiles/ Licensed Driver	Household Size
Blue collar	7,000	0.5	4
White collar	12,000	1	1

Market segments for level-of-service variables are defined as shown in Figure 4. Zones are broken into 2 parts. The near subzones are those areas within walking distance of line-haul-system stations. The far subzones are the areas requiring feeder service. The dividing line between the 2 areas is 0.25 mile (0.4 km) from a station; this is commonly called the walk refusal distance in urban areas.

These subzones face different travel choices, of course. Near subzone users are not at all concerned with feeder services, and, in general, are better served than are far subzone users, who generally experience relatively slow travel times (even with good feeder service) and perhaps higher fares and extra transfers.

Returning to the model, we determine the logit model utility equations for automobile and transit as follows:

$$U_{a,b} = 1.19 - 0.00411\ \text{OPTC} - 0.00658\ \text{IVTT} - 0.0879\ \text{OVTTD}$$

$$U_{t,b} = -0.00411\ \text{OPTC} - 0.00658\ \text{IVTT} - 0.0879\ \text{OVTTD}$$

$$U_{a,w} = 1.84 - 0.0024\ \text{OPTC} - 0.0131\ \text{IVTT} - 0.169\ \text{OVTTD}$$

$$U_{t,w} = -0.0024\ \text{OPTC} - 0.0131\ \text{IVTT} - 0.169\ \text{OVTTD}$$

where

$U_{a,b}$ = utility of automobile mode for blue-collar households,
$U_{t,b}$ = utility of transit mode for blue-collar households,
$U_{a,w}$ = utility of automobile mode for white-collar households,
$U_{t,w}$ = utility of transit mode for white-collar households,
OPTC = out-of-pocket travel costs in cents per round trip,
IVTT = in-vehicle travel time in round-trip minutes, and
OVTTD = out-of-vehicle travel time in round trip minutes divided by 1-way distance in miles (kilometers).

This particular model is 1 of the earlier models developed from the Washington, D.C., data base, but it has several less important variables that have been collapsed into the constant term for simplicity. It is a different model specification and is for different market segments than the model results given in Table 1.

It should be emphasized that this model is based on observed travel behavior at the household level and that these utility equations have been used in several studies and have given good results in each.

Several points should be made about this model. One point is that the variable OVTTD in its present form (divided by distance) represents the assumption that the importance of out-of-vehicle time decreases as trip length increases. It says basically that a 10-min wait is much more burdensome for a 1-mile (1.6-km) trip than it is for a 10-mile (16-km) trip. Another point is that the weights of travel time (IVTT and OVTTD) are much higher for the white-collar segment than for the blue-collar segment, which indicates their greater relative importance to the white-collar market segment. Cost is relatively less important to white-collar travelers than to blue-collar travelers. From the ratios of the IVTT and OPTC coefficients, one can infer that the white-collar group values its time at 3.25 dollars/h; the blue collar group values its time at about 0.95 dollars/h.

Using the models presented above, we will examine 4 technologies or systems in a hypothetical corridor as shown in Figure 5.

The highway system consists of an expressway whose average speed is 35 mph (56 km/h) in the peak period and local streets in each zone whose speed is 15 mph (24 km/h).

Automobile operating cost is 10 cents/mile (6.25 cents/km). Out-of-vehicle time for the automobile is 2.5 min for non-CBD trips and 5 min for CBD trips, which reflects the longer walking distances from parking place to eventual destination in the CBD.

Example 1: Light-Rail Transit

An LRT system is proposed for the corridor. Note that this is not LRT, the technology, but LRT, the service, which is characterized by surface operation (sometimes grade separated, sometimes not), close station spacing, low-platform loading, lower average speed than typical rapid transit service, and good area coverage with a heavy orientation to walk-access patronage. Its specific characteristics are as follows:

1. Line length: 6 miles (9.6 km) to CBD,
2. Maximum speed: 50 mph (80 km/h) (grade separated),
3. Station spacing: every ⅓ mile (0.53 km),
4. Headway: 4 min, and
5. Feeder: fixed-route, fixed-schedule bus with 12-min headways.

The average speed, assuming 3 stops/mile (1.9 stops/km) and 30 s/stop, is 22 mph (35.2 km/h). The percentage of travelers within walking distance of the system in zones 1 and 2 is 29.4 percent; the remainder must use feeder services; 58.8 percent are within walking distance of their workplace in the CBD. The fare policy assumed was 50 cents/trip for LRT and 25 cents/trip on the feeder vehicle.

We now construct the level of service for users of this system. Further defining

Table 1. Comparison of coefficients from work-trip logit-modal-split model estimation on 3 different data bases.

Data Base	In-Vehicle Travel Time (round-trip min) Variable Coefficient	t-Statistic	Out-of-Vehicle Travel Time/Distance (round-trip min/1-way miles) Variable Coefficient	t-Statistic	Out-of-Pocket Cost/ Income (round-trip cents/worker dollars per year) Variable Coefficient	t-Statistic
New Bedford	-0.199	-0.4849	-0.1013	-2.903	-87.33	-1.576
Washington, D.C.	-0.0154	-2.67	-0.1600	-4.08	-28.8	-2.26
Los Angeles	-0.01465	-2.25	-0.1860	-4.02	-24.37	-2.07

Note: 1 mile = 1.6 km.

Figure 3. Curve of $P(i:A_t)$ versus U_i.

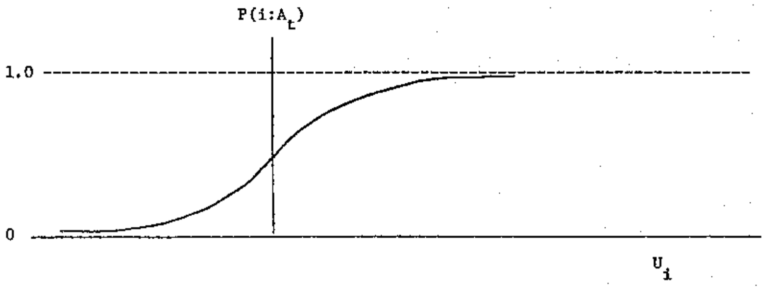


Figure 4. Market segments for level-of-service variables.

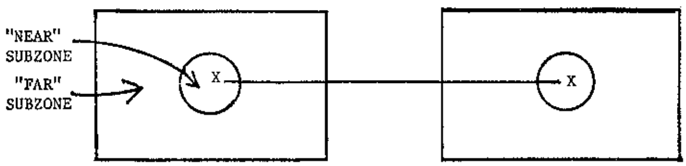
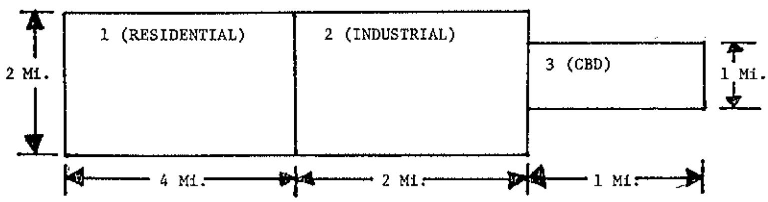


Figure 5. Hypothetical corridor.



Note: 1 mile = 1.6 km.

market segments based on their station-access characteristics results in 4 basic types of trips: near-near, near-far, far-near, and far-far subzone combinations for each zone pair. The level of service for the subzone combinations and the specific time assumptions made for each link of the zone 1 to zone 3 trip are shown in Figure 6.

Obviously, the percentage of trips in each category is affected by station spacing. The closer the station spacing is, the more trips there are that have one or both ends within walking distance of a station, but the slower the travel time becomes if all station stops are made. Demand analysis can help to make this design trade-off. When the demand models are applied, the flows given in Table 2 result for this LRT system.

Several issues are readily apparent from this table. The transit modal split is higher when walk access to the transit station is possible (near subzones). Transit share of the longer CBD-destined trip is greater because of the defraying of the out-of-vehicle time component and the transit fare over a longer distance and because of the higher parking cost and out-of-vehicle time associated with taking an automobile to the CBD. Blue-collar transit ridership is higher than white-collar ridership is, which is to be expected for anything other than superior service. It is also interesting that white-collar ridership drops off more steeply than blue-collar ridership does for far subzone trips because of the greater sensitivity (higher demand weight) to access travel times.

The policies one might use to increase this system's ridership would be quite different for the 2 groups as well. A drop in fare to 25 cents/ride for LRT and free transfer to feeder increase blue-collar ridership by much more than they do white-collar ridership as can be seen by the data given in Table 3.

However, policies that involve raising fares and providing a better level of service affect white-collar ridership more favorably than they do blue-collar ridership.

How would LRT modal split vary with walking distance to and from stations? Figure 7 shows the transit modal share versus the combined walking time at origin and destination for a 1-way trip from zone 1 to zone 2 (near-near subzone). If, for example, a 10-min walk at either end of the trip were assumed instead of a 3.3-min walk, then the modal share would drop from 17.3 percent to about 12 percent for blue-collar workers and from 7.2 percent to about 3.5 percent for white-collar workers. This would be about 50 percent loss of white-collar ridership and about 30 percent loss of blue-collar ridership, which is quite dramatic. White-collar-group sensitivity to walking time would be greater than that for the blue-collar group, as expected.

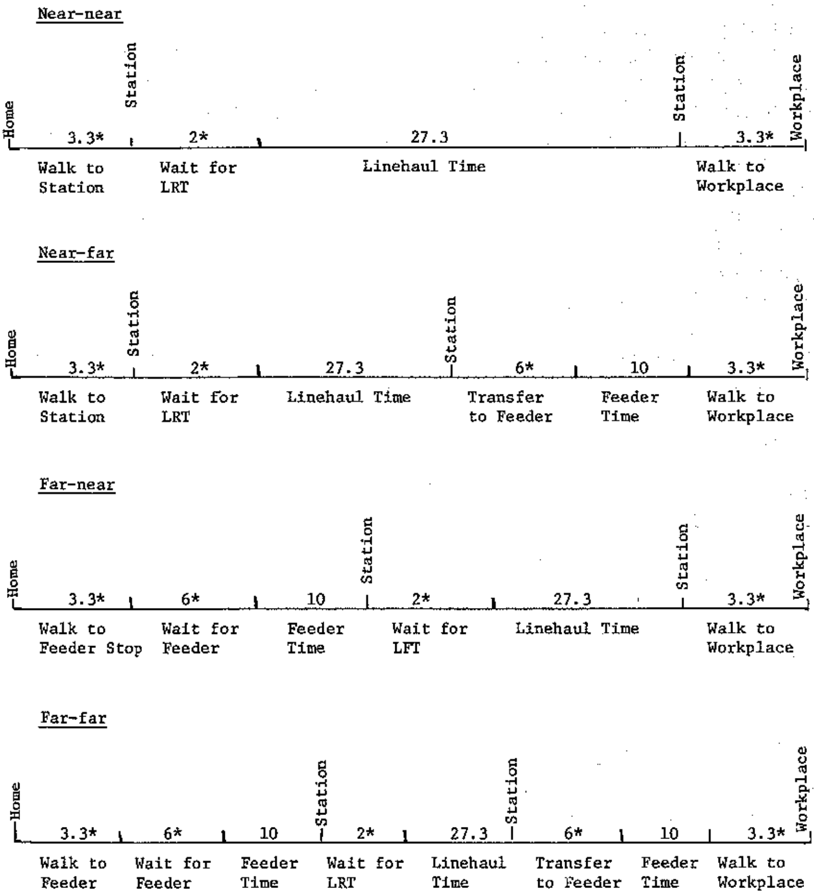
Example 2: Commuter Rail Transit

A commuter rail system for the corridor might have the following characteristics:

1. Line length: 6 miles (9.6 km) (short for such operations),
2. Maximum speed: 50 mph (80 km/h),
3. Station spacing: every 1.5 miles (2.4 km),
4. Headway: 20 min, and
5. Feeder: none in zones 1 or 2, same as for LRT in zone 3 (CBD).

