Light-Rail Transit:
PLANNING AND TECHNOLOGY

Proceedings of a conference by the Urban Mass Transportation Administration and conducted by the Transportation Research Board in cooperation with the American Public Transit Association

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Introduction

Stewart F. Taylor, Sanders and Thomas, Inc., Pottstown, Pennsylvania

When the first National Conference on Light Rail Transit (LRT) was held in July 1975, there was limited knowledge of the mode within the transportation profession. The general public had an even fainter awareness. Newsweek carried an article entitled The Trolley Clangs Back (1).

Development of LRT was just beginning on the North American continent. The standard light-rail vehicle (SLRV) was in production for two cities—Boston and San Francisco—that had initiated programs to upgrade their fixed plants. A third city, Edmonton, was starting construction of a totally new system. Toronto had placed orders for a fleet of new vehicles.

Since the summer of 1975 the pace of activity has quickened. The SLRV has entered revenue service in Boston, where extensive track and car shop improvements are nearing completion. In San Francisco every route kilometer bares evidence of transformation from a streetcar to a showcase LRT system.

Elsewhere, Pittsburgh concluded a tortuous selection process by choosing LRT rather than rapid rail, busway, or the much publicized Skybus. Buffalo was given approval by the Urban Mass Transportation Administration (UMTA) for an all new system, while Cleveland weighed bids from 10 suppliers to completely replace the Shaker Heights fleet. Across the Canadian border, Edmonton was joined by Calgary in developing a completely new LRT system, and Toronto broadened its LRT acitvities by authorizing a major extension to the existing 74-km (46-mile) system. An impartial observer would have to conclude that the first national conference had made a contribution to the accelerated growth of LRT.

However, there were also setbacks. UMTA said no to Dayton and Denver. Years of planning in Rochester appeared to have reached a dead end. Vancouver's progress toward an LRT starter line was deflected by a change in provincial administration, while Philadelphia has constructed little more than propositions. By contrast, there has been vigorous LRT activity elsewhere in the world. Most of the more than 300 systems in about 30 countries are pursuing programs of modernization and expansion.

In planning the second National Conference on Light Rail Transit, the TRB Committee on Light Rail Transit pondered these developments. A consensus emerged that the mode no longer required an introduction. There was a need, instead, to focus on specific aspects that have been recognized as critical—and sometimes difficult—steps in the successful implementation of LRT.

The program therefore makes a conscious shift away from basic hardware. By its very nature LRT uses off-the-shelf equipment. Vehicles, track, train control systems, and stations have already been manufactured in a variety of configurations to meet every conceivable requirement. In the eyes of the committee, the basic issue is how to introduce LRT into a community. The problem clearly has many ramifications both technological and institutional. The content of this special report shows that within the scope of the problem there is no dearth of topics to consider.

The opening session began on a high note by relating LRT success stories from numerous cities. Subsequent papers explored problems and issues that have frustrated significant LRT development in this country. A series of case studies showed where and how real progress has been achieved. The basic dichotomy between socioeconomic and technological issues in the implementation of LRT was reflected in papers on such topics as network planning, joint development opportunities, and the formulation of functional specifications and on fare collection, traffic engineering, and power supply. The final session drew on the past to make a candid examination of the future. A theme running through the papers emphasized the overriding need to inform decision makers at all levels about the characteristics of LRT. Ignorance and bias in institutions and governments must be removed before LRT can hope to move forward on a broad front.

The conference concluded on a chord of optimism and realism. LRT has palpably demonstrated its ability to improve urban transportation and the environment with relatively limited resources. However, these inherent attributes will not guarantee easy acceptance by new communities. Only strong, sophisticated, and perservering effort will transform aspirations into reality.

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Part 1
An Overview of Light-Rail Transit

Evolution of Light-Rail Transit

Lee H. Rogers, Institute of Public Administration, Washington, D.C.

Social, economic, and governmental needs frequently dictate changes in the use of urban transport technology. It is the evolution of public belief and policy that most influences the development of any technology. Overdependence on petroleum fuels for transport and industrial growth has cast doubt on long-term options for continued urban life-styles and mobility. There is a need now for planning and deployment of new light-rail transit (LRT) systems. LRT, like all forms of transport, must be judged on its benefits and social costs to both users and nonusers. A look at Ghent, Hannover, Mannheim, Zurich, and Utrecht can show the transit planner how five cities have developed and used their LRT services in a manner that provides greater accessibility for all citizens as well as less direct pollution and easier adaptability to the existing urban setting. The technology of LRT is simple when innovative planning and engineering are used.

The evolution of a technology is too often erroneously viewed as the change in the equipment and the size of the machinery used. Frequently the observer does not comprehend important underlying conceptual and organizational aspects.

For the first time in three decades numerous questions are being raised, in both Canada and the United States, about the continued development of all sectors of our economy. Urban passenger transport activities and the reasonableness of uninhibited private mobility are subjects of great concern. Since April 1977, strong interest has been shown in the general area of transport and energy. On April 18, President Carter stated, "The energy crisis has not yet overwhelmed us, but it will if we do not act quickly. . . . [The United States] is the most wasteful nation on earth. . . . With about the same standard of living, we use twice as much energy per person as do other countries like Germany, Japan, and Sweden." On April 20 he said further, "Transportation consumes 26 percent of all our energy—and as much as half of that is wasted. . . . I will propose a variety of measures to make our transportation systems more efficient." On April 22 he stated, "I think there will be a substantial shift toward increasing use of the public transport systems."

In the National Energy Plan, released on April 29, Carter wrote, "In the long run, mass transit by bus and rail must play a significant role in reducing energy consumption in the transportation sector. Reliable, inexpensive mass transit is needed to serve existing, spread-out metropolitan areas. New development patterns based on public transportation can bring homes and offices, churches and schools, shops, and other community buildings together and, at the same time, conserve energy."

Like many evolutionary events, these particular comments by President Carter were not underscored and projected by the media into the public forum because other portions of his speeches and plans had more momentary interest.

How does a society improve the quality of its well-being while nurturing the conservation of its environment and globally limited resources? What can be done with transport, a major factor in our life-style? Actually, in light of the critical warnings concerning our dwindling resources, transport must be reevaluated in two ways. First, it must be able to adequately meet society's needs and, second, it must make the most efficient use of the energy required in its performance. This is where light-rail transit (LRT) offers its most effective appeal.

Looking back over the last five centuries, rather than the last five decades, we find that conurbanation developed for a variety of reasons. Worldwide, a primary reason was to facilitate communication and interrelationships among people. When this urban concentration occurred, there was a noticeable reduction in the need for time-consuming and costly transport. During the last five decades, as it became easier for urban citizens to use private conveyances, the need for efficient movement seemed to languish. This phenomenon of private mobility looked good at the time, particularly within those short spans that planners and officials must often deal with.

The potential for redirecting transportation during the decline of energy sources is being realized. The U.S. Department of Transportation recently indicated that the total transportation activities of this nation accounted for 19.5 EJ (18.5 quadrillion Btu) of energy, or 53.4 percent of all the petroleum and liquid petroleum gas energy produced domestically or imported during 1972. Of this monstrous amount, the portion required for passenger transport was 12.5 EJ (11.8 quadrillion Btu) or 64 percent of the total. It was estimated that private automobiles used solely for urban trips consumed 36 percent of petroleum fuels. In other words, more than 1 out of every 3 L of gasoline was consumed for trips originating and terminating solely within an urban area; by comparison, only 7.2 percent was used for military purposes and 5.7 percent for all domestic commercial aviation. Statistics from 243 major cities confirm that much of this 36 percent of petroleum energy is expended along major corridors in which millions of private vehicles operate only in peak hours at suboptimal speeds with less than 25 percent occupancy. It should be evident that, within this vast flow of transportation, there are numerous corridors within our cities that would handle more than 4000 person trips/h in a peak period in one direction and 500 trips/h during the base period. Such patterns suggest a major market for the use of LRT systems.

Unfortunately, during the past 3 years the enlightened talk on future petroleum availability has argued about whether depletion will occur by 1985 or 2020. Such talk is a bit unsettling. Debaters seem to argue over the termination year rather than providing insight on the economy's options. This sounds like a cavalier economic attitude—that we need not worry about the disaster until it has befallen us. As prudent planners and citizens, we should examine and implement alternatives before events overtake us. Given the new limits of resource availabilities and the current rate of urban expansion, the need for development and deployment of new and more effective urban transport is upon us now. Every community and planning agency should give consideration to LRT now.

Since October 1973, the relevant factors in the management of urban development and regional transport have undergone a major metamorphosis. The criteria for project feasibility have changed. They are different because we can no longer depend on permanent, unrestricted, low-cost use of petroleum and the continued dispersion of urbanized development. Transport problems reflect but one aspect of this change. We have sewer moratoriums, water rationing, zoning restrictions, and citizen opposition to expanding development. We must reassess how urban areas will operate in the coming decades.

LRT AROUND THE WORLD

Nearly 26 months have passed since the first TRB conference on LRT. During that time, more than 300 cities around the world have successfully continued to operate and expand their LRT and tramway systems. These cities prove that LRT systems are a strong option for moving people and that they are acceptable to the community. There have been 2800 new light-rail vehicles (LRVs) put into service. A totally new LRT system is being constructed in Edmonton. Edmonton is the first North American city to actively embrace the development of LRT in an area that has no vestige of streetcar operation. Buffalo and Calgary are in the final stages of design and engineering for new LRT installations. An increasing number of cities has shown interest in the use of LRT systems, including Denver, Dayton, Detroit, San Diego, Cincinnati, Vancouver, and Portland, Oregon. The United States and Canada are not alone among nations that are reevaluating LRT technology. Designs for new LRT systems have been developed in Mexico, the Netherlands, France, Belgium, Colombia, and Brazil.

We do hear from many people about battery-operated automobiles, steam propulsion, and many other technologies that have been conceptualized but not very successfully tested in the recent past. The pragmatist must look at the options currently available to find the ones that will meet the traffic demands, budget constraints, and social objectives, while providing reliable service but minimal maintenance and operating costs.

Unlike some of the proposed alternatives offered by new and unproven technologies, the ability of the LRT system to perform successfully, efficiently, and economically is supported by nine decades of evolutionary development. Statistics abound—in West Germany during the last 2 years, the 35 cities that have LRT have handled more than 3.3 billion passenger trips over 503 million vehicle km (314 million vehicle miles).

This kind of performance shows why many urban transport specialists believe LRT technology is proven and reliable. It may be true, in some instances, that various models of new equipment may demonstrate some shortcomings in their performance. This does not detract from the overall merit of the technology. Although LRT technology is not a proprietary concept of one company or one government, it is not immune from the problems found within all other types of urban transport technology. All transport systems are sensitive to misguided overdesign and the constraints of funding requirements. Within LRT technology, one aspect of overdesign is the extensive use of tunneling. From the standpoint of operation and capacities, LRT can operate without long underground sections.

Opponents of LRT cite the fact that generating electricity incurs a sizable loss of energy in the combustion process. But, since this is true of all energy-generating technologies, the source of the energy needed to maintain the major flows of urban passengers should be evaluated along with other criteria. LRT systems can provide needed urban transport without total reliance on petroleum. Sixty-eight percent of centralized electrical generation uses coal, hydroelectric power, or fission. Whatever pollution is caused by this process is concentrated in one area, and the vehicles propelled by this electrical energy do not carry pollutants into the central business district (CBD) or the residential neighborhoods.

Advocates of LRT should not be downplaying the capital and operating costs of the mode. The merit of LRT is found in cost comparisons based on the projected traffic demand and needed capacity. While the operator's financial costs for a system are important, they are no longer the sole criterion for determining the financial, economic, and social benefits to society for the development of such systems.

In alternatives analysis it is necessary to be sure that comparable costs and service standards are used. The best comparison of costs is that between busways and LRT. LRT, like the busway, possesses the proven ability to branch into major transport corridors. However, LRT provides better access to activity centers and stronger civic commitment to service. The investment differences between LRT and other types of transit equipment have remained similar through our inflationary years, but LRT equipment offers longer service life, larger carrying capacity, and stronger productivity. During subway construction in Amsterdam, a city with soil conditions similar to those in New Orleans, it was found that the cost of 1 km (0.6 mile) of subway was the same as that of 3 km (1.8 miles) of aerial structure or 30 km (18 miles) of LRT installation. In costing, the planner should not be timid. Right-of-way investments escalate in relation to width and, on this basis, LRT can be very economic.

The attractiveness of this concept and technology lies particularly in the word light. It does not mean shoddy. It does not mean second class. It means creative design and engineering that require the economist, engineer, planner, and operator to use their training to develop the best system for the least cost. As the railway engineer Wellington indicated some 80 years ago, any fool can solve his problem given enough money (1). Today we must get the greatest amount of urban transport capacity into location and operation with the amounts of investment money available, since the treasuries at all government levels are not limitless in their bountiful giving to urban transport projects. We must continually monitor the worldwide development and use of LRT. Only through better understanding of the great flexibility of LRT can we best utilize its benefits.

The impact of any urban transport technology on the society within which it is used must be carefully evaluated for its merits and its liabilities. The private automobile, as used within the urban area, has not been immune from such review. In all forms of transport and urban activity, there continually arise questions about the equitable sharing of benefits and social costs between users and nonusers. This is true of airplanes, automobiles, buses, and LRVs. Questions of this type are not related solely to transport; they have been raised throughout the centuries of urbanization. Sixteenth century Parisian neighborhoods bristle when new types of buildings and developments, like the Pompidou Center, are forced on them. However, these neighborhoods and the citizens thereof forget that the accepted landmarks of today (such as the Eiffel Tower) were the objects of strong criticism during their construction. Further social and political conflict arises when the negative aspects of modern life-styles degrade the urban setting, as is the case with increasing levels of air pollution. Although the life-styles within the city may differ throughout the world, the impact of all types of development must be weighed. The effect of change and development on residents must be compared with the needs and desires of the whole community and its interests; this is how LRT technology and operation should be judged.

GHENT

The city of Ghent, Belgium, provides an example of the relative impact that various forms of urban transport infrastructure have. Ghent has retained its LRT and tramway systems at a time when major national highway construction was going on within the city. Today, some LRT lines still run within residential streets that have low traffic volumes. However, during the last decade, the city has upgraded many of the lines to reserved lanes. This has been done not simply to improve the physical separation of vehicles and services but also to improve the urban landscape through the placement of trees, shrubs, and small parks.

In the late 1960s, a major European expressway (E-3) was constructed through the southwest portion of Ghent. While the city did not argue about the national need for the highway, there was some dispute about the selection of its right-of-way. The compromise reached might not be the same if the issue were raised today, but this major highway was constructed on a huge elevated structure through the southwest neighborhoods of the city. Part of the compromise was that, to the southern side of the expressway, a grade-level LRT line was to be built. Within the community and neighborhoods, the six-lane expressway provides no capacity for local movement. However, the LRT services are currently scheduled to provide 200 seats/h in each direction during the off peak and to carry 1200 passengers/h during the peak hour. New community service buildings have been located near the LRT line. Overall, the cost of this 1-km (0.6-mile) extension of double-track route was less than \$300 000. The city had ordered new LRVs for the entire network, so that the added cost of this line was not specifically considered.

Along the other four LRT routes operated by the city, there has been a noticeable attempt to combine the provision of fixed-guideway public transportation with an attractively landscaped setting. Through the use of modest investment (and at low annual operating and maintenance costs), a program of traffic engineering and landscaping has been undertaken in the last 6 years to beautify the streets and neighborhoods and to encourage use of a quiet, pollution-free system of urban transit—LRT.

HANNOVER

In West Germany, the city of Hannover has retained and improved its network of LRT and tram operations. One benefit of this policy has been that the community's activities are concentrated in specific areas that promote resource efficiency within the urban economy. The use of this transit mode has permitted the redesign of the inner city and its activities and the retention of LRT services to give direct access to the attraction centers. Private automobiles and buses have been channeled out of the major activity areas and commercial streets of the city.

By using an innovative program of right-of-way development, the public transit authority has handled 83 million passenger trips/year without total reliance on exclusive rights-of-way. In the portions of the city where existing and projected traffic capacity permits, LRT mixes freely with other vehicles. In the intermediate areas, street lanes that have LRT guideways are sometimes emphasized by the use of rougher textured pavements designed to encourage a semiexclusive operation by the high-capacity transit vehicles. The city has begun the actual conversion of some mixed-use streets to reserved LRT routes. Within residential neighborhoods, these changes are increasing the capacity of passenger transport while reducing the throughput capacity for private vehicles. Such measures have reduced the noise level in the neighborhoods and improved the community's appearance.

The LRT lines operate easily through the median of tree-lined streets and traverse major public parks without causing disruption of the public's use of such areas or causing harm to the vegetation of the parkland. At intersections and other important street locations, LRT services have priority. This is handled through the use of overhead contactors that preempt traffic signals and initiate electric commands that permit greater reliability and performance for public transit vehicles.

The LRT system does not require expensive and complex station locations. It functions easily with low-cost passenger loading sites for both the CBD and the periphery. LRT is flexible in the route pathways it can use in residential areas. This mode permits the closer spacing of stops than does rapid transit or subway. The compromises that are possible between speed and flexibility of location cannot be obtained with other forms of fixed guideways. There is strong backing within the community based on the fact that the greater use of LRT on private rights-of-way provides a transit infrastructure that will not promote a greater use of private vehicles; it provides greater capacity for mobility of the population without encouraging the use of private vehicles.

At interchange points where feeder bus services terminate, off-street transfers are made. Passengers find these services attractive because of their strictly timed meets and short cross-platform boarding distances between vehicles. The new communities that are developing as satellites to Hannover are being connected to the center city by LRT services. To avoid conflicts at certain locations, LRT is routed into short tunnels and exclusive alignments to link the center of the satellite areas to the center of the city.

In 1976 two LRT lines to the CBD were relocated underground. The subway portions of this alignment are at shallow depths directly under the roadway and do not require complex and costly mezzanines and escalator installations. The transition from underground to the surface is made effectively and simply. In the southern portion of the CBD, this transition from underground to surface operation takes place just south of the university campus. Since, even underground, overhead electric wires are used, the operation can safely ascend within a built-up residential community.

This results in very direct routing of LRT services and permits it to enter any area where users want to go. The LRVs in use can operate over routes that have a mixture of design standards and still provide increased carrying capacity. The vehicles daily operate safely through areas that have high levels of pedestrian activity, and they operate easily in mix with other vehicles, including automobiles, through many of the city streets. These LRT vehicles provide ample seating for off-peak services and plenty of standing space for peak-hour loadings. On some lines there is a mixture of high-step and low-step operation to facilitate the entry of patrons of all ages.

MANNHEIM

Mannheim in West Germany provides an outstanding example of low-investment LRT development. This city of 400 000 people has shown no desire by passengers, merchants, officials, or the operator to convert major portions of any of the 18 LRT lines to underground operation. In 1973 the city closed two principal commercial streets to vehicular traffic and upgraded their use to an exclusive pedestrian mall and LRT corridor. This project has been very successful, and the business community has experienced continued expansion and increased sales. The main corridors of the LRT lines in and around the center of the city handle more than 9000 patrons in peak hours. Although there is one automobile for every three inhabitants, the people use LRT services for 40 percent of their local trips; this amounts to 48 million trips/year.

Rather than relying on aerial structures or subterranean levels, the LRT lines use a variety of surface locations to achieve their functional operation. LRT is found in reserved medians of several of the principal streets. It operates in exclusive and mixed configurations on conventional streets. At points of moderate congestion, track structure has textured pavement that permits automobiles and trucks to use the linear path but discourages them from extended operation over such pavements. The conflict with cross traffic is minimized through proper traffic engineering measures.

The impact of the LRT system on the city's activities and land use are minimized because of the strong comprehensive planning discipline of the city. In this city and other German cities, it has been found that the new large-capacity LRVs have attracted better patronage during weekdays. On some lines patronage is up 25 percent, while off-peak use has risen by more than 30 percent. These increases in patronage have occurred without official use of legal restraints on the use of automobiles.

The center of Mannheim is something like a new town because it was totally planned in the late seventeenth century. This total approach to comprehensive urban planning has continued even through the late 1960s when outlying satellite communities were developed. The satellite of Vogelstang is connected to the center of Mannheim by a new LRT line. Since the LRT uses its own right-of-way, the line has been able to penetrate to the very center of the new community without having the impact that would normally be made by a major highway. The major loading points on this line are in the lower level of a shopping center. The activity and design layouts would be similar to those of portions of LRT lines in Cleveland's Shaker Heights or Philadelphia's Media and Sharon Hill operations.

Of outstanding interest is the pedestrian and transit mall of the center city of Mannheim. In 1973, with a budget of about $2.3 million, the city and transit authority successfully converted more than 15 blocks to this new format. The result is that real estate prices within the center city are stable and the cost of public utilities (water, gas, and electricity) and telephone services have remained lower because of the greater concentration of activities. Several sidewalk cafes have been developed in the area and the LRT system passes within a few meters of social gatherings at such cafes. This shows that the necessary public movement of thousands of people through the central core of a city does not have to be disruptive to the life experience of the residents and workers of the center city.

ZURICH

In Switzerland, the voters in Zurich 5 years ago rejected a bond issue for construction of a heavy-rail transit system as the solution to their urban transport deficiencies. Since that time improvements have been made through various modest investment measures to strengthen the LRT lines and provide new LRVs. In Zurich, public transport handles the bulk of weekday trips, and the LRT lines accounted for 140 million annual trips (68 percent of the total). The city government has realized that the option of increasing automobile capacity throughout the street network would never solve the problem of mobility of people within the city. As a result, the city invested in public transport for peak-hour capacity requirements. LRT has given the city the ability to provide peak-hour capacity for 65 000 people without major negative impact on the city's beauty. On service lines 2 and 4, direct connection to a suburban railway is achieved at grade level. With cross-platform boarding, very modest investment is necessary for the linkage of these two service modes.

To the southeast of Zurich, an LRT line is provided to some medium- and high-income communities. The Forchbahn Railway shares trackage with the city system but then has its own separate right-of-way outside the city limits. New, attractive vehicles with seating for 86 patrons have been placed in service. The line provides a peak-hour capacity of 3000 spaces. This LRT service terminates in a very modest center-city area with a loop track arrangement around the perimeter of a scenic central park. The park's primary objective of enhancing the visual and physical ambience of the historic portions of the city has not been degraded by the LRT operation. This shows that city parks and public transport may not require separate locations.

In the western portion of the primary commercial street of Zurich, the Paradeplatz is being upgraded to an area reserved exclusively for pedestrians and LRT service. Seven LRT lines will converge at this intersection. The area is currently being reconstructed to exclude private vehicles after 3 years of experimental closure.

With such a variety of proven measures and designs, the LRT system has been able to provide both high capacity and reliable service while retaining its surface location within the heart of the city. The pedestrian and transitway development along Bahnhof Street in the center of Zurich is strongly supported by the business community, partly because of its wide acceptance by pedestrians. LRT brings thousands of people into a historic area of the city in a way that no other existing technology can. The pedestrian and LRT zone has been in use since 1972. During this time there have been no major accidents related to conflicts between the LRVs and pedestrians. As a result, thousands of commuters are transported through the center city daily in a manner that enables the city to retain the social amenities that encourage a pleasant urban life-style.

UTRECHT

Opponents of LRT technology frequently concede that such a system is fine but only works in cities that currently have some degree of conventional street railway operations. They indicate that the investment now required for the establishment of a totally new system makes it impossible to undertake. The best refutation is found in places like Utrecht in the Netherlands, which terminated all tramway services in 1938. Currently the metropolitan region around Utrecht is experiencing major suburbanized growth. It is now necessary to connect two satellite communities to the CBD and the railway station of the historic city. The authorities have therefore approved the construction of 11 km (7 miles) of totally new LRT line.

This project will create an LRT line that is not placed in an existing, abandoned railroad right-of-way. It will be placed in highway medians and along arterial roadways in a manner designed to minimize conflict and promote movement by this mode. It will connect the satellite communities with commercial and employment centers and with intermediate neighborhoods. In April 1977, construction of the maintenance base and administrative offices for this LRT system were begun. The line is being established as part of a comprehensive urban development in which the community provides new housing of mixed densities so that families and senior citizens can share more open surroundings. Alternatives analysis was undertaken to compare the costs and benefits of conventional railroads, busways, paratransit, and LRT. The technology that best satisfied the policies and goals of the region was a modern LRT system that promoted the development of houses and apartments in a manner that provided balance between green space and urbanization, while linking these new communities with the older city.

SUMMARY

The five cities reviewed here are by no means unique in their use of LRT technology. Unlike new systems, such as monorails or people movers, the operation and technical successes of LRT are not restricted to a few sites. In more than 300 cities in about 30 nations, the significance of LRT is shown daily. There are different options and objectives for the world's various societies, but there is a question as to whether we can continue to rely so much on the automobile. We need a combination of urban transport technologies in which each contributes positively. When we consider costs, accessibility, pollution, and adaptability to setting, there are many strong arguments for the use of LRT technology. LRT services can be combined with the use of private vehicles through peripheral parking lots.

However, it must be remembered that the choices available to urban planners and officials must be based on what the community and nation will permit the technology to do. One clear example of this relates to the amount of peak-hour capacity that is desired. If the transport capacity is to be provided by elevated expressway, the amount of land required and the impact of the structure will be several times greater than those for an LRT structure. In Cologne and Rotterdam, LRT installations exist and provide high-capacity transport with minimal impact on the residential and historic areas of the cities.

The materials, equipment and vehicles required for LRT use are available worldwide. New rolling stock is being supplied for Helsinki and for LRT operations in Fort Worth. The Boeing Vertol LRV is being built in Philadelphia for revenue service in Boston. This vehicle has been in revenue service since December 1976. The Pullman-Standard Car Manufacturing Company of Chicago has designed a new four-axle vehicle. In Ontario, there are in production both four-axle and six-axle vehicles currently slated for use in Toronto. An indication of the versatility of LRT technology for adapting to new social objectives is seen in Boeing Vertol's proposal for handling wheelchair patrons by providing a hydraulic lift within the vehicle.

When innovative planning in urban transport is encouraged, the difference between the design and cost of LRT equipment and those of heavy-rail equipment becomes very apparent. LRT technology combines design and equipment that adjust easily within the existing urban fabric and operate through the historic, recreational, residential, governmental, and business communities with ease. The idea that a railbound vehicle, operating in its own reserved or private right-of-way, must be expensive and overbearing on its surroundings is found not to be true in light of existing applications.

The planners and engineers interested in the use of this technology should review the methods used in other nations. However, such interest should not envision total and strict importation of another city's operation but rather should examine innovation in the urban transport planning process. In this manner, LRT will be feasible for expanded installation within many cities of North America.

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Current Trends: Problems and Prospects of Light-Rail Transit

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The difficult task of rescuing our urban transit systems from several decades of neglect has only started. Among the obstacles to transit improvements is our deeply rooted double standard for different types of expenditures: Purchase of wasteful items by consumers is considered to move the economy but the use of public funds, even for the construction of very useful projects, is often criticized as wasteful. Another serious obstacle to the development of rail transit in our country has been a lack of expertise in the planning, technology, and operation of these modes. We have virtually invented a new mode: unreliable rail transit. A concerted effort must be made to apply the technical skills that this technology requires to fully realize its great potential. A major step toward that goal would be made if the Urban Mass Transportation Administration would redirect some of its efforts from the development of exotic modes (some of which have little potential) toward the modernization of standard rail and bus technologies. In spite of these obstacles, light-rail transit (LRT) has recorded significant advances. It is now broadly recognized as a serious contender for major transit improvements in many medium-sized and large cities. Its modernization in Europe is continuing, new LRT systems are under construction in Canada, and several U.S. cities are actively planning or designing new LRT systems. There is also a major potential for extensive deployment of LRT in the large cities of developing countries that has not been fully recognized yet. President Carter has promised to pursue three important goals: to revitalize cities, to decrease unemployment, and to increase energy efficiency; if he takes a correct path toward these goals, we should see construction of LRT in a number of our cities in the near future.

Few areas incorporate and symbolize as many of the problems, conflicts, and challenges of modern society as urban transportation does. Among the most complex problems of our society is finding the right balance between the interests of individuals and society—the dilemma of where, how much, and in what manner to introduce public control over planning, development, and operation of systems that consist of private and public components; the serious problems of reconciliation of functional requirements with environmental protection and excessive energy consumption are also found in urban transportation in very acute forms. Moreover, the interdependence between urban transportation and the strength and character of cities is so strong that we often debate the merits of different modes (such as automobile versus transit) on the basis of the differences we have in our concepts of what cities should look like or, even more fundamentally, how prosperous and how livable cities should be. Public transportation is particularly closely related to the prosperity of cities. Its analysis must therefore be done in the light of an analysis of the general trends that affect cities.

RECENT TRENDS AFFECTING URBAN TRANSPORTATION

There has been a growing consensus that the private automobile, when favored over other modes and used indiscriminately as has been done for decades, is not compatible with an attractive urban environment and that some means of regulating and limiting its use are absolutely necessary if we want to have livable and healthy cities.

The first results of this changing attitude can be seen in the openings of numerous pedestrian malls and automobile-restricted areas in various cities. However, the more comprehensive measures, such as increased taxation for parking, limitation of automobile entry into certain areas, monitoring of traffic flows on various facilities, and extensive limitation of through traffic in cities, are still found only in theoretical discussions. The fact is that the greatly underpriced use of the private automobile in cities remains the key obstacle to efficient urban transportation. Until that problem is resolved, we will be facing financial crises in all urban transportation systems. We will also continue to have serious environmental problems and extremely high levels of energy consumption.

After a slowdown during the energy crisis, automobile ownership has continued to increase in virtually all countries. But it is highly significant that, despite this trend, many cities that undertook transit improvements have had a stable or increasing transit ridership. This has clearly shown that the automobile does not have an unexplainable magic but that urban travelers choose among modes with very rational judgment. Transit ridership has been stable or has increased in many European cities, as well as in Toronto, Edmonton, and several other Canadian cities. Relatively modest improvements of transit have also resulted in drastic increases of ridership in such cities as Pittsburgh, San Diego, Honolulu, and Minneapolis.

Most of these recent trends have contributed to an improved image and a greater recognition of the vital role of public transportation. In most countries, investments for construction of new transit lines and for operations have increased, and treatment of transit vehicles has been improved through various priorities. These improvements are significant, but the difficult task of recovering from several decades of total neglect of public transportation in our cities has only been started.

Several of these recent general trends have had a direct impact on the role and potential of light-rail transit (LRT) in cities in many countries. A particularly strong impact has been made by the tendency to improve the utilization of existing facilities, primarily through provision of various types of transit rights-of-way on the surface. We are finally beginning to recognize the fact that transit vehicles should be given priority over other vehicles at least in proportion to their higher capacity and efficiency. Provision of separate right-of-way and transit priorities at intersections have made LRT feasible and desirable in many cities in which only a few years ago rail technology was considered to be unacceptable.

The recognition of the potential of LRT has been aided by the success demonstrated in cities that gradually improved LRT for a number of years. They have now upgraded their most critical network portions and have clearly shown that medium-sized cities can effectively use rail transit on an extensive network. LRT is thus filling the wide gap between the low level of service and low investment required for buses and the high level of service and high investment required for rapid transit.

The relationship between LRT and modes adjacent to it in the spectrum of transit modes has been clarified somewhat, but it remains a subject of many discussions for specific applications. The discussions about the merits of LRT versus rail rapid transit (RRT) have been lively and often unnecessarily confused by two extreme points of view. On one side, there are those who believe LRT is so seriously impeded by its grade crossings or surface operation that it can never give satisfactory performance; RRT is therefore the superior mode. At the other extreme are those who believe that LRT has a greater flexibility of alignment and that, with proper design and regulation of crossings and street running, this mode can virtually match RRT performance; therefore LRT is superior to RRT in virtually all applications. It is rather easy to prove that both of these extreme views represent incorrect overgeneralizations.

It is interesting that there has recently been a tendency to develop systems that use many good characteristics of both modes: ability to have grade crossings or street operation of LRT and operation in trains of three or four cars on grade-separated tracks of RRT. Line A-1 in Frankfurt, line 8 in Gothenburg, the planned Buffalo line, and the second line of the Rotterdam Metro belong in this category. Thus there is a nearly continuous spectrum of modes from LRT to RRT. However, the fact remains that there is abundant experience to show that, despite the large overlap between the domains of the two modes, each one also has a large domain in which it is clearly superior to the other.

It should be pointed out that the desire to make all LRT systems as much like RRT as possible to avoid having an inferior LRT system has often been shortsighted and damaging. It is now rather widely recognized that the extremely high standards for LRT represent overdesign for many applications. For example, a recently developed, well-publicized European light-rail vehicle (LRV) has proved to have excessively complex electronics, cannot negotiate many existing curves, is much heavier than earlier models, and is inconvenient for low-platform boarding. Successful application of this LRV model in a couple of cities does not mean that such a large vehicle is applicable on most LRT systems.

The problem of overdesign (or goldplating) and the technical complexity of vehicles and infrastructure represent damaging factors; they actually decrease the domain of rail modes, which may be unnecessarily priced out of some applications. However, there are indications that a more economical design is now regaining its importance.

OBSTACLES TO LRT DEVELOPMENT

The slow development of LRT, particularly in this country, can be explained by a number of serious obstacles that we are facing. Let us again start with a review of the major general problems in our society that impede revitalization and modernization of our cities and thus also impede improvement to public transportation and LRT.

We have very deeply rooted double standards for different types of expenditures. We tend to consider all private expenditures desirable consumer behavior that moves the economy, while we tend to regard all public expenditures as suspicious investments that are often a waste of taxpayers' money. A popular view is that, if a person purchases an automobile that has a vinyl roof, push-button windows, power brakes, and so on (which consumes a great deal of fuel), this represents a desirable expenditure, while the construction of new public facilities, such as transit lines, is an investment that should be minimized by all possible means. Does that really make sense? Should we consider the automobile industry the most vital and desirable basis of our economy? Should we not include many public works for constructing permanent, efficient, and extremely useful facilities as an even more attractive mover of our economy? Let us not forget that a major factor behind the law that instituted the Interstate highway system was the creation of jobs and stimulation of our economy. We should now focus our forces on similar types of public works, but primarily on the projects that permanently benefit our cities and society. Improved mobility, stimulating development of desirable urban environments, and energy conservation are some of the potential major benefits rail transit offers.

Our country is obviously in a state that could be described as "closed-eyes happiness." It is quite unpleasant to think about the worsening energy problem, so we choose to totally ignore it. President Carter's energy program, which is rather modest and probably inadequate if his description of the seriousness of the problem is correct, has been attacked as too drastic. If the problem were not so serious, it would be quite amusing to observe many representatives in Congress declaring that, under the proposed additional 1.3 cents/L (5 cents/gal) gasoline tax, people will not be able to get to their work places. The same representatives do not express such concern when communities run out of funds to support minimal bus service to large segments of our cities. This let-them-eat-cake approach is hardly a sign of enlightened leadership.

A major oversight in the delineation of the energy program has been a virtually total omission of consideration of transit as a major factor in energy efficiency. President Carter's program takes a popular but incorrect view that contends that we cannot get people out of their automobiles and that the role of transit is not significant. The former has been proved wrong in many instances, while the latter is incorrect in its basic approach. It is neither the present volume of transit use nor its present role that should be considered. The potential of transit lies in its ability to serve a much larger share of urban travel if it is properly financed, designed, and operated. If ridership is increased, transit can effect a much greater energy saving than is now the case.

Organizational deficiencies in our cities also represent a major obstacle that has not gotten adequate attention so far. The multiplicity of governments in metropolitan areas makes a functional approach to such problems as transportation very difficult to achieve. Many organizations, such as the National Conference of Mayors, represent only central cities instead of metropolitan areas. How long can we ignore this deficiency?

An extremely serious specific problem is the very high degree of major errors made both in the design of rail transit systems and in the manufacture of rail vehicles, control systems, and other components. Due to the serious incompetence in these fields, we have actually invented a new version of transit modes: rapid transit with low reliability. This is directly contrary to one of the basic characteristics of rail transit. In dozens of cities around the world this mode has been operating with reliabilities very close to 100 percent for many decades. The new rapid transit system in Munich had two significant delays during its first year of operation. Some of our new systems have that many delays in a week or even in a day.

This problem is explainable by the lack of competence that results from decades of neglect of rail transit technology in this country, but it is not excusable, and it cannot be tolerated. The cost of this problem is extremely high. Frequent technical problems increase operating costs and cause user inconvenience and loss of riders. Moreover, they generate totally incorrect opinions among laymen about the characteristics of rail transit. The news media have recently displayed a shocking lack of basic knowledge and have contributed to confusion, with diligent assistance from the traditional opponents of rail transit.

Let me point out that, if the telephones in Albania do not work well, it is hardly proof that the telephone system as a means of communication is inefficient and unreliable. Yet the opponents of rail are trying to say that because some of our new rail systems have frequent breakdowns, rail transit in general is ineffective and unreliable. Not only transit operators but millions of rail transit users in New York, London, Berlin, and many other cities know very well that high reliability is one of the basic inherent characteristics of properly designed and competently managed rail transit. They also know that rail transit is a major asset of their cities.

While debates and criticisms of urban transportation planning can be useful and productive, this is only the case with constructive criticism. We do have, unfortunately, a vocal group of professional critics who are usually opposed to all improvements not only of public transportation but of cities in general. Because rail transit plays a major role in cities, this mode is their primary target. Most of these critics explain all conceivable problems very simply: They are due to rail technology. They are like the Luddites in England who, about 150 years ago, blamed machines for their unemployment and tried to solve the problem by destroying them. According to these critics, rubber-tired vehicles on highways, ranging from buses down to jitneys and car pools, would offer better and cheaper service. While this is true for some cities or areas, no responsible and knowledgeable professional can make such a categorical statement.

The fact that separate right-of-way is both the key to transit performance and its ability to compete with the automobile (regardless of transit technology) and the main element in investment cost (again regardless of technology) is completely ignored. Successful rail systems, such as the Lindenwold Line, are not mentioned.

It is unfortunate that the planning for the year 2000, which was based on extrapolation of past trends and often produced the unrealistically large plans that were typical of the 1960s, has now been replaced (at least in the United States and Great Britain) by an ultraconservative philosophy of no investment—a philosophy of thinking small and not far ahead. We have now been bouncing between the unrealistic, imaginary future and vague, irresponsible proposals that we should return to the free competition and primitive organization of urban transportation that was actually superseded at about the turn of the century. There has also been, however, an encouraging event in this area recently. Public Transportation and Land-Use Policy (1), a study performed by the Regional Plan Association of New York, is a major contribution toward better understanding of this important aspect. More studies of this type are needed.

REVIEW OF LRT PROGRESS

By far the best progress in actual development of LRT has continued to take place in a number of European countries, particularly West Germany, the Netherlands, Switzerland, and Belgium. The number of new systems, lines, and extensions has not been great, but the work on upgrading existing networks has been intensive and has had excellent results. Brussels, the Hague, Hannover, Cologne, Zurich, and many East European cities have introduced new sections of lines on separate rights-of-way, LRT in pedestrian malls, many innovative traffic-engineering measures for LRT priority, and so on. These cities have good coordination of LRT with buses and rapid transit, as well as park-and-ride systems and numerous new technical inventions, designs, and operational concepts. There are indications that this trend is now also spreading to those countries that had abandoned streetcar systems long ago, e.g., France and Great Britain.

A major problem of urban transportation is beginning to appear, or at least to be fully appreciated, in the developing countries. The number and sizes of their cities are increasing at a rapid pace and transportation is becoming a serious bottleneck in their development. Most of them have used low-cost solutions that result in only temporary relief. To even begin to create an adequate transportation system, most of these cities, such as Cairo, Bangkok, Teheran, Caracas, and Bogota, will have to have high-capacity modes. The potential for the use of LRT in these cities is great, but it has not been fully recognized by many planners. At the present time there is operation or construction of LRT in Brazil, Egypt, India, and several other countries. There is also rapid-transit construction in several cities in these countries.

Closer to home, LRT in Canada certainly deserves careful attention. Not only have Edmonton, Calgary, and Toronto made excellent progress in planning, but the approach and organization of their project implementation sets a good example for many U.S. cities. Indications are, however, that these developments of LRT are only the beginning of using the large potential this mode has in these and several other Canadian cities.

Progress in the United States during the 2 years since the first conference on LRT has been particularly successful in Buffalo and Pittsburgh, but other cities, such as Portland, Oregon, Dayton, San Diego, and Hartford, are also in the process of considering or planning LRT systems. However, this progress falls short of the needs of our cities and the potential of this mode to meet them. The new role that LRT has assumed was very noticeable at the meeting of the International Union of Public Transport in Montreal in May 1977. Not only was there an extensive discussion about this mode, but preparations are now under way to establish a committee on LRT within this organization, the largest on public transportation in the world.

PROSPECTS FOR FUTURE DEVELOPMENTS

In reviewing and summarizing the developments and various factors influencing the development of LRT, we can see that its potential is now very strong, certainly far stronger than most of us could have predicted several years ago. This potential is often underestimated. There is a continuing tendency to use the maximum (and often exaggerated) capacities as the required criteria for introduction of a mode. First, it is not true that we must have 40 000 persons/h for RRT, 20 000 for LRT, 10 000 for a busway, or 3000 for a surface bus line. These figures represent the maximum capacities of the modes—the upper limits of their applications. Each one of these modes can be justified at much lower volumes. LRT can effectively serve 2000 to 3000 persons/h, and bus lines can operate with a few hundred persons per hour. Further, peak-hour volume in one direction is not the only criterion: System performance and service quality are often the dominant factors. If this is properly understood, it is then obvious that a great number of our cities have corridors or entire networks that are suitable for LRT.

Unless we remove the serious obstacles to transit improvements and accelerate our progress in that direction, we will not be prepared for the worsening energy crisis, for the increasing economic and social problems in our cities, for recovery of our deteriorating urban environment, and for all the problems that extreme private affluence and public poverty bring with them.

President Carter, among others, has expressed three important goals: to revitalize cities, to decrease unemployment, and to increase energy efficiency, in which transportation is a major item. Improved public transportation, including construction of new rail transit lines, is certainly an obvious and logical method of achieving all three of these goals. More off-street parking is the last thing most of our cities need.

Our progress in urban transportation will accelerate considerably if the Urban Mass Transportation Administration (UMTA) focuses more intensely on two basic objectives: (a) to prevent or at least minimize the probability of major failures, such as technical problems and excessive costs, and (b) to undertake more programs of very practical, operational, and tangible improvements in our transit systems. The first goal will be achieved by fostering much better expertise in planning and design of transit systems, vehicles, and other components. UMTA has made valuable efforts in LRT system planning and design concepts, but its research and development efforts in vehicle development of all conventional modes have been less than successful. While many exotic technologies, some of which clearly have no future, have been given a lot of attention, several versions of UMTA-sponsored prototype vehicles using conventional technology (e.g., the Transbus and the rapid transit state-of-the-art car) have produced excessively complex, heavy, unreliable vehicles that are, in many respects, less advanced than the latest vehicle designs in Europe.

UMTA must monitor vehicle specifications and design of transit systems more closely. It must prevent a vehicle manufacturer that made numerous design errors on one rapid transit system from getting another order for cars in the future. We simply must reacquire the lost ability of building and operating reliable and efficient transit systems. Additional, stable financing and better training of technical personnel are required for that.

Another potential failure lies in the downtown peoplemover program. If we look back over experiences with new modes, we can see that virtually each one caused major problems, extensive criticism, and often lawsuits after its opening. Installations in Dallas-Fort Worth, Morgantown, and Toronto were not bright moments in transit innovation. Short-haul transit service is a missing link in many downtown areas but, if we learned very bitterly in Morgantown that testing a new transit mode on a line that is supposed to perform a regular revenue service is highly risky and usually damages the entire transit program, why are we now planning to use various combinations of new technologies, planning, and operating concepts in as many as 7 to 10 cities at the same time? Does it make sense that we take this serious risk in so many cities while the proven mode of LRT has been approved in only 2 of them?

The second goal, to make real progress in transit improvements, will be achieved if we not only provide transit systems with reliable hardware but also develop economical design and efficient operation. Our transit systems suffer from obsolete fare-collection methods, inconvenient scheduling, inadequate (or nonexistent) information for passengers, rampant vandalism, and strikes from which, often, no one benefits. Focusing on solutions to these problems may not be a highly glamorous task, but solutions to these problems are necessary if we are to offer reliable, comfortable, and economical transportation that passengers will accept and appreciate. We should never forget that it is the urban traveler for whom we are designing our systems and our urban population for whom we must provide better cities. The developments in Boston and San Francisco, which had difficult beginnings after years of neglect, show that LRT is one of the modes that, with the cooperation of various concerned agencies, can lead to major improvements at moderate costs. The need in many other cities is great, and urgent action is required.

REFERENCE

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Issues in the Implementation of Light-Rail Transit

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A conference on light-rail transit (LRT) invariably seems to draw out a highly explicit discussion about car design, the existence of rights-of-way for construction, and the great disparities between European advances and those in the United States. This paper suggests that, despite the high degree of competence that the technical community can claim in advocating LRT implementation, it is all little more than an academic exercise if the local, state, and national political realities are not recognized as integral aspects of implementation. The discussion in this paper is based on a survey conducted on a national scale of the key political figures in those states or areas considering LRT, as well as many key members of the agency and consulting staffs. The paper calls attention to the essential weaknesses inherent in current efforts to revitalize LRT as a primary element in urban transportation.

I intend to single out in this paper two issues I believe are extremely important to the implementation of light-rail transit (LRT), even though I am dealing with one of the least developed aspects of LRT implementation. I hope that this particular orientation may serve to channel our efforts in the most productive way conceivable so that we all might improve our efforts to implement LRT across the country.

In preparing this paper, I examined the planning and engineering studies of all the cities in North America involved in the development of LRT. Noticeably absent from these abundant descriptions of rights-of-way and technical specifications of cars is an attempt to identify the political climate in which this work is taking place. Ultimately, most if not all of the studies are at least temporarily sidetracked because the plans do not fit into the political environment or because they have run into problems in receiving funding from the local community, the state or province, or the federal government.

Those of us involved in the planning of LRT systems, although we are professional in our standards, are invariably buffs on the subject and consequently talk mostly to each other. In our planning and engineering studies, we use slides and diagrams to illustrate all the virtues of a technology that we have already acknowledged is part of our justification for pursuing the implementation of LRT systems. But in this talking to ourselves, I think we have somehow missed a far more critical issue involved—that of using our combined expertise in talking to the public or its political leadership.

The fruition of our technical skills—the building of an LRT line or network—in some city or a number of cities depends not so much on whether the vehicle is articulated or the vestibule can be entered from both high-level and street-level platforms or on the number of trucks that the vehicle has but whether such a scheme to build an LRT system is compatible with the wants of the general public and with the political priorities for the expenditure of limited public funds as seen by the various political jurisdictions. The competition for funds with which to construct LRT systems has never been keener than it is at present in our mildly depressed economic environment. It therefore remains for us to recognize that the public's perception of government and its current levels of expenditure are primary concerns to the public and consequently primary concerns of our elected officials. Keeping this in mind, it is highly advantageous to recognize not only the ability on our part to design the most efficient and fastidious system conceivable for the public good but also to take clearly into account an accurate reflection of the existing economic conditions at all levels of government.

In trying to assess the best means by which to assemble an accurate statement on the political and institutional problems associated with the implementation of LRT systems, the obvious and easiest means by which to do so would have been to identify from one's own experience and research what such impediments are and how a rational program to resolve these roadblocks to implementation might be established. In the case of this research, however, I have chosen to recognize that the strongest sources for identifying the problems associated with the implementation of LRT are the political leaders and planning technicians involved in the planning, design, construction, and operation of the various systems currently in operation or proposed for operation in various cities of North America.

To this end, contacts were made with key elected officials, people in the various operating agencies, people in the engineering community involved in the planning and design of such systems, and people in the various metropolitan planning organizations that have jurisdiction over the expenditure of public funds from the federal government at the local level. The response to this survey was exceedingly good. The process to be used in developing this paper seemed to be appreciated by the people involved from the various cities. There seemed to be a recognition that this was a better way to present the various points of view from all cities than to extrapolate a single point of view for all possible applications around the country. The following discussion is based on the identification of political and institutional problems at the various levels of government and jurisdictions from a broad cross section of operating properties and cities in which LRT has been proposed or is being operated in both the United States and Canada.

PROCEDURE

There are, no doubt, unique institutional and political problems associated with the implementation of LRT but, by and large, those problems would not differ measurably from problems of implementing a conventional rapid transit system. This seems to be the opinion commonly held by respondents in the United States and Canada to my query as to what political and institutional problems were identified in cities operating, constructing, engineering, or planning an LRT system. The areas contacted were

1. In operation: Pittsburgh, Toronto, San Francisco, Chicago (Skokie Swift), New Orleans, Cleveland, Boston, and Philadelphia;
2. Under construction: Edmonton and Vancouver; and
3. In the planning stage: San Diego, Santa Clara County, Detroit, Rochester, Denver, Aspen, Dayton, Portland, Oregon, and Los Angeles.

Although this did not cover all cities, it was felt that those included would offer a sufficient cross section for the purposes of this presentation.

In each city, various agencies were contacted to provide a multidimensional frame of reference, i.e., transit operators; metropolitan planning organizations and their consultants; and the local, regional, and state political leadership associated with their respective projects. Not all responded, but the responses received provided an excellent foundation for the paper and confirmed my suspicions about the role to which we have heretofore relegated the political and institutional realities of implementing a transit guideway project, LRT in this case. Most respondents replied in depth, indicating that the query had struck a tender spot that they had identified in their process of attempting to plan for or implement such a system.

Because of the nature of the questions posed, it is politic at this point to refer to the responses without naming the individuals concerned, their organizations, or possibly even their cities. The nature of the responses puts numerous cities, organizations, or individuals at odds with the Urban Mass Transportation Administration (UMTA), and I would not want this paper to further impede their relationship with that organization.

SPECIFIC INSTITUTIONAL PROBLEMS AFFECTING LRT IMPLEMENTATION

There is a rather wide range of problems of an institutional nature, ranging from those seen as purely local to those perceived as major roadblocks put in place by UMTA. The most commonly identified institutional problems related to the implementation of LRT were the following.

UMTA Administrative Procedures

The feeling was implicit in the problems identified by the respondents that UMTA has a very strong bias in favor of existing rail properties. UMTA is perceived as having a philosophy that it is more important to upgrade transit in order to help upgrade such cities as New York than to create new rail networks to help hold the line against the deterioration of various other cities.

UMTA is also considered shortsighted in preferring that various cities around the country develop expensive bus grids rather than create rail networks. The argument is made that UMTA may be using too short a range in comparing the advantages of bus and rail. If 1980 or 1985 is viewed as the horizon year, then the more capital-intensive rail network will not outweigh the cost advantages demonstrated by a bus network. On the other hand, if 1990, 1995, 2000, or some point beyond that (which is still well within the scope of the development of such a project) is used, then the longer period for amortization of the rail network offsets the higher capital cost. Simultaneously, the lower cost per unit of labor greatly favors the rail system as well.

UMTA is also seen as the "mighty bureaucrat of the East" that has little comprehension of the real problems associated with differing technologies or implementation strategies at the local level. It is seen as developing solutions to problems that are not themselves thoroughly understood, using technologies that have little practical adaptability. UMTA is also viewed as having an inadequate staff at the regional level, especially in certain parts of the country; the staff is not considered capable of working with the cities in each region in an effective way to help guide them.

One respondent noted that "there appears to be a constant flow of new federal requirements to justify expenditures for capital funding." A new set of buzz words is issued as the new official language of the federal government, and the cities are then all expected to proceed through a new set of hurdles to justify the inability of the federal government to come to grips with the true scale of the problem. The complex funding relationship between the local and state governments and UMTA is entirely too cumbersome and slow a process to be effective in terms of helping to solve urban problems. This slowness clearly has the effect of damaging the sensitive balance that local decision makers are often able to achieve among the various factions that are at odds in their communities. The long lead time often then breaks that cohesion down and puts that urban area back at square one in the process. One respondent expressed the opinion that, although that may sound terribly injurious to the local level, it does have the effect of deferring any judgment at the federal level.

The joint development of a transitway within the right-of-way of a highway has been proposed for a number of cities throughout the country, but this is an extremely difficult process to implement since distinctly different applications for funding are required by UMTA and the Federal Highway Administration.

Shortage of LRT Expertise

State departments of transportation have been identified as principal sources of difficulty in having LRT considered as a potential solution in urban areas in various states. First of all, the state departments of transportation are regarded as purely highway oriented, even though they have gone through the metamorphosis of a name change to enhance their images. In many cases their staffs do not have the resources to work effectively on LRT in its current state of development. In many cases, it was reported, even "consultants brought in by these organizations to bolster their own staff weaknesses are inadequate to meet the challenge, since many of the senior professionals are basically unfamilar with this technology."

A similar lack of familiarity with modern LRT technology is widely found among key decision makers. As a consequence, the stigma of the image of streetcars, overhead trolley wires, and safety problems militates against its application in many locations.

Proliferation of Political Entities

In most urban areas, the number of government bodies or other entities that have a voice in the decision-making process for transit is a critical factor in the problem of expediting the process. This heightens the problem of achieving consensus on any given transit proposal in general or, more specifically, on the technology to be applied within a given strategy.

A similar problem is found in several areas in which the regional authority empowered to provide a regional transit network has jurisdiction only within some parts of the region and not in the whole region. For example, the regional operator may have a political mandate to consolidate all transit service within its broadly defined jurisdiction, but the practical ability to achieve this goal is withheld by one of the key political figures in that area. If this person is committed to one particular transit strategy, even though a basic consensus has been achieved by virtually all other political entities within that region for a different strategy, he or she is, in effect, holding any transit project in the area ransom until such time as his or her own particular philosophy prevails.

Restrictiveness of Regulatory Commissions

Both commerce commissions and public utilities commissions produce institutional problems when they try to apply yesterday's control measures to the implementation of a new transit strategy. The excessively low speed limits these commissions prescribe in various jurisdictions and their requirements for drop gates and warning devices create a very difficult condition for the implementation of LRT. These limitations impair the range of benefits this unique mode has to offer. Railroad criteria have been used to evaluate applications for LRT operations at grade and in areas that would have at-grade crossings. Use of railroad standards implies an analogy between LRT and either high-speed, highly infrequent intercity passenger trains or the slow and cumbersome freight operations that also operate in these situations.

Transit Versus Highway Funding

The traditional split in funding between highways and transit is clearly an institutional problem in the implementation of LRT. The level of funding accorded to the potential development of LRT or even to research, especially at the state level, in many cases is grossly inadequate to foster this particular urban alternative.

Appointive Representation

A number of respondents in this investigation reported that the governing board of the operating authority had an imbalance between the city and suburbs, or at least a perceived imbalance. This imbalance or perceived imbalance creates an ideologic split between the city and the suburbs in relation to the distribution of funding and the generation of the local matching requirement. When the state was a partner in funding the local matching requirement for obtaining federal funding, the state was almost always perceived as having too much control over local decisions as a consequence of its involvement.

Conclusions

Some of the problems related to institutional considerations of implementing LRT are caused by misconceptions, including the fear by local traffic engineers that the free flow of automobile traffic may be impaired as a consequence of the at-grade operation of this mode. As one respondent wrote, "Carrying this perceived problem to the next step of absurdity suggests that the air quality of the region, or more realistically the subregion, may be jeopardized as a consequence of the impairment of automobile traffic at transit grade crossings. In the case of California, if this were a real problem, the project would then have to be justified to the Air Resources Board in terms of the California Air Quality Act."

The desire on the part of all elected officials and most planning technicians to provide an accesible transportation system for the entire population may well militate against the implementation of LRT. In the case of California, this presents a very real threat, since the state department of transportation has identified a need for full accessibility, which may well prohibit the development of any project that uses guideways.

Contrast some of these problems of U.S. cities with the situation in at least one Canadian city, in which transit is viewed as a city operation with full liaison among various city departments. The provincial government has provided two-thirds of the cost of construction with virtually no strings attached. This leaves the determination of options, routes, and strategies to the local decision makers. The other governmental entities involved in this process actually helped the local government rather than dictating additional or overlapping controls to the project.

SPECIFIC POLITICAL PROBLEMS AFFECTING LRT IMPLEMENTATION

These institutional problems, however, represented no more than minor roadblocks to the implementation of LRT when compared with the political problems associated with its implementation. The principal point of this research is to dramatize the fact that a recognition of the political environment is clearly the most significant factor to be weighed by the technicians involved in attempting to implement LRT. The key political factors identified by the respondents throughout the United States and Canada included the following.

Funding Split Between City and Suburbs

A problem found in each of the cities analyzed in regard to implementing a guideway project was that of allocation of funds between the predominant city and its suburbs. The split between city and suburbs on the question of transit construction stems in large measure from the fact that any increase in taxation to fund such a construction program would be levied uniformly throughout the taxing district but would be allocated in disproportionately large share to the urban center. As a consequence, the suburban fringe pays for a larger share of the project but receives a smaller share of any such construction, if it receives any at all. The central city sees in this split a disruption of the urban center in order to create ways for the suburbanites to get from their middle-class and upper-middle-class neighborhoods to downtown. The suburbanites see the split as a means to promote the black exodus to the suburbs.

In the case of at least one major urban center pursuing the implementation of a fixed-guideway project, for which one clear alternative is the implementation of LRT, the proposal for subway construction in the heart of the downtown area is viewed as another wedge being driven between the city and the suburbs. The suburbanites see the construction of a subway segment in the downtown area as providing a disproportionately larger share of the funding to that part of the urban area that is least capable of supporting such a system. The view is quite frequently expressed that the suburbs would like to have a fund allocation program that uses a formula based on the local tax revenues.

In one case in which the central city is pursuing a subway segment and the suburbs fear a consequential loss of funding for an extension to serve them, a coalition has formed to block the tax increase measure for it in the state legislature. Such divisiveness is quite common throughout the country. The suburban counties in this case have even gone one step further and produced a study of their own. It emphasizes the high cost entailed in conventional rapid transit construction and has consequently called for an expansion of the bus system throughout the suburban district and the urban core; LRT lines would be used as the principal arteries along existing railroad rights-of-way.

This kind of rift between the city and suburbs over who pays for public transportation and who receives the services makes it extremely difficult if not totally impossible to bring about a regional public consensus. This raises the question of whether there is a political mechanism by which the appropriate tax can be levied over the whole urban area but approved in two distinct ballot processes. The central city could vote on its tax increase in light of the particular benefits that would accrue to the central city. The suburban population would vote on a similar tax increase that would pay not for the central-city segment of the construction but only for the suburban segment of the total regional program; the two parts, of course, would come together.

This approach may also be able to provide a resolution to a conflict entailed in the view that regional transit is often proposed as the principal investment scheme for an urban area without a clear identification of how the potential rider will get to the regional transit system. The two-part approach could simultaneously address the question of who gets construction first—the city or the suburbs. The most common approach to the construction of a subway, rapid transit, or even LRT line is to begin in the urban core or the downtown area and build outward to the suburbs in increments. The suburbs are wary of this alternative since the funds may well run out long before they realize any benefit from the system. Whether that is the case or not, the benefit to be realized is so far removed in time that the perception of not receiving anything for their tax dollars is very clearly there.

The Ultimate Decision

As I have noted previously and as the reader is well aware, the ultimate decision is political. It is to be hoped that the political decision will be informed by technical advice, but this advice is often simply bypassed. The sensitivity to this issue is most clearly manifest when the government issues a strict set of guidelines that could divide the community but that are not only met but form the basis for a public consensus. If government does not then itself abide by those rules, the local consensus breaks down, and the animosity toward government, usually at the federal and state levels, becomes a paramount issue.

In one western region, the various political entities at the local, state, and congressional levels had reached a broad consensus for the development of a fixed-guideway LRT project in their principal city. But the congressional delegates from this area were low in seniority and apparently unable to bring influence to bear. When decisions were made near the time of the 1976 national election on funding a flurry of projects, this region did not get the needed funds, even though the project may well have been justified.

Another problem area involves the laborious process of alternatives analysis required by UMTA as a prerequisite for the funding of preliminary engineering studies, final design, or any construction. One urban area received a large amount of money (in comparison with the total amount available for distribution) without ever having done any of the prerequisite alternatives analysis. Los Angeles, on the other hand, which has studied every possible form of rapid transit for 50 years and participated in every UMTA-funded study program, had its application denied on the basis that it had to do yet another alternatives analysis.

SUMMARY

Those of us involved in implementing LRT systems may suffer a certain myopia because of our strong conviction about the capabilities of this mode of transit. We must broaden our list of advocates to include elected officials at all levels of government and simultaneously involve the people in programs that can open their eyes. It is a prerequisite to our success that both of these groups recognize that there is a limit to petroleum reserves. We must act as a catalyst to change the public's perception of the utility of the automobile. And then, after this groundwork has been laid, we can become LRT planners once again.

Part 2
Case Studies

San Francisco's Muni Metro, A Light-Rail Transit System

Rino Bei, San Francisco Municipal Railway

This paper describes improvements that are being made in San Francisco's light-rail (streetcar) transit system, the Muni Metro. The new dual-level Market Street subway accommodates Muni on the upper level and the Bay Area Rapid Transit System on the lower level. The new articulated light-rail vehicles, designed to serve the needs of both San Francisco and Boston, are described. In order to provide facilities for storage and maintenance of these vehicles, a new rail center is being constructed. The design of this facility was a particular challenge because of constraints imposed by the small size of the urban site used. Virtually all surface tracks in the city are being replaced. Muni had hoped to develop special transit rights-of-way in conjunction with the rerailing projects but encountered a political snag in the process. The power supply system that provides Muni's electrical power is unique, and the facilities it uses are also being upgraded. Finally, several route extensions contemplated by Muni are described. The new Muni Metro system is scheduled to be in full operation in late 1979.

San Francisco has always been oriented to mass transportation. Before World War II the entire city was covered by a network of streetcar lines. As in many other cities in the late 1940s and early 1950s, many of the streetcar lines were converted to diesel bus or electric trolley coach. However, a basic rail network was retained for those lines that were heavily patronized. Most of these lines served the predominantly residential areas in the western half of the city and transported riders to the commercial and financial districts, which are located in the northeastern section.

Between 1946 and 1952, the San Francisco Municipal Railway (Muni) acquired 105 Presidents' Conference Committee (PCC) streetcars (cars first produced in 1935 that had performance characteristics far superior to all previous models). These were used on the five streetcar lines that originate in the residential districts and then come together on Market Street, the main artery of the downtown business district. The downtown area of the city is the main destination of most of the Muni riders on the average weekday. These five lines, shown in Figure 1, carry an average of 96 000 riders/d.

A significant event occurred during the 1950s that was to have a substantial impact on Muni in the later years. This was the investigation of the feasibility of a rapid transit network for the San Francisco Bay Area. What finally evolved was the system that we know today as the Bay Area Rapid Transit (BART) System. During BART's study phase it was recognized that the BART system would serve primarily as a commuter rail system and would serve only one transit corridor in San Francisco. A second subway route was shown as a future rapid transit line following the streetcars' existing main trunk line along Market Street and through the Twin Peaks Tunnel. The report stated that this route would initially be used by the Muni streetcars.

In 1962, the voters of San Francisco, Alameda, and Contra Costa counties (both sides of San Francisco Bay) approved the BART bond issue; San Francisco provided the largest affirmative vote. The bond issue provided for the construction of a two-level subway under Market Street in which Muni would occupy the upper level and BART the lower level. Two proposed arrangements are shown in Figure 2. The Muni level begins at the foot of Market Street and proceeds westward through four joint stations. Beyond the Civic Center Station, the BART subway departs from the Market Street alignment and continues southward to its terminal across the county line in Daly City.

The Muni subway continues under Market Street to the first Muni-only station, Van Ness Avenue. Beyond the Van Ness Avenue Station there is a critical point for the subway. This is the Duboce Portal where the cars on two lines, the J and N lines, emerge from the subway and then follow their surface trackage (see Figure 1). The Duboce Portal is arranged as a grade-separated junction with the inbound Duboce track passing under the outbound Market track and merging with the inbound Market track. This was possible because it is the highest elevation on the Market Street subway.

Next are the Church Street and Castro Street stations. The Castro Street Station is unique in that it is constructed on a slight curve and connects directly to the Twin Peaks Tunnel, which was constructed by Muni in 1917. The tunnel is a horseshoe-shaped double-track facility. It is of particular interest that, when the tunnel was being designed in 1914, it was anticipated that there might be a subway under Market Street at a future date. The tunnel grade was set so that, in the last 305 m (1000 ft) of the tunnel, the track rose on a ramp to the surface. It was a simple matter, 60 years later, to match the tunnel grade to the subway grade.

The final 3.6 km (2.25 miles) of the underground portion of the Muni Metro will be in the Twin Peaks Tunnel. In essence, three lines (the K, L, and M) will run underground for a distance of approximately 9.6 km (6 miles). These three lines will emerge from the tunnel at the West Portal Station and then continue on their individual routes over surface trackage.

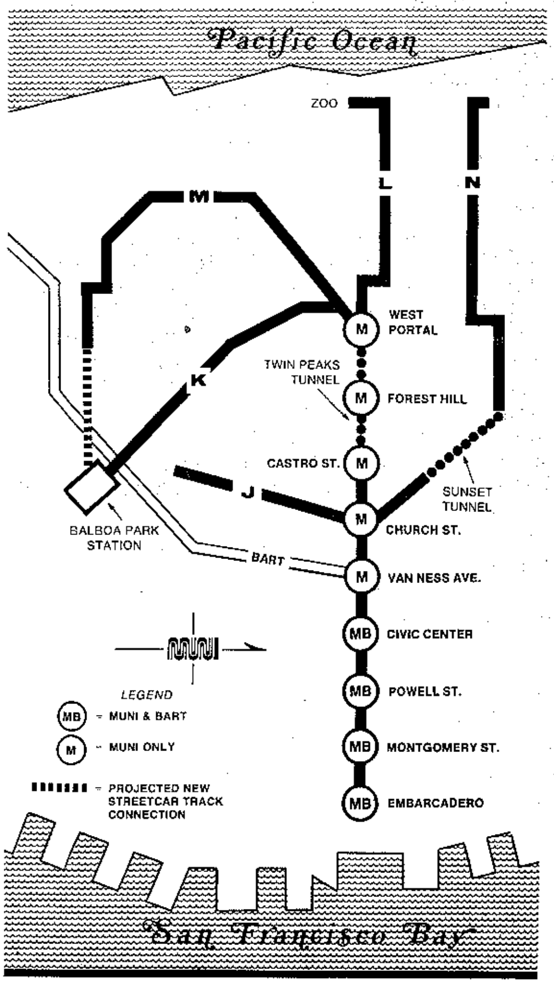
In the underground portion of the Muni Metro, the cars will operate through three different sections. From Embarcadero to Van Ness, two bored tunnels are used. From Van Ness to Castro, a reinforced concrete double-box section, constructed by the cut-and-cover method, is used. The final section is the Twin Peaks Tunnel, which is a twin-track horseshoe-shaped facility.

All sections of the subway under Market Street were constructed for Muni by BART. The stations and the tubes are constructed to BART dimensions and are capable of handling BART rolling stock. A total of eight stations will have been constructed by BART. A ninth station, Forest Hill, was constructed in 1917 when the Twin Peaks Tunnel was completed. This antiquated station will be completely replaced by Muni under a grant from the Urban Mass Transportation Administration (UMTA).

Muni and BART have executed a maintenance agreement that establishes their respective responsibilities and costs. Essentially, Muni and BART will each be responsible for their respective levels and areas of the subway and will share costs in such jointly used areas as the free areas of the mezzanines and the escalators from street level.

BART provided a complete subway, including trackage and architecturally finished stations. Muni's responsibility was to install all systems to make the subway operational. This responsibility included electrification, the subway signal control system (100 Hz), fare collection, an antenna system for communications, a public address system in stations, closed-circuit television for surveillance, and centralized train control.

Figure 1. The five lines of San Francisco Muni.



MUNI METRO CARS

The light-rail vehicle (LRV) that will replace Muni's PCC streetcars has been specifically designed to suit the unique conditions of the San Francisco terrain while using modern technological developments in transit equipment. The Philadelphia firm of Louis T. Klauder and Associates was retained by Muni to develop the specifications for a vehicle that would replace the PCC cars on all surface lines and also operate in the BART-constructed Muni subway. To get maximum use of the new subway and its nine subway stations, Klauder recommended that the vehicle be equipped with special doors and high-low steps to allow platform entry and exit in the subway as well as street-level entry and exit in city streets.

UMTA, which funded the joint purchase of vehicles for Boston and San Francisco, stipulated that the LRV should be standardized to the maximum extent possible. The length and width of the vehicle were limited by Boston subway clearances to 21.6 m (71 ft) and 2.64 m (8.67 ft) respectively. Sharp 12.8-m (42-ft) radius curves necessitated an articulated vehicle with three trucks. The articulation also made possible a longer vehicle that could carry more passengers per operator than the PCC cars. The salary of the operator is a significant portion of the cost of transit per passenger kilometer.

Prior to 1972, the UMTA Office of Research, Development, and Demonstration had sponsored a number of demonstration programs to advance rail technology and apply the advances from other fields to transit vehicles. However, there appeared to be small likelihood that these advances would be applied to production vehicles because of the reluctance of transit operators to purchase new and largely untried systems at costs that would not be competitive with the proven systems that formed the basis of most vehicle purchases.

The design of an advanced soild-state propulsion control system was one of a number of advances that had been underwritten by UMTA. The UMTA state-of-the-art car was equipped with such a control, called a chopper, and was demonstrated on a tour of major rapid transit systems in the United States.

In order to introduce a chopper control into the fleet of an operating transit system without undue financial burden on the system, UMTA established certain ground rules for the bidding on the 230-car order for Boston (150 cars) and San Francisco (80 cars); the order was later increased to 175 cars for Boston and 100 for San Francisco. There were to be two propulsion control options—a conventional cam control and an electronic chopper control. Also, if the total bid for vehicles with electronic chopper control was less than $71 million, the award would be made on the basis of that system regardless of the bid for vehicles with a cam control. Since the Boeing Vertol bid for vehicles with an electronic chopper control was $67 million, the award was based on a vehicle with a chopper control.

The chopper was designed to operate over a variable frequency range from zero (no motion) to 400 Hz at about 27 km/h (17 mph). At speeds above 27 km/h, the current is not chopped. It was discovered during testing that as the chopper swept through 100 Hz it caused electrical interference with the 100-Hz cab-signal control system. After a number of schemes had failed to completely eliminate potential interference, it was decided that the chopper's range would have to be altered so that it did not operate at frequencies below 150 Hz.

The manufacturer of the propulsion system, Garrett Corporation, developed and evaluated eight designs and finally settled on a field-weakening concept that allowed the entire redesign to be concentrated on one circuit card.

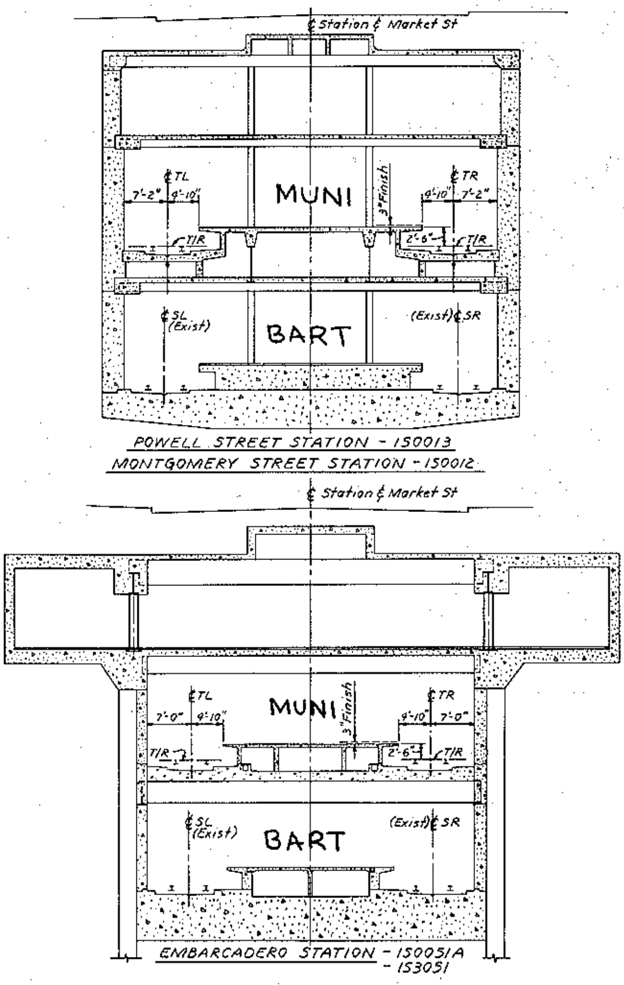
The vehicle developed, known as the U.S. standard light-rail vehicle, is a completely new vehicle and represents an enormous advance over the PCC car, which was the standard for the last 40 or so years. During the severe winter of 1976, the LRVs demonstrated a cold-weather capability superior to that of the PCC cars. In sub-zero weather the Boston riders enjoyed car interiors that maintained an even temperature of 21°C (70°F). Resilient wheels and an air suspension system provided a vastly superior ride.

In addition to the extensive tests on the Boeing Vertol test track starting in fall 1974, the vehicle was tested for 11 weeks in Boston in 1975. In fall 1975, three vehicles were sent to the U.S. Department of Transportation test track in Pueblo, Colorado. Over a period of about 6 months, the vehicles were tested singly and in two-car trains. Subsequently, other vehicles were tested in Boston in simulated revenue service.

The San Francisco LRVs will have 68 seats. To expedite turnaround at terminals, the six side and front destination signs will be automatically controlled from the operator's console.

San Francisco has five transit lines. Three lines converge, enter Twin Peaks Tunnel at its West Portal, and continue underground to the downtown terminal at Embarcadero Station. The other two lines converge and enter the subway at its approximate midpoint. LRVs that operate as single units on city streets will couple as

Figure 2. Station cross sections for the two-level subway.



they enter the subway. Two- and three-car trains will uncouple as they leave the subway and return to street service. Four-car train operation is possible. The specifications for the LRV call for it to have the capability of automatic coupling and uncoupling with a full load of passengers. Coupling and uncoupling are entirely controlled by the operator of the following vehicle. Coupling is used during peak hours to maximize the subway's available capacity. Single-unit operation would reduce capacity because of the distance the signal system blocks require between units.

When units are coupled, the operator of the lead car operates the whole train. All functions are operated from the lead car except the doors. The cab consoles on the following cars are locked out of service. Each operator operates the doors on his or her car. A light on the lead car's console signals when the doors on all cars in the train are closed. The coupling procedure at the portals will require precision operation in respect to schedules. Interference by automotive traffic or other sources during surface operation could have a substantial impact on schedules.

The San Francisco LRVs will accelerate at 1.34 m/s^2 (3 mph/s) to base speed with a 100-passenger load. The 157-kW (210-hp) monomotors on the end trucks are independently force ventilated. Braking is normally accomplished by a blend of dynamic and friction brakes, but disc brakes are capable of providing full-service braking. In addition, track brakes are capable of providing emergency braking in case of a prime power failure.

Power is collected at the trolley wire by means of a pantograph that uses contacts designed to negotiate the gaps in the wire at trolleybus crossings.

The vehicles' radios are equipped for the transmission of digital data, such as the vehicle's serial number, in addition to normal voice transmission.

SURFACE SYSTEM

All surface trackage—approximately 32 route km (20 route miles) of double track—is being replaced, including that in the Twin Peaks Tunnel. This trackage has an average age of 50 years. Rerailing consists of replacing the rails, ties, accessories, and ballast. If the tracks are in city streets, the street is also being repaved (this affects most of the routes). In some locations, open trackage is located on private right-of-way or in the median strips of wide boulevards.

It is very difficult to maintain streetcar service while the tracks are being rerailed. It is accomplished by using portable crossovers and single tracking in both directions over a stretch of track while work is proceeding on the adjacent track. The single-tracking length varies, but it usually is kept under 300 m (1000 ft) in order not to affect service. A temporary signal system is arranged to control movements. It is operated manually during construction hours and automatically at all other hours.

In order to reduce the impact of excavation on the neighborhood, we have under way a program in cooperation with the Department of Public Works (DPW) whereby any sewer work that needs to be done is included in the rerailing contract. The DPW has also been very cooperative in work on projects that aid transit, such as installation of preempting signals, lane markings, narrowing of sidewalks, and expediting permits for street work.

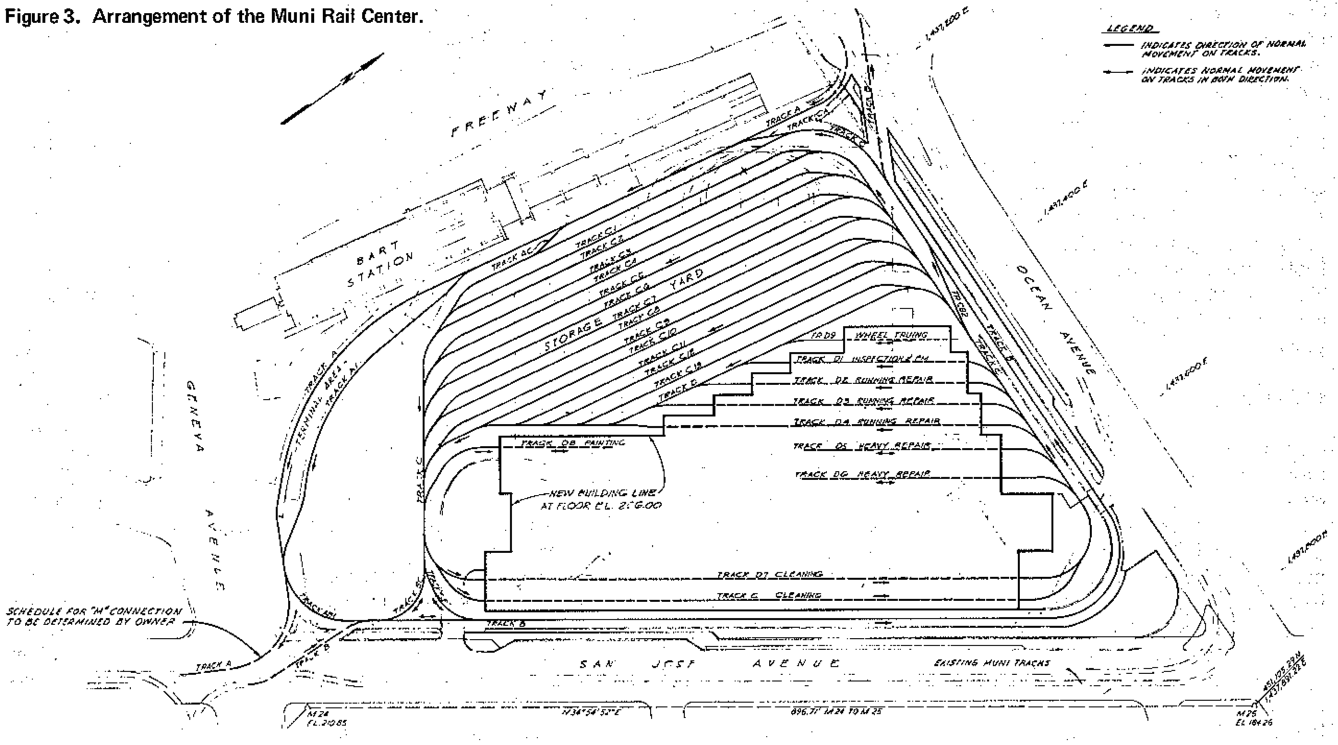
Where the tracks are located in the center of the street, the streetcars operate in mixed traffic. In order to enhance the operating environment for the new LRVs, which will require precision timing to remain on schedule for subway operation, we developed a right-of-way treatment for these locations. The tracks were raised 7.5 cm (3 in) above the adjoining traffic lanes. Contrasting exposed aggregate pavement was placed in the track area to define the transit right-of-way, and it was given a sloping edge. Legislative action was undertaken by the Board of Supervisors (equivalent to a city council) to amend the local traffic code to prohibit other vehicles from driving on a raised streetcar right-of-way except in an emergency or to pass a double-parked or disabled vehicle.

Our original plan was to use this right-of-way treatment wherever feasible on the surface routes. The first installation covered 10 blocks on the N Line. After completion of the first project, considerable controversy arose, both from the neighborhoods and from the drivers of other vehicles. Claims of interference with established traffic patterns and with ability to enter and leave driveways were voiced. The Board of Supervisors, while it acknowledged the transit benefits, yielded to political pressure from neighborhood groups and refused to permit Muni to continue this right-of-way treatment on the N Line or any other line.

Many transit planners have strongly advocated this treatment and, where wider streets than those in San Francisco are available, there is great merit in pursuing this idea. It is common practice in Europe. Unfortunately, the narrowness of most San Francisco streets makes it difficult to implement here.

Vehicles that are waiting on tracks to make left turns often cause delays. These delays accumulate as the car travels from its outer terminals toward the subway. In

Figure 3. Arrangement of the Muni Rail Center.



order to minimize interference by automotive vehicles with Muni Metro operations, the Board of Supervisors enacted no-left-turn legislation.

STORAGE AND MAINTENANCE

The new Muni Metro Rail Center is now under construction. This will be the storage and maintenance facility for the 100 new LRVs. It is located across the street from the Geneva Car Barn (constructed in 1902), where the fleet of PCC streetcars is stored. This location was selected because all trackage to the location had previously been installed.

Land in San Francisco is extremely precious; almost 700 000 people are squeezed into less than 117 km^2 (45 miles^2). There was no site that would meet all the requirements of the LRV fleet. It was therefore decided to use the 2.6-hm^2 (6.5-acre) parcel on which an existing bus division and old streetcar repair shops were located.

It was necessary to provide maintenance and storage facilities for 100 LRVs, a terminal for two lines adjacent to the BART Balboa Park Station, and a future Muni office building on this 2.6-hm^2 parcel. The task was assigned to the International Engineering Company of San Francisco, which worked in association with the architectural firm of Hellmuth, Obata, and Kassabaum. Various arrangements were studied; the solution finally approved is shown in Figure 3. One key feature of the arrangement is that it provides for movement predominantly in one direction, counterclockwise. Only two movements, exiting from the heavy repair area and exiting from the paint shop, require backing up.

A revenue-service loop completely encircles the site. The K and M lines will both terminate at a platform adjacent to the BART station. When BART was designing this station, Muni requested an access point for direct transfer. This was provided in the form of an opening in the station wall that is closed by a sliding grille. This transfer arrangement will be very beneficial to the 20 000 students at San Francisco State University, which is predominantly a commuter campus. Students from throughout the BART service area in the three counties on both sides of San Francisco Bay can travel on BART to this station and transfer to Muni. (Patrons who use Muni lines that feed the BART stations receive a 50 percent fare discount.) The M Line passes directly by the eastern edge of the campus. Another large traffic generator for Muni on the M Line will be the huge Parkmerced apartment complex that is immediately south of the campus.

The cars entering or leaving revenue service do so from the revenue-service loop. Cars of the J, L, or N lines pull out of the storage tracks, travel onto the service loop, enter Ocean Avenue, and then proceed to their terminals. Cars of the K and M lines continue around the loop to the terminal adjacent to the BART station, where they stand ready for revenue service. Cars returning from service pull in on the revenue loop and then are turned out to the ladder track.

After entering the rail center, cars proceed to one of the two service lines inside the building where there are stations for fare removal, sanding, washing, and cleaning. There is a car wash on only one service track since it is proposed that cars will be washed on alternate days. After they have been serviced, the cars emerge from the service line and either proceed to one of the running repair tracks or move onto the storage tracks.