The average speed of this system is 35 mph (56 km/h) assuming each stop takes 45 s. We assume the walk refusal distance here to be 0.5 mile (0.8 km) and that the park-and-ride option is available because there is no feeder bus operation. The dependence on park-and-ride for access to the station from beyond 0.5 mile (0.8 km) is a greater burden on the blue-collar potential transit users than it is on the white-collar potential transit users because this access mode requires either restricting the use of the family car or owning an extra car. With these additional automobile ownership effects accounted for in the constant term of the utility equations, the mode shares for transit become as shown by the data given in Table 4. (Automobile ownership was 1 of the variables in the original specification of the model used here, but it was collapsed into the constant term by using a regional average value of automobiles owned per household to simplify the model presented here.) In Table 4, the wait time was assumed to be 5 min

Figure 6. Zone 1-zone 3 light rail transit trips.



(time in minutes; * = out-of-vehicle time)

Table 2. Modal shares.

Zone Pair	Subzone Combination	Zone Trips (percent)	Share of Transit Mode (percent)	
			Blue Collar	White Collar
1-2	Near-near	8.6	17.3	7.2
	Near/far	41.5	10.1	3.0
	Far-far	49.9	5.7	1.2
	Total	100.0	8.5[a]	2.5[a]
1-3	Near-near	17.2	34.0	16.1
	Near/far	53.6	24.5	9.4
	Far-far	29.2	16.9	5.2
	Total	100.0	23.9[a]	9.3[a]

[a]Total mode share is the weighted average where percentages of trips in each subzone combination are the weights.

Table 3. Modal shares after a 25-cent/ride drop in fare for light rail transit and free transfer to feeder service.

Zone Pair	Subzone Combination	Zone Trips (percent)	Share of Transit Mode (percent)	
			Blue Collar	White Collar
1-2	Near-near	8.6	20.5	8.1
	Near/far	41.5	14.5	3.8
	Far-far	49.9	10.1	1.7
	Total	100.0	12.8[a]	3.1[a]
1-3	Near-near	17.2	38.7	17.8
	Near/far	53.6	32.8	11.6
	Far-far	29.2	27.4	7.3
	Total	100.0	32.2[a]	11.4[a]

[a]Total mode share is the weighted average where percentages of trips in each subzone combination are the weights.

Figure 7. Effect of walk time on LRT modal share for a trip from zone 1 to zone 2 with walk access used.

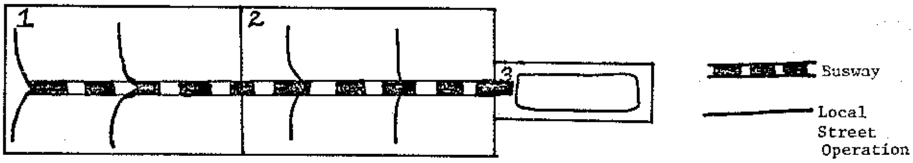


Table 4. Modal shares with additional automobile ownership.

Zone Pair	Subzone Combination	Zone Trips (percent)	Share of Transit Mode (percent)	
			Blue Collar	White Collar
1-2	Near-near	6.9	11.1	2.7
	Near-far	19.3	0	0
	Far-near	19.3	3.4	7.0
	Far-far	54.3	0	0
	Total	100.0	1.4[a]	1.5[a]
1-3	Near-near	13.7	30.0	12.0
	Near-far	12.5	24.1	9.6
	Far-near	38.7	6.7	16.5
	Far-far	35.1	5.2	11.7
	Total	100.0	11.5[a]	13.3[a]

[a]Total mode share is the weighted average where percentages of trips in each subzone combination are the weights.

even though the headway is 20 min because commuter rail schedules usually are reliably maintained. Users may be expected to know the schedule and arrive accordingly.

Commuter rail service can carry no trips destined to areas without feeder service even though it carries trips originating in areas with no feeders. Its share of long, white-collar trips is roughly comparable to that of the LRT systems examined, but its share of all other types of trips is less than half the LRT shares. Generally, modal shares from the far subzones for white-collar workers are high because of their increased automobile availability and free and easy parking. Moreover, walking time is out-of-vehicle time and white-collar workers have assigned a particularly heavy weight to that form of travel time.

The fares assumed for this commuter rail operation (75-cent base fare) are lower than usual; a fare increase would drive away more blue-collar users than white-collar users.

Example 3: Express Bus System

An express bus system for the corridor could operate with the following characteristics (Figure 8):

1. Line length: 6 miles (9.6 km),
2. Stations: none on expressway,
3. Headway: 12 min on each "route,"
4. Feeder: integrated with line-haul service, and
5. Cruise speed: 50 mph (80 km/h).

Each route operates as a local bus service on streets in its origin zone and then enters the busway for a nonstop run to the CBD where it again traverses local streets for distribution.

The average speed of this system is 50 mph (80 km/h) (line haul) because no stops are made; the feeder portion speed is 12 mph (19.2 km/h). Because there are no line-haul stations, the near-far subzone distinction does not exist; all users board on the feeder portion of the routes. Because there are no intermediate stops on the line-haul portion, intracorridor passengers must go into the CBD and back out again to use the service, which is a relatively unattractive option. The fare is assumed to be 75 cents/ride.

The express bus modal shares turn out to be as follows:

	Share of Transit Mode (percent)	
Zone Pair	Blue collar	White collar
1-2	4.5	0.9
1-3	34.7	21.3

In general, express bus modal shares would be high for trips focused on a particular destination area served by express bus and low otherwise. For CBD-bound trips, the service is good and the mode share is higher than it is for LRT service, particularly for white-collar trips. Note that, to the extent that white-collar trips are often more CBD-oriented than are blue-collar trips, the differential effects between the 2 groups may be even stronger than a simple examination of mode shares might show.

Example 4: Conventional Rail Rapid Transit

A conventional rail rapid transit system might have the following characteristics:

1. Line length: 6 miles (9.6 km),
2. Stations: every 1.5 miles (2.4 km),
3. Headway: 4 min, and
4. Feeder: fixed-route, fixed-schedule bus with 12-min headways.

The system is very similar to LRT except for station spacing. With a 50-mph (80-km/h) top speed and 30-s stops, the average speed is 39 mph (62.4 km/h). This system is clearly at a trade-off point with LRT. Fewer stations would produce a higher speed, but fewer riders would be within walking access of the system. A large majority would be forced to use the relatively unattractive feeder service.

The modal shares for this system turn out to be as shown by the data given in Table 5. The information in Table 5 ignores park-and-ride and kiss-and-ride options, which could increase ridership (white-collar ridership particularly); the same holds true for the LRT system and the express bus system examined above.

As might be anticipated the modal shares are generally lower overall than they are in the LRT example but higher for those close enough to the station to walk. Because the principal difference between the rail rapid transit system and the light rail transit system is increased speed versus longer station spacing, it would appear here that the numbers favor closer station spacings at the sacrifice of speed because the travel time minutes spent, both in the vehicle and out of the vehicle, in gaining access to the stations are so burdensome. Were the near-far percentages different, this might not be the case.

Total demand and trade-offs of service levels with operating costs are also factors. If trip density is great enough that the conversion of modal splits to actual ridership volumes leads to crowded cars, either more cars (lower headways) or larger cars (rail rapid transit) would need to be provided. If ridership volumes are very low in relation to rail rapid transit car capacity, the planner might consider going to LRT.

The results of the 4 basic examples are as follows:

		Transit Modal Splits (percent)			
Zone Pair	Market Segment	Light Rail Transit	Commuter Rail Transit	Express Bus	Rail Rapid Transit
1-2	Blue collar	12.8	1.4	4.5	6.6
	White collar	3.1	1.5	0.9	1.6
1-3	Blue collar	32.2	11.5	34.7	20.7
	White collar	11.4	13.3	21.3	7.8

CONCLUSIONS

There are several areas that this paper has attempted to deal with. A primary one has been to show that LRT and other systems have patterns of level of service that vary quite widely for different trips and evoke different ridership responses.

Typical LRT service offers good, relatively evenly distributed service to a CBD and to on-line stations. Therefore, it would be more appropriate for a corridor with heavy intracorridor riding rather than a major CBD focus. Particularly when combined with some kind of feeder bus service, it provides good area coverage at the sacrifice of speed and would appeal to blue-collar workers who are more cost sensitive than time sensitive. It is designed to operate together with walking access or, perhaps, with feeder bus access, but probably not as much with park-and-ride because users who could afford the higher automobile ownership levels required for park-and-ride would find the slower speeds and frequent stops unappealing.

Commuter rail operations provide good service to the CBD and on-line stations although, with their typically sparse feeder service, the on-line intermediate stations do not serve many destinations. The lack of access at the residential end of a trip

Figure 8. Express bus system in hypothetical corridor.

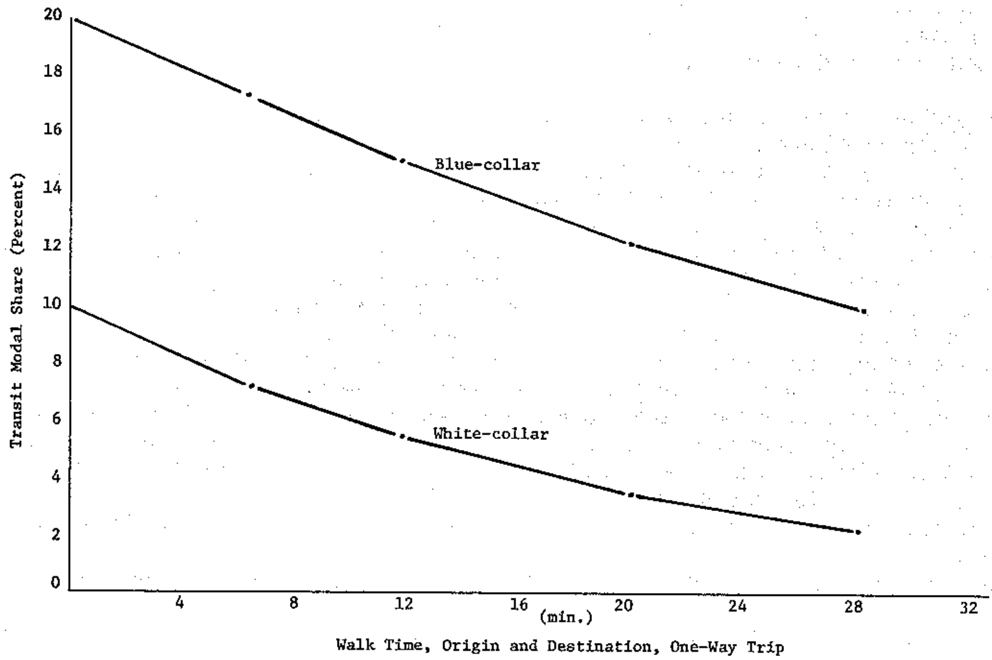


Table 5. Modal shares for conventional rail rapid transit.