There are four running repair tracks and associated pits and maintenance equipment. Diagnostic equipment and operations simulation test gear are used on these tracks. The last bay in the building contains the wheel-trueing machine; it can also be used as pit space. The heavy maintenance repair facilities consist of two tracks capable of handling four cars. Two cars are handled over pits and two car positions permit the raising of the car, by means of hydraulic jacking systems at lifting points, for truck removal. Truck repair areas are adjacent to this location. In addition, a truck drop table is provided on one of the running repair pits for unit replacement.

A complete machine shop for mechanical and electrical work is provided, as are a completely equipped electronic shop and paint shop, which is close by the body repair shop in order to give the crews in these two operations the necessary close liaison. The storage yard consists of 14 parallel tracks and is to be paved throughout. An extensive drainage system is included. The electrical overhead system is supported by steel poles.

One unique feature is that the yard was laid out in such a way that, when a market develops for the use of air rights, this will be feasible. The tracks were laid out in pairs, which will permit the installation of column footings for whatever structure might be built above. This would be an excellent source of revenue for Muni, and the structure would provide a "free" roof over the yard.

POWER SUPPLY

Of course, in order to operate the new Muni Metro there must be an adequate power-supply system. Because of San Francisco's commitment to electrical propulsion, an extensive electrical supply system exists, although it is ancient. The existing distribution and trolley overhead system is a combination of the original Muni system and that inherited from a private company that also operated in San Francisco and was acquired in 1944; most of the system was old then.

San Francisco made the decision to use electrical propulsion methods for many of its transit vehicles for two main reasons. One was the availability of low-cost hydroelectric energy from the Hetch Hetchy Water and Power System, a city agency under the jurisdiction of the city's Public Utilities Commission. Hetch Hetchy's Transit Power Division is responsible for supplying electrical energy to Muni's electrical vehicles.

The Hetch Hetchy project is located just north of Yosemite National Park in the Sierra Nevada Mountains and is the main source of water supply for San Francisco and many cities in the south Bay Area. Hydroelectric power facilities were developed in conjunction with the water supply system. There are three powerhouses with a total generating capacity of 300 MW. In a normal year, only 30 percent of the output of these plants is used for all of San Francisco's municipal needs, including Muni. Under these circumstances, Muni has an assured, low-cost supply of power. Hetch Hetchy supplies electrical energy to Muni at rates 45 percent lower than those charged by the local investor-owned utility that serves San Francisco.

The second reason for the commitment to electrical propulsion was that it is a quiet and pollution-free method. Furthermore, all the energy used is hydroelectric and aids in conserving our nation's resources. Muni operates 345 electric trolley coaches in addition to the streetcars, which will be replaced by LRVs.

The entire electrical distribution system and its network of substations is being replaced. All feeder cables are being placed underground, and the substations are being changed from old rotary converters to modern solid-state rectifier units to supply the required 600-V direct current. The number of substations is being increased from 19 to 25. It is to be noted that the distribution network supplies power to Muni and the many electric trolley coach lines.

All the electrical system improvements are being provided under a $50 million program, the major portion of which is covered by an UMTA grant. The program includes, in addition to those elements previously described, the electrification of the new subway. This consists of the installation of substation equipment, feeder cables, and trolley-wire overhead.

The entire trolley-wire overhead for surface operations is being converted to permit use of both the pantograph of the LRV and the trolley shoe of the present streetcars. This is necessary because there will be a period during which a mix of PCC streetcars and LRVs will be operating. We plan to convert one line at a time after the delivery of the LRVs has begun. Full Muni Metro service will be in operation after the conversion of the five lines.

PROPOSED EXTENSIONS

There are several planned extensions to the Muni Metro system. One is the extension of the M Line from its present terminal at Plymouth and Broad streets 1.44 km (0.9 mile) to the Muni terminal at the BART Balboa Park Station. As noted above, this would permit cars of the M Line to enter revenue service at the new terminal after leaving the rail center. Another extension is that of the K Line from its present terminal at the Phelan Loop to the same Muni terminal at the BART Balboa Park Station. Cars of the K Line will then also be able to enter revenue service immediately after leaving the rail center.

Under the current arrangement, all cars of the N and J lines must follow long deadhead routes from the storage facility to their terminals. N cars, especially, travel a long distance before beginning revenue service. When the Muni Metro service commences, these cars will have to travel all the way to the Embarcadero Station and then proceed to their outer terminals to begin revenue service. It is therefore proposed to construct a 3.4-km (2.1-mile) surface track connection from the rail center to the present J-Line terminal at 30th and Church streets. The new trackage would become an extension of the J Line and be used for revenue service. J-Line cars would then also be able to immediately enter revenue service. N-Line cars would use the new trackage and the J-Line tracks to proceed to their outer terminal. This would be a considerably shorter run than the long, circuitous route described previously.

The new trackage would provide total system flexibility since all routes would be interconnected. An ancillary benefit of this surface track connection would be its availability as an alternate route in the event of some catastrophe (such as a cave-in) in the 60-year-old Twin Peaks Tunnel. At present, loss of this tunnel would put all lines out of service. The proposed track connection would permit some operation of a truncated system.

The final extension proposed is short but very important. It would extend the Muni-level tracks east of the Embarcadero station to a loop track at the end of Market Street. At the present, Muni will use a double crossover west of the Embarcadero Station, a stub terminal arrangement. Muni asked for a turnaround, but BART stated that it could only afford the crossover. The new facility would be entirely underground.

The minimum headway possible with the double crossover is 2½ min during the peak hours. In order to reach the maximum subway capacity, a minimum headway of 1½ min must be achieved. After the loop-track facility has been completed, the double crossover will be available on standby for emergency use in the event that the loop track should become inoperative.

GENERAL

There were several key decisions that contributed immeasurably to the success of our program, including the purchase of common items that would be needed throughout the program. We were able to take advantage of the savings entailed in quantity purchases and eliminated delays in procurement by contractors working on the various construction and installation contracts. Bids were solicited for the following items, which were then stored in city facilities and provided to contractors as city-furnished materials or equipment:

1. Girder and tee rails and accessories—3.6 Gg (8000 tons),
2. Timber ties—57 000,
3. Feeder cables—427 km (1 400 000 ft), and
4. Rectifier units for 25 substations.

The first LRVs for Muni are currently scheduled to be delivered to San Francisco beginning in June 1978 at a delivery rate of approximately 10 units/month. Muni Metro service will be inaugurated in late 1978 and complete service is anticipated by summer 1979.

Edmonton's Northeast Light-Rail Rapid Transit Line

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Edmonton's light-rail transit (LRT) line has a total length of 7.2 km, 1.6 km of which is in subway. The line goes from the central business district (CBD) to the northeast sector of the city and uses the Canadian National Railways right-of-way. The project was approved at $65 million and is currently below estimates as well as ahead of schedule. The LRT line is the result of a balanced transportation plan that was finally adopted in 1974 to serve a city of nearly 500 000. The subway portion has two underground stations with full mezzanine floors. The mezzanine floors are part of an overall pedestrian system and connect with the basements of adjacent buildings. The subway was built to accommodate the largest standard subway car. The equipment specifications for the 14 articulated cars were based on performance and proven reliability. The construction methods used caused a minimum of interference in the CBD. Since relatively small portions were let successively, local contractors were able to use proven techniques to handle the work on a fixed-price basis. Despite the severe inflation of 1975 and 1976, costs were kept within reasonable limits. The proposed service will provide 5-min headways in the peak hour, giving a capacity of 5000 passengers/h. At midday the headway will be 10 min. The LRT line will be fully integrated with the bus transit system, and timed transfers will be provided between bus and rail. The LRT line in Edmonton makes use of available opportunities and provides the least expensive solution to the transportation problems of the northeast sector and its rapid residential development.

In September 1974 the city of Edmonton turned the first sod on a 7.2-km light-rail transit (LRT) line to serve the northeast sector of the city; inauguration of the service was scheduled for spring 1978. Extensions to this line and the construction of other lines are in the planning stages.

The LRT line under construction consists of a 1.6-km length of subway in the central business district (CBD) that has two underground stations and a 5.6-km surface section, which is contained within a Canadian National Railways (CNR) right-of-way, that has three surface stations. The line will use 14 articulated cars and will provide a peak single-direction capacity of 5000 passengers/h. The LRT line will be fully integrated with the Edmonton Transit surface bus system, which currently operates 590 buses that carry 57.1 million passengers annually, using the timed-transfer concept. The capital cost of this project is estimated at $65 million; at the present time approximately 99 percent of this project has been contracted, committed, or completed.

PLANNING

Edmonton has grown rapidly since World War II from a population of 160 000 in 1951 to 451 000 in 1976. The CBD has seen intensive high-rise development, while at the same time extensive residential development has occurred on the periphery. Older developed communities throughout the city are normally well maintained or redeveloped by private enterprise. City planning has a very active role in Edmonton and is constantly involved in forecasting studies, preparation and assessment of plans (at district and subdivision levels), and administration of zoning and development controls. The city's departmental organization provides that all municipal functions, such as engineering, utilities (the city owns its own electricity, telephone, and water utilities), traffic, and parks, work closely with the City Planning Department.

These developments in Edmonton have had a major impact on the transportation facilities and systems. Several major transportation studies have been conducted since 1960 and have recommended solutions ranging from a freeway network to a full rail rapid transit system, but these plans could not be implemented because of a lack of funds and difficulties in establishing rights-of-way. These studies and the general situation were reviewed in 1968, and a revised, more balanced approach was recommended that put greater emphasis on developing the arterial roadway system and improving the transit system to handle more of the peak loadings. Certain LRT routes were recommended for detailed investigation in corridors where there appeared to be available separate rights-of-way.

As a consequence of this review and subsequent public hearings in November 1972, a general transportation plan was finally adopted by the City Council on July 15, 1974. In the analysis of solutions for the transportation problems of the northeast sector, several alternatives were considered. Because it is limited by the river and the railway line, the existing road network was operating at capacity in the morning and evening peak hours. While the situation existing in 1974 was just tolerable, the new areas being developed in the northeast would overload the roadway system. The options considered were therefore the following.

1. A northeast freeway option: The transit compo-

nent would require 70 buses in the peak hours, including express services for the corridor. The impact of the freeway option would be severe on several neighborhoods. Land acquisition costs would be substantial. Because of the attractiveness of the roadway system, the transit patronage was expected to be half that of any of the public-transportation-oriented alternatives.

2. An all-bus option that would use 150 buses in the peak hours, including express services through the central area of Edmonton: The large number of buses would be expected to handle the majority of the growth in passenger peak traffic from the new northeast development area, but the buses would compete for limited roadway space and produce additional congestion. Allowances for bus priority methods would make it possible to maintain at least 1974 bus speeds.

3. An integrated bus and LRT option: This would use 75 buses in the peak hours, mainly as feeders and cross-city services, and 14 LRT cars on the Northeast Line. The LRT line would operate as an integral part of the transit network (only the hardware would be different). The same flat fare, with free transfer between routes and monthly passes, would be applicable.

In comparing the three alternatives, the capital and operating costs could be estimated and assigned, but the revenue allocations were somewhat arbitrary. The cost estimates were related strictly to the city's budget and did not include savings in time or other such factors sometimes included in economic analyses.

The justification for the project was based on the effect that the various alternates, which would provide approximately similar service, would have on the city budget. Edmonton did not have rail transit operating costs available, so Toronto's operating costs were used in the original estimates.

The initial calculations in 1973 allowed for a 6 percent annual inflation in labor costs and a 4 percent inflation in construction costs. The annual cost impact was then calculated for 1978 (the earliest year any of these alternatives might be implemented). In estimating revenues for the all-bus system it was assumed that fares and passengers would continue to increase, maintaining a constant deficit. In 1973 the budget impact (in terms of net annual cost to the city) was calculated and yielded the following results for 1978, allowing for inflation:

Option	Net Cost to City ($000 000)
Freeway	6.2
All-bus system	2.0
Integrated bus-rail system	1.5

By March 1974, it was clear that the calculations should be reviewed. Inflation was far more severe than expected, ridership had increased more than originally anticipated (but not enough to offset inflation), and fares had remained constant. The 1974 recalculation showed the following results:

Option	Net Cost to City ($000 000)
Freeway	9.7
All-bus system	5.4
Integrated bus-rail system	3.7

After 1974 the freeway option was not recalculated, but the provincial government made available capital and operating grants for transit; this made a substantial difference in the annual budget costs to the city. The capital grants could be applied either to buying buses or to constructing rail transit:

Option	Net Cost to City ($000 000)
Freeway	9.7
All-bus system	1.1
Integrated bus-rail system	0.2 gain

Every year at budget time, these estimates have been updated. Estimated costs have been replaced with actual costs where possible. The relative attractiveness of the integrated bus-rail option has remained the same despite inflation.

The City Council approved the construction of an LRT line to serve the northeast section of the city in August 1973, and a local engineering firm was commissioned to do preliminary design and estimating work for the project. Emphasis was placed on keeping the system and its functions simple and as inexpensive as practical from the outset. By the end of March 1974, this preliminary work was completed, and the City Council confirmed the plans for the line; approved the budget for the construction of the project, which was then estimated at $54.7 million; and called for the construction to be completed by July 1978, subject to obtaining funding assistance. The province of Alberta announced in June 1974 an urban public transit capital assistance program to provide $45 million over a 6-year period; the City Council allocated these funds to the LRT project. Due to severe inflation in 1975 and 1976, the budget had to be reviewed in 1976, and the estimated costs were raised to $65 million.

PRINCIPAL FEATURES

Subway Portion

The LRT line has a 1.6-km subway portion in the CBD that has two underground stations; see Figure 1. In order to allow for any future eventualities, the geometric standards chosen were for the largest standard car then on the market, the Toronto car. The curve radius used in the tunnel was 160 m.

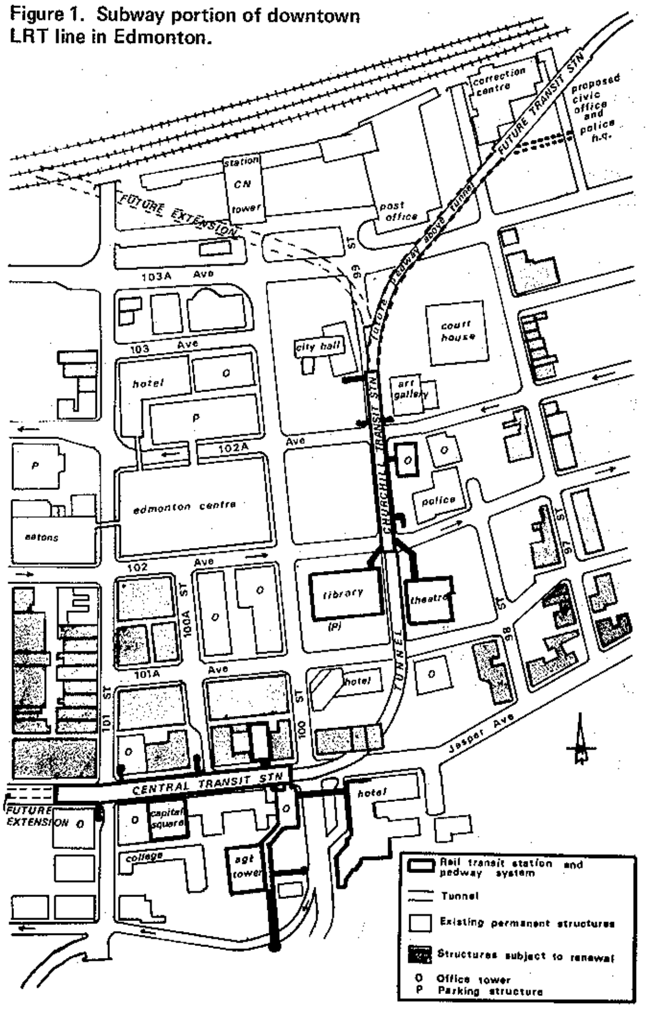
The stations are of the conventional subway type; they have a mezzanine floor that runs the full length of the station above the track and platform level. The mezzanine floor is connected with the pedway system that is being developed in downtown Edmonton. The mezzanine floor allows for interconnection with the basements of adjacent buildings. This floor has a clear span of 18.6 km, and space is provided for future commercial development.

Just before the point at which the subway surfaces, a third station shell has been built. The area east of 97 Street is subject to redevelopment, and this station can be activated when this redevelopment occurs. Immediately north of the Churchill Station, a wye-shaped stub has been built into the cut-and-cover portion of the subway to allow for a possible future extension to the north or northwest.

Surface Portion

Edmonton has been provided with a wide railway right-of-way to the northeast that cuts diagonally across the north-south and east-west grid pattern of roads. The original rights-of-way of the Canadian Northern Railway System and Grand Trunk Pacific Railway were side by side, leaving at present a space for two tracks and a platform between them. This space is rented from the

Figure 1. Subway portion of downtown LRT line in Edmonton.



CNR (a crown corporation formed from the amalgamation of these two railways) for $65 000/year.

The area that is served by the Northeast Line includes several special major destinations—Clarke Stadium, the Coliseum, and the Exhibition Grounds. In addition there is rapidly increasing residential development in the area. Stations have been located at the crossings of major arterial streets, thus allowing easy integration with the surface bus system. All except two of the crossings will be at grade. The system will be protected by signals that will be integrated and interlocked with the traffic control system and the railway operation. The signal system is described in more detail in the paper by O'Brien, Schnablegger, and Teply elsewhere in this Report. The two intersections that are grade separated are at 118 Avenue and Santa Rosa Road. It will be possible to have grade separations at other intersections in the future if it becomes necessary and funding is available.

The basis of operation is that there shall be no interference with the main line of the CNR. The subway portal lies between the CNR tracks, which provides in effect a grade separation; a second grade separation has been constructed at the main east-west CNR line just south of Belvedere Station.

The one crossing at grade with the CNR is at the rail transit car shops. The old Cromdale streetcar barns were located adjacent to the rail transit line. These barns were recently used only for storage, and the newer sections are now being refurbished. All equipment can be stored indoors; the cars will be assembled and outfitted by Siemens Canada Ltd. in these car shops. The entry into the yard is only suitable for LRT equipment and uses a track radius of 26 m.

The trackage has been designed with a well-graded, compacted, and drained subgrade, 0.6 m of crushed rock ballast, number 1 treated ties, and 45-kg rails—a high standard designed to reduce maintenance costs. The wheels of the cars have been contoured to the standards of the Association of American Railroads.

In the tunnel there are a few test sections that have a rubber mat placed below the ballast. In addition, the ties in the tunnels have been treated with phenol chloride to avoid the odors of the normal creosote-treated ties. The use of ballast in tunnels will reduce vibration and noise.

EQUIPMENT

The specifications for the equipment stressed the performance required rather than details of the car features. The primary aim was to use the production and designs developed for other customers in order to hold costs to a minimum, since the specific requirements for Edmonton were few. The second aim was to select a simple, proven vehicle. The Frankfurt U2 car was selected from the proposals received, since it provided the capacity required at the least cost and had 7½ years of experience and operation behind it; see Figure 2. Some relatively minor modifications were required to suit Edmonton's conditions, including extra heating, double windows, and a continuous-level floor for high-platform loading. It is possible to convert the cars to high- and low-level loading if that is required in the future.

The cars will be finally assembled locally; the local input will consist primarily of the wiring and assembly of the control panels. The installation of carpeting and the fabrication and installation of seating will also be done locally. The Edmonton model is now designated RTE 1. Fourteen articulated cars were ordered from the manufacturers, Siemens Canada and Düwag; the cars will provide a peak-hour capacity of 5000 passengers in one direction.

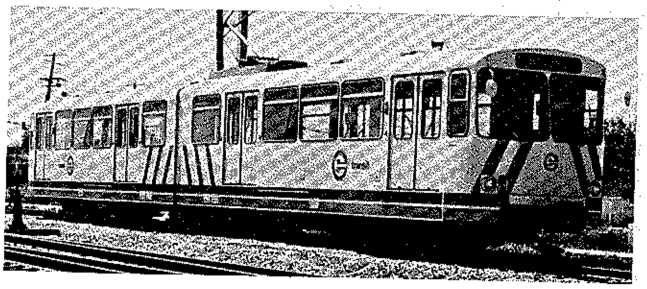
CONSTRUCTION

The Central Station, which will be the downtown terminal, is located on the busiest east-west avenue (Jasper Avenue) at the intersection of the busiest north-south street (101 Street). The year before subway construction was begun, the sewer and water utilities were placed under the sidewalk into two separate oval-shaped tunnels (1.8 m by 1.2 m).

The construction method had to cause a minimum amount of interference and disruption. The station is 18.6 m wide, 213 m long, and 15.2 m deep. The construction method allowed traffic to be restored 4 months after work began. A more detailed description of the time-saving method used is worth describing.

Holes for tangent piles 1.1 m in diameter were bored down through the soil. Reinforcement cages were then inserted, and concrete was poured. Every fifth pile came to the surface, while the four intermediate piles were stopped at the mezzanine level. A longitudinal excavation was then made along the lines of piles, and formwork was placed for a reinforced concrete grade beam. This beam was poured in place. This beam was 1.55 m wide and 2.10 m deep. Interlocking steel sheet piling was then driven on the property side of the grade beam down to the mezzanine level. Future access can therefore easily be provided to the basements of adjacent buildings by cutting through this sheet piling. The

Figure 2. Edmonton's light-rail vehicle.



owners of adjacent properties were responsible for any costs of connecting to the mezzanine floor.

The street surface was excavated after the sheet piling was in place. The excavations were dug as deep as time permitted but, in any event, not deeper than the mezzanine level.

Precast, prestressed standard highway bridge girders, which weighed 36 Mg and were 1.5 m wide and 1.8 m deep, were then placed, spanning the 18.6 m between the two grade beams. The beams were then grouted together. A waterproofing membrane was then applied. This was overlaid with 5-cm styrofoam insulation to minimize frost penetration. A lightweight aggregate concrete surface and a final 13-cm reinforced concrete pavement were then poured to the prescribed contour of the street surface.

After the pavement had been restored, the remainder of the soil was taken out by means of a ramp that was constructed into a side street. Excavation was first completed to the mezzanine level, and strut beams were poured on the excavated ground surface using sand as a trim. The mezzanine floor was then poured over these beams.

The excavation was then completed below the mezzanine level down to the track level. During this process the integrity of the foundations of adjacent buildings was protected by means of a temporary system of movable steel struts to prevent the bottom of the tangent piles from kicking in. When construction was completed, the track slab provided this bracing function.

The same method of construction was used at the Churchill Station and for the cut-and-cover construction northeast of City Hall. The remainder of the construction used open-cut and poured-in-place methods.

During the construction process, steel link fencing was used to protect the public while maintaining high visibility for the work in progress. This interesting feature of downtown life was used by the merchants along the streets to their advantage in promoting business during the 4-month closure of Jasper Avenue. In fact, many merchants enjoyed better-than-normal business during this period.

Central Station on Jasper Avenue and Churchill Station are connected by twin tubes. These tunnels were mined by means of a mechanical mole manufactured by Lovatt of Toronto. The contractor for this portion was the city's own sewer department, which has extensive experience in the tunneling of trunk sewers in Edmonton. The twin tunnels, which are 230 m and 220 m long, curve between the two stations and go underneath several existing structures. One building, the Plaza Hotel, was approved for construction when the LRT project was still in its early planning stage. Its foundation piles were therefore so placed that the two tunnels could be mined without any interference. Two other, older buildings required underpinning. A fourth, a two-story concrete-block building required no underpinning; the soil removal was so well controlled that no wall cracking or other damage to the building occurred.

It should be noted that the city of Edmonton is blessed with excellent soil conditions. The geology is perfect for tunneling or for cut-and-cover operations. There are no groundwater problems, since the groundwater is well below the subway grade. As a result of previous work done at the University of Alberta, the behavior of the till could be predicted with accuracy. The settlement above the tunnel was very small indeed (less than 1 cm).

CONSTRUCTION STRATEGY

The strategy selected for contracting was one in which the work was tendered in relatively small portions (approximately \$1.5 million to \$4 million each). The designs prepared used proven techniques and methods known to local contractors. Designs of subsequent portions of the project have taken advantage of the experience with previous contracts. Alternate designs have been prepared for many of the sections, and contractors have been encouraged to bid on their own alternatives as well. This approach has enabled a larger number of local contractors to undertake these jobs.

At the same time, these smaller portions could be let at a fixed price, since a contractor could see substantial completion of his work within a year's time. Prompt payment on progress payments has enabled contractors to keep interest costs low. By removing many of the uncertainties with respect to inflation of costs and making quick payment on construction expenditures, prices could be kept relatively low. In fact, the fixed prices then played a major role in maintaining a fast pace of construction, since inflation created the bonus or penalty to the contractor.

The project management team was kept small; the maximum staff was 11 persons including secretaries. When contracts got under way, the staff's prime function was to ensure efficient coordination with other contracts and agencies and to minimize delays or obstructions to the contractors in the performance of their jobs. In the management of the project there has been an efficient and close liaison between the owners, contractors, and consultants.

COSTS

The overall costs were approved at \$65 028 943, \$45 million of which is being provided by the province of Alberta at the rate of \$7.5 million/year (1974 to 1979 inclusive). The balance is obtained from debenture borrowing by the city of Edmonton. The debenture will be repaid from the revenues of Edmonton Transit.

The original cost estimate in March 1974 was \$54.7 million. This estimate included expected inflation of 12 percent/year during the construction period. Unfortunately the inflation in construction prices in 1975-1976 was greater than anticipated. In addition, the original estimate for equipment was based on Toronto's latest bid, which was \$3 220 000. Allowing for inflation at 12 percent for 2½ years, the financing estimate was \$4 402 700, but the actual bid was \$7 745 000. Another unexpected cost was a \$4 million increase in CNR's estimate for relocating their signal cables and tracks where required.

At the present time, all but \$380 000 of the work has been contracted or completed, and it is estimated that the cost to complete the project will be about \$100 000 below the approved budget of \$65 million.

Delivery of the cars started in April 1977. Testing of the equipment and various systems is now being carried out. Revenue service is scheduled to begin in February 1978, about 6 months ahead of the date originally set in March 1974. Considerations of time and money in a period of inflation encourage this kind of speedup.

OPERATIONS

The control system consists of a simple wayside block signal system. All red-light conditions will be enforced by magnetic inductive trip stops to provide maximum safety. Restrictive speeds of 30 km/h have been established in the subway curves, at the ends of the line, and at the approaches to all at-grade crossings. The restrictive speed zones are enforced by timed signal changes from red to green and the associated trip stops.

To facilitate traffic and train movements at the at-grade crossings, a special traffic-control system is being implemented that links and coordinates the LRT train-crossing signals with adjacent road intersection traffic signals.

The proposed service will provide 5-min headways in the peak hours for trains of two or three cars and 10-min headways at midday for one-car trains. The bus route system will be reorganized in the northeast sector to provide timed transfers between bus and rail.

The average speed of operation will be 30 km/h; the maximum scheduled speed will be 50 km/h. At midday three trains will be running; in the peak hours there will be six.

CONCLUSIONS

In 1974 Edmonton was faced with a rapid residential development in its northeast sector. After a careful analysis of the opportunities available, the least cost solution to the transportation problem was found to be an LRT line that used the CNR right-of-way. For the particular conditions in Edmonton, the LRT solution was able to be implemented within the budget of $65 million.

Calgary's Light-Rail Transit System

W. C. Kuyt and J. D. Hemstock, Transportation Department, City of Calgary

This paper describes some of the background to the development of the South Corridor light-rail transit (LRT) line in Calgary. Characteristics of the city, the corridor, and the existing transit system are also presented. The results of a recent study undertaken to determine the type and timing of transit improvements are briefly summarized. Alternatives studied in detail included LRT, busways, and exclusive bus lanes; LRT was selected and implementation has begun. Finally, the paper describes the vehicles and route chosen.

This report describes the light-rail transit (LRT) system that has been approved for construction in the city of Calgary. The urban context, the evaluation process, the vehicle type, and the alignment are described.

BACKGROUND

Planning for rapid transit began in 1966 with a series of studies carried out by Simpson and Curtin Ltd. Preliminary plans for an extensive network of rapid transit lines were developed. Two of the high-priority corridors were approved in principle by the City Council. This allowed protection of the right-of-way and acquisition of more than 25 hm^2 of the required land.

Since this study was completed, several significant changes have occurred. The population has grown more slowly than was expected; the population density is lower than was anticipated; the growth patterns have shifted; many proposed roadways have not been, and probably will not be, constructed; and construction costs have increased dramatically. These changes have made inadequate certain aspects of the system originally proposed. In particular, the capital cost of the proposed 32-km grade-separated network would now cost several hundred million dollars, which is clearly unrealistic for a city the size of Calgary.

The prime function of a report published in 1973 (1) was to develop a policy combining and coordinating transportation improvements. A road construction program on a much smaller scale than previous plans was proposed. A number of interim transit improvements were recommended, including an extended express bus system, installation and expansion of the dial-a-bus system, expanded bus-shelter installations, and installation of several traffic-control measures for the priority treatment of buses. Progress is being made in each phase of the program, and an increase in ridership has been observed.

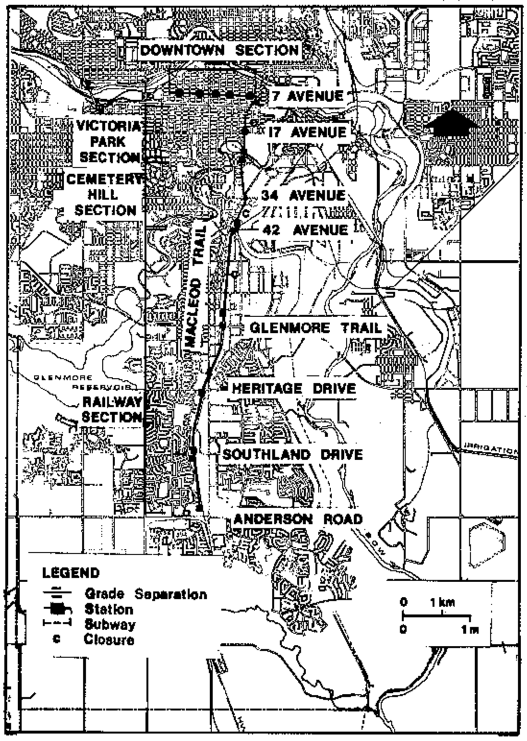
In 1975, the city of Calgary undertook two studies to examine the need for and to plan major transportation facilities. The reports (2, 3) described the need for rapid transit in the South Corridor and the staging of transit and roadway improvements. The City Council approved these reports in principle and directed the administration to proceed with functional planning and preliminary engineering for an LRT line in south Calgary.

Subsequent consideration, including consultation with officials of the government of the province of Alberta, led to the decision to commission a major, independent review of these and prior transportation studies to verify the appropriateness and costs of LRT in the South Corridor. This review was carried out by consultants, and the results were presented to the City Council in May 1977. The report essentially endorsed LRT and the council directed that detailed design and construction should start as soon as financing could be arranged. These arrangements were completed in July 1977, and implementation started on July 25, 1977, with the purchase of 27 light-rail vehicles (LRVs).

The City

In 1976, Calgary's population was 470 000, and the labor force was 207 500. The population is expected to reach 618 000 in 1986 and 778 000 in 1996. About 58 000 people, or 30 percent of the work force, are employed in the downtown area. There has typically been low-density development with a distinct separation between residential and employment areas. Despite the low density, development is contiguous, and there is little urban development beyond the city limits.

Figure 1. LRT alignment selected for Calgary.



The Corridor

The first leg of the LRT system extends 16 km to the south of the downtown area. Gross residential density is about 2000 persons/km^2. Single-family homes make up 70 percent of the dwelling units in the suburbs. Recently, higher density development has increased, and substantial opportunities for further development still exist.

A large industrial area lies to the east of the proposed line, as shown in Figure 1. In addition, two major shopping centers lie within 500 m of an LRT station.

Existing Transit Ridership

Service is provided by line-haul and feeder buses on fixed routes, express buses in the peak hours, all-day express service in major corridors, park-and-ride facilities, and a small dial-a-bus service. The existing bus fleet carries a significant portion of total trips, but it is less than the share carried by transit in some other Canadian cities of similar size. The system, which uses 410 diesel buses, carried 41 000 000 passengers in 1976. Ridership is currently 87 trips/person/year, an increase of 20 percent since 1971. In the prevailing direction at the peak hour, transit had about a 20 percent share of riders at a screenline 8 km south of the downtown area and a 35 percent share in the downtown area. Peak-hour transit demand in the corridor was 2600 persons/h in the peak direction in 1976 and is projected to increase to 4200 persons/h in the peak direction by 1982.

ALTERNATIVES ANALYSIS

The South Corridor could be expected to show a major deficiency in transportation capacity over the next two decades. This deficiency could be resolved by constructing certain road improvements and providing higher capacity transit service. Studies indicate that in the long term it will be impossible to accommodate travel demand by means of the road improvements that are politically and financially feasible. There are, however, several options.

Improvements to transit could either precede or follow road construction. If transit preceded road construction, several projects could be deferred for a substantial length of time. If the road improvements were staged first, however, transit improvements could be delayed only until the early 1990s. Potential savings, both financial and environmental, are therefore achievable only if transit precedes road construction. The effectiveness of this strategy depends on the extent to which transit increases its share of the market. This, of course, depends on the level of service and capacity offered and on the time of implementation.

Transit Alternatives

Three candidate solutions—exclusive bus lanes, LRT, and busways—were examined in detail. Previous work had demonstrated that other systems—heavy-rail transit (HRT) and personal rapid transit (PRT)—were not feasible. HRT systems were excluded because of the high capital cost. An extensive rail system on a completely protected right-of-way would exhaust the city's capacity to support debt repayment. Because of the particular characteristics of Calgary's LRT corridors, there is relatively little interference with other surface traffic; the benefits of complete grade separation are therefore small. Further, it was felt that the geometric requirements for HRT and the need for complete separation would pose unnecessary restrictions on construction staging. PRT was discarded after consideration of recent setbacks in its development. It was apparent that reliability would not be good and that development and construction costs would be too great to be borne by the city.

Comparative analyses of the three candidate modes assumed that all would operate over a 13-km surface route from the south side into the downtown area. The bus-lane system was assumed to occupy the curb lanes of Macleod Trail between Anderson Road and downtown. No stations, other than widened sidewalks with bus shelters, would be constructed. The LRT system would follow the alignment shown in Figure 1. The selected route was almost 13 km. Seven percent of the line would be underground and the rest at grade. Five structures would be built to separate cross traffic, and there would be about nine grade crossings outside of the downtown area. Twelve stations, spaced about 1200 m apart, would be constructed. The average vehicle speed would be about 32 km/h including make-up and layover time. The system is described more fully below. Minor deviations from this alignment were assumed for the busway in order to minimize the length of the busway that would be underground. All three systems would operate at grade through the downtown area on an exclusive transit mall.

Traffic Impact

A system of exclusive bus lanes would have the greatest impact on traffic because it would sharply reduce the capacity of roadways that already experience significant congestion. The interference with right-turning traffic (assuming curb lanes were used), local access, and cross traffic would make it impossible to achieve high speeds or reliable scheduling. The number of buses required would exceed the capacity (estimated at 300 buses/h in both directions) of the main transit corridor through the downtown area. This would necessitate the use of other streets for some routes, thereby increasing walking distances and again conflicting with other surface traffic. The busway would avoid most of the conflicts outside of the downtown area but would also entail the problem of congestion and capacity in the downtown area. LRT would have the least impact on traffic for several reasons. The headways would be longer, the dwell times would be shorter, and the signalling system could be more readily incorporated into conventional railway grade-crossing protection.

Flexibility to Increase Capacity

The capacity of the bus lanes and busway alternatives is limited by the available street space in the downtown area, as well as by the capacity of the stations along the line. Construction of a bus subway in the downtown area is impractical because of space limitations and cost. The LRT system would have greater capacity initially and could be incorporated into a downtown subway at some point in the future.

Level of Service

The assessment of level of service was based on a quantitative measure of travel time and the subjective assessment of comfort and convenience. The LRT alternative saves 500 000 passenger h/year compared with the busway and 1 500 000 passenger h/year compared with the bus lane. LRT and busways were felt to be comparable in terms of comfort since the improved ride quality and ventilation of the LRT offset the higher number of seats on the busway. Bus lanes would be less comfortable but could be more convenient because of the possibility of reducing the number of transfers.

Cost Comparisons

Capital and operating costs were prepared for each alternative; see Table 1. The operating cost estimates (in 1976 dollars) shown were for 4200 persons/h/direction and were based on standard 52-passenger buses or six-axle articulated LRVs. Bus lanes would be the least costly, but only because existing road space would be used. Should these lanes of traffic be replaced, the total cost of the system would be similar to that of the busway proposal. Busway and LRT costs were similar. The cost advantages of the busway are eliminated and reversed with increasing ridership. Indeed, the busway would become less economic after about 5 years of operation. It should also be noted that the annual cost of the LRT alternative is almost entirely debt repayment, while the annual cost of the bus alternative contains a large operating or labor component. LRT therefore provides some protection against wage-related inflation.

Social and Environmental Impacts

The alternative alignments and transit modes were evaluated against the following social and environmental criteria:

1. Visual intrusion—loss of privacy or views of unaesthetic features;
2. Open space—physical loss of existing public space or recreational facilities;
3. Residential—need to acquire existing housing stock;
4. Commercial or industrial—need to acquire existing commercial or industrial buildings;
5. Heritage buildings—need to acquire potential historical sites;
6. Pedestrian connectivity—reduction of pedestrian movements across the proposed LRT line or interference with pedestrian movements along it;
7. Noise impact—consideration of ambient noise readings for adjacent land use, rating increases over ambient as minor (0 to 3 dBA), moderate (3 to 5 dBA), or significant (greater than 5 dBA); and
8. Air pollution—assessment of the effect on air quality.

Table 2 summarizes the results of this evaluation.

RESULTS OF THE EVALUATION

On the basis of the evaluation summarized above, LRT was recommended as the most appropriate transit mode. LRT has less impact on traffic than the bus, and its potential to expand to other corridors and to increase capacity is greater. Annual costs are slightly higher, but the city would be protected to some extent from increasing operating costs due to inflation, growth, and reduced productivity. The environmental impact is low for all alternatives, but LRT is preferable for those alternatives that would use a new right-of-way (i.e., away from existing streets). Most importantly, however, it was felt that the level of service and capacity that could be offered would be essential in achieving long-term transit objectives.

Vehicle Selection

The transit line was designed for use by a six-axle articulated LRV. The Transportation Department has purchased 27 Düwag U2 cars that incorporate the modifications made for the city of Edmonton. This decision was taken after consideration of several factors. It is one of the largest cars available that is suitable for on-street operation. Since it was ordered by Edmonton, savings are anticipated in purchase (on the initial and follow-up orders), parts inventory, maintenance facilities, personnel training, service contracts, and so on. The car has been proven in revenue service and has a simple, rugged design, which makes it very attractive in view of the lack of LRT operating experience in Calgary and the small scale of operations. A number of minor changes (greater braking capability, anti-climbers, and so on) will be required, but none compromise the reliability or the design integrity of the car.

LRT Alignment

The LRT line consists of four distinct sections.

Railway Right-of-Way

The line will be constructed within the existing 32.8-m right-of-way of the Macleod Subdivision of Canadian Pacific Ltd. (CP). Railway service, about six trains/d, will be maintained. In the southern section (that is, south of Glenmore Trail), the line will occupy 9.5 m of the railway property. The CP line will not have to be relocated from its present position in the center of the right-of-way. Additional land will be required at the stations and has been obtained outside of the railway right-of-way. Figures 2 and 3 show typical stations in this section.

In the northern section, provision has been made to serve industrial sidings both east and west of the CP line. This is achieved on the west side by the provision of a parallel industrial lead, again within the existing right-of-way. Figure 4 shows this and other typical cross sections.

The LRT tracks will be grade separated from the industrial lead and from Forty-Second Avenue, the point at which the LRT line leaves the rail right-of-way. In addition, grade separations will be provided at Southland Drive, Macleod Trail, and Glenmore Trail.

Railway and LRT operations will be protected by conventional gates at crossings, by the usual operating rules, and by a Jordan rail (in case of derailment). The adjacent land use is primarily industrial, so little landscaping or buffering has been planned (although this would be included in adjacent parcels as they develop). There is existing residential development for about 2 km along one side of the line. Fortunately, there is also a 20-m strip of land on which some buffering can be provided.

Cemetery Hill Section

After the line leaves the railway right-of-way, it will enter a station and then follow a public street in a protected way for several hundred meters. At Thirty-Fourth Avenue it will enter a tunnel under Macleod Trail as it passes between two cemeteries. A subway was chosen for this section both because the grades would otherwise be excessive and because the available right-of-way is limited. Cut-and-cover methods will probably be used, but no temporary decking will be provided.

Table 1. Comparison of costs for bus-lane, busway, and LRT alternatives for Calgary.

Item	Cost ($000s)		
	Bus Lanes[a]	Busway[b]	LRT
Structures	5 280	52 620	53 310
Equipment and vehicles	7 380	6 800	22 450
Property and demolition	2 520	12 520	13 420
Utility relocation	—	3 770	6 870
Engineering and commissioning	790	6 480	9 270
Contingency	160	8 222	10 530
Total capital cost	17 570	90 410	115 850
Annual capital cost	1 820	7 870	10 360
Annual operating cost	3 710	3 360	1 900
Total annual cost	5 530	11 230	12 260

[a] The capital cost for bus lanes is significantly lower than those for the busway and LRT because the bus-lane costs do not include the replacement of two road lanes taken from Macleod Trail for exclusive bus use. To be financially compatible with the alternatives, the bus-lane costs should include the addition of a two-lane roadway (or widening of an existing roadway) in the South Corridor. While this additional cost was not specifically estimated in this study, its addition to the bus-lane cost would likely bring the total cost for this option to a level approximately equal to that of the busway alternative.
[b] The busway costs shown in this table are for operation of the busway with standard buses.

The subway will be 600 m long and will emerge on the north side of the hill.

Victoria Park Section

Between Cemetery Hill and downtown, the line will operate on one side of an arterial roadway. Property has been purchased to widen the existing road right-of-way by 15 m. Minor cross streets would be closed. Figure 5 shows a typical cross section.

Downtown Section

A short subway will take the line under the four-track CP line that runs through the city. The LRT line would then emerge and run at grade along Seventh Avenue. Five stations of the type shown in Figure 6 would be provided. Important features of the stations are (a) access to the intersections at each end of the stations, (b) access to Calgary's elevated pedestrian walkway system, (c) use of extensive glazing and curved forms to reduce the apparent bulk of the station, (d) offset train-loading locations to distribute passengers over the length of the station, and (e) space for turnstiles and accumulation of passengers, should these be required.

Private vehicles would be excluded from Seventh Avenue. This route would be turned over to the LRT vehicles, buses, and emergency vehicles. The stations are generally spaced three blocks apart; buses would thus have an exclusive lane westbound and need only use the track area for one out of three blocks. They would not, of course, be allowed to stop for passengers while they were on the LRT tracks. In the eastbound direction, an exclusive bus lane would be provided for the entire length of the downtown area. Buses could drive over the rails to pass other buses or to make left turns.

The operational problems and potential delays are recognized, but these are much less costly than subway construction. It should also be noted that this system may have a greater capacity, since the subway signalling system could limit headways to 90 s, while a much greater frequency is available under line-of-sight operation on the surface.

Fare Collection

Two options are being considered for fare collection. The first is the no-barrier system used in Europe. Passengers would purchase a ticket before boarding the vehicle and would be required to validate that ticket either in a station or on the car. Inspectors, empowered to levy stiff penalties, would provide supervision and en-

Table 2. Evaluation of the social and environmental impacts of the three alternatives.

Alternative	Criteria[a]							
	1	2	3	4	5	6	7	8
Bus lanes								
Downtown	-1	0	0	0	0	-1	-2	-2
Victoria Park	-1	0	0	0	0	0	-1	-2
Industrial area	-1	0	0	0	0	0	0	0
Residential area[b]	0	0	0	0	0	0	0	0
Busway								
Downtown	-1	0	0	8 buildings	1 building	-1	-2	-2
Victoria Park	0	+	30 units	3 buildings	2 buildings	-1	-1	-2
Industrial area	-2	-2	0	0	1 site	-1	-1	0
Residential area[b]	0	0	0	2 buildings	0	+	-2	0
LRT								
Downtown	-3	0	0	8 buildings	1 building	0	-1	0
Victoria Park	0	+	30 units	3 buildings	2 buildings	-1	0	0
Industrial area	-1	0	0	17 buildings	1 site	-1	0	0
Residential area[b]	0	0	0	2 buildings	0	+	-1	0

Note: + = positive impact, 0 = neutral impact, -1 = minor negative impact, -2 = moderate negative impact, -3 = significant negative impact.

[a] Criteria 1 to 8 are defined in the text. [b] South of Heritage Drive.

forcement. Such a system would save hundreds of thousands of dollars annually in labor and would simplify the design and operation of the station enormously. The alternative is to man the stations and provide control through barriers and turnstiles. It is proposed that Calgary have a free zone in the downtown. Passengers would need a validated ticket to enter a suburban station and would get off at a downtown station at which no barriers or turnstiles would exist. People could enter the car free in the downtown area but would need a validated ticket to be allowed to leave an outlying station. A decision on the fare-collection system will be made after experimentation on the bus system in Calgary.

Figure 2. Typical suburban station platform.

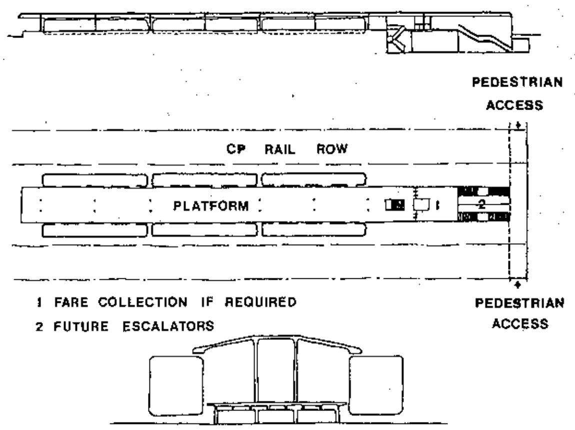
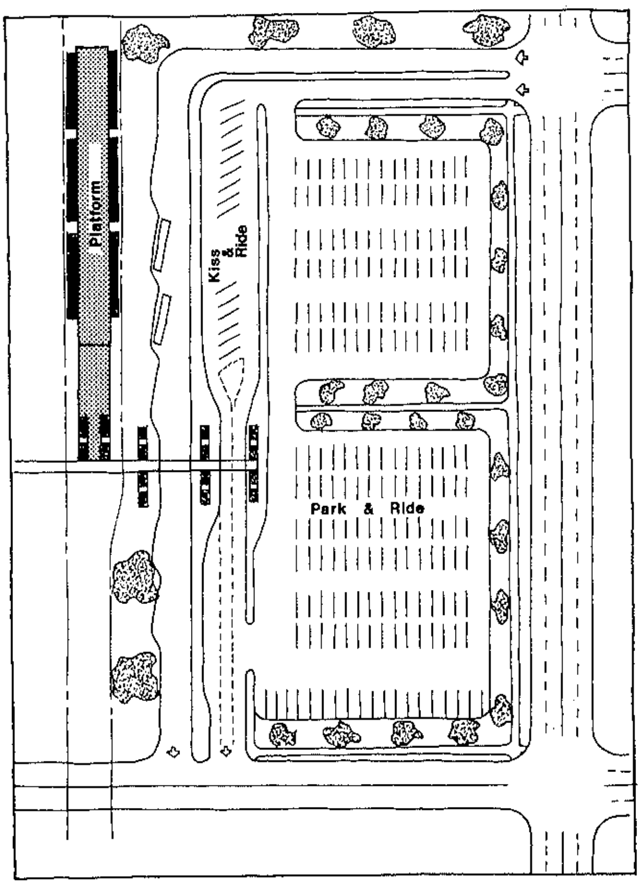


Figure 3. Typical suburban station area.



Shops and Yards

The shops and yards will be located on site at the extreme south end of the line. It is proposed to combine the facility with a bus garage. This site would have sufficient space to accommodate servicing, heavy and light maintenance, and cleaning and storage for a fleet of about 60 LRVs and 200 buses. It is anticipated that economies of scale will be realized by the joint use of this site.

Figure 4. Arrangement of LRT line and stations along railroad right-of-way.

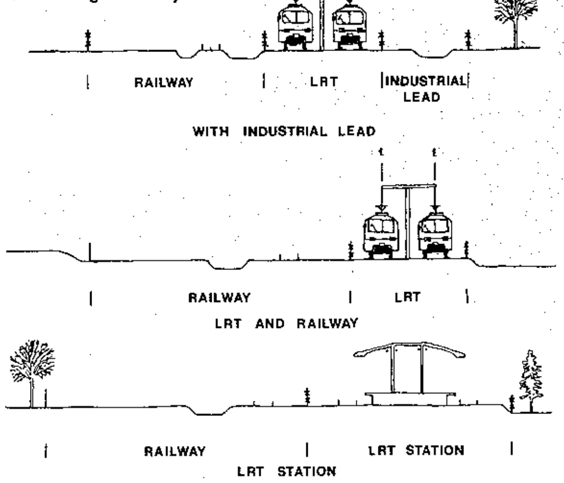


Figure 5. Arrangement of LRT line along arterial road.

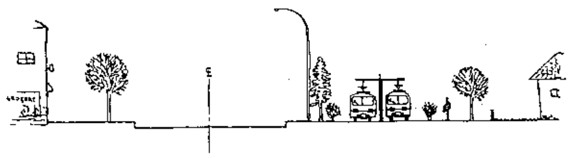
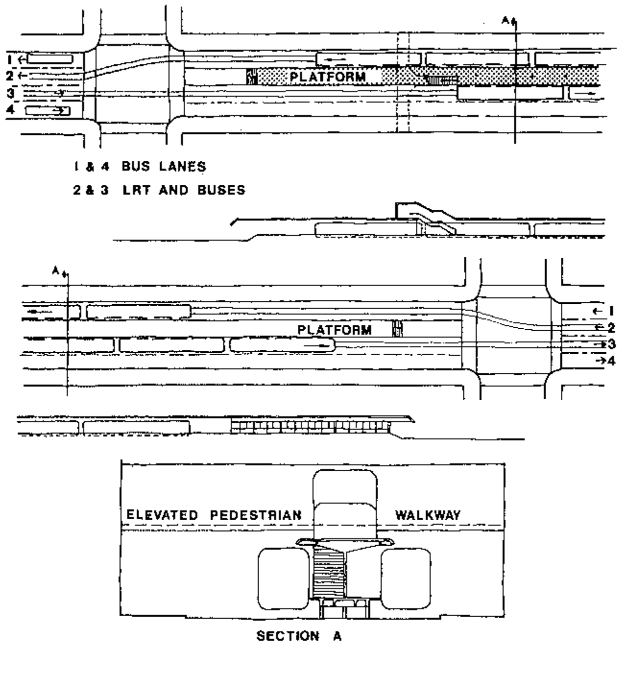


Figure 6. Arrangement of typical downtown station.



SUMMARY

In response to increasing congestion and related transport problems, the city of Calgary has conducted a number of studies of possible solutions. The most recent studies have examined the roles, costs, and impacts of roadways, exclusive bus lanes, busways, and LRT. It became apparent that long-term costs (both economic and environmental) could only be minimized by pursuing alternatives that have a strong transit component. LRT was chosen after an evaluation of alternatives that were felt to be appropriate for a medium-sized city like Calgary. Since it provides a high level of service at reasonable cost and substantial flexibility for improvement and expansion, LRT is the most suitable alternative to meet the city's objectives.

An alignment was selected in an area that has substantial redevelopment potential. The adjacent land use is such that there is little negative environmental impact and rights-of-way costs are low.

A number of at-grade crossings will be permitted in order to reduce the cost of implementation. Because relatively few roads cross the alignment, the operating speed will still be high. The flexibility to construct further grade separations in the future has been maintained. The designers, taking into account the small scale of operation and the unhappy experience of some other recent transit projects, have developed a technically unsophisticated solution. Economy, ease of implementation, and simplicity of operation and maintenance have been the cornerstones of the planning philosophy.

ACKNOWLEDGMENTS

Much of the work summarized in this paper was carried out for the city by Underwood McLellan and Associates Ltd., De Leuw Cather Canada Ltd., IBI Group, and L. T. Klauder and Associates. Their efforts and subsequent implementation have been generously supported by the province of Alberta through Alberta Transportation.

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Buffalo's Light-Rail Rapid Transit System

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The 1976 agreement in principle by the Urban Mass Transportation Administration (UMTA) to participate in the financing of Buffalo's $336 million light-rail rapid transit (LRRT) project was the culmination of almost 10 years of planning by the Niagara Frontier Transportation Authority and the western New York community for an integrated bus and rail rapid transit system. At least 5 more years of design development and construction lie ahead. This agreement also marked the end of a lengthy, and often frustrating, alternatives analysis process that helped to guide UMTA's development of federal policy on major urban mass transit investments. Buffalo will be the first U.S. city to have a completely new rail transit project that features the advantages of light-rail technology. This paper describes the LRRT project and reports on the results of the alternatives analysis process. Comparative cost-effectiveness statistics for various transit alternatives are included in the paper. The current phase of project development (general architecture and engineering) is described, and a schedule is given for the completion of the system.

June 10, 1976, was a very significant day for Buffalo. On that day, former U.S. Secretary of Transportation William T. Coleman, Jr., and former Urban Mass Transportation Administration (UMTA) Administrator Robert E. Patricelli committed UMTA in principle to participate in the financing of construction and implementation of a 10.3-km (6.4-mile) light-rail rapid transit (LRRT) system in Buffalo. This culminated almost 10 years of planning and design effort by the Niagara Frontier Transportation Authority (NFTA), local governmental agencies, and the Buffalo community, bringing the dream of improved public transportation for the area to fruition. Five more years of effort lie ahead but, with the assurance of federal financing for the project, the job can be tackled with much more enthusiasm.

LRRT is the term given by the NFTA staff to the 10.3-km rail component of an improved public transportation system for the NFTA area. It is a compromise solution derived from the analysis of rail alternatives studied for the system. LRRT combines the best features of both the heavy-rail transit (HRT) and light-rail transit (LRT) alternatives. Its annual operating and maintenance costs are minimized by eliminating on-board fare collection and using high-platform loading of vehicles. Maximum alignment flexibility is maintained in order to operate, wherever practical, at grade. Full system service can be provided for the nonambulatory handicapped.

The LRRT system was recommended by NFTA since it is cheaper to construct than HRT and can be operated more economically than LRT, while retaining most of that mode's flexibility. This is particularly true as the extended system alternatives are compared. The 10.3-km line is the initial portion of an approximately 27-km (17-mile) rail system that will eventually serve Buffalo, Amherst, and the Tonawandas with direct rail service. The initial network of integrated bus and rail service is shown in Figure 1. Future extensions to both Amherst (B) and the Tonawandas (C+E) are also shown. Figure 2 depicts the construction methods and stations of the system. Figure 3 provides a profile of this line.

Some basic facts about the metro system in the service corridor are presented below (1 km = 0.6 mile).

Category	Rail	Bus
Routes		
Number	1	58
Length, km	10.3	500
Vehicles	47	518
Daily revenue service		
Vehicle kilometers	10 000	65 100
Hours	314	3 650
Avg operating speed, km/h	36.5	18
Avg transit trip, km	5.2	4.0
Annual passenger kilometers (000s)	141 312	200 400

The route will run underground for 8.4 km (5.2 miles) and at grade for 1.9 km (1.2 miles); 8 of the 14 passenger stations will be underground, and 6 will be at grade. It is expected that in 1995 the system's daily patronage will be 92 000 by rail or a combination of rail and bus and another 92 000 by bus only; the annual patronage for the corridor will be 55 200 000. The rail system's peak load will be 7000 passengers in one direction. The modal split for person trips in 1995 is expected to be 13 percent for transit and 87 percent for automobile. The projected cost estimates for the LRRT project are as follows.

Item	Cost ($000)
Line and station construction	199 053
Systems	47 718
Rolling stock	31 208
Total construction	277 979
Rights-of-way	6 150
Design, construction management, insurance, contingencies	52 121
Total project	336 250

ALTERNATIVES ANALYSIS

In 1971, NFTA completed its mass transit study, which recommended an 18-km (11-mile) HRT system for the Buffalo-Amherst corridor. However, primarily because of community opposition to the predominantly aerial alignment, UMTA requested a restudy of the project.

During subsequent preliminary design, NFTA demonstrated that it was possible to design a rapid transit

Figure 1. The initial Buffalo bus and rail network.

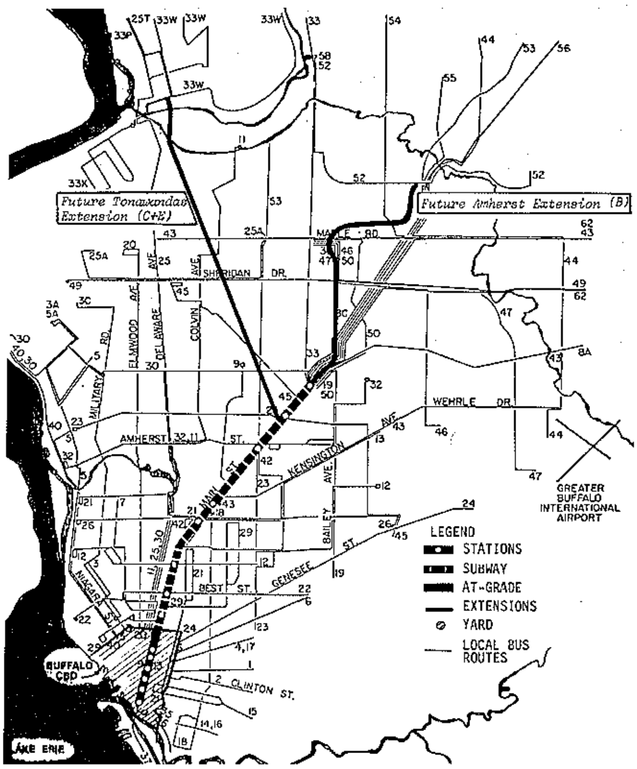


Figure 2. Route and stations of the initial 10.3-km LRRT line.

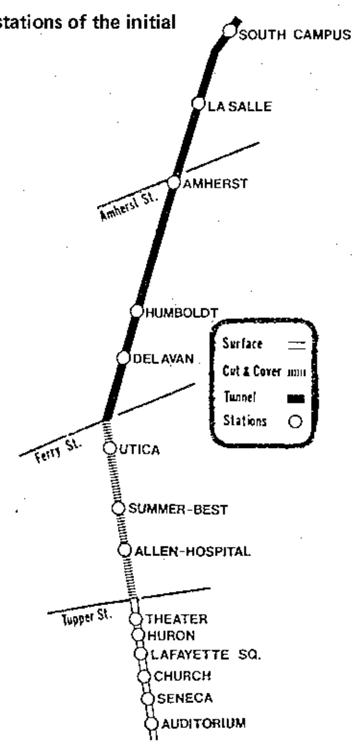
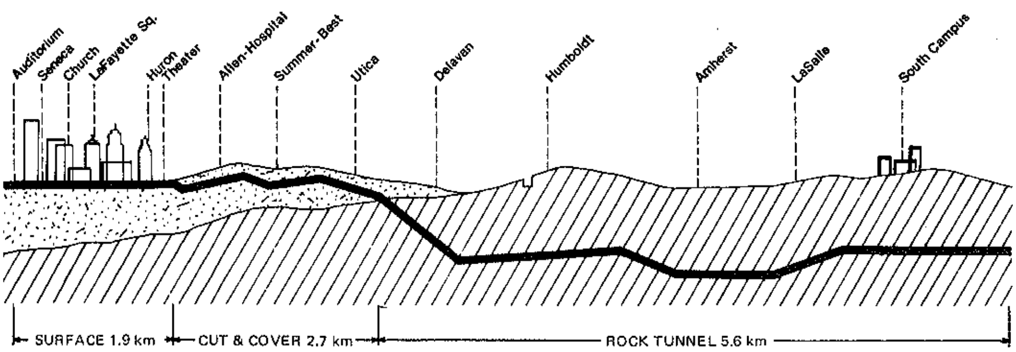


Figure 3. Construction profile of the initial LRRT line.



Note: 1 km = 0.6 mile.

system for the corridor that had widespread community support, something that was lacking in the planned 1971 system. However, because of delays in the construction schedule for the restudy and the increased cost of placing 76 percent of the alignment underground rather than the 40 percent projected in the earlier study, the cost of the system had risen from $239 million to $476 million. At about the time NFTA was finishing its preliminary design work on the 18-km HRT system, the need for alternatives analysis was added to the federal requirements for transit funding. In addition, incremental implementation received new emphasis because of the increasing requests of cities across the nation for funding assistance and the pressure these requests were placing on the UMTA budget. As a result, a comprehensive alternatives analysis was requested for the Buffalo project.

Transit system alternatives for an enlarged Buffalo-Amherst-Tonawandas corridor were developed featuring three primary travel modes: all bus, LRT, and HRT. These systems were analyzed and evaluated incrementally and as complete systems. A total of 21 alternatives was analyzed in all. Each of the alternatives developed was compared for cost-effectiveness with an improved bus system and the 18-km HRT system recommended in 1974. The following basic conclusions were reached.

1. The phasing of the 18-km HRT system improved the cost-effectiveness of the project. Even in the minimum increment systems, both HRT and LRT fulfilled the criteria of substantially reducing initial project costs while serving a greater number of riders at lower costs per ride than any of the other alternatives.

2. The 10.3-km minimum LRT system would have cost about $23 million less to construct than the corresponding HRT system. However, because LRT is more labor intensive than an HRT system and somewhat slower in operations, the annual operating costs would be higher.

3. The real capital cost advantages of an LRT system became more evident as system extensions were explored. The LRT concept held a distinct capital-cost advantage over HRT in extended systems. Potentially lower cost extensions are possible in LRT because of its flexibility to be used in a variety of urban settings without the need for completely grade-separated or private rights-of-way.

4. In order to combine the advantages of low capital cost and flexibility of LRT with the low operating-cost characteristics of HRT, a composite LRRT system was developed. This system would eliminate on-board fare collection and substitute in-station fare collection. High-platform station loading through all car doors simultaneously would speed service. When the capital costs of the three rail systems were compared for the initial phase of the project, the cost of high platforms and additional fare-collection facilities in the six downtown surface stations was more than offset by the deletion of one train from the system operating requirements as a result of faster train speeds.

5. On the basis of total costs, including both capital and operating costs, the LRRT alternative was more cost-effective than the other rail alternatives. This held true not only for the initial 10.3-km increment but for the extensions as well.

6. The LRRT concept minimized the system's annual deficit for all of the alignment alternatives studied. The deficit for operation of alignment A, the initial system increment, was only 6 percent higher than the deficit projected for an improved bus system. The LRRT system would carry almost 80 percent more riders per year in 1995; the operating deficit per passenter would thus be almost 40 percent lower than that forecast for the improved bus system.

7. Extensions to the minimum LRRT system, particularly in the Amherst corridor, greatly enhanced the system's financial performance. The costs per passenger carried were reduced, and total system deficits were reduced or eliminated, so long as costs do not escalate faster than revenues during subsequent years.

8. The surface-running LRRT system would become the central transportation feature of Buffalo's transit shopping mall on Main Street for a distance of about 1.6 km (1 mile). Construction of a surface system in the central business district (CBD) would mitigate many of the adverse environmental impacts often associated with cut-and-cover construction in a highly developed downtown area. Continuation and improvement of surface public transportation in conjunction with an automobile-restricted pedestrian shopping mall could have a significant positive effect on the downtown shopping district.

9. The LRRT alternative would facilitate access to the rail system by providing six surface stations in the CBD rather than the three underground stations previously planned. This would bring the stations to within easy walking distance for most CBD employees. Time lost in slower operating speed on the mall would be more than made up by more frequent stops adjacent to major downtown traffic generators. High-level boarding platforms would be used for the LRRT alternative.

10. Construction of the LRRT system could bring substantial economic benefit to the entire western New York area. The long-term transportation benefits and the quantifiable indirect community benefits offset a high percentage of the system's construction costs.

SYSTEM COSTS

System costs and revenues and cost-effectiveness indicators for the LRRT system are compared with those for HRT and LRT in Figures 4 and 5 and in Table 1. Data are presented for the minimum system increment (the 10.3-km alignment A), this increment with the Amherst extension added (the 18-km alignment A+B), and the future two-branch system serving both Amherst and the Tonawandas (the 27-km alignment A+B+C+E).

Capital Cost

Figure 4 compares the system capital costs graphically; the data are supplied in greater detail in Table 1. The cost savings involved in combining the surface LRT system with the planned downtown shopping mall in Buffalo's CBD are retained in the LRRT option. The savings over the HRT alternative is about $23 million in rail project costs.

Route alignment, as well as system technology, affects the comparative capital cost estimates for alignment A+B. During the last few years, numerous horizontal and vertical alignment alternatives have been investigated for the Amherst extension (B). The costs and length of the underground system in each vary considerably. The LRRT alignment assumed in the figure is identical to that developed in the 1974 preliminary design report for HRT, which follows Bailey Avenue for the Amherst extension. On the other hand, the LRT system could follow another alignment, the Grover Cleveland-Millersport Highway, that has a wider right-of-way and allows a more direct route to the State University of New York at Buffalo's North Campus and that can incorporate more surface construction. The capital costs would be lower. The LRRT system retains the flexibility to use either option or any one of a dozen or so intermediate options, depending on the outcome of continuing community discussions.

Cost estimates for the LRRT system in the Tonawandas corridor (C+E) assume the same surface alignment followed by the LRT system. This involves a total of seven at-grade crossings of streets in the 10-km (6-mile) Tonawandas corridor, which parallels the existing Erie Lackawanna Railway Company's freight line.

System Costs per Passenger

Figure 5 and Table 1 present data on system costs per passenger carried and supporting statistics on operating costs and revenues. The LRRT system, in each of the alignments considered, compares quite favorably with HRT and LRT, on the basis of both operating costs per passenger carried and total cost per passenger carried (the total costs combine the annual operating costs per passenger in 1995 with annualized total costs for the project). In Figure 5, a discount rate of 7 percent over a period of 50 years has been assumed in order to determine the capital recovery factor for the annualization of initial system costs. A sinking fund factor has also been included to allow for the replacement of rail vehicles every 25 years and buses every 12 years. The annual operating costs for the LRRT system are equal to or less than the operating costs for the HRT and LRT systems. These costs, though not the total costs, are also substantially less than the costs for the improved bus system.

The cost per passenger carried on the extended basic LRT system serving Amherst (A+B) can be reduced substantially simply by using the more attractive Bailey Avenue alignment. Obtaining the underground right-of-way would involve additional capital costs. However, further engineering and community discussion may develop an LRRT alignment that has more above-ground construction (which can be constructed at less cost) yet retains a high percentage of the HRT patronage and that will still generate the necessary public acceptance of the route. The flexibility to take advantage of this opportunity is retained by the LRRT system. As in Figure 4, the LRRT alignment assumed in Figure 5 follows the HRT underground alignment on Bailey Avenue and the subsequent aerial alignment to the North Campus of the

Figure 4. Comparison of system capital costs.

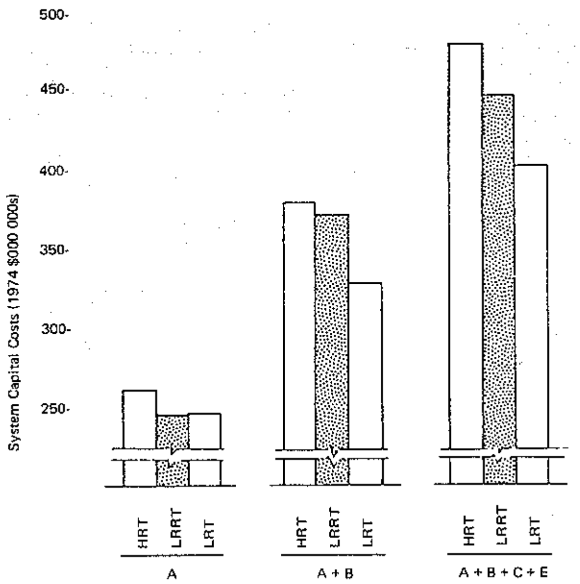


Figure 5. Comparison of 1995 system costs per passenger.

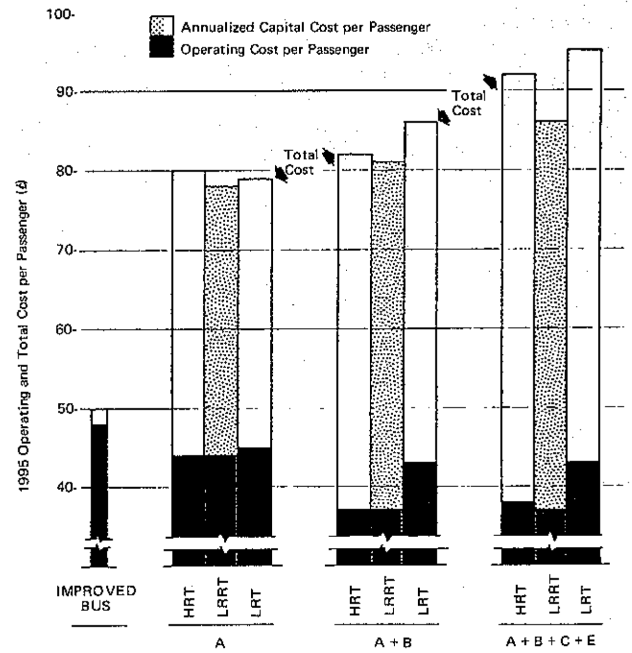


Table 1. Comparison of 1995 system costs and revenues per passenger.

Alternative	1995 Annual Patronage (000s) Rail and Bus	Rail and Rail/Bus	Bus and Rail/Bus	1995 Operating and Maintenance Costs ($000 000s) Rail	Bus	Total	1995 Annual Bus and Rail Revenue ($000 000s)	1995 Operating Deficit ($000 000s)	System Operating Cost per Passenger (¢)	Total Annualized Cost per Passenger (¢)	Operating Deficit per Passenger (¢)	Operating Cost per Passenger (¢) Rail	Bus	Operating Cost per Passenger Kilometer (¢) Rail	Bus
Improved all-bus	30 900	–	30 900	–	14.9	14.9	11.7	3.2	48	50	10.1	–	48	–	11.4
Alignment A															
HRT	55 200	27 600	50 100	4.6	19.8	24.4	21.0	3.4	44	80	6.2	17	39	3.0	9.6
LRRT	55 200	27 600	50 100	4.6	19.8	24.4	21.0	3.4	44	78	6.2	17	39	3.0	9.6
LRT	55 200	27 600	50 100	5.1	19.8	24.9	21.0	3.9	45	79	7.2	19	40	3.6	9.6
Alignment A+B															
HRT	63 600	39 200	51 300	6.1	17.5	23.6	24.2	0.6[a]	37	82	0.8[a]	16	34	2.4	10.2
LRRT	63 600	39 200	51 300	6.1	17.5	23.6	24.2	0.6[a]	37	81	1.0[a]	15	34	2.4	10.2
LRT	56 700	32 400	45 600	6.8	17.4	24.2	21.5	2.7	43	86	4.6	21	38	3.6	11.4
Alignment A+B+C+E															
HRT	66 600	43 800	52 800	7.4	17.8	25.2	25.3	0.1[a]	38	92	0.2[a]	17	34	2.4	10.8
LRRT	66 200	43 500	52 400	7.2	17.8	25.0	25.2	0.2[a]	37	86	0.3[a]	17	34	3.0	10.8
LRT	59 100	37 800	46 800	7.8	17.5	25.3	22.5	2.8	43	95	4.9	21	38	3.0	12.0

Notes: 1 km = 0.6 mile.
Dollar figures shown are 1974 dollars.

[a]Surplus.

State University of New York at Buffalo.

System Revenues and Operating Costs

Table 1 compares the system operating costs and projected revenues for 1995. The data in this table were derived by using the basic assumption that between now and 1995 there will be no differential escalation of costs over fares or revenues. This has not been the case, particularly in the last few years. Fuel and power costs, as well as wages and retirement payments and other fringe benefits, were generally low in the transit industry prior to public acquisition. These costs have been escalating rapidly during the last decade. Other assumptions regarding differential escalation for costs and revenues were made that showed just how sensitive system deficits are to these assumptions.

Using the basic assumption of zero escalation of costs and revenues for each alternative allows a comparison among alternatives. The data presented herewith should be interpreted in relative terms. In other words, an alternative that shows a surplus of revenue over costs indicates that this alternative outperforms those that show a deficit.

Deficits projected for alignment A range from $3.4 million to $3.9 million in 1995. This is not significantly greater than the $3.2 million deficit forecast for the improved bus system, in spite of the fact that the rail systems carry almost 80 percent more passengers. For each of the extensions, a substantial deficit is forecast for the labor-intensive LRT system. For the HRT and LRRT systems, a surplus is forecast. This is partly because the alignment used to develop the latter systems is expected to attract more riders. Table 1 also illustrates the desirability of completing the Amherst extension as soon as funding permits. Whereas operating the LRRT system over the minimum system involves a deficit of $3.4 million in 1995, operation of the extended system (A+B) would generate a surplus of $0.6 million in the same year.

Ridership is increased by the addition of a rail element in the transit system. The longer the rail element, the greater is the number of riders attracted to the system, primarily because of the significantly higher level of transit service. Both the HRT and LRRT systems, which use essentially the same horizontal alignment, attract significantly more riders than the LRT system in later stages of the project.

The process of alternatives analysis examined a number of other issues besides cost-effectiveness, including (a) flexibility for future extensions, (b) sensitivity tests for projected system revenues and costs, (c) economic effects of system costs and benefits, and (d) community and environmental impacts. The bases of UMTA's decision to participate in project funding were reflected in a letter from former UMTA administrator Patricelli to NFTA:

1. Buffalo is the nation's eighth most densely populated central city and urbanized area;
2. The corridor involved is not well served by readily available street and freeway capacity, and the community withdrew Interstate highways from its regional transportation plan in the late 1960s, partly in anticipation of rapid transit implementation;
3. Alternative all-bus proposals are not demonstrably more cost-effective or cost beneficial in the corridor in question;
4. The proposed transit system is an integral part of a comprehensive redevelopment plan aimed at revitalizing the downtown area, to which a substantial public and private financial commitment has already been made;
5. The project has evolved through a substantial citizen-participation process and has uniform support from civic, business, labor, and political leaders throughout the area;
6. The written commitment between contractors and construction unions for the peaceful resolution of any labor disputes without work stoppages during the construction of this project gives us the advance assurance we have been seeking that every effort will be made to avoid severe cost overruns;
7. The proposed light-rail line implements our stated objective to seek a promising opportunity for a grant to deploy a modern light-rail system;
8. The downtown light-rail transit mall concept, involving an automobile-restricted area, may help to demonstrate a lower cost technique for transit implementation in city centers that could have national importance; and
9. The availability of New York State funds more than adequately assures the local capital share of this project.

GENERAL ARCHITECTURE AND ENGINEERING

Following the UMTA commitment in principle to the LRRT project on June 10, 1976, a capital grant application was prepared. A formal public hearing on the request for $8 million in federal funds and $2 million in New York State funds was held August 10. On October 7, 1976, UMTA approved the application, and the project entered the general architecture and engineering phase of development. Mr. Patricelli had outlined several issues that had to be resolved during this design phase before an UMTA grant for final engineering and construction could be made.

1. The former environmental impact assessment, which covered some of the earlier alternatives examined but has been outdated by the [10.3-km] 6.4-mile LRRT proposal, must be updated with significant UMTA participation. A final environmental impact statement [EIS] must then be prepared and circulated by UMTA before a final decision on this project can be made.
2. The projected operating deficits of the entire NFTA rail and bus system should be examined and evidence provided of a state and local consensus on how they will be met.
3. The federal share of the project will not exceed $269 million. In accordance with UMTA's national practice, therefore, a contract will have to be entered into that will assure the availability of sufficient non-federal funds to complete the project should there be cost overruns.
4. The feasibility of recapturing for transit-financing purposes some of the increases in real estate values generated as a result of the transit investment should be explored.

The general architectural and engineering work will establish the standards and criteria to be used in final design and construction. Schedules and cost estimates will be refined and contracts identified that will be needed to complete the project. Safety and security during construction and operation of the system will be a primary consideration as design standards are developed, as will the effect of such construction and operation on Buffalo and its environment.

This intermediate phase of project development, between alternatives analysis and final design, is required to maintain the schedule by accomplishing as many preliminary tasks as possible while the EIS is being prepared, circulated, and approved. In September 1976, UMTA issued its statement of federal policy with respect to decisions on major urban mass transportation investments assisted under the Urban Mass Transportation Act of 1964 as amended. This policy requires that a joint EIS (in draft form) and alternatives analysis be prepared and approved before the final EIS on a recommended alternative is prepared and before preliminary design is begun. These definitive steps will preclude the need for a general architecture and engineering phase in future planning in other cities.

Figure 6 illustrates the phasing and organization of the LRRT project development. The general architecture and engineering work is being undertaken in two phases over a period of 18 months. Phase 1 of the overall work comprises conceptual design, criteria, standards development, and other non-site-specific tasks that will parallel work on the EIS for the project. This design period has been estimated to require about 6 months. Phase 2, which begins when UMTA approves the EIS, initiates definitive design and will cover a 12-month period.

One principal consultant has been engaged for each of three sections of the line (see Figures 2 and 3): (a) surface and transit mall (Memorial Auditorium to Tupper Street), (b) cut-and-cover construction (Tupper to Ferry streets), and (c) tunnel construction (Ferry Street to the South Campus of the university). These section designations relate to the type of construction to be used in each area. A fourth consultant has been retained for the development of transit vehicles, electrification, train control, and other vital engineering systems.

In addition to the four principal consultants, other support consultants will be employed. One consulting team is now working on the EIS. Other contracts have been let for general soils engineering, subsurface investigations, ridership and operations analysis, and surveys and mapping and for the services of a consulting architect.

The $10 million budget approved last October by UMTA has been apportioned as shown below. Work on each of the contracts identified is currently under way, or consultants have been selected and contractual negotiations have been initiated.

Contract Item	Approximate Contract Value ($000s)
Principal consultants	
Surface	800
Cut and cover	1 400
Tunnel	2 088
Systems engineering	1 963
Subtotal	6 251
Environmental impact statement	153
General soils consultant	446
Subsurface investigations contract	224
Ridership and operations analysis	430
Consulting architect	197
Control surveys and mapping	24
Other support consultants and contingencies	362
Project management (NFTA)	1 913
Total	10 000

There are a number of reasons for subdividing the general architecture and engineering work into several parts so that speciality consulting teams are working on each rather than electing to engage one general consultant for all the work.

1. NFTA can be more selective in its choice of consultants with specific applicable experience to undertake individual tasks.
2. The overall number of experienced personnel assigned to the project will probably be greater than if one general consultant were engaged for the entire job.
3. The opportunities for local design input are increased with a multiconsultant program rather than the

Figure 6. Phasing and organization of the LRRT project.

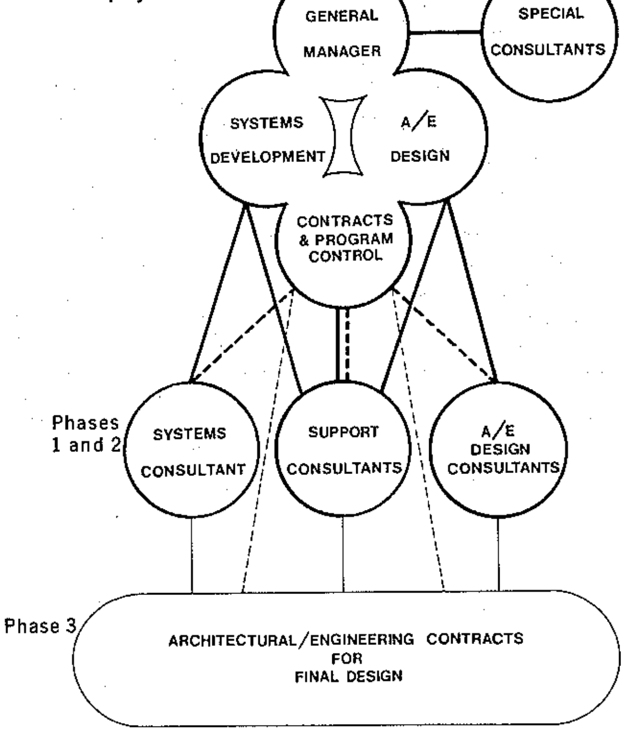
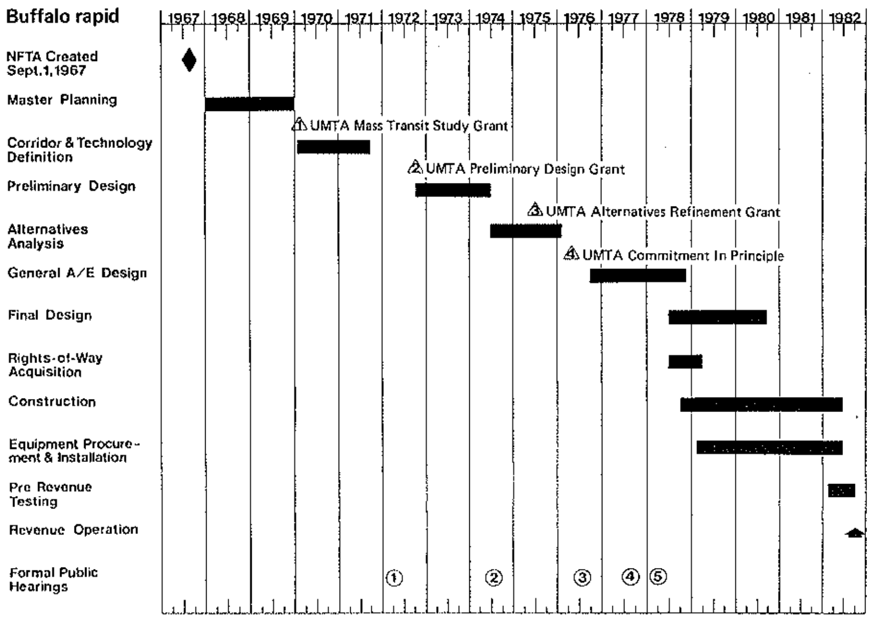


Figure 7. History and schedule of the Buffalo rapid transit project.



single-consultant alternative. For instance, a total of 30 firms will be engaged on the first 10 assignments. Of these, 17 firms either have their headquarters in Buffalo or already have local offices established in the area. These local firms are handling more than 60 percent of the work. This has a substantial positive impact in the professional community and is consistent with NFTA's goals and claims made in the alternatives analysis and EIS documents.

4. There is also some advantage to a team approach. If the members of a management group have had varying experience on several rapid transit projects, this stimulates discussion on key issues and tends to avoid the problem of assuming an approach is correct because it was done that way in a previous case.

Offsetting these advantages somewhat is the additional work entailed in seeking approvals and in administering and closing out contracts. In addition, the burdens of program control and coordination fall squarely on the owner. However, since the full responsibility for program control, direction, costs, and scheduling also rests with the authority or owner, it is not inconsistent for the owner to assume full control of these tasks. The management concept NFTA is attempting to encourage is that, once the general criteria for system design are developed and approved, the consultants will be responsible for the technical details without substantial input or interference from NFTA. To complete the design tasks within budget will require continuing vigilance, cooperation, and monitoring by all parties to ensure that duplication of tasks and effort is minimized.