Zone Pair	Subzone Combination	Zone Trips (percent)	Share of Transit Mode (percent) Blue Collar	Share of Transit Mode (percent) White Collar
1-2	Near-near	0.4	18.0	7.9
	Near/far	12.2	10.6	3.3
	Far-far	87.4	6.0	1.3
	Total	100.0	6.6*	1.6*
1-3	Near-near	1.7	36.0	19.7
	Near/far	29.1	26.1	10.9
	Far-far	69.2	18.1	6.2
	Total	100.0	20.7*	7.8*

*Total mode share is the weighted average where percentages of trips in each subzone combination are the weights.

generally is a bias against lower income groups, who would still require a car to be able to use this transit system. Commuter rail service would appear to appeal to longer distance, white-collar workers who want premium quality service (fast and reliable) and are willing and able to pay for it.

An express bus operation gives very good service (better than almost any other mode) to a major destination focal point such as the CBD, but it gives almost no service to intermediate areas. To the extent that white-collar trips are more heavily CBD oriented and blue-collar work trips are more heavily oriented to non-CBD industrial areas, this has differential effects on traveler groups as well.

Conventional rail rapid transit has service levels similar to LRT. It has higher speeds as soon as one gets to the system, but the system is less accessible to people because of its generally greater station spacing. Those who can use a car for access are more favored in this system than in LRT with its more frequent stations because access to the station by walking does not matter to them—they use their cars.

In any comparison between light rail transit and heavy rail transit, the transit planner or operator must trade off total demand, capacity, headway, station spacing, capital costs, and operating costs both from a demand and a cost point of view. Some of the levels of service specified in the examples in this paper may be prohibitively costly given the ridership volumes, for example. However, these examples should demonstrate the kind of trade-offs that need to be explored in evaluating alternative transit systems.

What does this imply for LRT? Several conclusions can be drawn. LRT as a technology has the flexibility to offer service levels comparable to all the other modes examined. There is no reason why LRT could not operate in the way the express bus, commuter rail transit, and rail rapid transit systems were assumed to operate.

There are certainly situations in which the service patterns that are commonly associated with these other modes are desired, but that does not automatically mean that that technology must be selected. LRT operating in an express-bus-type service pattern could be more reliable, less costly, produce less pollution, and allow more flexibility to change operating policy than a bus system could in some cases; thus it should be considered as an option in early analysis.

A study that only considered LRT operating in its typical way and an express bus system in its typical way could easily miss the most cost-effective mode-service combination. This is what was meant by our statement that a technology is not a system.

This paper has shown, hopefully, that many systems can offer many service levels in different implementations; therefore it only remains for this paper to emphasize again the issues involved in choosing the service levels a transit system should give.

If an area is very CBD oriented or if that is a regional goal, express-type service very well may be reasonable. If transit is being implemented in a highly white-collar area, commuter-rail-type service may be appropriate, and a generally expensive feeder system need not be run at a high level. If an area has many intracorridor trips, then a typical LRT or rail rapid transit service pattern may be in order. There are many reasons to believe that the costs and flexibility of LRT will make it as useful a transit option in this country as it has been in other countries. We have tried to show in this paper the many ways in which LRT can be used to provide different level-of-service patterns.

It is the level of service provided by a system, not the technology, that is of primary importance to attracting ridership. This concept, and the models that have been built around it, can provide many insights into LRT system design and operation in urban implementations. This paper has reviewed some of these issues briefly and simply. But hopefully it has explained what we feel is a key role for demand analysis in planning transit systems.

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LIGHT RAIL TRANSIT SOCIAL COSTS AND BENEFITS

Gordon J. Thompson,* Rockland County (New York) Transit Coordinator

This paper identifies the social aspects of light rail transit and categorizes them according to the viewpoints of the rider, those on the wayside, the community, and the contributor of capital funds. The physical characteristics and service qualities of light rail transit accumulate to benefits that are judged to outweigh the social costs. Highlighted is the light rail transit attribute of serving a greater number of persons' travel needs through extensive distance covered for a given investment, frequent stations, easy access, and short door-to-door travel time. The ability of light rail transit to condense the amount of time between ground breaking and operation of service is stressed. This is credited to simpler construction enabled by need for narrower rights-of-way, use of sharper curves and steeper gradients, and tolerance of grade crossings. The ability of light rail transit to evolve at a later date, through additional investment, into conventional rapid transit is acknowledged. The paper draws conclusions from a 1960 study in Frankfurt, Germany, that served as the springboard for the now extensive development of light rail transit networks throughout Europe. Instances of specific social aspects are cited.

Social aspects cover a community's welfare and quality of life. The social aspects of transportation facilities and services to which costs or benefits can be attributed encompass a wide range of changes to the economy, the environment, and the ecology. Social aspects include, for example, impacts on employment, such as decreasing the level of unemployment by creation of short-term jobs for construction of facilities and manufacture of equipment and long-range jobs for operation and maintenance. Social aspects also cover technical topics such as air quality, acoustics, visual aesthetics, water quality, and ecological impact resulting from construction, consumption of resources, and emission of wastes. Social aspects extend to the commitment (or recovery) of financial resources. These are, of course, features of all public works projects. Unique to transportation is the social aspect of urban mobility; transportation connects workers to job opportunities, students to education opportunities, shoppers to stores, and everyone to municipal and health services, cultural institutions, and recreation activities. Expressed another way, social aspects encompass concern for the conservation or judicious expenditure of material, resources, energy, time, and human endeavor.

Benefits are not free. To gain a social benefit, one must make a social investment (cost). For example, to transport an individual to employment (this has a positive connotation), it is necessary to commit time, land, materials, and funds, which, once committed, cannot be recovered (this has a negative connotation), and make certain irrevocable sacrifices in air quality, sound, and visual aesthetics (this has a negative connotation). The items that have negative connotations are costs; those with positive

*Mr. Thompson was with Tippetts-Abbett-McCarthy-Stratton when this research was performed.

connotations are benefits. Urban transportation facilities must be planned so that the benefits outweigh the costs.

The social aspects I have mentioned apply generally to all modes of urban transportation. The costs and benefits among different modes vary relatively as a function of technological (land requirements, power consumption), service (speed, frequency, route layout, passenger appeal), and financial (construction, maintenance, operation, revenues) characteristics and according to the numbers of persons who can avail themselves of the transportation service or be attracted to it. In cost-benefit analyses, the costs and benefits are tallied, compared mathematically, and expressed as a cost-benefit ratio. The ratios for alternative modes or projects can be compared. (Such an endeavor involves setting values. It is difficult—indeed, it is often impossible—to assign a dollar value to certain social costs and benefits.) In modal choice, according to local circumstances, one mode, in social terms, can be either more beneficial or less costly than another.

This paper explores briefly the topic of social costs and benefits of light-volume rapid transit (light rail transit). It treats the subject narratively rather than quantitatively because of the difficulty of placing dollar values on some of the costs or benefits without exploring in detail a specific instance of applying the light rail transit concept.

SOCIAL ASPECTS OF LIGHT RAIL RAPID TRANSIT

For convenience, the social aspects of light rail rapid transit are categorized according to 4 different viewpoints: those of the rider, the person on the wayside, the community, and the contributor of capital funds. These are not mutually exclusive viewpoints; there is considerable overlap.

Viewpoint of the Rider

From numerous studies and considerable debate on the value of a traveler's time, there is at least agreement that a traveler's time does have value that can be expressed in terms of dollars and weighted into modal-split analyses and cost-benefit calculations. So, if one mode will save more time than another mode, it is economically superior in that respect.

In what proved to be a milestone in transit planning, the city of Frankfurt in the Federal Republic of Germany conducted a study in 1960 in which it examined 3 alternative systems: supported monorailway (Alweg), light-volume rapid transit (light rail transit), and heavy-volume (conventional) rapid transit predominantly in subway (29). Table 1 gives a summary of some of the comparative findings. Notice in particular that the total peak passenger travel time is somewhat less for the light rail transit alternative.

The light rail transit system serves, in effect, as its own feeder, requiring fewer miles (kilometers) of bus routes. This is because of its ability to have branches, to extend for longer distances at low investment, and to have more frequent stations (3). These characteristics are reflected in total route length of railway, length of bus routes, and average distance between stations. Therefore, the lower average speed for rail systems for light rail transit, which is due to its making more stops, is more than compensated for by the considerably lower amount of transferring and the resultant lower amount of time lost in transferring.

Frankfurt pursued the light rail transit alternative and now has an exemplary public transport network (20, 24, 27, 39, 40, 54, 55, 56, 71, 72, 73, 74, 75). The Frankfurt experience spurred light rail transit development throughout Europe.

The shorter door-to-door travel time by light rail transit is not only a valuable saving for each individual rider but also a major factor in attracting more riders. Transferring is known to be a deterrent to transit use (7). In light rail transit networks, there is less need for transferring, and the chore of traveling can be made more convenient.

Table 1. Comparison of monorailway, light rail transit, and conventional rapid transit systems designed for Frankfurt.

Item	Monorailway	Light Rail Transit	Conventional Rapid Transit
Route length of railway, miles			
In tunnels	2.83[a]	13.15	23.76
On elevated way	36.30[b]	4.42	15.42
On separate roadbed	—	46.48	—
Total	39.18	64.03	39.18
Length of bus routes, miles	99.30	71.91	90.73
Year of completion	1968	1974	1981
Number of rail stations	82	192	91
Average distance between stations, ft	2,387	1,686	2,099
Total number of stations and stops	307	349	316
Average speed for rail systems, mph	17.76	16.02	17.53
Number of peak-hour passengers	95,600	95,600	95,600
Percentage of peak-hour passengers			
Not transferring	21.0	36.7	24.6
Making 1 transfer	44.3	47.8	45.3
Making 2 transfers	29.3	14.1	24.3
Making 3 transfers	5.4	1.4	5.6
Total peak transfer movements	113,500	76,519	106,812
Total peak passenger travel time, h	52,200	49,300	50,300
Adjusted annual cost of system for first 10 years (no interest), dollars	22,900,000	16,100,000	22,700,000
Annual cost as percentage of present street railway costs	95	47	93

Note: 1 mile = 1.6 km. 1 ft = 0.305 m.

[a]With alternate plan: 4.30 miles (6.9 km). [b]With alternate plan: 34.88 miles (55.8 km).

The rider viewpoint is often overlooked by the transit planner. In Image of the City, which I regard as required reading for transit planners, Kevin Lynch cautions that the urban dweller has a psychological need to be constantly aware of his or her location (34). Express buses on freeways that bypass development and conventional rapid transit in subways violate that need. Light rail transit, which characteristically is a surface operation, suits that need. Also personal contact of the passenger with the operator gives some sense of security. That is a lesson learned from the Lindenwold Line [a rail rapid transit line operated by the Delaware River Port Authority subsidiary, Port Authority Transit Corporation (PATCO), in the southern New Jersey suburbs of Philadelphia] where the operator is not walled off from the passengers. An appreciation of the scene is gained by the light rail transit passenger. The view is generally more relaxing than along freeways or in subways. Rai Okamoto's work for Seattle's rapid transit project is significant in its seeking to enhance the panorama seen by the rider (43). Associated is the high visibility of service; light rail transit cars are mobile billboards boasting of availability, speed, and dependability.