PROJECT DEVELOPMENT SCHEDULE

Figure 7 illustrates the 15-year history and schedule of the Buffalo rapid transit project. It has taken almost 10 years to reach the stage of approval in principle, and there are 5 more years of concentrated design and construction to go.

The general architecture and engineering part of the development program has two phases. Phase 1 has already begun; the draft EIS is already completed, and the principal consultants have been given notice to proceed. Approval of the final EIS document will mark the end of phase 1 and the start of definitive design work. The development criteria, general plans, and standards started in phase 1 will continue through phase 2 with increased emphasis on passenger stations and other facilities to be designed by section designers in phase 3 of the program. Phase 2, definitive design, will be accomplished by the principal consultants. It will generally consist of the preparation of design drawings, specifications, and contract documents for the construction of the line or between-station sections of the project. Specifications, design details, and standards developed during definitive design by the principal consultants will be used wherever possible in subsequent section design work of phase 3.

Phase 3's program of final design cannot begin until after submittal and approval of a subsequent capital grant request by both federal and state authorities. This is scheduled for early 1978. Construction of the system can begin in line sections designed by the principal consultants after approval of the final capital grant request. Groundbreaking for the first contract is now scheduled for fall 1978. If the entire program can be maintained on schedule, the system could be operational by the end of 1982 or early 1983.

A significant stipulation was contained in UMTA's June 1976 agreement in principle. It limited the federal share in the project to $269 million, or 80 percent of its estimated cost. The granting of a definite funding commitment by UMTA for construction in a specific dollar amount, based on a review of the capital grant application and detailed cost estimates prepared after preliminary engineering studies, is not part of federal policy. This policy places the onus on the transit system developer to ensure that system costs do not mushroom during the design process. However, it also places joint responsibility on all parties involved to ensure that the design and construction schedules are met.

With the approval of a capital grant application, the project automatically passes from the planning to the development stage. The planning phase is, of necessity, extremely tedious and drawn out. Communication with all levels of government and public participation are time-consuming but indispensible. Delays at this stage are inevitable but, once the decision is made to proceed with the capital project, delays become intolerable.

Any capital grant application includes a cost estimate that in turn is based on an assumed design-and-construction schedule. In a period of inflation it is absolutely essential to adhere to this schedule. Any delays, whether technical or bureaucratic, cost money—a lot of money. Often, such necessary actions as the fine tuning of designs or the negotiation and approval of architecture and engineering contracts can be carried to the extreme, well beyond their proper worth to the project. The old adage that haste makes waste is still true, and it is not suggested that the approval process can be dispensed with entirely. However, it must be placed in proper perspective during the development stage. The same federal effort must be put into the drafting and standardization of project management guidelines for system development that was expended in the streamlining of the EIS and alternatives analysis. Something must be done to reduce the tremendous volume of paperwork and to eliminate the lead time in getting under way with work on design and construction contracts.

Light-Rail Transit in Pittsburgh

Theodore C. Hardy, Port Authority of Allegheny County, Pittsburgh

The $228 million Early Action Program conceived by the Port Authority of Allegheny County in 1969 and funded by the local, state, and federal governments in 1970 was intended to end the seemingly endless series of biennial transit studies and begin the construction of a countywide rapid transit system on an incremental basis. It was to use various technologies, including existing trolleys, exclusive busways in the east and south, and the Transit Expressway (Skybus)—rubber-tired computer-controlled vehicles tied to an exclusive guideway—in the South Hills sector. Perhaps no rapid transit effort, especially the Transit Expressway element, has undergone as close public and technical scrutiny as has the Early Action

Program. The inability to implement the program expeditiously resulted in the Urban Mass Transportation Administration's suspension of further action in the South Hills sector in October 1974. In 1975, key representatives of local and state governments as well as the Port Authority began working together to break the deadlocked argument about a fixed-guideway transit system for the South Hills corridor. An independent consultant was selected to perform the final alternatives analysis. When the South Hills alternatives analysis was completed and the recommendation of light-rail transit (LRT) technology was accepted in March 1976, a community consensus had been achieved. As a result, the Port Authority amended the Early Action Program to substitute LRT for the rubber-tired vehicles on the Transit Expressway and is proceeding with engineering and environmental impact studies with the objective of having the first stage of the LRT system operational in the South Hills sector by the early 1980s.

The issue of fixed-guideway rapid transit development in Pittsburgh and Allegheny County has been debated for more than 70 years by engineers, planners, politicians, and the community at large. Each group has had to contend with the rugged topography, existing development patterns, and its own hopes and fears in trying to arrive at an acceptable course of action.

Surprisingly, lack of funding has not been the reason for not proceeding with the construction of a fixed-guideway system. Funds were committed for construction in 1919 as well as in 1970. The issue in the early 1920s was where to begin rail construction; in the early 1970s, it was disagreement over the selection of a system of rubber-tired vehicles after construction was already under way.

To break the local impasse and permit construction to proceed, the Port Authority of Allegheny County commissioned an independent consultant in early 1975 to compare four modes for the South Hills corridor and to make a recommendation for implementation. A light-rail transit (LRT) system was recommended in place of the rubber-tired system. Today, an engineering and environmental impact study for the first stage of the LRT line is under way. To give the reader a better understanding of the present LRT situation, it is important to review the key events leading to this decision.

In 1959, the Pennsylvania legislature assigned to the Port Authority of Allegheny County responsibility for acquiring, operating, and coordinating mass transit in Allegheny County. By 1964, the Port Authority had purchased 33 independent bus and streetcar companies and consolidated them into an integrated operation on a regional scale. Instead of 33 independent companies with 39 separate locations in Allegheny and contiguous counties, the Port Authority's 1000 buses and 90 streetcars are now operating from six strategically located divisional garages. Around-the-clock administration is conducted from a new main office complex, which also houses the primary maintenance shop. At the same time that bus operations were being consolidated, the board of the Port Authority and community leaders directed their energies toward the long-standing issue of rapid transit to achieve a balanced transportation system for the region.

After World War II, plans for the Pittsburgh renaissance, which was brought about by business and governmental interest in improving the city, placed improved mass transportation high on the agenda, along with new buildings, new jobs, and the checking of floods and air pollution. The public leaders in the early 1960s clearly noted that mobility was the key to sustained community development and regional growth. They posed the following question: "If trolley systems are not being built and are unavailable for medium-density cities such as Pittsburgh, if people are clearly in love with the riding qualities of automobiles, if buses are singularly inadequate to meet ridership demand as well as to negotiate the hills and narrow twisting streets of Pittsburgh, then how do we meet our local transit needs?" The answer proposed was the Transit Expressway, commonly referred to as the Skybus.

Skybus can best be described as a 10.7-m (35-ft) rubber-tired vehicle that is capable of being operated either singly or in multiple-car trains and that cannot leave the fixed track because the vehicle system is locked to a continuous center guideway. The concept was the brainchild of Westinghouse Electric Corporation and was made into a reality by the combined capabilities of at least 30 major companies in Pittsburgh that contributed to its development. Skybus is a product of Pittsburgh.

The first-generation vehicles and test track were funded by local, state, and federal governments and constructed in 1965. The 3.2-km (2-mile) test track located in a county-owned regional park (South Park) still exists today as the only high-speed test track for rubber-tired transit vehicles in the United States. Although no trunk-line rapid transit application exists today, the concept is being successfully used in downtown people movers in four locations in the United States.

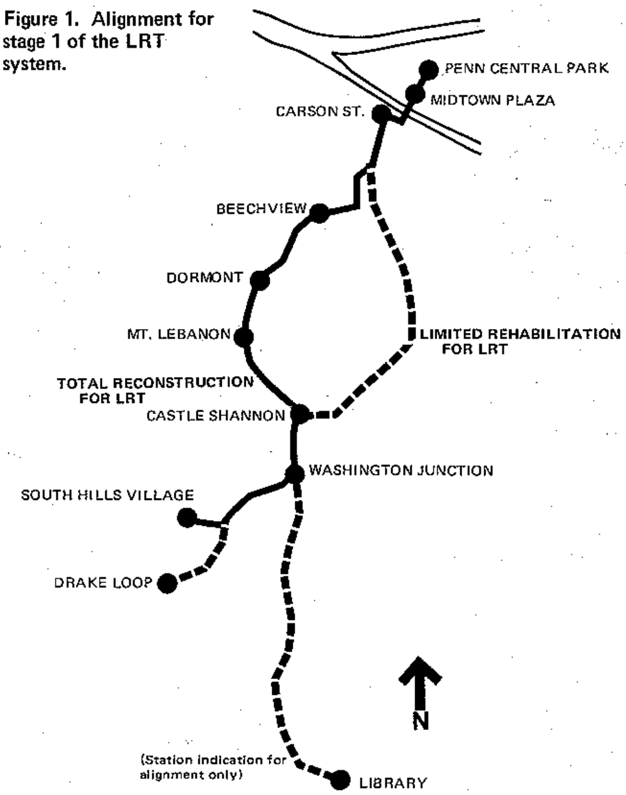
EARLY ACTION PROGRAM

On the basis of the recommended staging priorities for constructing a 96-km (60-mile) rapid transit system in Allegheny County (1) and the successful test results of the rubber-tired Skybus, the Port Authority in 1969 developed a series of early actions aimed at proceeding quickly with the first steps of the countywide rapid transit system by using various systems in the high-priority corridors as well as demonstrating the feasibility of the Skybus technology in revenue operations.

As approved and funded in 1970 at the local and federal levels, the Early Action Program consisted of four major elements: the exclusive busways (a) to the south—7.2 km (4.5 miles)—and (b) east—12.9 km (8 miles) and (c) the rehabilitation of a portion of the existing South Hills trolley system—27 km (17 miles)—in order to continue operations until the final element—(d) the 16.9-km (10.5-mile) Skybus system—was operational in the remaining sector of the corridor. These early actions affecting approximately 64 km (38 miles) of exclusive right-of-way transit improvements were estimated to cost $228 000 000. The southern and eastern sectors of the county had high priorities for rapid transit improvements because of the growth and development in these sectors, the age and deterioration of the existing South Hills trolley fleet, and the availability of right-of-way.

From the inception of the Early Action Program in 1968, the Skybus demonstration element was embroiled in controversy at the local level. Argument and counterargument were advanced by both sides in response to such questions as: Is the system safe? Will it perform day in and day out? Will it perform in rain and snow? Are not steel wheels better than rubber tires? Will it cost more than the estimate? Why must I lose my favorite trolley stop? Should the vehicle operate automatically? Meanwhile, as each year passed by, Pittsburgh's transit controversy continued to build only a historic paper trail. It was the first transit program to have public hearings (not federally required) televised in their entirety on public television (1969), the first major Urban Mass Transportation Administration (UMTA) project to undergo the environmental impact procedure (1971), the subject of a 69-d hearing in the Court of Common Pleas of Allegheny County on a request for a preliminary injunction (1972), and the recipient of technical support from UMTA for fixed-guideway rubber-tired vehicles for line-haul service on two separate occasions (1970 and 1974). As a result of changing political leadership during this period at all levels,

Figure 1. Alignment for stage 1 of the LRT system.



steady cost escalation due to delay and inflation, and the resurgence of the light-rail vehicle (LRV) in the United States, the Skybus controversy became deadlocked in mid-1974.

Although UMTA reassured the local area of its continued support for the rubber-tired vehicles, it was made clear that the Port Authority of Allegheny County must decide how it wished to proceed. While awaiting this decision, UMTA suspended further administrative actions on Skybus in October 1974. At the same time, UMTA also suspended further administrative action on the busway to the east as a result of the problems involving the Penn Central Transportation Company. (When the Consolidated Rail Corporation was created in April 1976, UMTA lifted this suspension; final engineering studies and acquisition of property are now under way, and construction is scheduled for completion in 1981.)

SOUTH HILLS CORRIDOR

In early 1975, key representatives of the city, county, and state governments began working together at the request of the Port Authority to try to reach a consensus on transit improvement in the Pittsburgh area. The deliberations of this special task force led to the conclusion that the various proposals for constructing fixed-guideway transit in the South Hills corridor should undergo a final independent evaluation—another study.

In accordance with the guidelines prescribed by the task force, De Leuw, Cather and Company began work in August 1975, under contract with the Port Authority, on a comparative analysis of four alternative modes of transit for the South Hills transportation corridor: (a) a rubber-tired, rapid-transit system, (b) a steel-wheeled, light-rail transit system, (c) a conventional rail rapid transit system, and (d) all-express bus transit. The study's basic objective was to provide sufficient data to determine which transit system would be most suitable for the South Hills communities, taking into account such factors as financing feasibility, operational efficiency, public acceptability, service characteristics, technological accessibility, safety, and environmental impact.

In March 1976, the independent consultant reported that, on the basis of these major considerations, "LRT would offer the most cost-effective and financially feasible alternative.... It would have sufficient advantages to allow it to be considered the leading candidate system for implementation in the South Hills corridor" (2). In comparison with the three alternative transit modes analyzed, the independent consultant concluded that the LRT system was preferable in the South Hills corridor primarily because

1. It had the lowest capital and operating costs per passenger and thus the lowest requirements for government subsidies, as well as being easily staged for construction and capable of expansion into other corridors;
2. It could produce the highest number of daily transit trips (particularly nontransfer trips) within the South Hills corridor and give the highest degree of accessibility to passengers;
3. It would require the least displacement of businesses and residences and was best in meeting noise, air-quality, energy, and land-use standards; and
4. It presented the least risk in terms of both technological reliability and opportunity for procurement since it is a tested and proven technology and does not rely on highly innovative or experimental features that could create an obstacle to commercial production.

In making the recommendation, the consultant stated that:

> One of the most important advantages favoring LRT development in the South Hills corridor is that it would be compatible with the guideway technology that currently exists there. The system could be easily staged. Existing PCC [Presidents' Conference Committee] cars and new light-rail vehicles could operate interchangeably over the new and old parts of the system. Trolleys operate on downtown streets today in greater numbers and over greater lengths of street than would be proposed in the recommended plan. Were it not for the above factors, LRT possibly would not have had the cost and financial advantages over the other alternatives as determined in this study.

After review by the technical committee of the special task force and after public meetings, the independent consultant's recommendation to construct and equip the 35.7-km (22.3-mile) corridor with an LRT system substantially on the right-of-way now used by the existing South Hills trolley at a cost of $384.5 million (in 1975 dollars) was adopted by local and state officials and the Port Authority's board in April 1976 and forwarded to UMTA for its concurrence.

IMPLEMENTING STAGE 1

As the result of a 6-month joint review period with UMTA and the identification of new budgetary constraints at the federal level, a set of immediate improvements to the existing South Hills trolley system was proposed. These improvements would cost approximately $200 million and were consistent with the independent consultant's LRT recommendations as well as the Port Authority's operational objectives.

In April 1977, the Port Authority signed a contract with the joint venture firm of Parsons Brinckerhoff-Gibbs and Hill to undertake engineering and environmental impact studies for stage 1; see Figure 1. The draft environmental impact statement (EIS) and cost estimate, as well as other contract items were to be received by December 1977, and stage 1 should be 40 percent complete by August 1978. If the EIS and full funding have

Figure 2. Consultant's proposed alternative for downtown on-street operations.

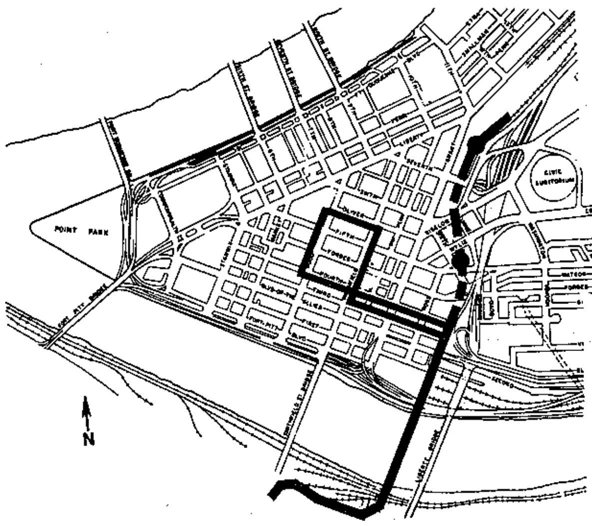
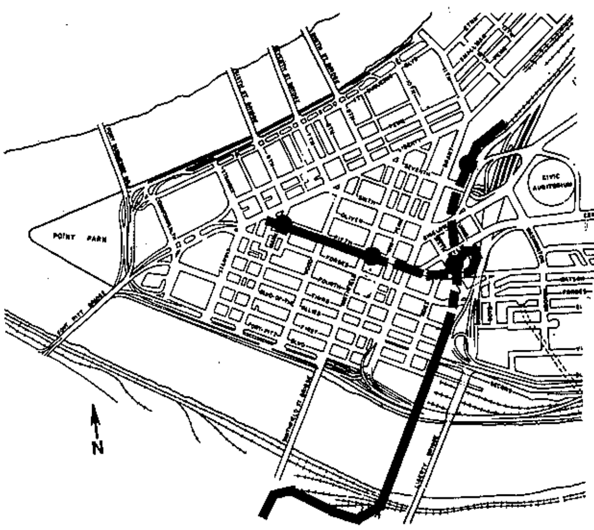


Figure 3. Traffic management study's proposed alternative for downtown on-street operations.



been approved by August 1978, the Port Authority looks forward to the completion of contract documents and commencement of construction early in 1979. The objective is to have the work completed and 80 new LRVs operational early in the 1980s.

The scope of work for stage 1 will set priorities for solving current trolley system problems within the budget constraints, while at the same time continuing trolley operations throughout the 35.7-km corridor. The tasks to be accomplished are exacting.

1. The existing trolley fleet is worn out and must be replaced. The current car barns at South Hills Junction were never intended to provide a full maintenance facility. This facility does not function properly today due to lack of space and could never accommodate the new LRVs and their sophisticated equipment needs. The Pittsburgh LRV is intended to use already available technology to the greatest extent possible. Competitive bidding consistent with UMTA's policy will be encouraged. Until the completion of stage 2 sometime in the late 1980s, both existing trolleycars and new LRVs will be operating over the same track.

2. There must be a river crossing into the Golden Triangle that is reliable and permits multicar operations in trains. The 100-year-old Smithfield Street Bridge can currently carry only 1 trolley/span in each direction. Multicar express operations on exclusive right-of-way are only possible into the downtown area without massive disruption if the soon-to-be-abandoned Panhandle Railroad Bridge and right-of-way are used. This is the same alignment as that proposed for Skybus.

3. A systemwide signal system, power transmission, and distributors are needed. All existing facilities are old, obsolete, and in need of replacement. Stage 1 will include replacement of all such facilities throughout the 35.7-km corridor to ensure reliability and permit operations by both PCC cars and LRVs.

4. A track system must be built in areas previously proposed for abandonment. New track will be constructed along the alignment previously proposed for Skybus since no resources were allocated for renewing trolleys in the 16.9-km corridor. The remaining South Hills corridor trackage will be reconstructed in stage 2, since initial upgrading has been accomplished as part of the current rail rehabilitation element by the Early Action Program.

5. Bridges located in the corridor formerly scheduled for a transit expressway will be renovated or reconstructed to support the LRV. Although further engineering study will be required, recent bridge work performed in the Saw Mill Run Valley and in the Library extension as part of the Early Action Program should prove satisfactory until stage 2 of the LRT plan is initiated.

6. The on-street operation of vehicles in downtown Pittsburgh is a subject of considerable discussion. The Parsons Brinckerhoff-Gibbs and Hills team is currently examining three basic schemes. One is the alternative recommended by the independent consultant; see Figure 2. This loop arrangement includes LRT tracks on selected downtown streets adjacent to the curb, the creation of an exclusive right-of-way between street intersections, and the operation of LRVs against the flow of vehicular traffic. The second is Pittsburgh's traffic management study alternative; see Figure 3. This stub-ended alternative places the LRT line exclusive on Fifth Avenue; the alignment is underground at Grant Street and operates at grade on the remainder of Fifth Avenue to Liberty Avenue. The third is an underground alignment yet to be determined that provides at least the same level of service as the recommended on-street alignment. The narrow streets—58-m (36-ft) travelway and 88 m (55 ft) between building faces—necessitate detailed engineering studies and trade-off analyses. No aerial alternatives have been suggested since they would have a negative visual impact.

7. Throughout the 35.7-km corridor, isolated improvements are scheduled to increase operational safety, efficiency, and reliability and to improve ridership. These items include (a) double- rather than single-track operations in restricted areas, (b) park-and-ride facilities at some stations, and (c) grade separations and extensions of exclusive right-of-way.

When the stage 1 improvements are completed in the early 1980s, stage 2 is planned to follow immediately thereafter; it is scheduled for completion in the mid-1980s. This will bring the South Hills LRT system to completion as planned.

CONCLUSIONS

Pittsburgh is now moving ahead with stage 1 of its LRT system as the result of an independent consultant's 1976 study of alternative systems in the South Hills corridor. The recommendation was based on a variety of measurements, including financing feasibility, operational efficiency, public acceptability, service characteristics, technological accessibility, safety, and environmental impact.

One of the most important advantages of an LRT system in the South Hills corridor was that it would be compatible with the existing guideway system; it could also be easily staged. Both PCC cars and the new LRVs could operate over both the old and the new parts of the system. Trolleys operate on downtown streets today in greater numbers and over greater lengths of street than was proposed in some of the recommended alternatives.

The process Pittsburgh underwent may hold some lessons that could be of assistance to other cities in completing rapid transit systems regardless of the mode selected.

1. We know that a consensus must be reached before transit actions and expenditures can be initiated; however, we have also learned that a consensus must be sustained for a long period of time.

2. Major capital expenditures for rapid transit programs may therefore have to be committed for the time that political office holders will remain in power. To sustain a program that is not well under way before a major political change is made seems to be difficult, if not impossible.

3. Planning incremental programs seems to be the correct approach to constructing large systems; however, they too must be completed expeditiously.

4. Pioneering new technology is exciting, but experimenting in a dense urban environment is demanding and exceedingly difficult. These efforts must be made with great care, great control, and great budgets to accommodate the unknown.

5. Wise allocation of scarce resources requires careful review of what is available and in place locally rather than initial advocacy of new programs that uproot and replace.

The 10-year controversy over the South Hills corridor seems to be at an end; perhaps progress will now indeed be rapid to assist the citizens of Allegheny County in moving more freely and reliably by public transit.

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Part 3
Planning and Socioeconomic Aspects

Light-Rail Transit: Less Can Mean More

Peter Straus, San Francisco Municipal Railway

Perhaps the single most appealing and most useful characteristic of light-rail transit (LRT) is its inherent flexibility. Yet engineers and planners have sometimes overlooked the opportunities that accrue from this flexibility and have tried to use LRT to create a system as much like conventional rapid transit as possible at less than rapid transit's cost. This paper explores LRT's flexibility to operate in a conventional rapid transit environment, as well as its ability to not operate in a rapid transit environment. LRT is also at home in contexts more typical of the bus mode. This provides for a broad range of designs between these two extremes and allows optimal design choices to be accommodated. Design options considered in this paper include right-of-way treatment, approaches to fare collection, grade and curvature alignments, high- versus low-level platforms, signal and vehicle-protection requirements, and trade-offs between speed and capacity.

Every conference or meeting concerned with light-rail transit (LRT) in the few years since it once again became respectable seems to have included several papers that attempt to define what this reborn creation—LRT—really is. But between the definitions and the applications, transit professionals have sometimes demonstrated a reluctance to forsake the full-scale rapid transit on which many of us were nurtured in favor of the full potential that LRT actually holds. We have frequently tended to shoot for the moon. Fortunately or unfortunately, that is not where our potential patrons wish to go.

When the early advocates—or more properly the defenders—of LRT sought to retain and improve the remnants of the nation's streetcar empires in the 1950s and 1960s, this attitude was understandable and necessary. It was essential that some of the attributes commonly associated with conventional rapid transit be introduced to upgrade streetcars into what is now known as LRT, but it is equally important to stress today that LRT still stands for "light-rail transit" and not necessarily for "light rapid transit."

It is a difficult distinction to draw; certainly LRT service should be as rapid as possible. But the connotations of what we know as rapid transit go somewhat further. The term "rapid transit" is associated with multiple-unit operation, high-level platforms, and completely grade-separated rights-of-way. Although LRT is flexible enough to operate in such an environment, the point is that LRT is flexible enough not to operate in this environment as well, and that is perhaps what distinguishes it.

LRT is often defined as an intermediate-capacity mode appropriate for 5000 to 20 000 passengers/h. It can be that, but it can offer much more. The flexibility of LRT gives it a chameleonlike ability to blend with its surroundings.

Until the resurgence of interest in LRT, the workhorses of domestic public transit service were two: heavy-rail transit (either commuter rail or conventional rapid transit) and the local-service bus. These modes define two extremes; when either one satisfies local needs and requirements fully and cost-effectively, LRT has relatively little to offer as an alternative.

However, the situations we face as planners are frequently not so simple. In considering transit improvements in an urban corridor or region, particularly on the microlevel of analysis, there will typically be a segment in which the characteristics of high-speed, high-density, grade-separated rapid transit will appear very attractive, while relatively low-density, single-vehicle service is all that is called for elsewhere, and only a minimal capital investment seems justified. Planners, like everyone else, seek the best of both worlds and struggle to avoid such choices.

What are the choices? One is to provide a trunk rapid transit facility with extensive feeder bus networks connecting to it. But LRT offers another alternative when the capacity of full-scale rapid transit is not called for: It can serve both the rapid transit line-haul and local feeder functions with a single vehicle, reduce the need for transfers between modes, and reduce the need for compromise. On a systemic basis, LRT may offer a greater number of network trips with fewer transfers.

Cannot express buses serve that function equally well and at lower cost? Costs of course are deceptive, since capacities differ and a light-rail vehicle (LRV) can be expected to remain serviceable two to three times as long as the average motor coach—20 to 30 years versus 10 to 15 years—and so on. On the basis of amortized costs, buses may remain less expensive, but the gap narrows. Buses remain unable to achieve such benefits of rapid transit trunk-line operation as high capacity and its corollary, high operator productivity; the speed and safety of operation afforded by signaling, automatic speed protection or full automatic train operation; or high-level, and hence high-speed short-dwell (and fully accessible), boarding and alighting of passengers.

Again, for LRT these are design choices rather than design requirements. The options for different levels of service and different levels of cost (1, 2, 3, 4, 5, 6) are shown in Table 1. The potential range of alignments is represented in Figures 1 to 5, which show various portions of San Francisco's Municipal Railway (Muni) system. Other major design options offered by LRT in virtually any permutation that suits a given context include:

1. Four-axle nonarticulated, six-axle two-section articulated, eight-axle three-section articulated, or larger units;
2. Single-unit, coupled-train, or fully train-lined multiple-unit (usually up to four-car) operation;
3. Fully manual operation, manual operation with wayside signaling, manual operation with automatic speed protection, or automatic train operation;
4. On-board, station, or self-service fare collection;
5. High-level or low-level platforms or street loading;
6. Single-ended or bidirectional vehicles; and
7. Urban, interurban, or suburban passenger operation or mixed passenger and railroad freight service.

Almost without exception, these choices are nonbinding: Any combination can be made compatible with almost any other combination elsewhere in an integrated system and usually even elsewhere on a single line. LRT allows high-speed, fully grade-separated facilities to be built and used to advantage where they are desirable, feasible, and affordable. But on other portions of a line, where geography, cost, politics, or service considerations suggest or require a simpler facility, semiexclusive or even mixed-traffic route segments can readily be taken in stride. There is even a location in Cologne in which a short single-track segment is used to advantage to ingeniously provide the simplest of turn-back facilities in the center of a narrow street on a relatively low-density branch. Double-ended cars can stop, wait, and reverse without blocking either traffic stream (Figure 6).

Table 1. Capacities and costs of six options for LRT alignments (1976-1977).

Option	Passengers per Hour (000s)	Cost of Two-Track Right-of-Way ($000 000s/km)	Station Cost ($000 000s)
Exclusive subway right-of-way	20 to 30	12 to 22	5 to 15
Exclusive aerial right-of-way	20 to 30	2.5 to 11	1 to 5
Exclusive grade-separated surface right-of-way	20 to 30	0.6 to 3.1	0.5 to 4.0
Semiexclusive surface right-of-way in median or at side of road with grade crossings	10 to 20	0.4 to 0.6	0.2 to 1.0
Separated but in-street (or mall) surface right-of-way (incremental expense)	10 to 20	0.6 to 0.9	0.2 to 1.0
Mixed-traffic surface operation	5 to 10	0.6	0 to 0.5

Note: 1 km = 0.6 mile.

Figure 1. Exclusive subway right-of-way: Muni's Castro Street Metro Station during tests.

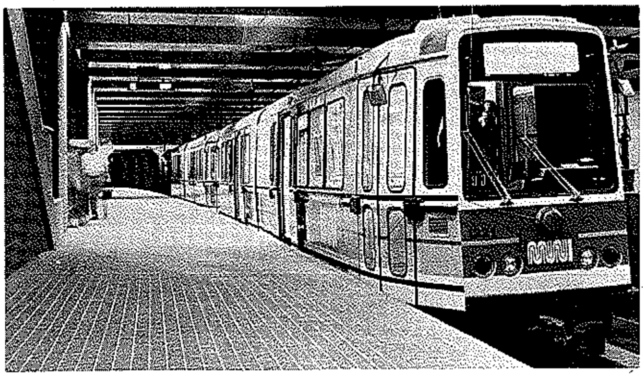
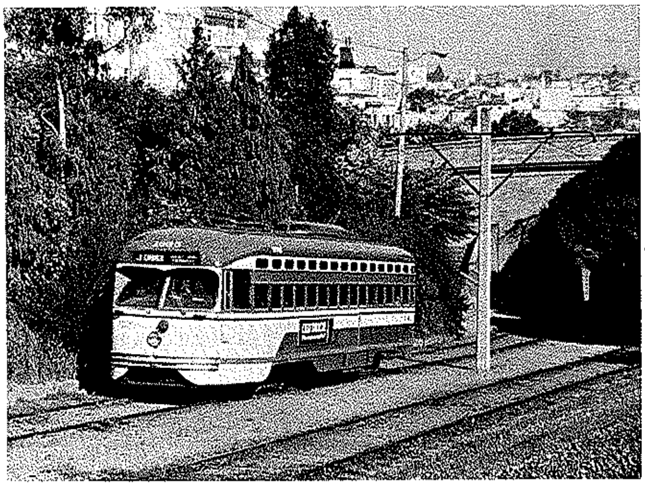


Figure 2. Exclusive surface right-of-way: J Line in Mission Dolores Park.



SIX ASPECTS OF LRT SYSTEM DESIGN

Automated Versus Manual Control

In most contexts, manual operation or manual operation with automatic speed protection can provide the same level of service as more automated systems but at lower capital and maintenance-related labor costs and with less potential for operating problems. The benefits of full automation accrue only when it is applied to a full line, which must then be fully grade separated; this is usually not the case for LRT. Advanced technology is unnecessary unless the benefits can be clearly demonstrated.

Figure 3. Semiexclusive surface right-of-way: Junipero Serra Boulevard on K Line.

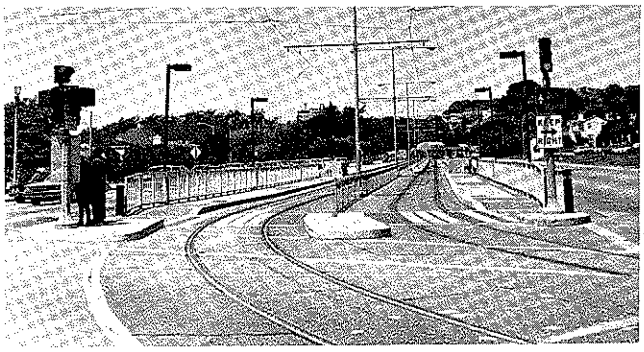


Figure 4. Separated in-street surface right-of-way: raised median on Judah Street along N Line.

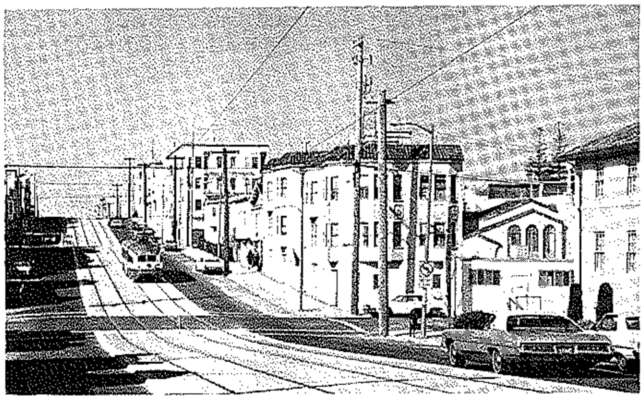


Figure 5. Mixed-traffic surface operation (with boarding islands): Ocean Avenue on K Line.

Railroad, Rapid Transit, and Streetcar

It seems to be necessary to make a conscious effort to fulfill LRT's potential for maximal service from minimal facilities and to avoid inadvertantly achieving minimal service by overbuilding the facilities. Building to railroad or rapid transit standards of speed, grades, and signals may produce designs geared to needlessly overbuilt rights-of-way and needlessly limited capacity. Safe LRT operation can be maintained with minimal train-protection features. Line-of-sight operation, supplemented by cab or wayside signals, is fully adequate in most situations. For most surface applications, those not familiar with LRT should be encouraged, when considering signaling and vehicle and right-of-way protection, to think more in terms of what bus operation entails than of the usual conventional rapid transit or railroad practice. This concerns not only engineers and planners but also legislators and regulators, who are beginning to express an interest in the establishment of regulations and standards for design, construction, and operation of LRT systems. If LRT's principal utility derives from its flexibility, it is crucial that this flexibility not be needlessly circumscribed by the regulatory pen.

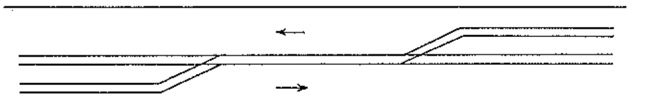
Fare Collection

Off-vehicle, station fare collection is very attractive in concept, but even in a center-city context it may carry with it needlessly high labor costs. For nine stations, Muni will require nearly 70 station agents, as well as supervisory personnel, at a cost that may exceed $1 million/year. If the expected passenger volumes will permit on-vehicle collection, at least at certain hours, a system might be planned to allow an option that does not require fully manned stations at all times. San Francisco's LRVs will not readily accommodate on-board collection at high-level station platforms. The key in this case lies in system planning: Station fare collection costs can be controlled by car design, station design, or fare-structure design.

In high-volume transit operations, boarding time frequently becomes a major source of delay. In San Francisco it was found that on several central-area trunk bus-route segments, boarding accounts for an average of about 14 percent, and sometimes as much as 33 percent, of vehicle running times (7). Typically, the percentages are far more significant than those associated with the traffic delays planners habitually lament. As Table 2 indicates, "general backup" was never either a primary or secondary cause of delay. The usual rail transit solution, based on station fare collection with agent-staffed stations, is excessively labor intensive for most LRT and even some rapid transit applications. One LRT alternative that has emerged from European experience has been the use of prepaid, self-service fares. This system, developed for LRT to permit multisection high-capacity cars and multiple-unit train operation on surface lines without conductors or operators on each unit, typically requires each passenger to purchase a valid ticket or pass before boarding. All doors are then available for boarding or alighting, even at simple street-level stops, and there are no delays at the fare box. Inspectors check that all passengers have valid tickets or passes on a random basis; fines cover most (or potentially all) of the combined costs of cheating and inspection.

The self-service fare system has proved so successful in reducing costs and increasing labor productivity—not to mention improving service—that it has been applied to conventional buses, rapid transit, and railroad trains as well.

Figure 6. Diagram of single-track segment on Dürener Strasse in Cologne.



Grades and Curvature

Since they had their origins in streetcars, LRT systems in existence, when implementing system improvements, have continued to exploit the fact that there are fewer limitations on gradients and curvatures for LRT than for conventional rapid transit (8, 9). These limitations are typically as shown below (1 m = 3.3 ft):

Type of Vehicle	Maximum Gradient (degrees)	Minimum Radius of Curvature (m)
Boeing Vertol LRV	9.0	13
Conventional rapid transit	5.0	75 to 180

As in the case of other items, these are not rigid limits. Conventional rapid transit can be designed to less demanding standards, and some LRT equipment cannot achieve the limits described above, although historically ordinary streetcars have frequently operated over tighter curves and steeper grades, too. But these figures indicate that LRT can be comfortably designed (and components are readily available) to operate on alignments far less restrictive than those necessary for a conventional rapid transit design.

The grade and curve alignments typical of LRT obviously allow it to be brought to where the customers are far more readily and at far less cost. Conventional rapid

Table 2. Major and secondary causes of delay on selected San Francisco street segments.

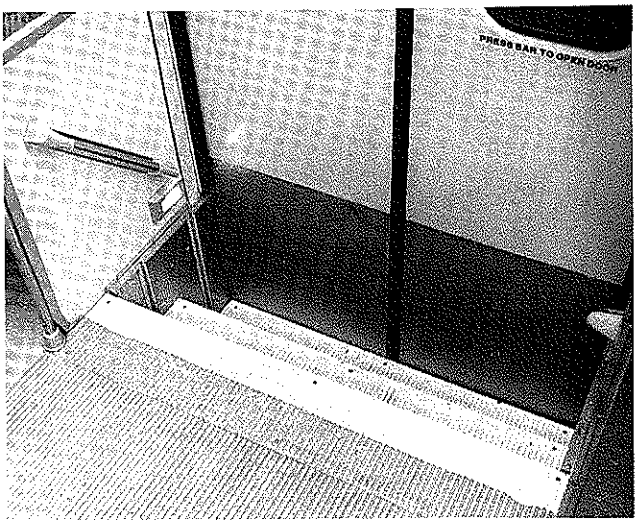
Street	Segment Length (km)	Major Cause of Delay	Percentage of Running Time	Secondary Cause of Delay[a]	Percentage of Running Time	Street	Segment Length (km)	Major Cause of Delay	Percentage of Running Time	Secondary Cause of Delay[a]	Percentage of Running Time
Sacramento	1.16	Loading	33.5	Signal	9.9	Chestnut	0.56	Loading	15.4	—	—
Third	0.97	Loading	27.0	Signal	13.9	Castro	0.24	Loading	14.8	Signal	9.1
Columbus	1.77	Loading	24.2	Signal	15.9	Sutter	0.56	Signal	16.5	Loading	12.3
Kearny	1.03	Signal	26.0	Loading	24.0	Post	0.85	Signal	21.8	Loading	11.8
Mission	2.26	Loading	23.0	Signal	11.1	Divisadero	2.26	Loading	10.5	Signal	9.0
Clay	1.18	Loading	22.4	Signal	15.0	Stockton	1.63	Loading	10.4	—	—
Geary	1.87	Loading	21.6	Signal	10.9	Clement	1.16	Loading	7.5	—	—
Van Ness	2.89	Loading	20.7	Signal	14.8	O'Farrell	1.60	Signal	9.7	Loading	6.3
Union	1.21	Loading	20.5	Signal	11.1	Polk	1.11	Signal	4.0	Loading	4.0
Carl and Irving	1.77	Loading	16.7	Signal	6.0						

Note: 1 km = 0.6 mile.

[a] If greater than 5 percent of running time.

Figure 7. High-low step on Boeing Vertol LRV in raised position for high-level platform loading.

Figure 8. High-low step on Boeing Vertol LRV in lowered position for surface operation.

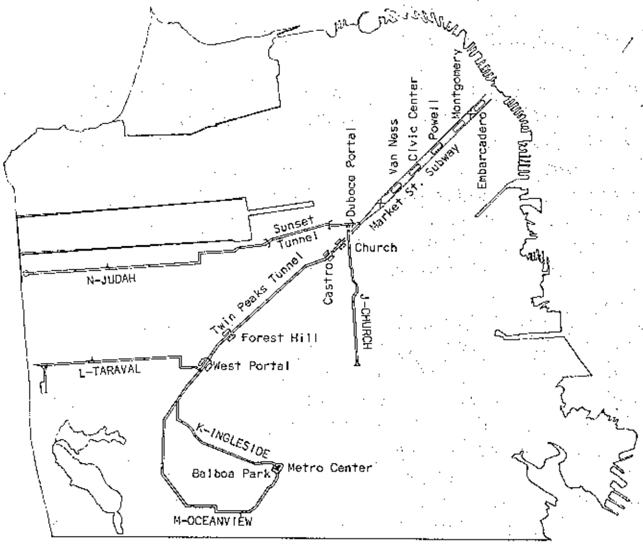


transit usually requires a compromise among fewer feasible alternative alignments; its final design is likely to be more costly than that of LRT, yet it still may not be able to achieve the station designs and locations that are feasible for LRT.

Speed

High operating speed can become an elusive goal. Earlier this year, the Bay Area Rapid Transit system reduced its normal maximum operating speed from 129 to 113 km/h (80 to 70 mph) because it was found that the lower speed would result in improved reliability and performance of traction motors, which in turn would result in a slightly slower but more reliable and less breakdown-prone operation. Reliability is generally more important in attracting and maintaining patronage than speed per se. Also, higher speed operation re-

Figure 9. Muni Metro system's existing and committed facilities (not to scale).



quires greater distance between trains, which in turn can mean lower capacity as measured by the number of trains that can be safely operated past any particular stop. In a system with close stop spacing, even the difference between 56 and 81 km/h (35 and 50 mph) in maximum speed operation can become insignificant. On Muni's system, LRV trains will be able to run from Van Ness Avenue to the Embarcadero Station, including 15-s station stops, in about 4.3 min with a top speed of 81 km/h; at a top speed of 56 km/h, it would take about 5.2 min (10). In percentage terms this would appear to be significant, but it is still only 1 min.