Dependability (regularity, adherence to schedules, and freedom from in-service equipment failures) is a major factor, but most difficult to quantify for modal-split models, in the ability of rail transit to attract greater numbers of riders than buses. Particularly when it operates on an exclusive right-of-way, light rail transit exhibits this characteristic. The all-weather dependability of rail transit deserves mention. In addition, light rail transit has the flexibility to absorb sudden increases in ridership, such as those "foul-weather friends" who descend on the transit system when ice, snow, or heavy rain immobilizes their automobiles.

The viewpoint of the rider also is covered by Jessiman and Kocur (79).

Viewpoint of Persons on the Wayside

The viewpoint of persons on the wayside includes the viewpoints of those who might not be users of the transit service.

In league with electric commuter railways and conventional rapid transit, light rail transit is an efficient user of energy and produces no air pollution at the wayside. Although a central power plant, in generating the electricity, emits some air pollution, it is lower in quantity and toxicity than that produced by automobiles or buses carrying the same number of persons. The Skokie Swift, Chicago's hybrid light rail transit line operated by the Chicago Transit Authority, was heralded soon after its opening in an analysis by the Northeastern Illinois Planning Commission as having effected a 40 percent reduction in hydrocarbons in the 40-mile^2 (104-km^2) area served by the rail line (10). Light rail transit generally produces less pollution, even at the power plant, because it consumes less energy than conventional rapid transit (2, 60, 62). If the conventional rapid transit alternative employs rubber tires instead of steel wheels or if it is predominantly underground, more energy is consumed for overcoming rolling resistance, for overcoming air drag on restrictive subway walls, for tunnel lighting and ventilation, for station lighting and air conditioning, and for escalator operation—features that are usually not associated with light rail transit projects. Streamlining of light rail transit cars as is done in Europe and Canada and was done formerly in the United States significantly reduces power consumption (5, 15, 37). Based on wind-tunnel tests, Pawlowski found that 70 percent of the energy used to propel a conventional electric railway car was consumed in overcoming wind resistance. His later tests for the Philadelphia and Western Railway in 1931 found that the streamlining for the railway's Bullet cars saved the amounts of power given in Table 2, which are significant at rapid transit operating speeds. The Bullet cars operated through much of their careers on the Philadelphia and Western Railway in express service at 85 to 90 mph (136 to 144 km/h). They continue to be run by the Red Arrow Division of the Southeastern Pennsylvania Transportation Authority between Sixty-ninth Street in Philadelphia and Norristown in regular service at speeds up to 70 mph (112 km/h). This 13.4-mile (21.6-km) line with 23 stations is a hybrid light rail transit line: Its main variations are power collection from a third rail, loading from high-platform stations, and full grade separation.

A light rail transit line introduces less noise into a neighborhood (60). Because light rail transit lines generally run on the surface, the noise that is produced is not projected as far from the right-of-way. It is typical for light rail transit to follow a freight-railroad or be in a highway median. In these cases, trains and motor vehicles already have made the sound invasion and light rail transit cars will not add significantly to ambient noise. An accumulation of features (resilient wheels, skirting covering underbody components, general operation at a lower top speed, and use of catenary instead of third rail for power collection) make the light rail transit car inherently quieter than its conventional rapid transit counterparts, and both of these are quieter than motor buses. This quality of quietness can be exploited by placing light rail transit operation in closer proximity to occupied buildings, thus enabling economies in line location and right-of-way acquisition.

There is less community disruption in the construction and operation of light rail transit. By using existing rights-of-way, grades, and roadbeds (such as little-used or abandoned railways, dismantled interurban or suburban trolley lines, electric power

Table 2. Power savings resulting from streamlining (5).

Speed (mph)	Power Saved (percent)	Speed (mph)	Power Saved (percent)
10	5.5	60	39.5
20	17	70	41.5
30	26.5	80	42.5
40	32.25	90	43.5
50	37		

Note: 1 mile = 1.6 km.

transmission lines, former canals, and highway and boulevard medians), one can save in costs and elapsed time in bringing a project from concept to service. Because light rail transit can surmount steep gradients and tolerate sharper curvature in line location, it is possible to provide the way for the transit facility at less cost and without the heavy construction generally associated with conventional rapid transit. This minimizes disruption to established neighborhoods. Light rail transit can slip past delicate situations, such as those involving historical buildings where no right-of-way is available, by reverting to paved streets. However, it must be acknowledged that such a practice might interfere with dependability. In some instances, adherence to schedules can be enhanced by separating the light rail transit tracks from automobile traffic by curbs or simply by painted stripes accompanied by prohibitions and enforcement. Where street space is limited but is sufficient to segregate the tracks, it would be useful to revert to left-hand operation to minimize the amount of space taken from the pavement and still provide for stations (36). In some cases, this may obviate cutting trees to widen street pavement.

An important concern is visual intrusion into a neighborhood. Light rail transit intrudes less than other modes do. It blends in better and can operate successfully in close proximity to the natural environment. Shaker Heights, Ohio, Rapid Transit runs in the grassy median of attractive Shaker Boulevard and Van Aken Boulevard, which are fronted by expensive homes. In Mexico City, the Servicio de Transportes Electricos del Distrito Federal's 53-Tlalpan and 54-Xochimilco light rail transit lines in Calzada de Tlalpan blend in far better than the Sistema de Transporte Collectivo's heavy-volume rapid transit Linea 2, which replaces it for part of the way. Transport of New Jersey's 7-City Subway line forms a suitable perimeter for Newark's Branchbrook Park. Similarly, Massachusetts Bay Transportation Authority's Highland Branch (Green Line—Riverside) blends in alongside Back Bay Fens and through Hammond Pond Park; San Francisco Municipal Railway's J-Church line blends in alongside Mission Park; and Southeastern Pennsylvania Transportation Authority's 101-Media line blends in through Smedley Park. The former D.C. Transit System 20-Cabin John car line followed a narrow way along the palisades overlooking the Potomac River. The George Washington Memorial Parkway had to rearrange the topography and remove thousands of mature trees to make space for a safe highway in the same area.

Light rail transit is compatible with people, too. Safety is inherent in the smooth contour of most light rail transit cars and the practice of shrouding underbody components. Consequently, people and light rail transit cars mix successfully in pedestrian malls in Geneva and Zurich, Switzerland, and in Bremen, Frankfurt, Kassel, and Magdeburg, Germany (52, 69).

In the development of light rail transit lines, the urban environment can be enhanced through the use of textured pavements, plantings, and plazas. At light rail transit stations, where on-board payment of fares usually prevails, there is no need for unsightly fences to separate the fare-paid areas. A by-product of this feature is that stations are more easily approached by riders. Aesthetics are covered more thoroughly by Rogers (80).

The collection of electric power from overhead wires can be a visual problem. Most U.S. examples of light rail transit inherited their overhead wires from an era when wood and labor were so cheap that they warranted forests of guy poles (instead of more costly catenary for longer spans). Little care was displayed for the visual aspects of public transit during this era. But modern applications of electric railroading in Europe and Japan have led to overhead systems that are both economical and sensitive to appearance. Weight-tensioning of the overhead wire (Bremen, Germany, and Göteborg, Sweden) is a successful way to keep the overhead as delicate as possible (57). Where overhead wires are absolutely prohibited, light rail transit cars can collect power from a third rail, but the right-of-way must be fenced. Deserving of attention in such circumstances is the conduit system formerly employed for aesthetic reasons in New York City, Washington, D.C., London, Berlin, Paris, Lille, Nice, and Brussels. The power rails in the conduit cannot be reached; therefore, the transit line need not be fenced or specially protected. Chandler recommends a modern, economical design of conduit track (8).

Viewpoint of the Community

The viewpoint of the community is that of the entire population (residents, taxpayers, and voters).

As shown by Beetle (81), light rail transit enjoys an inherently lower cost of construction. This allows a given investment to be spread more widely over the urban area. Notice in Table 1 that the total route length of railway for the light rail transit alternative is $1^2/_3$ greater than either monorailway or conventional rapid transit, yet the cost of the light rail transit facilities (given in the table on an annualized basis) is only 70 percent of the cost of the other 2 alternatives (29). Therefore, a community decision in favor of light rail transit can mean that the investment will be lower or that the money that might have been spent on a conventional rapid transit line can instead be used to provide light rail transit service over a wider area. For example, the Pennsylvania Department of Transportation estimates the funds that would have to be spent to produce the 10.6-mile (17-km) Skybus line in Pittsburgh's South Hills Corridor will more than cover development of 25.5 miles (41 km) of light rail transit line in the same area; obviously, this will reach more potential riders (45).

Because for light rail transit projects there is a shorter period of time between ground breaking and commencement of service, the community benefits earlier from its investment. In 1959, the 10-mile (16-km) Highland Branch of the Massachusetts Bay Transportation Authority was put into service in exactly 1 year (13, 21). The diminutive light rail transit line operated by Leonards Department Store in Fort Worth (Leonards M&O Subway) took only 10 months from ground breaking to opening of service in 1963; and this included construction of a 0.25-mile (0.4-km) subway section (33). The Chicago Transit Authority 5-mile (8-km) Skokie Swift moved from application for federal funds to public use in only 4 months (9, 26). It can be seen that light rail transit can offer prompt relief from traffic congestion. (Today, using federal-grant funds, these cited projects would take longer. More intensive feasibility studies are demanded as justification and bureaucratic processing of paperwork take as long as or longer than implementation. Nevertheless, once a grant is approved, implementing light rail transit would consume less time than a busway or conventional rapid transit would in a typical corridor.)

It is possible to use short segments of light rail transit lines even before completion of an entire line. This is often not possible or is uneconomical with conventional rapid transit lines. Inexpensive alternate routings also can be employed while permanent routes are being designed and built. For example, Shaker Heights, Ohio, Rapid Transit opened service with street running from East Thirty-fourth Street to Cleveland's Public Square until Union Terminal was completed 10 years later (6). In the meantime, people were able to use the service, and new residents established their travel habits. Göteborg, Sweden, extends its several light rail transit lines station by station as urbanization grows outward (18).

Because light rail transit is more of an operating concept than a mode, it can evolve into conventional rapid transit if necessary. Meanwhile, an area can enjoy the benefits of rapid transit service well before conventional rapid transit might be warranted. In Europe, some cities design their light rail transit systems with no expectation that their evolving into conventional rapid transit will ever be necessary. [Light rail transit has sufficient capacity to carry the loads of most conventional rapid transit lines (47).] Other cities, such as Brussels (11, 12, 48, 53, 65), Vienna (30, 31, 41), and Oslo (22, 67), design specifically for later conversion, and much of the cost of the later conventional rapid transit (costs for long stations) is incorporated into the original project. Other cities, such as Cologne (17, 24), design feeling that later conversion may be required but do not make advance investment. This art of "evolution" was used in the United States in the past. Conventional rapid transit lines in North America that began their existence as light-volume rapid transit or its early-era equivalents include: Massachusetts Bay Transportation Authority's Blue Line between Bowdoin in downtown Boston and Revere Beach; Chicago Transit Authority's Congress Route between Laramie and Des Plaines; Sistema de Transporte Collectivo's Linea 2 from Chabacano to Tasquena; and New York City Transit Authority's "Franklin Avenue Shuttle" and "Brighton

Line" from Franklin Avenue via Prospect Park to Stillwell Avenue, "Sea Beach Line" between Ninth Avenue and Stillwell Avenue, "Rockaway Park Line" from Hammels to Rockaway Park, "Culver Line" between Ditmar Avenue and Stillwell Avenue, "Dyre Avenue Line" from 180th Street to Dyre Avenue, and "Flushing Line" between Grand Central and Hunters Point Boulevard. Operating light rail transit lines that were designed for later conversion to conventional rapid transit are Shaker Heights, Ohio, Rapid Transit at Cleveland (6), Philadelphia's 100-Norristown High-Speed Line (operated by Southeastern Pennsylvania Transportation Authority's Red Arrow Division) (15), and Transport of New Jersey's 7-City Subway line in Newark. The demand for conversion never arrived, but in the intervening years, millions of passengers have been carried.