Station Platforms

High-level platforms will speed boarding and be more convenient for passengers but, unless all stops are at high-level platforms, will require a car with a high-low step device, such as that shown in Figures 7 and 8. San Francisco, like a number of West German LRT systems, has opted to accept this combination—high-level subway platforms and low-level surface loading. We do not regret this decision, but it is unfortunate that our car's design does not allow a high-low step to be provided at the front door, which effectively prevents on-board fare collection in the subway. This restriction is vehicle specific, however, and is in no way a general characteristic of LRV design.

Neither Boston, Toronto, nor other present North American LRT operators, however, have chosen to convert their LRT systems to high- or mixed-level boarding, and the Boston and Toronto cars on order do not provide for movable steps. The existing domestic operators, other than Muni, have for the moment at least chosen to avoid the cost of even limited conversion. Although new systems will not be faced with this constraint, high platforms (or a car design that requires off-vehicle fare collection) are still features a new system may not wish to include in an initial operation, e.g., upgrading an existing rail line. Another point to consider is that high-level platforms, particularly for typical American LRT car widths of 2.60 to 2.75 m (8.5 to 9.0 ft), would interfere with normal railroad clearances; mixed passenger and freight use of a rail line would therefore require either low-level platforms or gauntlet or bypass tracks. Again, LRT has the flexibility to allow (but not require) the simpler construction of surface loading, if only initially.

SAN FRANCISCO'S EXPERIENCE

It may be appropriate at this point to cite some further examples from Muni's experience in San Francisco. Muni operates five streetcar lines, currently using Presidents' Conference Committee (PCC) cars, which feed into a Market Street surface trunk line at present. As San Francisco phases into what will be called Muni Metro operation with LRVs, the five surface routes will funnel into a Market Street trunk subway instead (see Figure 9).

Neither now nor in the foreseeable future will the system be converted to full rapid transit. San Francisco, even with federal assistance, could not afford to build five fully grade-separated rapid transit lines on the alignments of all five present lines. The expected passenger volumes could not justify such construction, nor would a reduced system with additional transfers and several short rides be a desirable option in an area as physically small as San Francisco. It may also be crucial that none of these alternatives would be acceptable to San Francisco's residents.

And so, as was illustrated in Figures 1 to 5, San Francisco is now reconstructing its lines for LRT operation in private rights-of-way, in semiexclusive rights-of-way, and in streets for mixed-traffic operation. Is there a price—in longer running times, less reliable schedules, and so forth? Of course there is, but there are also the benefits of better coverage, fewer transfers, more convenient neighborhood access, fewer undesirable impacts as perceived by residents, and a far lower capital cost.

Another example is provided by the subway facilities into which San Francisco's five surface branches will run. This facility has been built to full rapid transit standards. Indeed, it was originally intended to function as such, although now it is extremely unlikely that any such full-scale conversion will ever take place.

High platforms in the subway, unlike those used by similar LRVs in Boston, will make boarding quicker and easier. But they will also increase our labor costs appreciably because of the probable need to provide station agents at all hours of subway operation. This is not to suggest the subway should necessarily have been built with low platforms, which would have allowed front-door entry and on-board fare collection. Once again, however, future systems would do well to ensure that, by virtue of station design, vehicle design, and fare-system design itself, conventional rapid transit fare collection at stations is not required when less costly options available to LRT may be preferable, at least at certain hours.

BUILDING BLOCKS: PRE-METRO AND SEMI-METRO

The varied system components that have been discussed can be assembled to form two generic types of LRT systems. Under one approach, called pre-metro by our European colleagues, LRT represents an incremental strategy in which the ultimate goal is seen as conventional rapid transit and LRT is introduced initially to hold down investment until full rapid transit capabilities are actually required. Two examples of pre-metro systems are the Brussels and the German Rhein-Ruhr systems; the closest domestic example may be the Ashmont-Mattapan portion of Boston's Red Line. The other approach is to build LRT simply as LRT, without viewing upgrading to full metro rapid transit standards as an ultimate goal at all. In Europe the term semi-metro is used to describe such a system.

In practice, planners have sometimes preached the latter approach but followed the former. Needlessly designing to pre-metro standards can be both extremely wasteful and limiting.

It should be noted that even some of the European pre-metro systems are having second thoughts as to the necessity for that approach. With the successful development of several designs of high-low step devices (which allow LRT vehicles to use high-level platforms in a subway) and similar features, there is no need for a clean break between LRT and full metro status. Instead, lines can be improved and upgraded on a systemwide incremental basis, with no need to focus on a single line to elevate it from pre-metro status. Brussels, the best known example of a pre-metro operation, built a first line it intended to later upgrade from pre-metro low platforms to a high-platform metro line. Although this is being completed, subsequent lines will probably follow a semi-metro design with incremental upgrading. Similarly, the Rhein-Ruhr system is being established as a high-grade LRT system, and the original concept of formal upgrading to conventional rapid transit will probably be abandoned. Other systems that initially considered a pre-metro or metro orientation and switched to a commitment to simply high-quality LRT include Hannover and, for that matter, Muni.

CONCLUDING COMMENT

LRT can offer solutions for many of our cities' transit needs. When considering LRT, planners need to examine both ends of the LRT spectrum. The point is that less can mean more, that LRT offers low-capital and low-operating-cost choices, and that it is frequently in scaling down that the opportunities offered by LRT are found.

LRT is attractive because it is a workable, flexible, proven system. New technology and sophistication are not ends in themselves. The goal is simply good, reliable, affordable transit service, and LRT can help provide it.

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Effect of Varying Light-Rail Design Standards

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Light-rail transit (LRT) is a flexible transit mode that can be implemented in a variety of ways. This complicates the task of comparing it with other modes when carrying out the alternatives analysis required by the Urban Mass Transportation Administration to secure federal funding for fixed-guideway transit projects. A recent study for Santa Clara County, California, dealt with this problem by evaluating four possible variations in LRT design standards. This paper draws on the results of that study. It features a description of the study area and site conditions, a definition of the four LRT design standards considered, analysis of the different capital costs associated with each design standard, a discussion of the range of estimates of expected patronage, and a review of the resulting operating requirements and costs. The paper then presents a detailed comparison of the cumulative impact of these design differences on the cost-effectiveness measures for the bus alternatives that were also analyzed in the Santa Clara County study. It was found that, while capital costs for LRT can vary significantly according to the assumed design standard, the cost-effectiveness is primarily dependent on other factors. It is therefore concluded that alternatives analysis requires the study of only one LRT design standard to establish the relative advantages and disadvantages of transit mode alternatives for a given metropolitan area.

Santa Clara County is a dynamic urban area located at the southern end of San Francisco Bay. Once known for its famous fruit orchards, today the county is one of the world's foremost centers of advanced technology. As a result of expected continued growth in the computer, laser, electronics, and space satellite industries, Santa Clara County is projected to grow to about 1 500 000 people and 725 000 jobs by 1990, the design year for which the current transportation studies are being undertaken. The urbanized area of the county encompasses some 712 km^2 (275 miles^2), most of which are contained in a broad, flat valley with relatively few topographical restrictions.

The county developed very rapidly in the years following World War II and followed a leap-frog pattern of single-family subdivision development that was fostered by an abundant supply of cheap land and an ever-expanding highway system. No strong downtown area exists today, but the largest city, San Jose, has a population of almost 600 000. Commerce and industry developed principally in a linear form along the main-line railroad and freeway that connect San Jose with San Francisco, 80 km (50 miles) to the north.

The county's existing transportation system consists of an excellent system of freeways, expressways, and arterial streets on which more than 800 000 motor vehicles operate, a fledgling transit system consisting of 234 buses, and a commuter railroad line to San Francisco. Plans and funding exist to expand the transit system to 516 buses by 1980, and recent studies have recommended the upgrading and expansion of the service offered by the commuter railroad line.

The county has adopted a long-range goal of serving 30 percent of the region's daily trips by public transportation (1). Seeking to move toward this goal, the Santa Clara County Transit District in 1976 undertook a study of the engineering and economic feasibility of implementing a light-rail transit (LRT) system within five designated study corridors representative of typical conditions encountered in Santa Clara County. In addition, an alternatives analysis was undertaken as part of this study; it included consideration of a number of different bus alternatives (2).

The five corridors designated for study by the county totaled 56 km (35 miles) in length. They were selected for a variety of reasons, including ready availability of right-of-way, the need to provide service to portions of the county that lacked major highway links, and expected relief of traffic congestion. The right-of-way conditions encountered in these corridors generally fell into three major categories that had distinctly different design conditions. The first type of right-of-way consisted of land that was originally purchased for major freeway facilities that may never be built. These rights-of-way are quite wide; they vary from 46 to 76 m (150 to 250 ft) in width. The second category involved the use of excess land adjacent to existing rail lines. These rights-of-way were generally narrow—23 to 30 m (75 to 100 ft)—and had a single freight track down the center of the right-of-way. The third right-of-way category involved the use of the medians of arterial streets. These median strips either already exist or could be readily created by reconstruction and widening of the streets. Many arterial streets in Santa Clara County have sufficiently wide rights-of-way to permit a raised median of 7.6 to 9.1 m (25 to 30 ft) for two LRT tracks. In most cases, however, this would also require closing a number of minor cross streets and eliminating most left-turn lanes, which would affect local traffic circulation.

In order to minimize the capital cost, as well as for other considerations, it was decided that the study should focus principally on at-grade construction, with no underground facilities at all; aerial construction would be used only where it would be clearly advantageous to do so.

DESIGN STANDARDS CONSIDERED

The first LRT design standard to be considered was based on a review of modern European LRT design practices. It was termed the base-case design alternative and represents a workable solution that could be implemented with a high degree of safety. It may not, however, be completely in conformance with the existing regulations of the California Public Utilities Commission (PUC) and is not completely consistent with the stated requirements of the Southern Pacific Transportation Company (SP) for possible joint use of railroad rights-of-way. In the base case, the light-rail vehicles (LRVs) to be used were assumed to be capable of accelerating at 1.3 m/s^2 (4.3 ft/s^2) to a top speed of 100 km/h (60 mph). Station locations were selected that resulted in an average spacing of 1.3 km (0.8 miles) throughout the five study corridors. Station dwell times were assumed to be 10 to 15 s on the average. The right-of-way assumed in the base case was a fully reserved, at-grade right-of-way with traffic signal preemption at all cross streets. Grade separations were provided only at crossings of freeways and heavily congested arterial streets. The average LRT operating speed resulting from all of these conditions was estimated to be about 43 km/h (27 mph).

The SP-PUC design standard did try to fully meet the requirements of the PUC and the SP. It featured complete grade separation of railroad and LRT facilities at all railroad crossings (including spur tracks) and a separate, fenced right-of-way when the LRT alignment was at grade and adjacent to a railroad line.

A lower cost design standard assumed a minimal-cost LRT system that shared right-of-way and bridge structures with the railroad wherever possible, had grade separations only at freeway and railroad main-line crossings, and had a minimal signaling and control system. Its average speed was estimated to be about 35 km/h (22 mph).

The higher cost LRT design standard differed from the base case in that additional structures provided for complete grade separation of all major arterial streets and all railroad main and branch lines; increased amenities and higher architectural design standards were provided at stations; and improved landscaping was provided along the route. Some at-grade crossings of railroad spur tracks and minor cross streets were still permitted, however. The resulting average speed was estimated to be about 51 km/h (32 mph).

The comparison below further defines the differences among the four LRT design standards described above (1 km = 0.6 mile).

Item	Base Case	SP-PUC	Lower Cost	Higher Cost
Guideway, km				
At grade	53.84	48.66	55.19	42.60
Aerial	4.13	9.32	2.78	15.37
At-grade crossings				
Highway	58	46	61	24
Railroad	15	0	16	3
Stations				
At grade	39	33	41	18
Aerial	5	11	3	26
Estimated avg speed, km/h	43	43	35	51

CAPITAL COSTS

The unit costs used in preparing the estimates of capital costs for each transit alternative were based on the latest available information, including bid prices, manufacturers' estimates, and data developed recently by De Leuw, Cather and Company for similar transit studies in Pittsburgh, Denver, and Los Angeles, as well as a national LRT study sponsored by the Urban Mass Transportation Administration. Prices were updated to June 1976 dollars, and adjustments were made for specific construction-cost conditions currently prevailing in Santa Clara County. It is important to note that these study cost estimates were very general and were based on limited field investigations and conceptual development of the alternatives. Although this provided a valid basis for comparison, more detailed cost estimates would eventually be required for the selected alternative. A contingency allowance of 25 percent was included to cover unexpected or unforeseen costs that might arise during detailed design or construction.

The LRT capital cost estimates considered such individual cost elements as guideways; trackwork; power supply; control and communications; stations and stops; parking lots; street, railroad, and utility relocation and reconstruction; yards, shops, and maintenance facilities; right-of-way acquisition; vehicles; agency costs; design preparation and construction supervision; and a contingency allowance for unforeseen items. The capital costs for each of the four design standards, summarized in Table 1, were all based on the five-corridor network specified by the county and involved a combination of the rights-of-way described earlier. For all design standards except lower cost, a six-axle articulated LRV similar to the Boeing Vertol car was assumed. For the lower cost alternative, purchase of used and reconditioned Presidents' Conference Committee (PCC) vehicles (such as the San Francisco cars) was assumed.

The cost for the SP-PUC standard is higher than that for the base case primarily because of

1. Increased guideway costs for the addition of grade separations at all railroad crossings,
2. Increased guideway costs for a 2.4-m (8-ft) high fence in sections that are at-grade and adjacent to a railroad,
3. Additional station costs where stations had to be aerial rather than at grade,
4. Additional station costs for pedestrian overpass structures over railroad tracks at appropriate stations, and
5. Increased right-of-way costs wherever the alignments are at grade along a railroad to cover the additional cost of the wider section required for a separate, fenced transit right-of-way.

The capital costs for the higher cost standard varied from the base case design alternative principally in the following areas:

1. Guideway costs were significantly higher because of additional grade separations,
2. Signalization and control costs were lower because of fewer at-grade crossings,
3. Landscaping costs were increased to allow for some additional beautification,
4. Additional station costs were included since some stations had to be aerial, and
5. Station costs were increased to allow for additional architectural design treatment and amenities.

For the lower cost design standard, the major sources of differences from the capital costs of the base case were

1. Lower vehicle costs as a result of the assumed purchase of refurbished PCC vehicles,
2. Lower guideway costs due to fewer grade separations and the sharing of freeway crossings with the railroad wherever possible on existing railroad structures, and
3. Lower overall control costs since there would be a minimal signal system with no automatic train protection system (but some increased control costs due to more at-grade crossings or signals and gates).

It can be seen from the data presented in Table 1 that varying the assumed LRT design standard significantly affects the system capital costs. Using the SP-PUC

Table 1. Capital cost estimates for the four LRT design standards.

Cost Element	Base Case ($000 000s)	SP-PUC ($000 000s)	Lower Cost ($000 000s)	Higher Cost ($000 000s)
Guideways	55.29	79.55	48.15	120.89
Trackwork	25.55	25.55	25.55	25.55
Electrification	29.83	29.83	29.83	29.83
Control	27.24	25.96	13.16	22.05
Landscaping	2.15	2.15	2.15	4.25
Noise barriers	0.61	0.61	0.61	0.61
Stations	2.85	5.75	2.05	17.00
Parking lots	18.30	18.30	18.30	18.30
Street reconstruction	11.45	11.76	11.45	9.66
Relocation of railroad tracks	1.40	1.40	1.40	1.40
Utility relocation	1.70	1.70	1.70	1.70
Right-of-way	17.60	15.02	17.60	14.54
Vehicles	33.75	33.75	4.69	33.75
Communications	0.29	0.29	0.38	0.29
Yards and shops	10.00	10.00	10.00	10.00
Yard right-of-way	0.86	0.86	0.86	0.86
Agency cost	28.66	31.50	22.55	37.28
Total	267.53	293.98	210.43	347.96

Note: Dollar figures shown are June 1976 dollars and include a 25 percent contingency allowance on all elements except agency costs.

Table 2. Projected operating requirements, annual costs, and fare revenues for the four LRT design standards.

Design Standard	Fleet Size[a]	Annual Vehicle Hours Operated	Annual Vehicle Kilometers Operated (000 000s)	Annual Cost ($000 000s)	Fare Revenues ($000 000s)
Base case	45	115 000	4.3	5.53	2.92
SP-PUC	45	115 000	4.3	5.53	2.92
Lower cost	75	140 000	4.6	5.85	2.43
Higher cost	45	100 000	4.8	6.00	3.40

Note: 1 km = 0.6 mile.

[a]Vehicles are similar to the Boeing Vertol LRV, except for the lower cost alternative, which is based on single-unit vehicles like the PCC cars.

standard instead of that for the base case would result in a cost about 10 percent higher, while the higher cost and lower cost alternatives would result in 30 percent higher and 21 percent lower capital costs than the base case respectively. The total difference between the most costly and least costly LRT design alternative was $137.53 million; this is more than 65 percent of the estimated cost of the lower cost design alternative. This results in an average capital cost per kilometer that varied from $3.6 million to $6.0 million ($5.8 million to $9.6 million/mile) depending on the design standard assumed.

Where absolute capital cost is of prime importance in transit mode selection, it is obvious from the above figures that the LRT design standard assumed will be of great significance. Most cities, however, will wish to base their choice of a transit system on a much broader set of criteria than capital cost alone. The following sections of this paper illustrate the impact of alternative LRT design standards on such other key areas as patronage, operating costs, and other factors needed to judge overall system cost-effectiveness. To place these in perspective, comparable figures for all-bus surface alternatives and a busway alternative are then presented.

SYSTEM PATRONAGE

A disutility factor model was used to estimate patronage on the LRT network and its supporting collection and distribution local-service bus system (2). It was found that the use of this model produced a base-case patronage forecast for the LRT system of 10 000 peak-hour riders in 1990; there would be an additional 11 500 riders on the local bus network. This combined transit ridership represented about 5.5 percent of the total expected peak-hour travel in the county in 1990.

The SP-PUC design standard would not operate in ways noticeably different from the base case and consequently was estimated to attract the same patronage. The higher cost LRT design standard, on the other hand, could be expected to have average operating speeds about 20 percent higher than the base case since it would experience fewer transit delays as a result of more grade separations at intersecting cross streets. The lower cost design standard would use older vehicles, which would have lower performance capabilities, and would also encounter additional street intersection delays; it would therefore have average speeds about 20 percent lower than the base case. These variations in average speed of operation were used to estimate corresponding differences in probable LRT ridership demand.

The estimated elasticity of transit ridership in response to average line-haul transit speed was found to be 0.7 in the Santa Clara County patronage-forecasting model. Thus the higher cost design standard was estimated to gain 14 percent more riders than the base case, while the lower cost design standard was estimated to attract 14 percent fewer riders.

SYSTEM OPERATIONS, OPERATING COSTS, AND FARE-REVENUE ESTIMATES

The cost-effectiveness comparisons and economic analyses for the different LRT design standard alternatives are dependent on both annual operating costs and farebox revenues. Operating and maintenance costs were developed for the various design alternatives based, insofar as was possible, on experience with similar systems elsewhere (updated to June 1976 cost levels) and adjusted to the specific conditions anticipated for Santa Clara County. Analytical cost data obtained in past studies were also used to temper the empirical cost data. The results are shown in Table 2.

Although there is no noticeable difference between the SP-PUC alternative and the base case, the lower cost LRT alternative is significantly different. Since it would employ smaller, single-unit PCC-like vehicles, 75 of these would be required to handle the same passenger loads as 45 large, articulated LRVs. Its average speeds and passenger demands would be about 20 and 14 percent lower respectively than those of the base case. The same unit cost was used to arrive at an annual operating cost figure of $5.85 million, which is about 6 percent higher than that of the base case alternative.

The higher cost alternative would have an average operating speed about 20 percent higher than the base case, resulting in a corresponding increase in ridership demand and, consequently, an increase in the vehicle-kilometers of service required of about 11 percent. The unit cost would be somewhat lower (about 5 to 10 percent) due to increased vehicle utilization. The higher cost alternative was projected to cost $6.0 million/year to operate, or 8.5 percent more than the base case.

Table 2 also presents the annual fare revenues estimated for each of the design alternatives. Assuming a base fare of 25 cents, fare revenues ranged from a low of $2.4 million to a high of $3.4 million.

COST-EFFECTIVENESS EVALUATION

Benefit/cost analyses were performed for each of the alternatives, and transit efficiency measures, such as costs per passenger and costs per passenger kilometer, were examined. For comparative purposes, data were prepared for the various bus alternatives that were also under consideration in the Santa Clara study. The composite findings for economic cost-effectiveness are presented in Tables 3, 4, and 5. The data displayed in these tables clearly show that the different cost-effectiveness measures attributable to the varying LRT design standards are so closely grouped that they produce the same conclusions when compared to corresponding measures for the various bus alternatives analyzed.

Benefit/Cost Calculations

Two types of benefits were evaluated: primary benefits and potential additional benefits. Primary benefits were time savings for continuing transit-users, time savings for nondiverted automobile users, cost savings for diverted automobile users in automobile operating and maintenance expenses, savings in parking costs, reduction in highway accidents, and time savings for commercial vehicles. The potential additional benefits were those that might be attributable to containment of urban sprawl, reduction in costs of owning second and third automobiles, and time savings for nonwork trips. Discount rates of 7 percent, 4 percent, and 10 percent were used in view of the current lack of unanimity regarding the appropriate discount value for studies of this kind.

The benefit/cost ratios for each of the transit mode alternatives and the design alternatives, both with and without the potential additional benefits, are shown in Table 3. It can be seen for instance that, at an assumed 7 percent discount rate, the benefit/cost ratio for the LRT design alternatives ranged from 0.83 to 0.91; the value for the base case was 0.87. Far more important changes are attributable to varying the discount rate, which results in a benefit/cost ratio of 1.14 at 4 percent, and 0.71 at 10 percent for the base case LRT design. If potential additional benefits are included, the base-case benefit/cost ratio at a discount rate of 7 percent increases to 1.24. It was also assumed that the busway alternative could be implemented under a variety of design standards. Consequently, the benefit/cost ratio for the busway alternative followed a pattern similar to that for LRT. Much smaller ranges are noticeable for the other two bus alternatives.

In no case was the relative ranking of LRT in comparison with the bus alternatives dependent on the design standard assumed. The absolute value of the benefit/cost ratio for the LRT system was more dependent on the discount rate used and whether or not potential additional benefits were included than on the design standard assumed.

Transit Efficiency Measures

Transit efficiency measures are criteria used for evaluating alternative transit systems in terms of their economic efficiency in attracting and moving passengers. They are concerned only with the quantity of direct transit use and service produced by the alternatives and the direct costs associated with providing these.

The productivity measures and costs used in the transit efficiency analysis are based on the patronage levels forecast for 1990. Thus, the transit efficiency analysis is a snapshot in time; that is, the measures depict the efficiency of the transit alternatives at one projected patronage level. The relative transit efficiency of each alternative may be significantly different at other patronage levels. However, no attempt was made to measure the efficiency at different patronage levels or to determine the cumulative efficiency over the life of the transit system. The LRT system, which has larger vehicles capable of operating in trains, is particularly capable, for example, of absorbing additional patrons with only minimal cost increases, whereas bus-oriented systems generally show cost increases almost directly proportional to patronage increases.

Transit efficiency measures provide one means of assessing the economic effectiveness of a transit investment. When viewed together with the results of the benefit/cost analysis, they provide a more comprehensive view of the relative economic effectiveness of the systems under consideration than is possible using either set of indicators alone.

As can be seen in Table 4, there is nearly a direct trade-off in cost-effectiveness between the LRT and busway alternatives; the former are preferred in all operating and maintenance cost categories, and the latter are preferred in all annualized capital cost categories. Both of the nonguideway bus alternatives are superior to either busways or LRT in the total system capital costs per passenger and per passenger kilometer and inferior in measures of operating and maintenance costs.

Total system costs are the traditional bottom line in the measure of overall transit network efficiency. In the base case, the LRT total cost of $1.72/passenger trip is virtually identical to that of the busway alternative ($1.71). Each has a total cost of $0.50/passenger·km ($0.31/passenger mile). This means that either guideway system combined with the 516-bus baseline bus system, which is $0.48/passenger·km ($0.30/passenger mile), would be equally cost-effective; the slight difference reflects the longer average trip length on the guideway alternatives. Both the baseline bus alternative and the bus-preferential-treatment alternative show lower total system costs per passenger trip than the LRT alternative ($1.34 and $1.61 respectively).

There were virtually no significant differences in total costs per passenger-kilometer. Varying the design standards for the LRT alternative did not result in any significant changes in total system cost per passenger or per passenger kilometer and did not produce any change in the relative ranking of LRT in comparison with the bus alternatives.

Subsidy requirements (the total operating cost minus fare revenues) represent a significant continuing cost of the system that is not paid for by transit users and must be paid for by taxes from local, state, or federal governments. The subsidies required per passenger and per passenger kilometer are important indications of the efficiency of a transit system. These data for the Santa Clara County study are presented in Table 5.

The base case LRT alternative shows about a 10 percent subsidy cost advantage over the busway ($0.94/passenger versus $1.05) because it both carries more passengers and costs less to operate. There is a similar difference in subsidy per passenger kilometer for the total combined system. Actually, the significant

Table 3. Benefits, costs, and benefit/cost ratios in 1990 for the transit mode alternatives.

	Primary Benefits Only									With Potential Additional Benefits and 7 Percent Discount Rate		
	Discount Rate of 7 Percent			Discount Rate of 4 Percent			Discount Ratio of 10 Percent					
Alternative	Annual Benefits ($000 000s)	Annualized Costs ($000 000s)	Benefit/ Cost Ratio	Annual Benefits ($000 000s)	Annualized Costs ($000 000s)	Benefit/ Cost Ratio	Annual Benefits ($000 000s)	Annualized Costs ($000 000s)	Benefit/ Cost Ratio	Annual Benefits ($000 000s)	Annualized Costs ($000 000s)	Benefit/ Cost Ratio
Baseline bus system	—	45.98	—	—	44.49	—	—	47.61	—	—	45.98	—
Bus preferential treatment	8.94	15.22	0.59	8.94	14.31	0.62	8.94	16.21	0.55	11.66	15.22	0.77
Expanded bus system	24.38	41.03	0.59	24.38	39.62	0.62	24.38	42.58	0.57	32.74	41.03	0.80
Base case												
Busway	20.58	24.03	0.86	20.58	19.84	1.04	20.58	28.74	0.72	29.59	24.03	1.23
LRT	25.84	29.14	0.87	25.84	22.67	1.14	25.84	36.33	0.71	36.25	29.14	1.24
SP-PUC												
Busway	20.58	26.17	0.77	20.58	21.28	0.97	20.58	31.61	0.65	29.59	26.17	1.13
LRT	25.84	31.14	0.83	25.84	24.02	1.08	25.84	39.06	0.66	36.25	31.14	1.16
Lower cost												
Busway	16.26	22.33	0.73	16.26	18.33	0.89	16.26	26.78	0.61	24.16	22.33	1.08
LRT	20.58	24.71	0.83	20.58	19.58	1.05	20.58	30.43	0.68	29.59	24.71	1.20
Higher cost												
Busway	29.75	32.57	0.91	29.75	25.88	1.15	29.75	40.02	0.74	41.04	32.57	1.26
LRT	32.55	35.87	0.91	32.55	27.43	1.19	32.55	45.25	0.72	44.22	35.87	1.24

Note: Benefits and costs are marginal and are expressed in 1976 dollars.

Table 4. Measures of transit efficiency for the alternative modes in 1990.

	Annual Passenger Trips (000 000s)		Annual Passenger Kilometers (000 000s)		Capital Cost per Passenger Trip ($)		Capital Cost per Passenger Kilometer ($)		Operating and Maintenance Costs per Passenger Trip ($)		Operating and Maintenance Costs per Passenger Kilometer ($)		Total Cost per Passenger Trip ($)		Total Cost per Passenger Kilometer ($)	
Alternative	Total System	Incremental	Total System	Incremental	Total System	Incremental	Total System	Incremental	Total System	Incremental	Total System	Incremental	Total System	Incremental	Total System	Incremental
Baseline bus system	34.3	—	248.4	—	0.21	—	0.08	—	1.13	—	0.40	—	1.34	—	0.48	—
Bus preferential treatment	40.0	5.7	335.9	87.4	0.27	0.63	0.08	0.11	1.34	2.03	0.42	0.34	1.61	2.66	0.50	0.45
Expanded bus system	48.6	14.3	352.1	103.6	0.30	0.49	0.11	0.18	1.56	2.38	0.56	0.85	1.86	2.87	0.68	1.03
Base case																
Busway	42.9	8.6	379.7	131.1	0.49	1.60	0.14	0.27	1.22	1.20	0.35	0.21	1.71	2.80	0.50	0.48
LRT	45.8	11.5	379.7	163.3	0.61	1.79	0.18	0.32	1.11	0.76	0.32	0.14	1.72	2.55	0.50	0.47
SP-PUC																
Busway	42.9	8.6	379.7	131.1	0.54	1.85	0.16	0.31	1.22	1.20	0.35	0.21	1.76	3.05	0.51	0.50
LRT	45.8	11.5	411.9	163.3	0.65	1.96	0.19	0.35	1.11	0.76	0.32	0.14	1.76	2.72	0.51	0.51
Lower cost																
Busway	41.5	7.2	377.3	128.9	0.49	1.84	0.14	0.26	1.23	1.29	0.35	0.18	1.72	3.13	0.51	0.43
LRT	42.9	8.6	379.7	131.1	0.54	1.85	0.16	0.31	1.18	1.03	0.35	0.18	1.72	2.88	0.51	0.48
Higher cost																
Busway	47.2	12.9	428.0	179.4	0.61	1.66	0.18	0.31	1.13	0.87	0.32	0.18	1.74	2.53	0.50	0.48
LRT	48.6	14.3	444.1	195.65	0.70	1.85	0.19	0.35	1.06	0.66	0.31	0.13	1.76	2.52	0.50	0.48

Notes: 1 km = 0.6 mile.
Dollar figures shown are 1976 dollars.

Table 5. Subsidy requirements for the alternative modes in 1990, expressed in 1976 dollars.

	Operating and Maintenance Costs, Including SP Service ($000 000s)		Fare Revenues ($000 000s)		Subsidy Required ($000 000s)		Subsidy per Passenger ($)		Subsidy per Passenger Kilometer ($)	
Alternative	Total System	Incremental	Total System	Incremental	Total System	Incremental	Total System	Incremental	Total System	Incremental
Baseline bus system	38.60	—	5.83	—	32.77	—	0.96	—	0.34	—
Bus preferential treatment	53.60	11.60	6.80	0.97	46.80	10.63	1.17	1.86	0.35	0.32
Expanded bus system	76.00	34.00	8.26	2.43	67.74	31.57	1.39	2.21	0.50	0.79
Base case										
Busway	52.30	10.30	7.29	1.46	45.01	8.84	1.05	1.03	0.31	0.18
LRT	50.70	8.70	7.78	1.95	42.92	6.75	0.94	0.59	0.27	0.11
SP-PUC										
Busway	52.30	10.30	7.29	1.46	45.01	8.84	1.05	1.03	0.31	0.18
LRT	50.70	8.70	7.78	1.95	42.92	6.75	0.94	0.59	0.27	0.11
Lower cost										
Busway	51.20	9.20	6.92	1.09	44.28	8.11	1.07	1.13	0.31	0.16
LRT	50.85	8.85	7.29	1.46	43.56	7.39	1.01	0.86	0.29	0.14
Higher cost										
Busway	53.20	11.20	8.06	2.23	45.14	8.97	0.96	0.70	0.27	0.13
LRT	51.40	9.40	8.26	2.43	43.14	6.97	0.89	0.49	0.26	0.10

Notes: 1 km = 0.6 mile.
The total-system subsidy requirements include the baseline figures in all alternatives; the incremental subsidy requiremens are based on the costs or revenues accrued as a result of alternative implementation and therefore do not include baseline bus figures.

Table 6. Factors important in the evaluation of four LRT design standards.

Factor	Base Case	SP-PUC Amount	SP-PUC Difference (%)	Lower Cost Amount	Lower Cost Difference (%)	Higher Cost Amount	Higher Cost Difference (%)
Avg line speed, km/h	43	43	0	35	-20	51	+20
Daily ridership (000s)	70	70	0	60	-14	80	+14
Capital costs ($000 000s)	267.5	294.0	+9.9	210.4	-21.3	348.0	+30.1
Operating and maintenance costs ($000 000s)	5.5	5.5	0	5.8	+6.3	6.0	+9.0
Capital cost per passenger, $	0.61	0.65	+6.6	0.54	-12	0.70	+15
Operating and maintenance cost per passenger, $	1.11	1.11	0	1.18	+6.3	1.06	-5
Total cost per passenger, $	1.72	1.76	+2.3	1.72	0	1.76	+2.3
Subsidy per passenger, $	0.94	0.94	0	1.01	+7.4	0.89	-5.3
Benefit/cost ratio	1.24	1.16	-6.6	1.20	-3.3	1.24	0

Note: 1 km/h = 0.6 mph.

subsidy difference between the alternatives is obscured in the system totals because of the dominance of the subsidy for the baseline bus system ($32.77 million annually) over the incremental subsidy of $6.75 million for LRT and $8.84 million for the busway. This difference is better shown by the incremental subsidy cost of $0.59/passenger trip for LRT versus $1.03 for the busway (which is 75 percent greater than that for LRT); the difference is 57 percent in terms of cost per passenger kilometer. Thus, the LRT alternative has a major subsidy advantage. In comparison with the baseline bus system, the LRT alternative will reduce the total system subsidy required, both per passenger trip and per passenger kilometer.

It should be noted that all LRT and busway designed standard alternatives have subsidy requirements similar to those of the base case and that the ranking preference of LRT over busway never changes, while with respect to the other bus alternatives it shifts only once. Use of the lower cost LRT standard results in a subsidy of $1.01/passenger. This is only slightly greater than the baseline value of $0.96, whereas the base-case standard subsidy per passenger of $0.94 was slightly lower. Such small differences, however, should be judged with caution.

SUMMARY AND CONCLUSION

The factors found to be important in evaluating the effect of different LRT design standards on cost-effectiveness measures are shown in Table 6. Although the values shown were derived from the Santa Clara County study, they lead to conclusions that may be applicable elsewhere, particularly in western cities where similar rights-of-way are available. Thus, when these factors were incorporated into benefit/cost and transit efficiency comparisons with other transit modes, it was found that the use of any one of the possible LRT design standards would lead to essentially the same conclusions concerning the relative attractiveness of LRT and other transit alternatives.

It should also be noted that other important mode-comparison factors in addition to those shown in Table 6 (e.g., compatibility with local, regional, and national plans and goals; socioeconomic and environmental impacts; direction of urban growth; and community and political support) are relevant considerations in the evaluation and selection process.

We therefore conclude that, for the conduct of similar alternatives analysis studies in other areas with similar conditions, the time and cost required to evaluate a variety of LRT design standards is neither needed nor justified. While any one of the potential design standards would lead to essentially the same conclusions concerning the relative attractiveness of LRT, a base-case standard reflecting good modern European LRT design practice is recommended for purposes of comparison. In adopting this standard for alternatives analysis, it should be recognized that a higher level of service and greater attraction of patronage can be achieved but only at a greater capital cost; conversely, while a lower capital-cost LRT design is possible, it will reduce the level of service and the number of patrons attracted to the service. Operating costs are also affected. These changes due to varying design standards tend to cancel each other out; the net result is no significant difference in the LRT cost-effectiveness measures and no significant changes in its relative attractiveness with respect to other transit mode alternatives.

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Network Planning for Light-Rail Transit

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A common problem in the approach to light-rail transit (LRT) planning is the development and testing of less than optimal networks. This problem arises from an incomplete understanding of the application of the mode and of the opportunities inherent in its application. This paper describes how unique characteristics of LRT can be exploited by developing networks to make better use of the mode. Guidelines for network development are described and illustrated by examples. A distinction is made between techniques applicable specifically to LRT and those applicable to other transit modes. The concept of tuning a network (to match the level of investment to patronage and other benefits on a segment-by-segment basis) is presented, together with a discussion of the advantages of retaining as many future options as possible in long-range transit planning.

A number of recent urban transit development studies and corridor studies have been based on initial assumptions that establish the basic network, corridor, and sometimes even alignments. If network decisions are made prior to the selection of a mode, however, the transit designer is left with little opportunity to consider each mode in the context of a network configuration optimized for that mode. For instance, a busway may have no need for continuous construction and may be effective with only fragmentary improvements to the highway system. It can be designed to eliminate delay points and maximize the main advantage of bus transit (the one-seat ride) through selective use of surface streets.

By contrast, a heavy-rail transit (HRT) network must be continuous and grade separated, and it should be laid out to secure the highest possible level of service in major corridors in order to compensate for the need for a higher level of feeder service and a greater proportion of transfers than a bus or light-rail transit (LRT) network. Incidentally, although the term light rail often gives rise to explanatory contortions that seek to link the term to car or rail weights, it is a contraction of the term light railway, which probably originated in Britain where it is used to describe a railway constructed under the provisions of the Light Railways Act. The purpose of this act was to encourage the construction of railways early in this century in areas that could not justify the expense of building a railway to the rigorous standards of the time. A light railway was permitted to use ungated crossings and unfenced right-of-way, to operate without full signal protection, and to run in street right-of-way. Light railways could be built under a simple Light Railway Order and so did not require an expensive Act of Parliament. Staffing requirements and operating rules were less strict, and speed restrictions were imposed on unprotected right-of-way. The first light railways were powered by both steam and electricity and included some high-quality streetcar lines. Although the term still has a legal meaning in Britain, it has also come to refer to the form of transit now more generally known as LRT; it has no more literal meaning than does the analogous term highway.

While great attention has recently been focused on the technology and operating characteristics of LRT, much less has been given to the planning of test network configurations that make best use of this mode. If alternative rapid transit modes are compared on almost identical test networks, the result is not an evaluation of alternate modes but only of the alternate vehicle systems. Some communities have considered LRT for specific corridors as alternatives to freeway construction or a means of establishing transit networks in existing urban freeway or railroad corridors without considering other right-of-way options. By making such alignment decisions prematurely, the community may foreclose the opportunity to develop a logical and effective network before it has even been considered.

It is widely held that the need for urban transit will continue to grow in the years ahead. At the same time, there is concern that, unless we can become proficient at planning and constructing less costly transit facilities, rail transit will be very largely confined to a few major corridors in the largest cities. By contrast more than 50 cities in Western Europe now have rail transit, mostly LRT.

A major attraction of LRT is its potential to extend the range of rail transit to communities or corridors in which a more costly transit mode is not warranted but, while LRT may be less costly to construct, it is not easier to plan. The complexity of its conceptual design can rival or even exceed that of a fully grade-separated transit system since a great variety of right-of-way treatment is possible for individual segments and it entails a need to interact with a broad spectrum of professionals, all of whom must understand the characteristics of LRT. LRT is a relatively new transit concept, the best examples of which are still overseas; few can therefore yet claim either academic or direct experience with modern applications of the mode.

In addition to widespread unfamiliarity with the mode, there are the lack of promotional efforts like that mounted by the developers of proprietary modes, negative residual memories of streetcars in this country, and the desire to build big. This latter phenomenon, sometimes called the edifice complex, focuses on building the largest project fundable rather than matching the technical solution to the scale of a problem; it was particularly noticeable in the 1960s in Europe when a number of medium-sized cities (Bielfeld, Ludwigshafen, Nurnberg, Rotterdam) planned HRT in medium-demand corridors. In the new economic realities of the 1970s, some cities dropped these plans (Bielfeld and Ludwigshafen), while others curtailed their programs (Nurnberg and Rotterdam) to completion of segments already committed.

IDENTIFICATION OF OBJECTIVES

The first stage in developing an effective fixed-guideway network is to define the benefits expected from the investment. This enables the planner to seek a network that is focused on obtaining particular objectives rather than to respond to seductive right-of-way opportunities. Developing a fixed-guideway transit network is not an end in itself but rather the means to achieve certain transportation-related community goals. Although these goals will differ for specific communities, they will generally include many of the following:

1. To capture a larger share of the total transportation market,
2. To provide a better opportunity to hold the line on transit operating costs (compared with an all-bus system),
3. To reduce the need for automobile travel and the construction of new highway facilities,
4. To reduce the potential negative economic and social impacts of automobile disincentive measures,
5. To establish an infrastructure to guide future planning and land-use decisions,
6. To support national fuel conservation and environmental goals,
7. To provide increased capacity on the existing street system (compared with all-bus use or mixed bus and automobile use), and
8. To develop a transit infrastructure that can function effectively in a range of future energy and transportation situations.

NETWORK PLANNING CONSIDERATIONS

An understanding of the basic concepts that influence the planning of LRT networks can save much time and lead to a more effective planning process. Some of these concepts address right-of-way treatments, while others are more concerned with alignment selection. Some are valid for any fixed-guideway transit mode, while others are applicable primarily to LRT. Above all, each urban area is unique, so that there is no universally applicable approach, and a concept that is of primary significance in one place may be irrelevant in another. The rest of this section outlines some major network design considerations and discusses their application, pro-

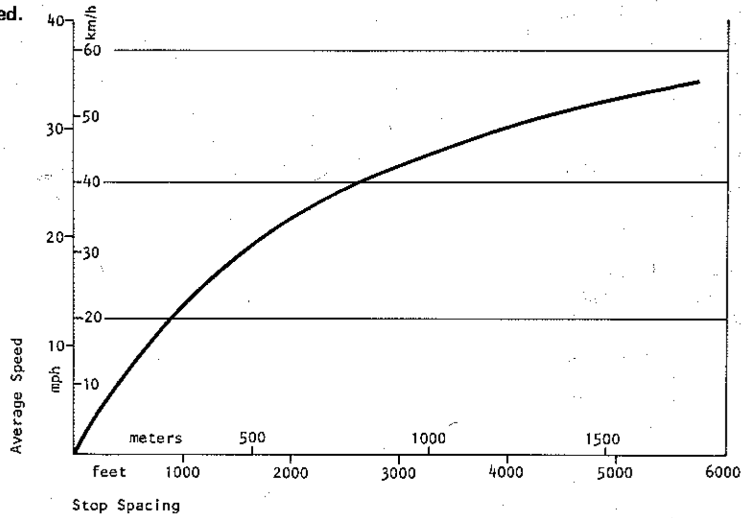


Figure 1. Relationship between stop spacing and operating speed.