A little-used freight railroad need not be completely abandoned before rapid transit on it can be considered. Light rail transit and continued freight service are compatible on light-density branch lines. Careful scheduling can obviate interference, or freight can be relegated to night hours. Thus a community need not suffer employment loss by shippers to gain rapid transit. In fact, joint use with light rail transit can serve to secure the permanent availability of freight service for industries not on main lines.

Light rail transit has several safety advantages. Its general use of overhead catenary instead of third rail makes the right-of-way less hazardous. Over the years, people have come to respect a railway facility. This is not the case with a busway, which becomes an attractive nuisance and is trespassed on rather casually unless it has difficult access (such as the busway in the median of Shirley Highway and I-95 in the Northern Virginia suburbs of Washington, D.C.). Philadelphia's R-Ardmore busway (operated by Southeastern Pennsylvania Transportation Authority's Red Arrow Division) has become a neighborhood hiking and biking trail. Runcorn, a new town in the vicinity of Liverpool, England, has difficulty warning strolling mothers with perambulators off its busway. Intermittent use of busways by buses compared with their frequent use of city streets is deceptive. Morris (82) has covered this more thoroughly.

Perhaps, at first thought, the tendency to tolerate grade crossings for light rail transit would seem hazardous. Even if the motorman feels inclined to slow for crossings, the high rate of acceleration of the light rail transit car allows the car to rapidly reachieve top speed with almost no discernible loss of time. Most light rail transit stations are situated at intersecting streets so that the instances of cars speeding through grade crossings are minimized. Although full grade separation would be useful to remove a capacity constraint, it is not really necessary from a safety standpoint (76). Adequate protection can (and should) be provided with automatic gates and flashing lights (35, 63) or traffic signals actuated by the passage of light rail transit cars (23). Tippetts-Abbett-McCarthy-Stratton (TAMS) has designed such a system to expedite the movement of Green Line Light Rail Transit cars on Commonwealth Avenue in Boston. (As part of a computer-controlled traffic signal system, TAMS designed a priority system for light rail transit cars along Commonwealth Avenue where the Green Line is located in a broad median; it is to be provided where the light rail transit movement can be accommodated without any conflict and where far-side platforms can be situated.) Otherwise, grade crossings provide the ideal way for passengers to approach the station—on ground level.

Viewpoint of the Contributor of Funds

Fourth is the viewpoint of the contributor of funds. In these times, transit improvement projects cost so much that federal grants (and, in many places, state grants) and local-government contributions are needed. In addition to providing technically sound justifications and weighing cost effectiveness, one must persuade elected government officials that financial participation is in their best interest. This is difficult to do with a project such as a typical conventional rapid transit project that will consume 7 to 10 years from adoption to public service. The shorter time span for constructing a light rail transit line is more in harmony with the short tenure of political terms of office. In a more positive sense, measurable value from the grant or investment is gained earlier.

The value of light rail transit is not so much that it is more quickly built or that its facilities are less costly; it is that light rail transit can extract full value from earlier investments. An abandoned railroad grade, for example, represents right-of-way assembly, grading and drainage, and construction that already has been amortized. In a light rail transit project, the only cost representing this earlier work would be the acquisition of the property. To convert the abandoned railroad into a conventional rapid transit line might require the high cost of full grade separation. To develop the abandoned railroad as a busway generally would obviate the advantages of the earlier investment. Light rail transit is more likely to use the abandoned facilities as they are with a minimum of expenditure for modification. Developing a light rail transit line to use Cincinnati's subway is an extreme example of the capability of light rail transit to exploit past investment. The city's taxpayers have fully paid the bonded indebtedness incurred to build the subway. Owned by the public, the facility would be "free" for use in a new project.

With light rail transit, there is greater flexibility in areas where traffic might increase later. Increased patronage can be accommodated by purchasing additional rolling stock, by double-tracking initial single-track sections, and by effecting full grade separation in place of initial street-running sections while still remaining within the light rail transit concept. The initial lower investment takes some of the risk out of commitment of funds by government officials. Should the light rail transit project not achieve the predicted level of patronage, the people are left with an operating transit facility rather than a "white elephant." In the meantime, the citizens have enjoyed a useful transit service instead of having a pie-in-the-sky volume of recommendations gathering dust on the library shelf.

Net Benefits

The social costs of light rail rapid transit include

1. Committing land space for right-of-way and stations;
2. Allocating public funds;
3. Tolerating noise, dust, and some disruption during construction;
4. Tolerating some visual intrusion;
5. Committing energy resources;
6. Accepting a slight addition to ambient noise; and
7. Accepting protected grade crossings instead of grade separation in some localities.

These social costs are more than offset by the benefits of light rail rapid transit, which include

1. Less obtrusive construction on a narrower right-of-way,
2. Blending in with the urban and natural environment,
3. Conservation of energy and relatively small contribution to air pollution,
4. Rendering useful service sooner,
5. Serving more people's travel needs more directly,
6. Providing a quicker door-to-door trip,
7. Safety, and
8. Flexibility of evolving to conventional rapid transit if necessary.

CONCLUSION

Social costs and benefits are probably more variable from city to city and project to project than are construction costs, operating costs, and revenue forecasts. Therefore, firm dollar values cannot be assigned nor rules of thumb coined. Light rail transit, compared to an urban busway, could mean increased benefits at no increase in costs. Or, compared to conventional rapid transit, it could mean a decrease in investment at no loss of benefits. And, compared to an electric commuter railway, costs and benefits could come out even, depending on population location and density, length of line, and related factors. Any comparison should be made on an area basis rather than a line-by-line basis because it might be possible for 2 light rail transit lines to serve more people yet be less expensive to build and operate than a single conventional rapid transit line.

No single mode can serve all situations. However, I would conclude generally that, wherever busways, rapid transit, or commuter trains are being considered, it would be well to measure the costs and benefits of versatile light rail transit as an alternative.

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LIGHT RAIL TRANSIT SYSTEM EVALUATION

Tom E. Parkinson, Consultant, Toronto, Ontario, Canada

Evaluation of a light rail transit system involves many considerations that are specific to sites or systems and cannot be treated in a general study. However, it is possible to establish a value for reductions in running time relative to reductions in direct operating cost, savings in passenger time, and increases in net system revenue. These values, which depend on passenger volume, can be related to capital cost improvements. These include eliminating on-street running, eliminating grade crossings, instituting high-platform loading, and varying fare-collection systems. Brief commands are included on other factors of system evaluation including reliability, safety, and provision for future growth. The paper concludes that, although certain intensive improvements are likely to be justifiable, these must depend on a more detailed system-specific evaluation. In general it suggests that the planning and design of light rail transit should keep the system as simple as possible and, on the surface, avoid automatic application of rapid transit or railroad standards—and costs.

Light rail transit encompasses a wide range of electrically propelled, steel-wheel vehicles. Many costs, both capital and operating, are site specific or system specific. This makes a general economic evaluation of LRT systems difficult and, in some respects, dangerous because applying general conclusions out of context is too easy.

This report will concentrate on the economic trade-offs between capital and operating costs with specific respect to the 2 predominant advantages of LRT: its low infrastructure costs when existing rights-of-way are used and the increased labor productivity possible with higher speeds, larger vehicles, and multiple-unit operation.

LRT involves a system with a basic infrastructure cost of 1 to 2 million dollars/mile (0.6 to 1.2 million dollars/km), excluding land and vehicles but including most basic stations and spacing signals. Vehicles and their storage and maintenance facilities will add 400,000 dollars/mile (249,000 dollars/km) for every 1,000 passengers per peak-hour direction (phd) at a typical schedule speed of 20 mph (32.2 km/h). (Vehicle cost is inversely proportional to speed and can be factored accordingly.) Major increases to the infrastructure cost will occur if grade separations, elevated or below-grade operation, elaborate stations, sophisticated signaling, or remote power supervision is required. In part, an economic justification for these extra infrastructure costs can be related to reductions in operating costs.

Operating costs used in this evaluation are in Canadian dollars and are derived from 1975 estimates by the Toronto Transit Commission (TTC) for new 4-axle light rail vehicles operated under union requirements with a basic hourly operator rate of $6.50. These operating costs can then be adjusted for 6-axle and multiple-unit operation as outlined in Table 1. For the multiple-unit operation we assume that the union will tolerate 1 person per train and either off-vehicle or self-service fare collection. Either fare collection procedure may incur additional costs. Although the factoring of costs by 2 or 3 for multiple-unit operation is not strictly correct because of the fixed and variable components of these costs, it is adequate for this exercise. The

TTC estimates are for a fleet of 200 new cars and high standards for track maintenance and overhead. The costs were derived for average schedule speeds and have been adjusted to a 20-mph (32.2-km/h) average. Adjustments for other average speeds can be made accordingly. Maintenance of track and overhead are approximately independent of speed in this range. Power and fuel; vehicle maintenance, cleaning, and service; and transportation and fringe benefits are inversely proportional to average schedule speed at the respective approximate ratios of 25, 50 and 100 percent.

TIME VERSUS COST

There is little question that the major trade-off in an economic evaluation of light rail transit is that between travel time and capital cost. In a planning study that examines an inventory of possible rights-of-way in potential corridors of demand there are 2 considerations:

1. Deviations from the low-cost right-of-way to better serve the corridor, particularly potential major patronage generators; and
2. Improvements in the low-cost right-of-way to decrease travel times.

The deviations mentioned in item 1 could involve massive increases in basic infrastructure cost to provide a new at-grade, elevated, or below-grade alignment. These are wholly site specific and are outside the realm of this paper. The improvements mentioned in item 2, whether they be grade separations, route relocations, or high-platform stations to reduce loading time, involve the same time-cost relationship.

The dollar value of reducing travel time has 3 major components and is, of course, volume dependent. The 3 components are direct operating cost, value of passenger's time, and time elasticity.

Direct Operating Cost

The most tangible savings are lowered direct operating costs resulting from reduced running time. The data given in Table 1 indicate the following direct operating cost (DOC) savings per train minute saved:

1. 20.3 + 86/V cents/min/single 6-axle car,
2. 20.3 + 172/V cents/min/2-car train, and
3. 20.3 + 258/V cents/min/3-car train.

V is the average system schedule speed in mph (km/h). The values are for instances with 1 operator per train. If each vehicle must have an operator, the single-car factor can be multiplied accordingly.

The number of vehicles required to carry 1,000 passengers/phd/mile (1.6 km) of line at V mph (km/h) with a speed margin and layover allowance of 10 percent is 14.67/V, based on an average peak-hour occupancy for a 6-axle vehicle of 150 passengers. Peak-hour service with buildup and build down involves this number of vehicles per mile (kilometer) of line operating 6 h per day for 300 days per year. It is reasonable to assume that off-peak service for 14 h a day plus weekends will double this annual "peak" figure to produce

1. 52,800 annual vehicle h/V per 1,000 passengers/phd/mile (1.6 km) of line and
2. 52,800 annual vehicle miles (84,955 annual vehicle km) per 1,000 passengers/phd/mile (1.6 km) of line.

The assumption is based on a typical Canadian urban load distribution. Operations with high peaking or no attempt to provide full transit service for 18 to 20 h/day and 365 days/year will involve lower savings. Again, this is a system-specific evaluation.

Note that, although there will be the average 150 passengers per vehicle in the peak hour, the load factor over the peak period and off-peak period will be substantially lower. The annual cost savings for each 1-min reduction in running time can then be expressed in 1975 dollars as 528 (20.3 + 86/V) per 1,000 passengers/phd/year/min reduction in travel time. This expression can be applied to a range of light rail operations.

1. A line with passenger demand of 2,000 passengers/phd at a schedule speed of 20 mph (32.2 km/h) would save 26,000 dollars/year/min reduction in travel time.
2. A line with passenger demand of 5,000 passengers/phd at a schedule speed of 20 mph (32.2 km/h) is likely to involve multiple-unit operation in the peak period. If an operator is required on each vehicle, the savings per minute is 65,000 dollars/year/min reduction in travel time. With maximum labor efficiency, the savings would be 50,400 dollars/year/min reduction in travel time for a 2-car, multiple-unit operation.
3. A line with passenger demand of 8,000 passengers/phd and headways of just more than 1 min would produce savings of 104,000 dollars/year/min reduction in travel time for a single-car operation. However, at this headway, 3-car, multiple-unit trains are appropriate and would show a savings of 87,000 dollars/year/min reduction in travel time.
4. A line with a demand of 12,000 passengers/phd would have a savings of 156,000 dollars/year/min reduction in travel time with 1 operator per car or 131,000 dollars/year/min reduction in travel time with 1 operator per train.

The results of these 4 hypothetical systems are given in Table 2. The annual reductions in DOC have been capitalized at 10 percent. This exercise can be repeated for any patronage level and easily can be tailored to the specifics of any projected system. Therefore, more than the mere generalizations and assumptions in this paper can be used.

Value of Passenger Time

It is possible to assign a value to passenger time savings in a cost-benefit analysis. Cost-benefit analysis is a much abused field, and some practitioners can prove that almost anything is economical if they are given enough leeway with the intangible factors. However, cost-benefit analysis does have some value, particularly in comparing reasonably similar alternatives when the input factors are clearly defined.

The value assigned to time savings is often taken as half the average hourly income of the community being studied. For the purpose of this exercise, 4 dollars/h will be used. The average includes not only the salaries of hourly income earners but also those of professionals. (The value used for Shaker Heights, Ohio, would be greater than that used for Newark, New Jersey.) A peak-hour volume of 1,000 passengers/phd corresponds to some 6,000 daily riders in the United States and some 8,000 in Canada (the difference is due to the significant difference in off-peak transit use). In this paper, we shall be working with the Canadian pattern of riding.

A reduction of 1 min in running time will save 40,000 passenger h/year per 1,000 passengers/phd, which is a value of 160,000 dollars. This amount is independent of average schedule speed or multiple-unit operation. The resultant savings are given in Table 3 for the 4 hypothetical systems.

Time Elasticity

The final factor in this evaluation is the effect of time on ridership and the generation of any extra revenue. Time elasticity is a difficult but important subject. Time elasticity applies to overall transit travel time and cannot be used on a per-mile (per-kilometer) basis as the other factors can. This makes it a system-specific evaluation, but, if we take a 10-mile-long (16.1-km-long) line with an average speed of 20 mph

(32.2 km/h) and an average ride length of 7 miles (11.3 kilometers) and assume that the access-egress time averages 15 min, then we can conclude that an elasticity of +0.35 will give a passenger a gain of about 1 percent/min reduction in running time.

It can be expected that a passenger increase in the peak hour would involve extra transportation cost, but increases in the shoulder of the peak or at off-peak times will only slightly increase the load factors and thus will produce extra revenue with no DOC increase. If we assume that half the passenger increase is in this category and that revenue approximates 6 cents/passenger mile (3.7 cents/passenger km) less approximately 20 percent to reflect senior citizens' fares, then we can conclude that the corresponding annual savings is as that given in Table 4.

The dollar amounts given in Table 4 are minor compared to the DOC decrease or the value of passengers' time. However, passenger generation has other important benefits that cannot be quantified here. These include reduction in road traffic, lowered congestion, fewer road accidents, and less pollution. These factors are more important in the overall comparison of light rail, the transit status quo, and other modes of potential transit improvement than they are in a cost-benefit evaluation of light rail capital improvements.

The capitalized savings given in Tables 2, 3, and 4 could be summed, but it is undesirable to consider together tangible and less tangible benefits. One of the sad features of cost-benefit analysis is the confusion of assumption with truth.

CAPITAL IMPROVEMENTS

Let us now relate the savings that result from reduced running time with possible capital improvements.

On-Street Operation

Where no suitable alignments are available, street operation is possible. In mixed traffic, speeds of 10 to 15 mph (16.1 to 24.1 km/h) are typical for transit outside the city center. This is 6 to 4 min/mile (3.7 to 2.5 min/km) compared with the 3 to 2 min/mile (1.9 to 1.2 min/km) that light rail is capable of on private right-of-way, which represents a potential running time savings of 1 to 4 min/mile (0.6 to 2.5 min/km). The options to be examined would be preferential lane marking and traffic signaling at minor cost; elevated operation at some 10 to 15 million dollars/mile (6.2 to 9.3 million dollars/km); or below-grade operation at 15 to 20 million dollars/mile (9.3 to 12.4 million dollars/km), excluding stations. A new private surface right-of-way requires a minimum of 3 acres of land/mile (0.75 hm^2/km), which will vary greatly in cost; it could involve acquisition of thirty 60,000 dollar residences for a total cost of 2 million dollars. Examination of Tables 2, 3, and 4 will show that the 2 lower cost alternatives have a positive cost-benefit ratio but that the high-cost alignment options will balance approximately only if the less tangible cost savings associated with passenger time savings are taken into account.

Grade Crossings

Ideally, there should be no delay where grade crossings can be fully protected and light rail transit can be given absolute priority. There may be opposition to the potential traffic delays, and it is important to note that, unlike conventional railroad crossings where protection circuits have to guard against slow trains in addition to fast trains with potentially long cycle times, light rail transit has fast, uniform service that will minimize crossing time. For example, 5,000 passengers/phd can be served by 3-car, 6-axle trains on 5-min headways that require two 20- to 30-s occupancies per headway period; this would hold road traffic for less than 10 percent of the time. No speed restrictions on light rail transit should be necessary or tolerated at grade crossings.

Table 1. Estimated operating costs for new light rail vehicles.

Item	Single-Unit Vehicle (cents/mile)		Multiple-Unit Vehicle (cents/mile)	
	4-Axle	6-Axle	2 × 6-Axle	3 × 6-Axle
Maintenance of track, overhead, traction, power distribution, and buildings	27	34	68	102
Vehicle maintenance, cleaning, and service	15	20	40	60
Power and fuel	8	11	22	33
Transportation	51	51	51	51
Fringe benefits	10	10	10	10
Total	111	125	191	256

Note: 1 cent/mile = 0.6 cent/km.

Table 2. Reduction in direct operating cost for a 1-min reduction in running time.

Line Volume (passengers/phd)	Annual Savings in Direct Operating Cost (1975 Canadian dollars)		Capitalized Value (1975 Canadian dollars)
	1 Operator/Car	1 Operator/Train	
2,000	26,000	26,000	260,000
5,000	65,000	50,400	504,000
8,000	104,000	87,000	870,000
12,000	156,000	131,000	1,310,000

Table 3. Value of passenger time savings for a 1-min reduction in running time.

Line Volume (passengers/phd)	Annual Savings for Passenger Time (1975 Canadian dollars)	Capitalized Value (1975 Canadian dollars)
2,000	320,000	3,200,000
5,000	800,000	8,000,000
8,000	1,280,000	12,800,000
12,000	1,920,000	19,200,000

Note: These figures are valid only at the "peak point" on the line. If the time savings is at the outer end of the line, fewer passengers will benefit and the results must be factored accordingly. Reduce the figures by 25 percent to apply it to a U.S. case with low, off-peak ridership.

Table 4. Net revenue increase for a 1-min reduction in running time.

Line Volume (passengers/phd)	Annual Increase in Net Revenue (1975 Canadian dollars)	Capitalized Value (1975 Canadian dollars)
2,000	8,000	80,000
5,000	20,000	200,000
8,000	32,000	320,000
12,000	48,000	480,000

Where grade crossings are at or close to signalized road intersections, light rail transit passage will have to be phased with the control cycle. Preemption is possible, although there is some controversy over its value; for example, at close transit headways, it can be more effective to ensure that the transit headway will be a multiple of the traffic light cycle times along a route. Average holds at a traffic light with random arrival times average approximately 25 percent of the cycle time and are typically 15 to 20 s long. However, light rail vehicles (LRVs) must approach such a signal at a speed permitting a full stop; this restriction together with retardation and acceleration time can increase the average delay to 30 to 60 s. Grade separations using the low headroom of light rail transit and 6 percent ramp grades can be built under a 4-lane road (without major underground utilities) for as little as 500,000 dollars. Reference to the capitalized value of 1-min time savings shows that such a separation could be justified at relatively moderate passenger volumes.

Where grade crossings occur at stations, vehicle speed either entering or leaving will be quite low; therefore, any effect on running time will be minimal. Passenger-pedestrian grade crossings similarly are unlikely to have an effect on running time. This means that, in many cases, the cost and inconvenience of passenger underpasses or overpasses at stations are unnecessary, although traffic volume, approach speeds, and operator line of sight must be taken into consideration for safety purposes.

High-Platform Loading

Station dwell times can accumulate to an appreciable portion of total travel time. The time spent at stations can be reduced with high-platform loading, which in effect eliminates the steps into the vehicle. Certainly, all moderate-to-high-volume stations should be considered for high platforms. The cost increase need not be high. If all on-street stops are eliminated, a high-platform system will both minimize station dwell times and reduce vehicle capital and maintenance costs associated with the high-low loading mechanism.

An evaluation of high platforms actually is site specific, but let us consider, for example, a system with 2,000 passengers/phd, which is equivalent to 2,400,000 annual trips. A savings of 1 s/passenger (for loading and egress) would save around 40,000 dollars/year or a capitalized value of 400,000 dollars assuming 2 sets of double doors on single 6-axle cars. Time saving and its value at stations now take us into the question of fare collection and multiple door use.

Fare Collection

Fare collection is too large a subject to discuss in detail. Requirements for an efficient system are to minimize delays to vehicles and inconvenience to passengers. Where multiple-unit operation is suitable, it is desirable to avoid operators on other than lead cars. This introduces the difficult problem of union requirements; present staffing rules on North American properties have 1 person per car on light rail lines but not on rapid transit lines despite their somewhat nebulous difference. Off-vehicle collection, fully automatic or with station collectors, and passenger-operated doors can remove the need for more than 1 person/train, but can themselves introduce problems and high costs. European semiautomatic or self-service fare systems can be the best solution for multiple-unit light rail service. The self-service or semiautomatic fare collection common in Europe is quite distinct from the honor fare collection where no check is made on passengers' honesty. This system is used primarily in the Soviet Union. Honor systems would be totally unworkable in North America. Self-service systems can be used with an operator monitoring fare payment; in fact, exact cash fare is a type of self-service fare system. New systems may be able to introduce modifications to these methods. For example, in peak periods a few high-volume stations (usually in city center) can have off-vehicle collection; at other stations boarding passengers can use only the lead car where the operator is located. Off-vehicle pass and ticket sales at a variety of outlets will minimize the inconvenience that results from exact-fare requirements. Pay-as-you-exit inbound and pay-as-you-enter outbound requirements are necessary with centrally staffed stations.