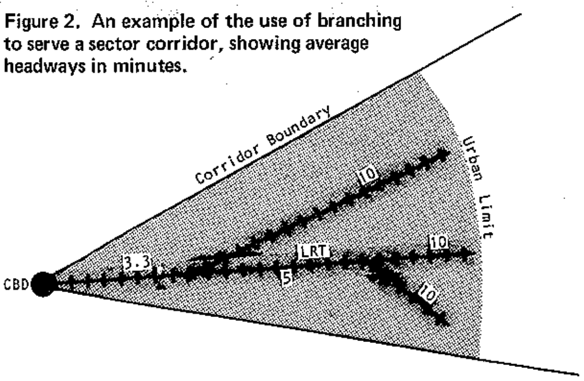


Figure 2. An example of the use of branching to serve a sector corridor, showing average headways in minutes.

viding examples. Wherever possible, recent examples have been selected since these tend to illustrate the application of planning theory in a contemporary context.

General Network Guidelines

Stop Spacing

On any guideway system with on-line stations, the maximum possible operating speed is governed by the spacing of stops and, to a lesser extent, by dwell time and vehicle performance capability. This is true regardless of mode. In downtown San Francisco, the San Francisco Municipal Railway's LRT subway will have operating speeds similar to those on the parallel lines of the Bay Area Rapid Transit System that have stops at the same stations. It follows that lines that are regional in nature should have fewer stops in order to avoid excessive travel time. This, however, requires greater walking time to reach ultimate destinations or more frequent transfer to feeder services. Most large metropolitan areas in Europe solve this conflict with a two-tier rail system. Regional transit is provided by a suburban railroad system, while LRT or HRT provides a service with more frequent stops in the denser central area.

A few cities in the United States (Boston, New York, and Philadelphia) have similar two-tier rail systems but, in major metropolitan areas in which these do not exist, the temptation to provide both types of service with a single system should be resisted lest the result fail to provide either local or regional travel in a satisfactory manner. Rail may be suitable for regional travel, local travel, or both. If, for example, loading on the regional transit links is lighter and more diffused than the local demand, then the rail transit should be targeted for local service, e.g., up to 16 km (10 miles), while the second tier is provided by a freeway-oriented bus system that serves the longer, less heavily used express links.

Figure 1 illustrates the relationship between stop spacing and average speed calculated for the Boeing Vertol light-rail vehicle (LRV). Since LRVs may need to make additional stops on surface sections because of other traffic, this will increase travel time. Figure 1 is based on a vehicle that has a maximum speed of 80 km/h (50 mph), acceleration of 1.25 m/s^2 (4.1 ft/s^2), deceleration of 1.57 m/s^2 (5.1 ft/s^2), and a dwell time of 20 s.

Access Time

Accessibility to stations plays a significant role in the convenience and hence the use of a transit system. Each rider must have access to the system twice (to and from stations) on every trip. The trip made by a rider through the system thus has different characteristics than a trip made by the transit vehicle. High speed by the latter is useful to the rider only if it can be achieved without incurring increased access time. Yet high operating speed requires widely spaced stations, for the reason outlined in the previous section; although this station spacing may lead to faster train speeds, it may actually lower the average rider's speed by increasing the access time. A recent study of the Bloor line in Toronto (1) shows that riders with between-station origins and destinations experienced an increase in average trip time for trips of up to 8 km (5 miles) when the subway replaced surface streetcars, despite the fact that the average train speed was more than twice the speed of the streetcar in mixed traffic. Even for origins and destinations at stations, the streetcar had, on average, been faster for trips of up to 3.2 km (2 miles) because of the increased headway and station access time required by the subway. Access time can thus play a major role in transit planning that is easily overlooked; this can lead in turn to less than optimal route design (2).

Difference Between Freeway and Transit Networks

Freeway and transit networks generally have different basic characteristics. Freeway networks are primarily designed to avoid major trip generators; they pass instead relatively close to them and rely on the surface street network for collection and distribution. Freeways are almost never constructed through a central business district (CBD), since they can serve it with less disruption by passing close to it. An effective transit network, however, must serve pedestrian destinations; to do otherwise requires feeder service, which increases trip time and operating cost. Effective transit systems must penetrate within walking distance of major trip generators.

A further difference between freeway and transit networks is that freeway networks tend to have strong circumferential as well as radial links. A freeway network that was primarily radial would experience enormous traffic concentrations at its focal point. By contrast, a transit network tends to have a strongly radial form with weaker circumferentials. On a well-planned transit system, the absence of strong circumferential routes is not very important because most circumferential trips can be made on radial lines, while radial trips can seldom be made on circumferential lines.

Connectivity

An important consideration in any transit system is the connectivity among the lines. Ideally, every rapid transit line should connect with every other rapid transit line, so that any trip through the system can be made with only one transfer. This goal is facilitated by constructing through lines rather than lines that turn back in the central city. Networks that have through lines avoid the need for turnback and layover facilities in the central area and are simpler from the user's point of view. The efficient application of through routing requires the interconnection of radial lines that have approximately equal demand (train size and headway).

LRT Network Guidelines

LRT is unique among fixed-guideway modes in that the designer may vary the right-of-way treatment (and hence its cost) to attain an appropriate service standard for individual segments of a network. The effective exploitation of this versatility is the key to LRT network design.

Branching

Most transportation corridors in a city are shaped approximately like a slice of pie. The apex of the sector is in the CBD but the corridor gets wider the further it is from the center. To provide transit coverage throughout the sector, the transit network must match the sector shape; this requires branches (Figure 2). Not only can LRT lines be readily branched, but the quality of construction and hence the cost of the individual branches can be made less than that of the main line in response to the anticipated patronage.

This is a fundamental LRT design concept since it provides a technique for optimizing the level of investment, segment by segment, systemwide. Multiple branching is characteristic of most well-developed LRT networks, including Boston and San Francisco. These systems also demonstrate the technique of varying investment on a segment-by-segment basis. The number of branches is limited by headway constraints and can seldom exceed five. New construction in Europe in Hannover, Braunschweig, Karlsruhe, Rotterdam, and Utrecht illustrates the contemporary application of branching (Figure 3).

Service Level

A related concept is the matching of service to patronage demand. This is achieved both by branching and by turning part of the service short of the outer terminus of a line. Figure 4, originally prepared for another report (3), illustrates how Karlsruhe matches service to demand by using both branching and short turns. Most LRT systems exhibit similar characteristics.

CBD Options

A number of network alternatives are available for the CBD, including grade-separated lines in subways or on elevated alignments and lines that operate in transit lanes on the street or on pedestrian malls. The use of design concepts similar to those now being tried for bus lanes in many U.S. cities permits the application of a variety of on-street options. The use of a contraflow LRT lane on a one-way street can simplify property access by permitting automobiles to make left turns into driveways. It can also simplify the development of a traffic-signal progression to favor transit.

Overall line length or average trip length may provide an indicator as to whether a line should be grade separated. If a line is long, grade separation may permit a significant saving in trip time. The freedom from interference from other traffic tends to increase the reliability of grade-separated lines. This is a particularly important consideration in networks that do not have emergency detour routes.

On the other hand, surface facilities in the CBD are less costly to build. They also offer greater accessibility by providing simpler, more frequent stations. A surface alignment can be expanded more readily to increase CBD coverage or system capacity. For short LRT lines, e.g., less than 10 km (6 miles), the lower speed of surface operation is not likely to be of primary concern since even the longest trip will be of short duration. Most medium-sized European systems do not plan grade separation in the CBD. Good examples include Bremen, Braunschweig, Mannheim, and Zurich.

Capacity Limitations

One of the potential limitations of LRT is that, in heavy-demand corridors or under conditions of future growth, key links in the network may become overloaded. The patronage level at which this could occur is often assumed to be 20 000 or more in the peak hour, the exact number depending on mode of operation and acceptable level of crowding.

One solution to this problem is to plan for conversion to HRT, as was done in Brussels and was once planned in several other cities. This upgrades line capacity at the cost of severing direct connection with the LRT surface lines. In Brussels the conversion of pre-metro Line 1 changed an LRT subway with five surface branches into a heavy-rail subway with two branches, greatly increasing the use of transfers. Since, as discussed earlier, speed is not a direct function of mode, travel time for many riders would have been less if the line had been upgraded with improvements on the street segments and larger cars had been used to increase capacity.

The significance of this has not been lost on European planners. The other pre-metro lines in Brussels will not be converted to metro, and they are now being equipped with new large LRVs. Early in 1977, it was decided to change the plan for the second line of Rotterdam's Metro to a semi-metro LRT line, even though construction had started. The saving in cost was suffi-

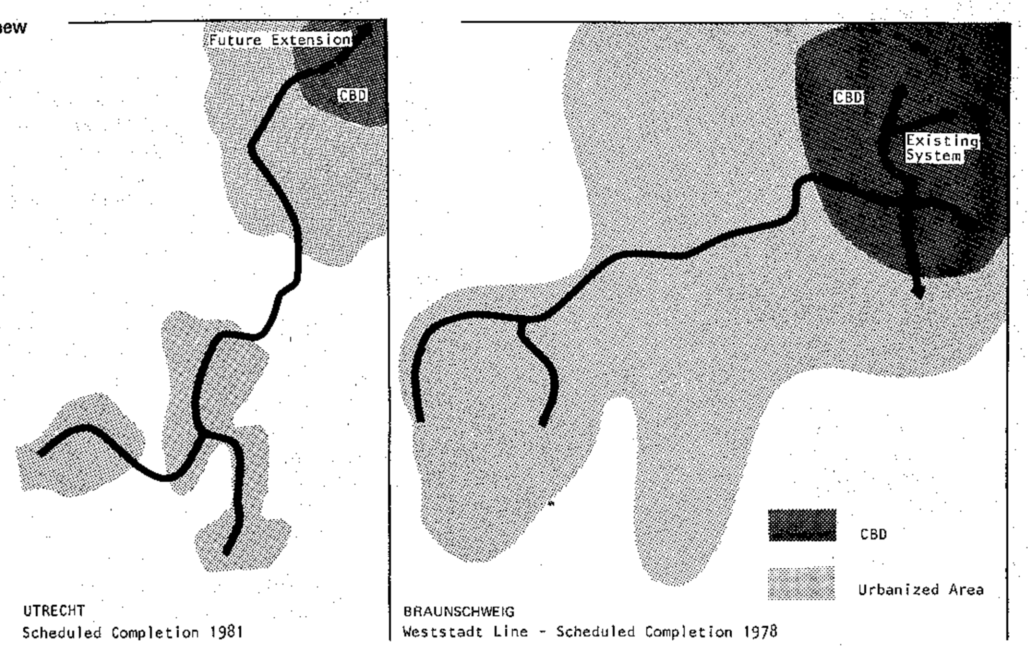


Figure 3. Use of branching on new LRT lines.

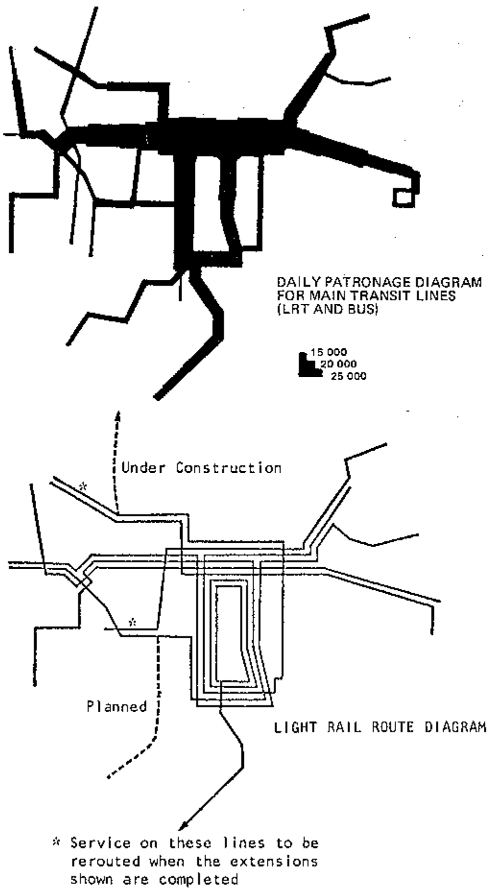


Figure 4. Balancing service and patronage: the Karlsruhe transit system.

cient to pay for an additional segment of tunnel at the west end to connect it to an existing LRT line. The change will also simplify the construction of several future suburban branches and give better coverage than the proposed metro project (Figure 5). In Germany, the pre-metro concept adopted by several cities (Stuttgart, Cologne, Dusseldorf, Bielfeld, Essen) has receded into the indefinite future, superseded by more immediate and less costly improvement concepts.

However, the capacity problem can also be approached as an opportunity. By building a duplicate section to relieve the overloaded segment, excessive concentration in a single corridor can be avoided, coverage in the CBD can be increased, and each line can function as a distributor to the other, thus providing "people-mover" circulation in the CBD as well as the line-haul function. The use of multiple LRT subways in the CBD is best illustrated by the Hannover system. The long-range plan calls for four LRT subways and one surface LRT line in the CBD. Through the use of branching, this system will ultimately serve no fewer than 16 radial lines (Figure 6).

An additional consideration, particularly for a surface alignment, is its ability to function in the event of an accident or other service interruption. On a multiline system, alternative routing may be possible. Generally the provision of additional turnback facilities and a short response time for emergency services is the most economical treatment for such situations. Bus substitution is also occasionally an effective measure.

Operating Economy

A major reason for establishing a fixed-guideway transit network is to reduce the rising operating cost of an all-bus system. The implication for the network designer is to seek to replace as many bus kilometers as possible with the minimum of LRV kilometers. In Edmonton, the northeast line will replace some 37 buses with 14 LRVs. A recent line extension in Karlsruhe added a branch to the LRT network that, by adroit operational changes, replaced 6 buses without the need for any additional LRVs (Figure 7).

Replacing close-headway buses with less frequent LRVs reduces bunching and improves the reliability of the transit service. At longer headways (more than 10 min), the potential disadvantage of the lower frequency should be compensated by regular and reliable schedules and timed connections with feeder services.

Opportunity Alignments

Opportunity alignments are those in which LRT can be readily implemented, usually because of an available right-of-way. Opportunity alignments often do permit economical construction of an LRT line, but this fact must never be allowed to substitute for a critical appraisal of the service value of each segment. In some cases the use of an obviously suitable alignment for LRT has been proposed almost as an end in itself rather than

Figure 5. Evolution of Rotterdam's Metro Line 2 to semi-metro status.

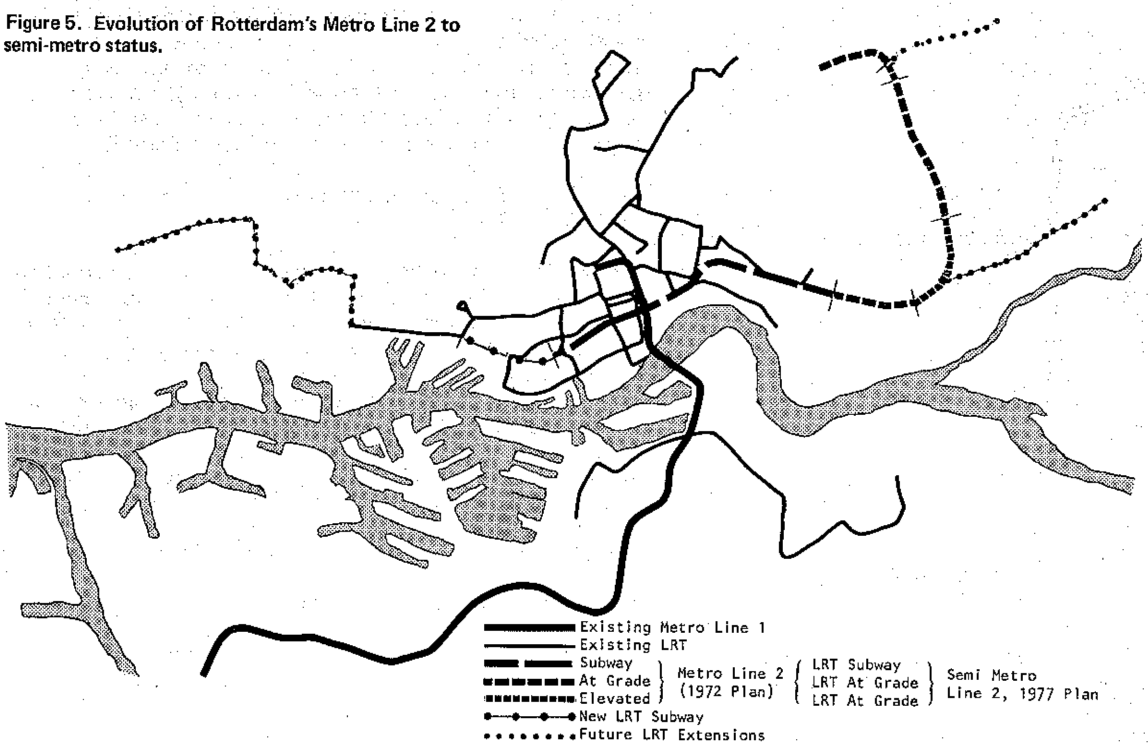


Figure 6. Planned LRT network for the Hannover CBD.

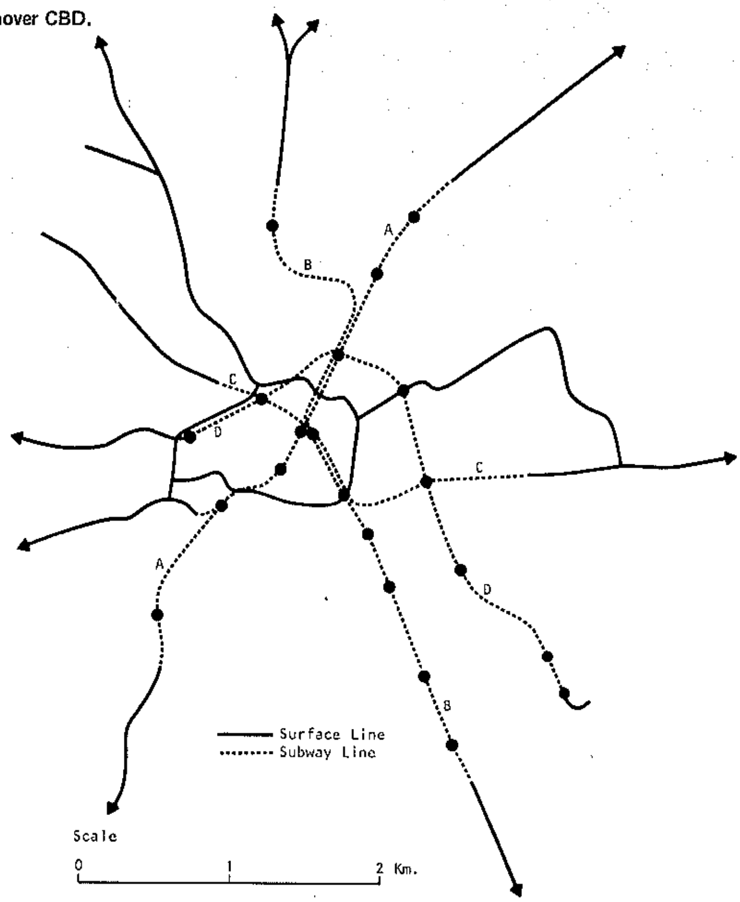
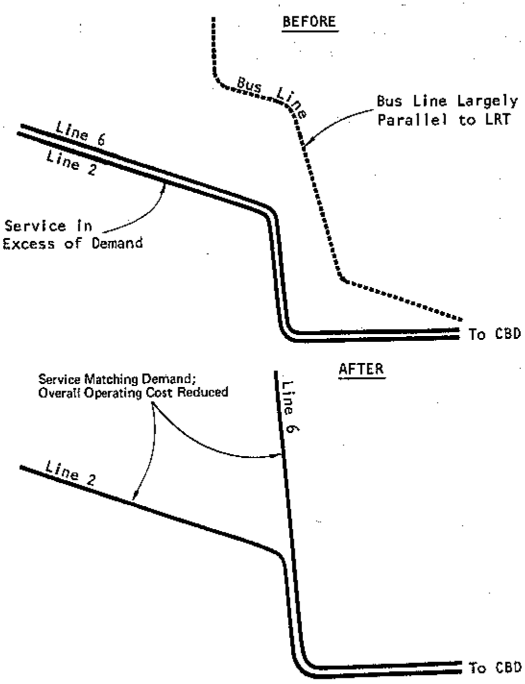


Figure 7. Extension of LRT line to replace feeder bus in Karlsruhe.



as the means to achieve a transportation goal. Other LRT proposals have been stated as a direct substitution: 10 km of LRT to replace a proposed 10-km freeway. Such proposals can seldom stand up under detailed analysis unless a wider perspective is considered.

It is an unfortunate characteristic of many opportunity alignments that they do not serve the places the transit system should serve. For instance, railroad alignments are often not well located within the corridor they are intended to serve since recent development has not been influenced by the railroads. Freeway alignments are often worse, since the characteristics of a freeway network, as discussed earlier, are different from those of a rapid transit network. Generally, freeways also occupy the corridors in which the existing highway network is least deficient (and hence show less need for transit investment). Opportunity alignments should therefore be considered cautiously and used only when they are well located.

Lack of negative impacts can never, of itself, be a valid network determinant. One common but often overlooked opportunity alignment is that of the old arterial streets frequently found in large cities that are now bypassed by the construction of freeways. These streets were often widened to increase their capacity prior to the construction of the freeway system to which their traffic was largely diverted. These arterial streets frequently penetrate the heart of the corridor and serve many of the major trip generators. By using appropriate deployment of right-of-way treatments, such streets can provide a favorable setting for an LRT median with little traffic or community disruption and considerable service potential.

Design Versatility

The problem of fitting LRT to an existing urban environment calls for great design versatility. Localized widening of a right-of-way to permit a station or the moving of houses to increase their setbacks are two techniques of potential value on major arterial streets.

The designer should not be hesitant to vary the right-of-way treatment when necessary to achieve network objectives, such as penetrating major trip generators or passing through a bottleneck, that are attainable in no other way. For instance, if the only affordable way to penetrate a community center is to operate on a street, then short sections of streetcar track should be constructed that incorporate traffic engineering measures designed to ensure its reliable and safe operation. Likewise, streetcar operation over a major bridge may be feasible when the alternative of constructing a new alignment would render the entire line unfeasible.

Selection of an Appropriate Level of LRT Technology

LRT can be developed at a variety of levels of sophistication. Many of the reports from Europe come from the handful of cities that have developed forms of LRT that have enhanced its complexity but not necessarily enhanced performance or economy.

It should be incumbent on designers to adopt the most basic form of LRT that is adequate for their particular application and meets their design goals. High-low platforms, double-ended cars, high speeds, and elaborate controls may sometimes be appropriate, but they may also prove an unwarranted expense, as Kudlick and Minister note in their paper elsewhere in this Report.

Exploiting At-Grade Capability

The capability to operate at grade is central to the LRT concept. At-grade operation is usually considered a disadvantage and, if poorly exploited, may be just that. The benefits must be understood to be realized. There is a clear design dilemma. Some LRT systems in Europe, as in the United States, are moving toward increased or total grade separation. Others, equally advanced technically, are not. Essentially the choice requires a judgmental approach, and there is as yet an insufficient body of experience to reach a generally applicable conclusion.

For the operator, at-grade operation is always inferior. It may decrease reliability and speed and sometimes causes accidents. For transit, as for highways, grade separation leads to operational improvement.

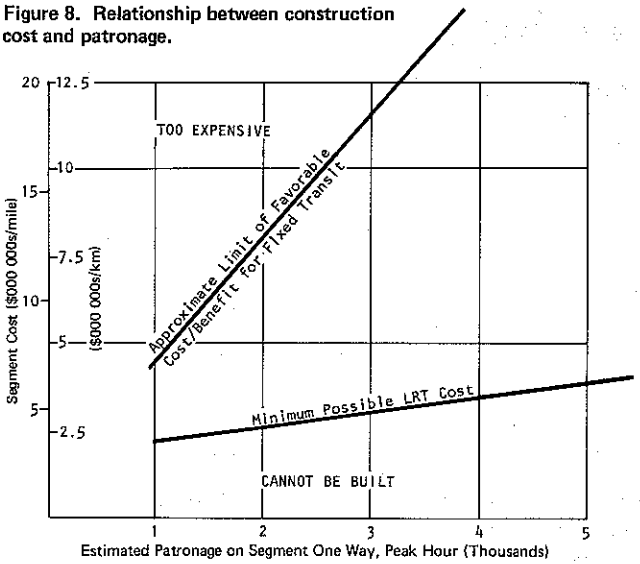
For the transit planner, there are other considerations. At-grade operation permits the use of right-of-way that would not otherwise be available. It increases accessibility, changes impacts, and can make a transit line feasible that would otherwise be too costly. Certain specific treatments, such as redeveloping a run-down street as a boulevard with an LRT median or constructing an LRT and pedestrian mall, may even be better urban design treatments than a subway alternative.

For the passenger, grade separation offers a higher quality of service in terms of speed and reliability, but at the expense of increased station access time and a smaller affordable network. Which is preferable can be decided only on a case-by-case basis by considering demand, local conditions, and right-of-way options available.

TUNED NETWORK

LRT is unique among fixed-guideway transit modes in that the designer has the ability to vary the right-of-way treatment (and hence its costs) from segment to segment of the network. The effective exploitation of this versatility is basic to LRT network design. A network in which line construction costs, service levels, and patronage are proportionately matched could be described

Figure 8. Relationship between construction cost and patronage.



as a tuned network. A tuned network would exhibit most of the following features:

1. High level of regional coverage with minimum dependence on feeder buses;
2. Investment in line segments that is proportionate to estimated patronage on a segment-by-segment basis;
3. Service levels that are responsive to patronage demand on a segment-by-segment basis, which is achieved by branching or short turns; and
4. A CBD configuration that is appropriate to the extent and loading of the network and is designed to avoid overloaded links and to function in the event of a link failure, if it is on the surface.

Although real-life constraints seldom permit the design of exactly such a network, this concept can be perceived in many existing LRT systems (e.g., Karlsruhe, as shown in Figure 4). Figure 8 illustrates the relationship between the limits of construction cost and patronage for a tuned network.

FUTURE OPTIONS

One of the few certainties in transit planning is the uncertainty surrounding transportation needs for more than a few years ahead. Consider the change in attitude toward public transportation over the past decade. One prudent response to such changes is to avoid foreclosing future options. The capability inherent in LRT to use a variety of rights-of-way, to use low-cost branches, and to respond to increased capacity needs is consistent with such a goal. It should also be noted that the direct-current electrically powered steel wheel and the steel-rail mode, now in use for more than 80 years, have proved remarkably adaptable to technical evolution and are still compatible with almost any existing or experimental train-control or power conditioning technique.

COMPATIBILITY OF RAIL MODES

The rail transit modes from streetcar to HRT have the capability to be made compatible with each other, a capability that is seldom exploited (4). In Cleveland, the LRT lines share tracks with the HRT system over part of their length; the converse is not technically possible since HRT trains cannot be safely operated on at-grade LRT segments.

The new Rhein-Ruhr system in Germany goes one step further by using identical equipment on the grade-separated and at-grade lines. This system will eventually consist of some 300 km (190 miles) of rail transit. The regional lines, between urban centers, will be largely grade separated, since high speed is required. The local lines will use the new subways in the central areas but operate on the surface elsewhere. Thus the subways will achieve higher utilization than would occur with only regional service, and the local lines will function as semi-metro operations, which would not be warranted for local service alone.

The idea of technically compatible LRT and HRT is a powerful concept of potentially great relevance in large metropolitan areas such as Los Angeles. It has inherent flexibility to respond to a range of future options; this is an idea worthy of greater attention.

CONCLUSIONS

During the last decade, interest in LRT has developed rapidly. The changed horizon of transit planning and the growing awareness of limited energy and other capital resources are forcing a search for more effective means of serving urban travel. Effectively deployed, LRT can meet that need. The effectiveness of LRT planning is dependent in large part on developing test networks that apply the mode in a manner that is appropriate to the particular application. The concepts discussed in this paper are intended to provide guidelines for achieving this goal and thereby to lessen the effort invested in studying deficient networks.

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Pre-Metro: Conversion Now or Never

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This paper develops as a case study the 60-year experience of a light-rail transit system that was conceived as a pre-metro line with the option for eventual conversion to full metro or semi-metro status. It describes the metro features originally included and the added facilities aimed toward upgrading to metro. It explains the opportunities for full conversion that were passed by and the conflicts between incompatible regional rapid transit plans and competing rail technologies. The accumulation of factors both physical and political that finally arrested the development of this light-rail operation are laid out step by step. Forces and counterforces that acted on this system as the wider community worked slowly toward regionalization of transit are described. Special attention is given to those local community concerns that finally closed the door to metro conversion when at last the opportunity and funding to convert seemed to be available. Guidelines are developed for planners, designers, and civic and transit leaders.

The former Shaker Heights Rapid Transit System (SHRTS) was constructed in large part on open land to encourage house and lot sales in the Van Sweringen brothers' real estate development, which was begun in 1907 on the uplands east of Cleveland. From the beginning, the long-term plan was that this operation would reach its own terminal in downtown Cleveland entirely independently of the street railway system. The designers of the system called for heavy all-steel suburban cars with steps and traps and for eventual installation of high platforms at locations with sufficient volume. This particular technique was used by several systems from 1900 to 1930; it was really a compromise between interurban and commuter railroad designs and can be described as a final maturing of interurban technology. The term semi-metro is now used for at-grade systems with high platforms.

To obtain transit service for the land development as quickly as possible, it was decided to build SHRTS from the outside in, by using the existing street railway network for temporary entrance to the central city. This was done in two stages. From 1913 to 1920, the northern (Shaker Boulevard) branch was operated by the Cleveland Railway under contract as a southern parallel branch of their Fairmount streetcar line, which began operation in 1907. Conventional single-unit streetcars were used. Access to Fairmount Boulevard was via Coventry Road. The combined Shaker-Fairmount operations were entirely on private right-of-way through a golf course and on boulevard medians as far in as Cedar Road in Cleveland Heights. Following a short stretch of street operation, there was considerable additional private right-of-way used by three car lines from the top of Cedar Hill to Euclid Avenue.

This interurban arrangement, with its long slow ride downtown along Euclid Avenue, was replaced in 1920 with a much faster approach that used a new high-speed exclusive right-of-way from Moreland Circle (later Shaker Square) to East 34th Street. At that location a ramp provided access to the inner-city tracks of the street railways. The southern (now Van Aken) branch of SHRTS was also completed at that time. Thus, the system entered its second and better-known interurban state; it was commonly referred to as the Cleveland Rapid Transit System. During this period it was operated under lease by Cleveland Railway, which was reimbursed for the sizable operating losses. A 5-cent premium was charged for rides east of East 34th Street, which made the total fare 10 cents. A fleet of streetcars built in 1914 was modified for higher speed operation and converted to multiple-unit use as traffic grew; the fleet increased from 4 cars initially to 36 by 1927.

Various combinations of streetcar routings for SHRTS were used in downtown Cleveland while the Union Terminal project was being completed. Although operation on the street railways was slow because of the conflict with city streetcars and motor vehicles, the downtown distribution pattern finally selected was highly effective. However, the developers of the rapid transit system wanted to promote their own complex of new buildings in the immediate area of the new terminal irrespective of the needs of their transit riders. This was the largest American development of commercial buildings in a coordinated group until Rockefeller Center. It was an unanticipated outgrowth of the original Van Sweringen rapid transit plan, which had envisioned a subway and a simple terminal at the western edge of downtown, on the edge of the river bluffs, even more remote from the center.

In 1930, operation into the Union Terminal was begun, and the remainder of street running was given up at once. A completely new operating organization was started; its wages were lower than those paid by the Cleveland Railway, and it had its own new maintenance shops but the same old multiple-unit streetcars. Fares were raised from 10 cents to 15, and riding volume immediately dropped 30 percent. Some of this decrease must be attributed to the sacrifice of good downtown distribution. The faster running time to the outer ends of the branches made possible two extensions in 1930 while preserving the by-then rigidly established 1-h round trip. Operating losses were reduced by a combination of lower wages, reductions in distance traveled made possible by a new yard at the outer end, and very strict economy measures.

PRE-METRO FEATURES

The most conspicuous pre-metro characteristic of the original SHRTS construction was the large clearance envelope provided in tunnels and underpasses. These were built to standard railroad clearances in effect at the time of original design (circa 1912). In addition, all overpasses were built to Cooper E-60 loading capacity, a typical steam railroad standard (1). The distance between track centers was greater in cuts than on fills or at surface level in order to allow for portal overhead catenary supports on fills while leaving space for side drainage and center-mounted T-shaped supports in the cuts. Because of shortages of materials during World War I, the line was built largely with center-mounted concrete interurban railway poles, a temporary feature that has lasted until today. The approach to Union Terminal from East 34th Street (opened in 1930), was built to the original specifications with structural steel mainline railroad catenary designed for 3000-V standards; this demonstrates that the original pre-metro design was still very much in the minds of the engineers. Oddly enough, the outer extensions opened at the same time were given typical street railway overhead that used center-mounted steel poles.

Platforms for the light-rail transit (LRT) lines in Union Terminal were all built "temporarily" at the top of the rail or slightly above. The yellow pine wood used has lasted until now, with replacement only in areas of high wear. All stairways up to the concourse level began their permanent construction at a high-platform level with steps of wood from the low level to the doors. The reverse was done in Kenmore Square in the newer part of Boston's Central Subway (Green Line), where the inside tracks at station platforms were temporarily installed at a high level to allow later conversion to metro status while keeping the platforms intact.

At the time Moreland Circle was redesigned and converted to Shaker Square in the late 1920s, the Van Aken line was relocated for about 0.4 km (0.25 mile); a tedious reverse curve with generous track centers was built to allow for large cars. Third-rail ties were installed on this work, just in case exclusive Shaker Heights chose third-rail power pickup from high-platform cars rather than the more conspicuous overhead catenary. Fortunately, the third-rail idea never got beyond that one relocation job.

METRO PLANS

Proposals were developed for permanent stations at several locations. Most of the drawings remaining show high platforms in a semi-metro style. Strangely enough, the only permanent station structures actually built in the 1920s (Lynnfield, Coventry, and Courtland) all had low platforms at commuter railroad height. This ambivalence at that early date is typical of the history of the system and is an important part of what developed later.

Most of SHRTS was conceived in the 1920s by the Van Sweringen interests as a high-platform line to run alongside their Nickel Plate Railroad, and the platforms for it in Cleveland Union Terminal were built accordingly. Actually, when the line was finally completed in 1954, the track level in Union Terminal was raised slightly to conform with the modern car-floor height, which was somewhat lower than had been planned.

Other rapid transit lines to the far corners of Cuyahoga County were also planned by the Van Sweringens when their railroad empire was at its height. All these followed existing railroad rights-of-way, except for proposed extensions to the Shaker Heights branches. Strangely, none of the proposals in other directions took off cross-country into open land. The developers were promoting their Union Terminal complex but did not get involved in trying to repeat their original success through additional suburban real estate. All new lines were intended to be high-platform commuter operations imitating the recently rebuilt Illinois Central Gulf Railway Company facilities in Chicago, which had some semi-metro characteristics. The spacing of openings in bridges built over the Nickel Plate Railroad in that era allowed for a third rail in the center strip between pairs of future transit tracks, an interesting engineering hedge against the later choice of technology.

Preliminary design was begun on rolling stock that would serve the entire rapid transit network, including the Shaker Heights lines. The surviving drawings show a car that looks like a somewhat shrunken Illinois Central or Lackawanna-Morris and Essex car. It is not clear from the plans what degree of grade separation was to be provided, but the bridge projects already completed in the central city assured that the inner parts of all the lines would permit high-speed running.

This concept and its routings conflicted with a 1919 subway plan prepared for the city of Cleveland in which the Cleveland Railway streetcars were to operate in subways downtown in the manner of Boston's Central Subway (2). The Cleveland plan did not attempt to coordinate the rapid transit system then coming into being with the local street railway system, although the SHRTS streetcars could have used the never-built downtown trolley subway. The 1919 plan was to include metro clearance standards for tunnels in case it was later decided to go to full-scale rapid transit. It even suggested eventual use of long stretches of elevated railways down the main streets of the outlying districts, a concept that would be intolerable today; see Figure 1.

CONTINUED USE OF LRT EQUIPMENT

When the SHRTS lines began operation into Cleveland Union Terminal, the vintage 1914 streetcars leased from Cleveland Railway were kept in use as an economy measure. The depression struck, SHRTS was taken over by creditors, and all thought of new rolling stock was put aside. Survival became the order of the day. Work on the rapid transit line to East Cleveland was abandoned, even though structures for catenary were in place and rail, ties, and wire to finish the job were on hand (3).

The multiple-unit center-door streetcars required two persons in the lead unit; this causing the management to run long trains as infrequently as possible in the rush periods. The receivers brought in an imaginative marketing person as general manager, and soon second- and third-hand single-unit low-capacity deluxe lightweight interurban cars took over the evening and Sunday service and some base-period day work (4).

When the municipality of Shaker Heights bought the line in 1944, the selling banks required the buyer to agree to replace the rolling stock within a set period. The banks wanted to encourage continuing development of the open land the line ran to, since they were holding many mortgages. Near the end of World War II, the newly formed Cleveland Transit System (CTS) prepared a plan for system conversion that involved wide use of LRT in the outer city and inner ring of suburbs with high-speed private right-of-way service through the central city and used as a trunk line the unfinished rapid transit system with short extensions on each end (5). City service was to emphasize trolley coaches. This plan was highly compatible with SHRTS in its arrested form; indeed its lines were shown as elements in the countywide network; see Figure 2.

On the basis of that endorsement of LRT and the desire to keep the purchase cost down, in 1946 SHRTS ordered (as an add-on to an order then being built for Chicago Surface Lines) a fleet of 25 extralong multiple-unit all-electric Presidents' Conference Committee (PCC) cars 2.7 m (9 ft) wide. It was hoped these cars would be compatible with the Cleveland rapid transit services that would be built.

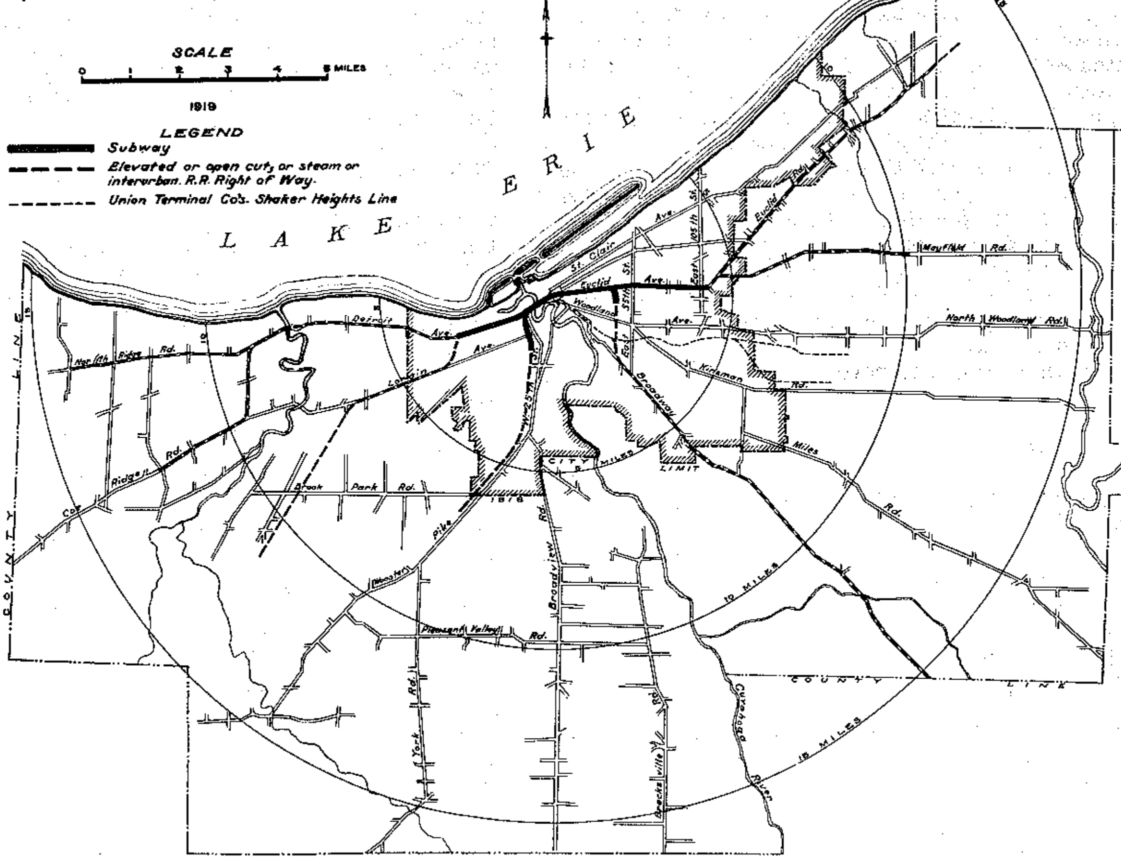
Meanwhile, CTS bought 75 PCC cars capable of later conversion to multiple-unit use. The plan was to use these new cars first in surface work until the rapid transit system was completed and then to use them on the new service. Unfortunately, the more popular 2.5-m (8.3-ft) width was selected. This was the width of existing Cleveland cars at the time, and it was felt that mixing widths in street running would be hazardous. However, this dimension is not suited to two-and-two transverse seating ahead of the center door.