The potential for improved operator productivity on light rail systems with and without multiple-unit operation is substantial as shown by the data given in Table 1. Every attempt should be made to design the system and its fare collection and to negotiate with the unions to take full advantage of this potential.

OTHER FACTORS

Reliability

What are the chances for service disruption and how long will it last? Light rail without a wholly segregated right-of-way is difficult to analyze. At specific levels of maintenance, the interval (miles or kilometers) between in-service vehicle breakdowns can be predicted. Given the economic limitations on maintenance, vehicle breakdowns will occur, but disruptions can be minimized because LRVs can tow or push each other. Power supply, communications, and any signaling also will have failures. External incidents, such as trees taking down overhead wires, stalled automobiles on a street section, and building fires along the right-of-way, are likely to introduce the most problems.

These incidents may amount to two or three 2-h downtimes per year; on the average, operator strikes may lose 1 or 2 days of service per year. It is economic nonsense to provide central power supply supervision and power supply component redundancy in substations. These safeguards are only protecting against a 2-h outage every second year, and they can double or indeed triple the capital cost of the power supply system. All things are relative to the weakest link, and care should be taken not to overdesign specific items merely because of existing standard practice in rapid transit or railroading.

Safety

Light rail as an amalgam of surface transit and rapid transit should combine some safety facets of each. Collision damage should be less than what is normal for a bus system. Suicides will occur occasionally as they do on rail systems. Again, care should be taken not to overdesign to avoid every eventuality. Accidents and claims will be within the range of and probably less than normal transit experience. Recently, in my Vancouver light rail work I was arranging for a light rail median in a soon-to-be-rebuilt arterial road with a 35-mph (56.3-km/h) speed limit. The highway engineer was concerned that a road vehicle could veer from its lane and strike an LRV or that an LRV might strike a left-turning road vehicle where a turn lane trespassed on the track allowance. I had difficulty making the point that occasional incidents would be tolerable and that a 3-ft-high (0.9-m-high) concrete barrier or an elevated section would not be necessary. In the end I said to think of an LRV as a bus that has the advantage of running in a fixed, predetermined path. Light rail vehicles have the cross-section, axle-loading, and braking capabilities of a bus and are operated manually by an equally trained and capable operator. At times they should be regarded and treated just as a bus (but, I would hope, with higher traffic priority).

Light rail transit in subways will require the usual rapid transit safety elements. Greater power supply redundancy, ventilation control, and means to evacuate passengers in an emergency are appropriate only where long subway sections are planned. Short tunnels can have adequate safety without the expense and maintenance of such measures. How short is short will depend on the grade, natural ventilation, station location, and spacing.

Future Growth

How much allowance and cost should the initial design allow for future growth? The pre-metro concept of light rail transit can be advantageous, but it requires initial construction with large radii of curvature, lower grades, greater axle load, and slightly larger profile, all of which add to cost. Very few of the intermediate capacity corridors in North America that are candidates for light rail transit are likely to generate demands greater than 25,000 passengers/phd. If they do, good planning may indicate 2 intermediate capacity routes rather than 1 heavy route. Also there may be lower cost options that help to handle greater volumes such as staggered work hours.

Planning for upgrading to full rapid transit is important. But what is more important is to ensure that moderate growth within the scope of a light rail system can be accommodated. There must be adequate land adjacent to the maintenance and storage depot to hold a larger fleet of cars; station entrances must be able to accommodate higher passenger volumes; and platforms must be able to be raised or lengthened without crippling problems and costs.

CONCLUDING COMMENTS

It should be apparent that a general paper on system evaluation cannot answer the many planning and design questions in the application of light rail that are system specific and site specific. The basis for several economic trade-offs has been shown. There will be situations where it is cost effective to move to more massive infrastructure costs. However, the basic recommendation must be that light rail transit should be kept simple and on the surface. Light rail transit should be treated as its own genre, and automatic application of rapid transit or railroad standards and their ensuing costs should be avoided. Where appropriate, establishing union roles and fare collection systems specifically tailored to light rail operations should be considered.

Although a pragmatic systems evaluation is an important part of the planning process, planners should aim at a system that is less than 100 percent perfect because perfection is unnecessarily expensive. Light rail transit is a well-proved, flexible mode that tolerates compromise; therefore, compromise confidently. A single light rail line in operation is worth much more than a gross of planning studies in the files.

PUBLIC CONSIDERATIONS OF THE ECONOMICS AND MARKETING OF LIGHT RAIL TRANSIT

E. L. Tennyson, Pennsylvania Department of Transportation

The term light rail transit is defined for its use in this paper. This paper is concerned with that type of rail transit that permits electric operation of rail vehicles, singly or in trains, and is capable of subway, elevated, at-grade, and in-street operation on any given route. Economics and marketing are related in the same manner that revenue and expense are related. Adaptation of the service to maximize public response at reasonable cost will confer public benefits to both the user and the taxpayer when more costly alternatives are relieved or avoided. The unique aspects of light rail transit in developing and conferring benefits are reviewed and analyzed. Light rail transit is often less costly and more convenient than full-scale rapid transit; it is often more efficient, attractive, and economical than conventional bus transit within its proper area of operation.

To consider the economic and marketing aspects of light rail transit, one must define the term. Light rail transit, as it will be used in this paper, is that type of electric railway that permits flexible operation of a light rail service over elevated structures, in subways, at grade, or on private rights-of-way and in city or suburban streets without alteration of the vehicle or change of vehicle en route. Except for this characteristic of flexibility, there is no essential difference between light rail transit and heavy rail transit or between rail transit and commuter rail transit. A heavy rail rapid transit car may be lighter than a light rail car. [Chicago's full-scale rapid transit cars weigh as little as 42,000 lb (19 051 kg); an articulated light rail vehicle weighs 65,000 lb (29 484 kg), which is more per unit of length than the heavy rapid transit car.] A light rail service may have prepaid fare collection; a heavy rail service may use on-board collection although this is not usually the case. Step-loading capability from the street is perhaps the essential distinguishing characteristic of light rail transit. The difference between light and heavy rail transit, if in fact there is a difference, is found in local adaptation to the environment. Heavy rail is less flexible, more constricted, and more formally organized.

A light rail car typically is propelled by 8 wheels on 4 axles, is capable of a 3-mph/s (1.35-m/s^2) rate of change of velocity in the lower speed ranges, and is capable of a 50- to 70-mph (80- to 112-km/h) safe maximum speed. Variations with articulation are included. Car length is approximately 24 ft (7.4 m) per truck although 30 ft (9.2 m) is possible. Width varies from 8.33 ft (2.6 m) to 9 ft (2.8 m). Wheel diameter is usually 26 in. (66 cm). Multiple-unit operation is common but usually without train doors between cars. Street operating capability requires an operator on each separate unit and overhead power collection at safe voltages such as 600 or 750 V. The density of vehicles on line usually determines direct-current supply. Doors are arranged for double-stream loading or unloading, and fare collection is at the door nearest the operator. Vehicles may be single end (like buses) or double end (like rapid transit cars) and have doors on the curb side or both sides of the vehicle. Seating capacity will vary from 50 to 62 depending on aisle width, but peak-hour scheduled loading is limited to 1.7 passengers/ft of length (5.6 passengers/m of length) for comfort.

RATIONALE

Buses are capable of flexible operation almost everywhere, and heavy rail rapid transit is capable of carrying from 10,000 to 40,000 passengers/track/h. Therefore, one wonders why we should have light rail transit at all. It has neither the lowest first cost nor the greatest capacity.

Economics

Light rail is required, where justified, to reduce the cost of moving people. Cost includes 2 primary factors: labor and fixed investment. The sum of the 2 per passenger carried or per population unit directly benefited must be minimized if service is to be maximized or if the use of public funds for deficits and capital is to be optimized. Light rail transit is, in its proper application, more efficient than the bus because the labor input can produce significantly more passenger miles (kilometers) per employee hour in many cases. This is true for 2 primary reasons. First, a single operator can carry from 78 to 120 peak-hour passengers depending on whether the vehicle is a standard size or an articulated unit, and 5 ft^2 (0.5 m^2) gross per scheduled peak passenger is allowed. The maximum for an integral bus by law and practicality is 67 passengers; for an articulated bus, it is 98 passengers. The rail vehicle has a 16 to 20 percent labor advantage. Because both buses and rail cars can be articulated, this feature will not be discussed further.

Second, light rail also can produce more passenger miles (kilometers) per hour in those applications for which it is best suited not only because of size but also because of its ability to accelerate faster, operate on viaducts or in subways, and, where required, operate in trains with positive guidance under fail-safe controls. Buses making convenient frequent stops fall to 3 or 4 mph (5 or 6 km/h) when maximum volumes are reached, but, under the same conditions, light rail transit can hold 12 mph (19 km/h) or more. Light rail transit also can operate safely in subways, which is impractical for bus operation because of odor, noise, and guidance and capacity problems. When the cost of guideway or roadway maintenance is added to bus operating costs, the cost per passenger mile (kilometer) usually will average 50 percent higher than light rail operating costs. [Light rail transit costs 8 cents/passenger mile (5 cents/passenger km); for equivalent conditions, buses cost 9.5 cents/passenger mile (5.9 cents/passenger km).] Capital costs of exclusive rights-of-way are not too different.

Marketing

Operations are a sterile and futile exercise unless significant public needs are met. In previous years, the profit motive directed transit operators to optimize their marketing effort, but, as free roads and sometimes free parking for motorists have removed the profit from transit operations, minimizing costs has taken such precedence over transit marketing that ridership has fallen 72 percent across the nation. From 1947 to 1973, as bus transit increased its share of the market from 44 percent to 70 percent, ridership declined from 19 billion to 5.3 billion (1). Marketing is matching the public's needs and desires with the operator's product capabilities and budget. It is not merely advertising and promotion.

Light rail, properly applied, has 7 significant marketing advantages that the public agency sponsoring transit service must consider. These advantages are

1. Comprehensible, predictable fixed route;
2. Superior comfort with reduced on-board injury risk;
3. Fume-free, non-petroleum-dependent electric propulsion;
4. Higher speeds and safety;
5. Lower operating cost per passenger mile (kilometer);

6. Ability to use varied forms of available rights-of-way; and
7. Higher carrying capacity per lane.

Comprehensible, Predictable Fixed Route

The flexibility of bus service is often suggested as a great advantage for serving growing or changing areas with low ridership potential. This is both true and important. For access to a major central business district (CBD) or to a major suburban center with its own good transit access to the CBD, however, fixed-route transit service is a superior generator of ridership, as shown by Shultz (2) and the record of patronage for existing light rail lines. [Newark, San Francisco, and Shaker Heights rail lines together carried almost as many peak-hour riders in 1974 as they did in 1954 (or 1945 if comparable data could be separated). Fleet size on these 3 light rail systems has been increased over the years from 225 to 233; all surface rail and bus line fleets have declined 19 percent in the same period.] The attribute of a clearly identifiable spine with consistent regular service is a most significant factor in a successful transit service. In bad weather, such as fog, ice, or snow, light rail transit can turn in a reliable record of sustained service when highway traffic is severely hampered. This, by itself, is a ridership generator. The avoidance of prolific branching of routes also results in superior headways, which are a major factor in attracting park-and-ride patronage, the largest single source of riders in the outer suburbs.

Superior Comfort With Reduced On-Board Injury Risk

Guidance by rail provides superior amenities for the prospective transit rider. When properly welded rail is in good surface and is aligned, there is no bumping and bouncing. The added dimensions of the rail vehicle provide considerably more comfort for each passenger. There is a lower noise level and no odor. During air-conditioning season, the interior air always can be kept cool. Internal combustion vehicles must, of environmental necessity, turn off the air conditioning during layovers or end-of-line recovery periods, resulting in uncomfortable heat buildup, opening of windows, and loss of subsequent air conditioning.

Rail cars do not swerve to the curb or to another traffic lane during deceleration, which is often rapid. The Baker report to the American Transit Association and confidential data from operating agencies indicate that the record of on-board injury rates favors fixed rail operation because the rate of change of velocity is much more predictable than it is with a steered vehicle.

Fume-Free, Non-Petroleum-Dependent Electric Propulsion

Although accountants reported for years that electricity cost more per mile (kilometer) than diesel fuel, recent changes in price have changed this relationship, but price itself is not the controlling factor. Central station power offers clean, powerful, quiet acceleration not available in diesel vehicles together with reduced shuttling of the vehicles to the fuel pump and water hydrant. Electric vehicles do not have to be fueled each night or stored indoors (or heated) in northern climates. Comparing diesel with electric locomotives in the same service clearly identifies the superiority of electric vehicles. In the transit area, the larger size of the electric vehicle together with its superior rate of acceleration requires a higher rate of fuel consumption per vehicle mile (kilometer) but not per passenger mile (kilometer) per hour, which is the significant common denominator. Diesel fuel is most objectionable in subways not only because of odor and fumes but also because of fire hazard in accidents. Block signal protection for buses has not yet been perfected.

Higher Speeds and Safety

Although safety is not economical or marketable per se, it is obviously an overriding legal and moral requirement that must be met before operation can be considered. Speed is marketable and economical. In fact, it is unavoidably essential to significant transit ridership. As a rule, street transit service attracts only 25 percent of its riders by choice; 75 percent are captive—a small market indeed. Fifty percent of rapid transit riders ride by choice in the city; 75 percent ride by choice in the suburbs, where ridership attraction is essential to justify any transit service at all. The unexpanded Shaker Heights system with competition from the newer Cleveland Rapid Transit and suburban shopping has lost 40 percent of its weekday riders over 20 years compared with the national average loss for expanded suburban bus lines of 54 percent. Pittsburgh light rail transit attracts 60 percent of the CBD trips of automobile owners; buses attract 40 percent of all of the CBD trips of automobile owners. Light rail transit in Newark attracts the highest peak-line ridership in the city from the thinnest territory. In the suburbs, there are few captive riders to support conventional bus service. Commuter rail lines transport as much as 60 to 70 percent of the CBD trips. Radnor Township, Delaware County, Pennsylvania, has a population of 36,000, 1 commuter rail line, 1 light rail line with heavy characteristics, and 2 bus lines. Passenger volume is 4,100/day for light rail transit, 4,000/day for commuter rail transit, and 100/day for bus.

Rail safety is enhanced by both the guidance factor and well-developed automatic safety features, such as deadman control and positive automatic block signals with automatic train stop, as well as the vehicles themselves. Ice and snow pose little or no safety problem. Loss of control by the operator provides an immediate stop without loss of guidance. Vehicle structures are solid and usually protect the passenger in unfortunate circumstances. The greatest safety weakness of the rail car is slippery rail (when ice or snow is not involved), but the provision of magnetic track brakes offers a double ensurance against this problem. Not only do the magnetic brakes clean the rail, but they also add to the adhesion of the car itself.

Lower Operating Cost per Passenger Mile (Kilometer)

Because guideway (track) maintenance is charged directly to light rail vehicles, cost is increased by 10 to 30 cents/vehicle mile (6.25 to 18.75 cents/vehicle km). Electric power may cost 5 cents/vehicle mile (3.1 cents/vehicle km) more than diesel fuel. There can be little argument that light rail service will cost an additional 15 to 35 cents/vehicle mile (9.4 to 21.9 cents/vehicle km) over street bus service. Cost per mile (kilometer), however, is not a proper basis for meaningful comparison of dissimilar services. The marketing factor and production output also must be included.

The closest cost comparison between bus and rail is city street operation. In this area, the rail car (single integral unit) can be reasonably expected to produce 78 peak passenger miles/car mile (78 peak passenger km/car km); therefore, the added guideway and power cost will vary between 0.19 and 0.45 cents/passenger mile (0.12 and 0.28 cents/passenger km). Bus cost per passenger mile (kilometer) in major urban areas (excluding Boston, Chicago, and New York) approximates 13 cents/passenger mile (8.1 cents/passenger km); therefore the added cost of guideway is from 1.4 to 3.4 cents/passenger mile (0.87 to 2.1 cents/passenger km). The actual all-day load factor on the rail vehicle will be only 20 percent; therefore the total impact of guideway maintenance will be 7 to 17 percent of total cost.

In the other direction, the light rail car has a peak-load capacity at 5 ft^2 (0.5 m^2)/passenger, which is 16.5 percent greater than that for the largest bus. In almost all cases where ridership is high enough to justify light rail service, the efficiency of the vehicle exceeds the added cost of guideway maintenance. Added patronage from the fixed route visibility and the superior vehicle characteristics are a plus. Past experience has suggested a 3 percent factor for this difference, which more than offsets any added guideway cost after derivation of cost per passenger mile (kilometer). At peak hours, the added riders are a social benefit; in the off-peak period, they are a financial benefit as well.

It is when transit moves to an exclusive right-of-way that light rail advantages become clearly apparent. The speed of the vehicle rises markedly, increasing all-day productivity from 125 passenger miles (200 passenger km)/vehicle hour to 210 passenger miles (320 passenger km), a 68 percent increase. At least 67 percent of the cost of operation is hourly related; therefore, cost per passenger mile should be between 12 or 13 cents to 7.5 or 8.5 cents/passenger mile (7.5 or 8.1 cents to 4.7 or 5.3 cents/passenger km) in the private right-of-way. This is also true of buses, insofar as street costs are concerned, but the maintenance cost of the guideway, including salting, stop cleaning, and plowing, must be added to this. Depending on volume, this will add from 0.8 to 2 or more cents/passenger mile (0.5 to 1.25 or more cents/passenger km), which leaves the cost of this type of operation at 8.5 to 11 cents/passenger mile (5.3 to 6.9 cents/passenger km). This is about 13 to 29 percent higher than for rail service, and this is without the amenities that attract maximum ridership. If 20 percent is the median between 13 and 29 percent, rail car costs will average 9 to 10 cents/passenger mile (5.6 to 6.2 cents/passenger km) depending on volume and the amount of exclusive right-of-way. Bus costs will be 11.5 cents/passenger mile (7.2 cents/passenger km), which is less than for typical street bus service but 2 cents/passenger mile (1.2 cents/passenger km) more than for light rail service. Each light rail vehicle should produce 500,000 to 600,000 passenger miles (800 000 to 960 000 passenger km)/year, which is worth 10,000 to 12,000 dollars/vehicle, or a 20 percent saving. For a 100-car operation, the public implications of saving more than a million dollars per year in subsidy costs is most significant. (It should be noted here that the length of the exclusive lane is an important factor. A short link for many bus lines would be far superior to a short rail link for 1 line. Conversely, a long suburban radial rail line might be superior to several divided headway bus lines.)

Where narrow structures such as bridges or subways are required, the superiority of the light rail vehicle over buses is so clear (for cost, capacity, aesthetics, and reliability) that there should be no further analysis needed. The large size of the vehicle and its positive guidance, automatic protection, and train capability indicate best use of costly capital facilities.

Ability to Use Varied Forms of Available Rights-of-Way

The light rail vehicle is the only transit vehicle that can operate in a single run over a combination of available rights-of-way. For example, it can run as a subway in the CBD, and it can run on a reserved median in an arterial street, an elevated structure over a natural barrier, a branch-line railroad track, and a suburban street to an outlying population and business center. In the real world of high-cost fixed facilities and ridership dependent on both local stops and short elapsed time, it is the optimum form of transit service where it is applicable.

Because of ventilation and cost problems, a bus should not use a subway, unless it is very short and has no passenger stations. Narrow trestles are not advisable for unguided buses. Railroad tracks cannot be used at all because buses cannot enjoy rail signal protection, rubber on rail is slippery, automobiles could not be kept out if the track area were paved, and in case of accident a bus cannot withstand collision with rail cars.

Full-scale rapid transit subways cost roughly 40 million dollars/mile (25 million dollars/km), and other rights-of-way cost from 10 million to 15 million dollars/mile (6.25 to 9.4 million dollars/km). A 10-mile (16-km) line that is half subway would cost 250 million dollars or more. The same territory, if developed for the light rail configuration suggested, would cost about 115 million, which is a saving of 54 percent. This saving is not related directly to the vehicle but rather to the ability of the vehicle to use more varied rights-of-way. Trip time would be slower, but access would be superior, and some feeder bus operation and approach restraint would be avoided.

Ridership on light rail transit should be close to or superior to that for rapid transit depending on the specific variations in local convenience.

Higher Carrying Capacity per Lane

Single light rail cars have the same operating characteristics as buses (120 vehicles/h down 1 lane at low speed on a city street). This provides a peak capacity of 9,360 persons/h/lane compared with 8,040/h/lane for the bus. What the bus saves by being shorter, it loses by single-door loading and lower acceleration rate.

When the system is moved to a private right-of-way, capacity improves to 133 vehicles/h at higher speed to provide a peak capacity of 10,375 for a single-unit rail vehicle and 8,910 for a bus. Higher figures in various theories involve unworkable assumptions such as perfect flow with platoons, double lanes, or no stops. Passenger loading is an inherent restraint that cannot be avoided. Reduction in traffic interference and intersection signals improves mobility. In Philadelphia, with block signals, light rail transit has operated on 27-s headways under Market Street.

Where volumes exceed two-thirds of these figures, multiple-unit train operation is advisable. Buses do not operate practically in this mode, but rail capacity with 2-car units increases about 67 percent, allowing for the restraint of longer trains. Three-car units will provide 133 percent more capacity or 24,000 more passengers/peak h/lane with stops. Although 4-car trains are possible, economics and speed strongly suggest use of heavy rapid transit for volumes requiring them.

PUBLIC CONSIDERATIONS

Operation, speed, and cost determine ridership and subsidy levels. Value to the public is the major public consideration. This value can be measured best by marketing and economic techniques. A system with low ridership is not worthy of much public consideration beyond the minimum for essential captive riders. A system with high unit cost is offensive to public considerations. Marketing and economics for public consideration go far beyond the transit system itself. Each rider gained by transit is a saving in highway police, accident cost, street construction, air pollution, energy consumption, and property deterioration. Each dollar saved on transit operation is not only a saving to the taxpayer who pays the bill through agencies such as state departments of transportation and city and federal governments but also is a potential saving to the rider, to whom savings are a significant factor in modal choice.

CONCLUSION

Light rail transit, in optimal operation, produces a superior transit service at minimum cost. The added ridership and lower cost for this system not only assist greatly in maintaining useful transit service but also relieve the taxpayer of many high and intangible costs of traffic congestion, loss of property values, accidents, air pollution, energy consumption, and automobile operation.

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