In 1953 and 1954, a group of very fine, wide PCC cars compatible with SHRTS' new fleet became available from the Twin Cities. SHRTS bought 20 of these to fulfill its commitment to the banks to replace all the original rolling stock, and the sellers converted 15 of them to multiple-unit use. In recent years, these cars have been given full two-and-two seating; they are now considered the best in the fleet.

LRT VERSUS RAPID TRANSIT

At the end of World War II, new management came in at

Figure 1. Plan proposed in 1919 for a rapid transit system for Cleveland.



CTS. Streetcars were considered obsolete, and a recommendation was made to abandon the whole street railway network, including those outer parts that had been included in the 1944 LRT plan. The rapid transit concept was changed radically; a high-platform subway-and-ground-level trunk line with no grade crossings along the Nickel Plate Railroad route and the inmost part of SHRTS was to intercept most of the outer-area riders at transfer points, doing at lower cost the job that had been planned for the LRT network (3). Ability to run long trains staffed by only two persons and the elimination of all street trackage were cited as great advantages of the changed plan. Thus Cleveland was back to the Van Sweringens' plan, with its nearly full metro characteristics.

Objections were immediately made by riders, political leaders, and citizens' groups to the introduction of a need for transferring where none had existed before. Also, difficulties arose in obtaining the necessary agreements from the railroads for right-of-way. Another report by the same consultants a little more than a year later (6) proposed alternate trunk-line routes using the streetcar viaduct over the Cuyahoga Valley and the median of a never-to-be-built urban freeway. This plan recognized the option of a full return to the LRT idea.

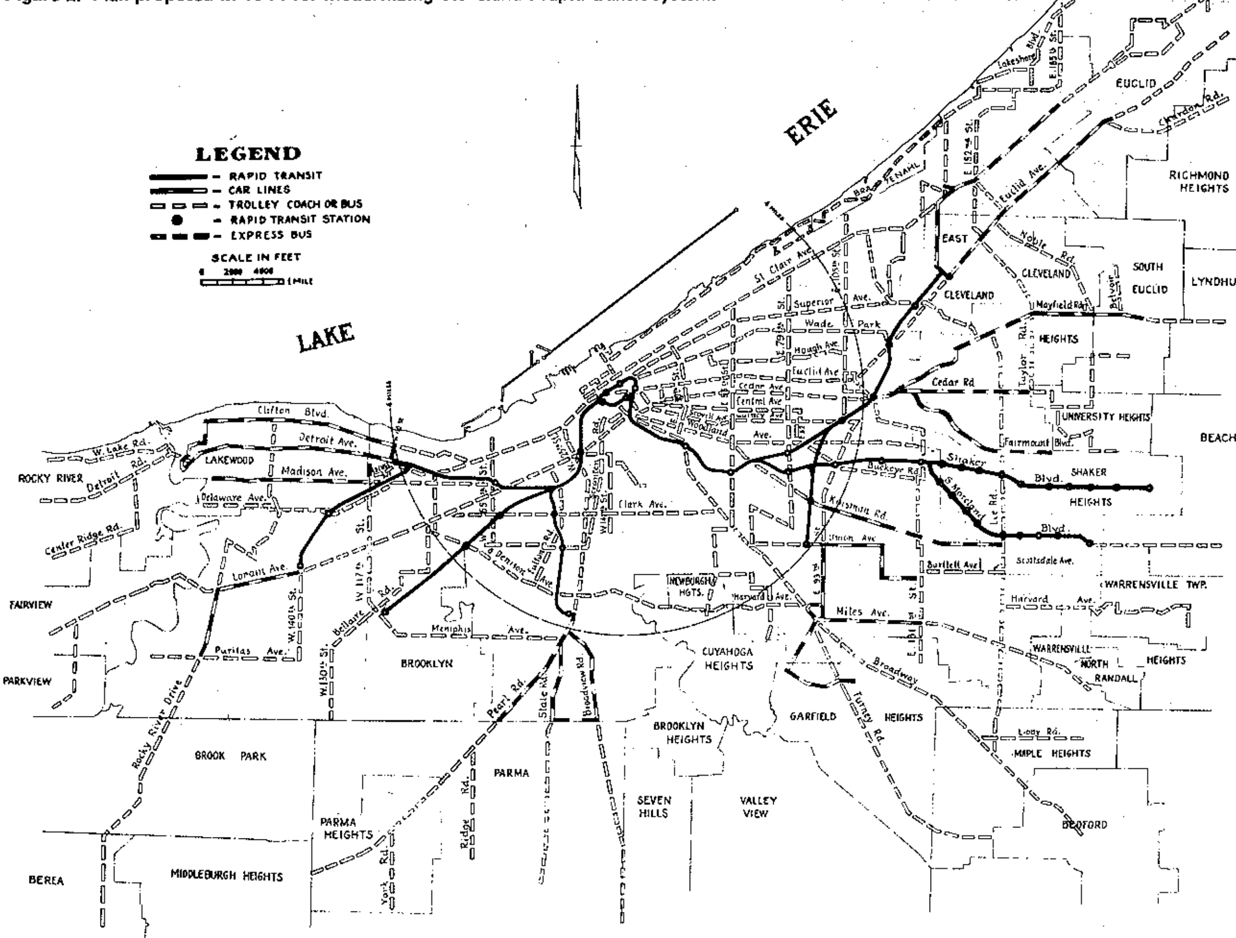
However, the idea of high-platform service with transfer from surface lines finally won out, as the popularity of the streetcar declined nationally. The street-railway network abandonments were speeded up and, well before the end of service, the 75 narrower PCC cars were sold to the Toronto Transit Commission. They were converted to multiple-unit use and are still running today; this fact is brought up periodically by a local columnist as a "Cleveland joke."

The management of SHRTS, already committed to half a fleet of new rolling stock, vigorously opposed the high-platform plan, stating that it would introduce a great stumbling block to the eventual unification of the two rapid transit systems. It was claimed that operation on the same tracks of two types of rail cars that had different floor heights and rather different weights was inherently unsafe. A compromise plan calling for a third track in the shared area was nearly adopted. Nevertheless, by terms of their lease with Cleveland Union Terminal, SHRTS was finally forced to accept a high-platform line using the same two tracks for 4.1 km (2.5 miles). To enhance safety, an automatic-stop signal system with trip levers on the cars was provided; this gave surface cars the problem of false stops as a result of snow and ice buildup at grade crossings.

A downtown subway loop distributor had always been a vital part of every Cleveland rapid transit plan, and SHRTS at first believed its cars would be prohibited from building a high-platform subway because the cost to provide additional low platforms would be considered unjustified (3). However, preliminary designs recognized the option of both levels at the same stations. As their consultants and those of the Cuyahoga County commissioners recommended, the Shaker Heights officials in the end decided to stay out of the proposed subway rather than reduce frequency or add cars to adjust for the longer running time. Their declared nonparticipation did much to bring about the eventual shelving of the project (7, 8). The never-built loop subway with tight curves stuck CTS with a fleet of very short rail cars that were ill suited economically to their present use. A review of the various subway plans for downtown Cleveland since 1909 would make a full-length paper in itself and might teach some lessons in the techniques of nonimplementation (8).

Consultants repeatedly recommended the absorption

Figure 2. Plan proposed in 1944 for modernizing Cleveland's rapid transit system.



of SHRTS into the far larger CTS, and the existence of two such different types of rail equipment was always brought up as the supposedly greatest obstacle. This incompatibility was a false issue, of course, as is illustrated by the mixed-rail networks of Boston and Philadelphia, which do not even share tracks as is done in Cleveland (9). Talk of unification always recognized the need to replace SHRTS' rolling stock and erect high platforms along the boulevards, as for a semi-metro system. The supposed savings entailed in eliminating one of the two stations in the Cleveland Union Terminal appeared attractive. The temporary low platforms could be abandoned, and perhaps the rental payments for SHRTS' facilities could be avoided.

As time went on and ridership declined on both rail systems, concepts were hinted at that seemed to call for the abandonment of one or both branches of SHRTS under CTS ownership and conversion of the fully grade-separated main line west of Shaker Square to a branch of the CTS high-platform line. This truncation would supposedly sidestep the community resistance to semi-metro operation and would balance the rail transit load between eastside and westside lines. It was even suggested seriously that the branches east of Shaker Square (which have many grade crossings) be converted to busways, as was done with a Red Arrow branch in suburban Philadelphia.

Naturally the cause of unification was hindered by the widespread belief that loss of control over SHRTS would cause Shaker Heights to no longer have any control over the physical characteristics of the line, half of whose trackage and a third of whose patronage were within Shaker Heights. Overtures from CTS to buy or lease the line were ignored, and all attempts to develop a transfer arrangement or joint fare failed. The only positive coordination was the addition of a high platform at a little-used station midway in the stretch of trackage used by both systems. This improvement provided an easy along-the-platform interchange and did much to show that the two rail technologies might coexist in a unified transit organization. Incidentally, that station now has a substantial volume of transfers among both rapid transit lines and the surface bus network; it functions as a peripheral secondary downtown access point.

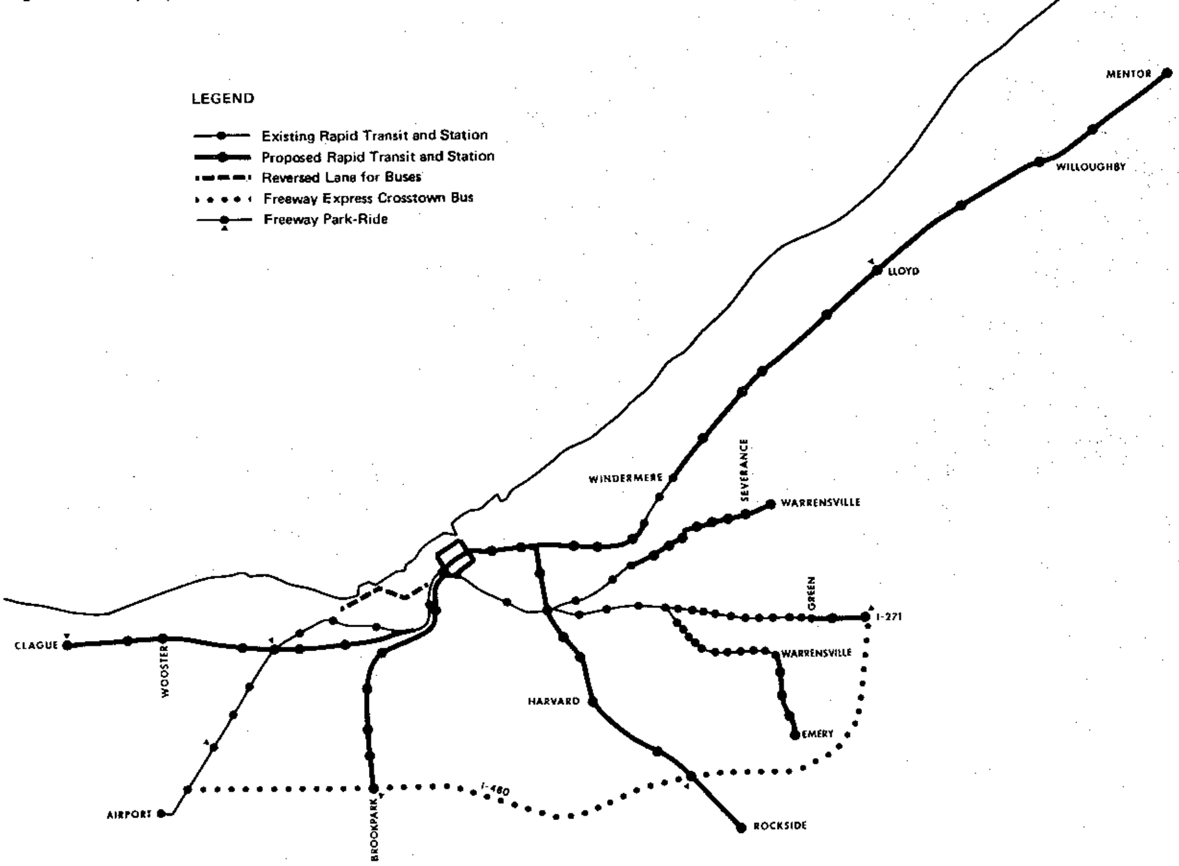
COMING OF THE REGIONAL TRANSIT AUTHORITY

Like transit lines throughout the country, CTS and SHRTS experienced deteriorating financial conditions in the late 1960s. By the early 1970s, it was obvious that survival required tax subsidy. Regionwide unification of all transit under a sound tax umbrella became a community objective. Areawide planning studies called for expansion of transit in several directions, much as had earlier plans for private enterprise in the 1920s and municipal ownership in the 1940s and 1950s (10).

SHRTS saw the trend toward tax-supported regionalization as an opportunity for exercising some permanent control over the character of its system while relinquishing the burden of purely local tax support. A Shaker Heights citizens' committee that had won its laurels defeating a proposed freeway parallel to SHRTS was given the assignment of developing a well-thought-out future for SHRTS.

Six physical alternatives were carefully analyzed; they

Figure 3. Plan proposed in the 1970s for extending Cleveland's rapid transit system.



ranged from complete abandonment with bus substitution on streets through busways and a semi-metro systems at grade to full cut-and-cover metro. Various combinations of some alternatives were evaluated. A minority of the committee members favored conversion to a busway on available right-of-way reaching nearly to downtown Cleveland and a wide variety of options for street distribution in the CBD. There was no support for conversion to a metro or even a semi-metro system that had platforms and clearances compatible with the CTS system. In the end, preservation of the existing pre-metro system was the overwhelming choice of the committee, even though it was believed that federal funding could become available for at least the semi-metro conversion, which would offer through routing to Cleveland's west side and airport.

The community at large, the new Regional Transit Authority (RTA), and the areawide planning agency all accepted continuation of LRT for the SHRTS lines. Regional plans (10) actually showed extensions of both branches and a load-balancing LRT line on the west side to the edge of Parma, including the option of possible future street running in that community; see Figure 3. In the special election held to provide funding for the RTA, the countywide 1 percent sales tax for transit was approved by more than 70 percent of the voters; seven out of eight voted yes in Shaker Heights.

The agreement transferring SHRTS to the RTA provided for the purchase of new LRT cars with a total capacity of 4000 seats by September 5, 1980. The size, performance, and other characteristics of these cars were closely controlled to assure the continued LRT character of the system while providing fast service. A federal grant for 80 percent of the estimated cost of those cars has been authorized, and bids have been received from two American and several overseas manufacturers. At the time this paper was written, the bid award was imminent.

Further provisions in the transfer agreement require a high level of rehabilitation of the physical plant and a specified continued maintenance program. Under the new RTA, riders are enjoying low-fare transit throughout the county and universal transfers between lines. SHRTS is at long last functioning as a major trunk line in a unified network with a high volume of transfer riding. The future of America's best-known pre-metro in its arrested-development form seems assured, at least for the life of the new generation of rolling stock.

CONVERSION PROBLEMS

The outcome of this drawn-out chain of decisions and counteractions stretching over a 60-year span casts a cloud on the whole pre-metro idea. Here was a well-developed and timely concept of pre-metro that did not go metro when the opportunity came. Indeed, the federal government was not even approached concerning whether such a conversion might be funded. There are some general lessons to be drawn here respecting conversion of LRT to full metro or semi-metro status.

One obvious drawback to conversion in the SHRTS case was the great difficulty of adding grade separations at existing crossings. There were three main objections to this.

1. Construction of grade separations would disrupt the fabric of a mature community already undergoing the pains of aging. Arterial road traffic would tend to overload alternate routes during the construction process. It was believed this activity would impair property

values, a very sensitive issue in the inner-ring suburbs.

2. Completed grade separations would take the form either of overpasses that would obstruct the views and cast shadows or of box cuts that would require fencing, continual litter removal, or even a lid; the cut-and-cover method of providing full metro service in two parallel boulevards was regarded as the ultimate extravagance and as hypocritical for a community that had so vigorously opposed a freeway in the same corridor.

3. Such a radical change in the physical characteristics of the line would require a disruption of rail service during construction, either through relocation of tracks or by temporary substitution of bus service. Because of the relatively light volume in each branch, where nearly all the grade crossings are, bus substitution carried with it the danger of permanence. It was remembered that this type of service had worked well in 1968 for 5 d when 15 rusted-out poles fell over on the Shaker-Green branch.

A second major drawback to metro or semi-metro conversion was the whole matter of style. High-platform rail lines at surface level would probably not be tolerated in boulevard center strips through residential areas, even if there were a high degree of grade separation. The cars are too big, the platforms introduce too many aesthetic problems, and the need for safety protection by fencing the gates is thought to be greater than for LRT lines.

An additional drawback was the belief that the danger of accidents between motor vehicles and rail cars would be magnified for a semi-metro system with grade crossings. This may have been a false issue, since new LRT cars can be as heavy, as fast, and nearly as high to the floor as high-platform cars. It was felt that federal agencies funding semi-metro service would require full protection (crossing gates with lights and bells). Considering the 0.5 km (0.3 mile) average spacing of cross streets in Shaker Heights, this apparatus at such frequent intervals was viewed as highly objectionable by the committee planning the line's future.

GUIDELINES FOR PRE-METRO DEVELOPMENT

This case study on what did not happen to SHRTS provides guidelines to those planners who want to build a pre-metro system and keep the conversion option really open over a reasonable period of time. If these points cannot be followed, then including pre-metro characteristics at the beginning may be unnecessary, and the additional costs to provide them might be avoided in favor of a somewhat lower cost straight nonconvertible LRT system. Following are the guidelines.

1. Do not wait 50 years or more to face the conversion question. The built-in resistance to change may become overwhelming.

2. Plan the grade separations in the first place and keep the needed property clear.

3. Do not use a boulevard center strip in an area of single-family houses if you ever expect to be able to convert.

4. Do not be mysterious about your ultimate plans; make sure the community knows from the beginning that conversion is an option that is being kept open.

5. Do not get into a second generation of purely LRT rolling stock; convert before that occurs or abandon the idea of conversion.

6. Do not change your plan in favor of keeping the LRT status quo and then expect to be able to change it back to metro conversion.

7. Do not mix any nonconvertible elements into the system as time passes; doing so gives comfort to the standpatters.

8. Never allow rivalry centering on choice of rail technology to develop between two transit agencies; pride may become stronger than reason.

9. Do not study the conversion question to death; changing times will bring everything full circle and provide studies to support every viewpoint.

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Governmental and Public Constraints to the Implementation of Light-Rail Transit in Dayton, Ohio

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This paper discusses the local, state, and federal governmental and institutional constraints to the implementation of light-rail transit. The experiences of the Dayton region are used in an attempt to draw broad-based conclusions and general recommendations applicable to other medium-sized urban areas. The planning process that led to the selection of the light-rail mode in Dayton is also described.

There are a number of local, state, and federal institutional constraints that can be expected in the implementation of light-rail transit (LRT) systems. These constraints will particularly apply to an area that has no existing rail transit facilities. Due to the simplicity of the concept and technology, LRT provides a great deal of flexibility in planning, design, and building, but here the simplicity ends. The governmental and public constraints that must be overcome make the job much tougher than it looks on the surface. Despite the design or technical advantages of a new LRT system, such a system is an unfamiliar and sometimes costly competitor to established travel modes. The public, local government, and technical agencies are experienced with planning, funding, improving, and operating highway and bus transit systems. In contrast, LRT is an unknown that makes demands on the imagination and resources of voters, elected officials, and technicians. Using the experience of Dayton, Ohio, as an example, we will outline the problems encountered at all levels of government in the implementation of an LRT system. An attempt will also be made to draw broad-based conclusions and general recommendations applicable to other medium-sized cities.

First it is important that we define the mode of transportation being considered. One problem that has been encountered at both the local and federal levels is a misunderstanding of what LRT is. The public and even the chief agents in transportation planning often do not know what LRT is and what it can do. For those with a highway background, LRT might be compared to the expressway, which has control of access and some at-grade intersections. Heavy-rail transit or commuter rail may be thought of as the freeway of transit—total separation of grades and complete control of access. Bus transit can be thought of as the arterial system of transit and feeder buses as the collector system.

LRT, as envisioned for Dayton, would consist of a rail guideway system whose route configuration may include portions that are not grade separated. LRT may operate in city streets with vehicular traffic or in reserved right-of-way with vehicular crossings at intersections. Light-rail vehicles (LRVs) are electrically powered, are capable of operating singly or in trains, and can be constructed to accommodate loading from either high or low platforms.

DAYTON PLANNING PROCESS

A description of the Dayton LRT proposal and a brief history of the transportation planning process that led to the selection of the light-rail mode will be given. This historic overview will be used as a basis for pointing out the constraints and problems that have been encountered and how some of them have been resolved, although others remain. Many of these constraints are typical of those faced by other communities throughout the nation and should be anticipated by any area seeking to implement LRT. The review of the planning process will show the logical connections among the long- and short-range planning efforts within the region as well as spell out the series of steps that have carried Dayton to its present status.

Dayton has a population of more than 200 000 in a metropolitan area that contains about 850 000 people. The need for some form of fixed-guideway transit facility was recognized by area planners in the early 1960s. During that time, a regional transportation plan was developed and adopted that called for high-speed transit service in three corridors to the southeast, northwest, and northeast of the Dayton central business district (CBD). As in most urban areas in the 1960s, Dayton devoted most of its energies to the implementation of highway facilities. A unique opportunity presented itself in 1970, when the U.S. Department of Transportation (DOT) announced it was accepting applications for its Urban Corridor Demonstration Program. The purpose of this program was to demonstrate ways of improving peak-period flow into downtown areas. The Dayton regional transportation planning agency submitted an application to evaluate the use of an abandoned railroad in its southeast corridor. A grant was awarded, and a number of alternative transit systems were analyzed. Near the completion of the study, the planning agency and its consultants were ready to recommend a busway to serve the corridor; however, due to the increased interest in LRT technology in the United States, concerns about jurisdiction, and a particularly vocal private citizens' group, it was decided that LRT should be given further consideration.

In 1972, the region requested funds from DOT to evaluate the feasibility of LRT service in the corridor. In October 1973, a feasibility study was completed, and its conclusion was that this was a feasible transit mode for the Dayton area. A comparative evaluation was then made of the busway and LRT, and in December 1973 the regional transportation policy board instructed its staff to take the necessary steps toward implementing the LRT system.

During the first half of 1974, a committee made up of representatives of the six jurisdictions in the corridor developed a formula for allocating the local funding share of the program. In the last half of 1974, a preliminary implementation application was prepared for submittal to the Urban Mass Transportation Administration (UMTA) and the Ohio Department of Transportation. The application was formally submitted by the Miami Valley Regional Transit Authority in January 1975.

During UMTA's 11-month review of the application, a number of meetings were held in Dayton and in Washington, D.C., to discuss the program. In December

1975, UMTA rejected Dayton's preliminary application. UMTA felt that Dayton did not have its nonfederal funds securely committed and that sufficient consideration had not been given to alternatives to an LRT system. In responding to the question of other options, Dayton's regional transportation planning agency has prepared a work program for conducting an alternatives analysis as required under UMTA's September 1976 regulations. The question of local-share funding will be addressed below.

PROPOSED RAIL TRANSIT SYSTEM FOR DAYTON

As it is now envisioned, the route for Dayton's southeast corridor would use LRT technology in a 95 percent exclusive right-of-way system connecting downtown Dayton with communities extending about 19.6 km (12.2 miles) southeast to Centerville via a currently underused freight branch of an existing railroad system. This would be the first of several lines proposed to serve the metropolitan area. The program meets the essential criteria of performance and cost for a mass transportation system serving a medium-sized city. Off-the-shelf technology and equipment will be used and a well-located railroad right-of-way requiring a minimum of remodeling is available. Since feasibility studies have indicated that this mode is applicable to the Dayton region, it is important to note that the geographic and demographic characteristics of this area closely resemble those of other urban areas throughout the United States.

The roadbed for most of the route will consist of a double track with continuously welded rail and resilient pads between the rails and ties to ensure quiet operation. There will be 15 stations. They are to be simple but attractive and functional. There will be boarding platforms for both directions, bus loading areas, automobile pickup points, and parking areas. A total of 2700 parking spaces is planned at 7 of the 8 southern stations at which the necessary property can be easily acquired. Feeder buses will operate on a demand-responsive basis out of a number of stations to provide flexible, convenient access to the system. Feeder-bus schedules will be coordinated to match arrivals and departures of rail vehicles so as to minimize transfer delay.

Rail cars for the system will use an overhead electric power source and standard-width track. The LRV required for the Dayton system is a single-unit car that seats 55 passengers and has the ability to operate in trains of up to four units. The cars will be able to average 56 km/h (35 mph) while making 15 stops. At many points along the corridor, they will be able to attain speeds of up to 80 km/h (50 mph). A trip from one end of the line to the other will require 22 min. The same trip by automobile currently takes 35 to 45 min during the peak hour. Service would be provided at all times except early morning hours, when freight service would continue to be provided for industrial customers.

The capital investment in the system will be about $65 million, or about $3.3 million/km ($5.3 million/mile). This system offers most of the advantages of more complicated and expensive facilities currently being planned or built; however, the Dayton proposal is much more cost-effective and can be implemented in a relatively short time.

CONSTRAINTS TO IMPLEMENTATION

Barriers to the implementation of LRT service have been encountered at the local, regional, state, and federal levels. These constraints have proved to be somewhat different from those that affect other modes and seem to be unique to LRT for the medium-sized city.

Local Constraints

The first category of constraints concerns those at the local level. Local questions involve which corridor should be developed first, how the local cost of the project should be divided, which agency should operate the system, who should subsidize the system once it is in operation, and what are the land-use implications of LRT. The complexity of local concerns in the Dayton area is indicated by the fact that the first line proposed would serve 4 municipalities and 1 township, all of which are in one county. The ultimate rail system currently being evaluated would serve 13 municipalities and 10 townships and involve the cooperation of two counties.

The mid-1960s regional transportation plan for the Dayton area called for three high-speed transit lines serving the Dayton CBD. The one to the northwest would provide transit to the city's most densely populated residential area. The northeast line would serve Wright-Patterson Air Force Base (which has 27 000 employees), Wright State University, and the city of Fairborn. The southeast route would serve the more affluent suburbs and areas that contain substantial portions of the region's elderly population.

When the area planners selected a corridor for evaluation in the Urban Corridor Demonstration Program, the southeast corridor was chosen because of the availability of an abandoned railroad right-of-way. It was felt that the projects selected by DOT would need to have some unique characteristics, and at that time the federal agencies were particularly interested in preserving railroad rights-of-way for transportation purposes. Therefore, funding for implementation of the southeast line was requested first because advance studies had been completed for this routing.

When the various communities were passing resolutions of support for the preliminary application for the southeast LRT line, the city of Dayton requested assurance that work would continue toward implementation of the other two corridors, because it was felt that these two lines would be more beneficial to Dayton residents than the southeast route, which served a number of suburban communities as well as the city of Dayton. This assurance was given; the regional transportation plan was reevaluated for these three corridors as well as four others that were being studied in detail with respect to requirements for the year 2000.

One constraint that develops at the local level in the early stages of a project involves how the project is visualized. The initial reactions of some officials to consideration of an LRT proposal for the southeast corridor of Dayton suggested that in their minds the transit line was a one-way facility in the outbound direction. Officials in the center city saw the potential of allowing the commercial activity of the city to travel outward to suburban shopping areas. They also saw it as an aid to the more affluent residents of the city to move to the suburbs and have easy transportation access to their downtown jobs. Officials in the suburbs, on the other hand, in some cases saw the project as a way of bringing the socially deprived to their community. The planners, in one sense, also saw the proposed line as a one-way facility inbound, since they and the promoters of LRT pointed to the developmental value of such a service to the center city and downtown activities. The planners also saw the system as providing an alternate mode of travel to suburban residents, i.e., providing mobility to the young and the elderly in the suburbs that is not readily available to them in an automobile-dominated system.

All of these conceptions had to be addressed and the fears overcome. One must not overlook such problems in developing major transit facilities in a regional plan. Some of these perceptions depend on the current concerns of other planning services in the region. If, for instance, the housing opportunities plan is currently generating a great amount of discussion, then the issues related to housing opportunities become issues of the transportation corridor; if it is not a matter of current concern, then those issues may not provoke a constraint. Each area must examine its current activities and anticipate how they affect one another as they go into the planning process for a particular project.

There have been no further problems in Dayton regarding the selection of the line to be built first; however, this is an item that must be given serious consideration in the initial stages of any planning process. A compromise among the needs and desires of all the communities involved must be reached in order for the jurisdictions to continue to work together toward the implementation of a staged, coordinated, and comprehensive system.

A second local constraint involves construction funding. Where the local cost of a program of this magnitude would come from is certainly a basic question for the jurisdictions involved. Assuming that 80 percent of the cost would be provided through an UMTA capital grant, a committee made up of representatives of the six jurisdictions (four cities, a township, and a county) involved in the Dayton program was formed to decide the source of the remaining 20 percent, the local share. The committee members, who were appointed by their respective councils, board, or commission, spent 4 months dealing with a number of complicated formulas involving existing and forecast land use and service areas and weighed the various schemes before reaching a decision on how to assign the local shares. The funding formula was then endorsed by each of the governing bodies.

This approach is recommended for solving the local-share question. There is no standard formula or approach, yet all jurisdictions must be satisfied or they will not provide their share of the cost. Since high-level representatives of all the communities had discussed the funding problems in detail and reached a common recommendation to take back to their respective policy boards, it proved easier to obtain support for the formula than if a single agency or city had proposed a scheme. This situation has pointed out the need for additional research in such fields as value capture, tax-increment funding, and model funding formulas. This research is essential and must continue to be supported by the federal government.

The local aspects of subsidizing the deficits of operating an LRT system obviously must be addressed as the issue of the feasibility of LRT is evaluated. The problems involved in providing for that subsidy are the same as those described in regard to capital grants. An important issue in both cases is the definition of a local builder and operator. That problem may not be as severe in some other urban areas as it is in Dayton, since in some areas of the country the service area of a single public transit authority covers the proposed service area for such projects; in Dayton that is not currently the case.

The problem of the operating subsidy is complicated by the cash-flow problem in UMTA's operating assistance program that is created by the slowness in processing section 5 applications. We believe this problem can be overcome. Sometimes the problem is partly the result of slowness at the local level in filing the application and all of the necessary supporting documentation (in a form acceptable to UMTA) to get the project moving expeditiously. We have experienced cash-flow lags of more than 1 year in the operating assistance program as a result of the combination of slowness from these two sources.

It is apparent that UMTA would require some assurance or guarantee of the local matching funds required to subsidize the anticipated operating deficit of a proposed new system before it would make any commitment for capital expenditures. This commitment would have to be based on the local regional transit authority's budget or be guaranteed by commitments from the local jurisdictions involved in the program. If the local communities are to provide the funds, this would be based on a formula involving estimated operating expenses and ridership forecasts. Given the lack of reliability that such estimates carry, it is very difficult to get a local governmental body to commit itself to such expenses.

Another concern of local communities will be the land-use impact of LRT in an area that does not currently have rail transit service. The Dayton implementation application to UMTA for the construction of the southeast line proposed a before-and-after land-use evaluation, particularly around station sites and in the Dayton CBD. The purpose of these studies would be to provide other cities with a basis for estimating impacts and to make information available for use in future corridors in the Dayton region.

The cities have been concerned about what will happen to land use around a transit station. Will high-rise development occur? What will happen to land values? How can growth and change be controlled? What can be expected from a joint development program or special assessment districts? The goals and objectives of each community involved must be given thorough consideration in the planning and design of the system. It seems logical that this work begin with a detailed land-use analysis of what currently exists within the corridor and how the communities want these areas to develop. Many of these land-use aspects have not been tested from a legal standpoint; further research is necessary in this area.

It is obvious that rail stations will have an impact on surrounding land and, if there is proper consideration before implementation of the transit system, the communities can turn this transportation asset into a complete land development advantage for their citizens. It cannot automatically be assumed that every community along the route wants high-density development or redevelopment to occur adjacent to the stations.

The subject of a before-and-after land-use evaluation in the Dayton area remains a consideration within the elements of the alternatives analysis. The major tasks in this analysis are

1. To analyze possible needs for public facilities directly related to the corridor,
2. To determine general development and redevelopment potentials in the corridor,
3. To evaluate the feasibility of joint development projects within the corridor,
4. To evaluate the market potentials of sites, and
5. To investigate possible value-capture techniques within the corridor.

It is suggested that land-use evaluations at least this detailed are required to properly develop a high-quality transit line.

Regional Constraints

The next category of constraints deals with problems at the regional level, including such questions as who should operate the system, how the right-of-way is to be preserved, how rail freight should be handled, and what role citizen participation should play.

Any region that implements a new type of transit service will have to determine who will operate the system. For the calculation of operating expenses, the consultant who prepared the LRT feasibility study for Dayton assumed that the Miami Valley Regional Transit Authority would operate the system. As previously noted, the first leg of the proposed regional system lies within six jurisdictions, but the existing transit authority only includes two of these communities—the central city and its oldest, most affluent suburb. Under this structure, the nonmember jurisdictions would have to contract for service or join the authority. A contractual arrangement would involve a direct, annual general fund expenditure for the four jurisdictions; joining the authority would require levying a 2.73-mill annual property tax on their citizens. A third mechanism permitted under Ohio law would have the existing authority disband and be reconstituted as a countywide authority. This was done in June 1976. To provide a funding base for the new authority, the people of the county were asked to vote a 0.5 percent increase in the sales tax, which would have produced $7 million/year. The issue failed, and the old two-city transit authority was reinstated. Any single jurisdiction could operate the system, but it would have the same problem of contracting with the remaining communities that the transit authority has.

In many urban areas there may not be a question as to who the operator of the system will be. The existing transit authority may already cover the area to which service is to be supplied, but the proposed service area frequently extends beyond the authority's jurisdiction, e.g., across a county line. In such cases, early consideration should be given to the operating mechanism.

Another subject for concern in Dayton's southeast corridor is rail freight service. There are a number of small industries along the southern portion of the existing line that are receiving rail freight service from a connecting railroad. The decision was made early in the planning process to continue rail freight service in this corridor. Due to the nature of some of the industries being served, the expense of trucking their supplies and products would be prohibitive, and they would be forced to relocate if rail service were removed. In an effort to conserve right-of-way, it was also decided that the transit and freight vehicles would use the same track. The transit vehicles would operate from 5:00 a.m. to midnight, and the freight vehicles would have the use of the tracks from midnight to 5:00 a.m.

An additional question related to the issue of freight service is who should operate the service. The consultant who evaluated the feasibility of LRT in the southeast corridor of the Dayton region recommended that the transit agency should have control of all movements along the right-of-way. Under these circumstances, the most effective way to arrange for the freight service would be for the crew to be employees of the transit agency, which would operate the system as a short-line railroad. An alternative approach would be for the transit operator to lease the freight rights to a second party.

Having the transit and freight services use the same track is an approach used successfully in some European cities. It has the added advantage in Dayton of replacing a deteriorated track with a new facility that will enhance its freight potential. However, it is recommended that cities planning LRT facilities make every effort to separate the transit and freight tracks within a corridor. This would eliminate the complicated legal entanglements and operational conflicts that can evolve with joint use of track. In other corridors within the Dayton region, it is anticipated that railroad right-of-way would be leased, and the transit lines will be constructed parallel to the existing freight tracks.

In many situations in the northeastern part of the United States, the opportunities for using low-density rail lines are being lost. Since the Consolidated Rail Corporation is not taking over the lines, they are being sold to private interests. We have proposed that either the federal government or our state government establish a land bank to purchase and hold all abandoned rail rights-of-way for future transportation use.

An element that is critical to the success of implementing any public improvement on the scale of a mass transit system must have early, strong, and continuous citizen participation. Establishing a mechanism for this is a requirement under any alternatives analysis and is a part of the Dayton region's work program for further evaluation in its southeast corridor. However, the formal mechanism for establishing citizen participation already exists in the Dayton community, as it does in most urbanized areas, through a citizens' transportation council. This is an advisory group to the transportation policy board; its major function is to obtain public input.

For most projects, citizen involvement must be aggressively sought if any feedback is to be obtained at all. However, in the case of Dayton's LRT project, it was actually a group of private citizens who forced the issue of giving LRT further consideration at a time when the local planners were about to propose a busway. The group, the Citizens Committee for DART [Dayton Area Rail Transit], prepared a voluminous report outlining an LRT system for the southeast corridor just before a busway report on this same corridor was released by the regional transportation planning agency and its consultant. Unlike the vague, often unbalanced work of the typical ad hoc commitee, the citizens' report set out ideas and concrete proposals that quickly gained wide attention and support. As a result of their efforts, a consultant was retained to study the feasibility of LRT in the corridor. This group has continued since 1971 to promote the LRT plan among citizens, business leaders, civic clubs, and local, state, and federal politicians. Their members have also been active in national conferences on LRT.

Overall, this unofficial citizens' committee has been effective in promoting LRT service for Dayton. However, because of their lack of knowledge of governmental functions, the committee has often caused problems for the regional transportation planning agency; in some instances it has actually delayed progress on the program. It is therefore recommended that attempts be made to direct the energies of unofficial citizens' groups or private individuals into a more formalized mechanism, such as a council of citizens that works more directly with the regional transportation policy board, which can channel citizen input to the appropriate officials and maximize its impact. Local, state, and federal funds are available for obtaining citizen input to the planning of new transit facilities and should be used to their fullest extent.

One of the major problems when aggressive private citizens promote a particular transportation concept, in this case LRT, is the occasional mixing of concepts and ideas within their approach to promoting a mode. In our case, for example, too often the value to a community of land development was promoted on the basis of the kinds of land development that occurred in connection with heavy-rail commuter lines in and around stations.

That issue has been mixed in with the justification for LRT. Similarly, the idea of the ultimate flexibility to upgrade an LRT system to a subway or heavy-rail commuter system has been promoted as an advantage when, in reality, no one today can envision a city of Dayton's size requiring that kind of rail system. For all reasonable purposes, the LRT system is the ultimate level for Dayton's transit system. This mix of promotional aspects adds to the confusion that exists in dealing with public knowledge and public support of a transportation mode.

In our area there is another constraint that is a barrier to carrying out the requirements of an alternatives analysis. Although transportation planners can go through the process of analyzing an exclusive busway as one alternative to LRT in the same right-of-way, if that is not an acceptable alternative to the citizens of that corridor, it is not a practical alternative. The reason it is not acceptable in this case is basically that the public sees it as a way of putting a strip of concrete pavement down the railroad right-of-way so that the decision can later be made to stop providing bus service and start letting cars run on that pavement; this would make it a backdoor way of obtaining a highway. Although this has never been anybody's intention, that possibility has been raised in the minds of the residents of that corridor, and that fear can be played on by the advocates of other modes; this has good and bad points. A good point is that it aids in promoting the LRT concept. The bad point obviously is that it makes redundant the alternative of a busway. Developing a freeway for automobile use, possibly with bus routes operating on it, is a technical alternative and previously was considered for a portion of our first corridor. But the public came to the conclusion that it did not want a freeway, and the Dayton City Commission has adopted an informal resolution clearly stating that it would not construct a freeway in that corridor. This is another technical alternative that is not politically practical and therefore not worthy of further investigation.

State Constraints

The next area of constraints involves those at the state level. In the Dayton area these have concerned state participation in the local funding share and the issue of integration of proposed intercity rail passenger service with local operations. In the preliminary application submitted to UMTA in 1975 for implementation funds to build Dayton's rail facility, it was proposed that 10 percent of the financing would be obtained from the state of Ohio. Funds for the Ohio Department of Transportation are allocated by the state legislature on a biennial basis. Thus, it is impossible for the state to commit funds to a project such as Dayton's, which is estimated to take 6 years for implementation.

Assuming a total project cost of $65 million, the state's share would be $6.5 million. If this figure were distributed over a 6-year period, the state would need to commit $1.1 million/year to the program. Since the region must compete with areas such as Cleveland, Cincinnati, and Columbus and a number of smaller operators, it is not realistic to believe that Dayton can obtain an adequate share of available funds. It is possible that the project could be programmed on a cash-flow basis with a state obligation at the front end of each stage and state funds provided at the time of contract signing. However, UMTA's acceptance of such an arrangement is not certain at this time.

The state funding levels and budgetary practices vary widely throughout the country. This is an area that must be investigated thoroughly in a region's early planning stages for an LRT system. Special agreements and new legislation may be needed to assure adequate and timely state support.

The second point for consideration is the integration of intercity and local rail transit service. The Ohio Rail Transit Authority, a statewide rail transit planning agency, entered into an agreement with a consultant in February 1977 to study the feasibility of high-speed intercity rail passenger service in Ohio. One or more of the lines under consideration would connect the cities of Dayton and Cincinnati. The statewide lines would serve a corridor similar to that served by the local line but with a different level of service. Again, similar plans are being prepared for other states, and their potential must be considered. The question of joint use must be evaluated under these circumstances.

Possibly the greatest constraint at the state level is the fact that most state departments of transportation are recently converted highway departments; they generally lack a commitment to transit and support for a fixed-guideway concept. In Ohio we have been fortunate to receive state support, but that support comes within the fiscal constraints of Ohio law. To take a specific project of this type to the state legislature for special funding consideration produces the image of proposing pork-barrel legislation. That image is difficult to overcome. Our solution is to develop the nonfederal share guarantees at the local level and then run our own risks with the state; this should remove it from the concern of UMTA.

Federal Constraints

Since no project of the magnitude of an LRT system can be constructed and put into operation today without the assistance of federal dollars, it is necessary to comply with federal law and regulations and to deal with the federal bureaucracy. When most people in the transportation profession criticize the federal government, they address the problem of the absence of a national transportation policy. While we can agree that there is not an officially adopted national transportation policy, we believe that in fact one does exist, even though it was partly backed into by the adoption of laws, rules, and regulations in areas not specific to transportation. In fact, we contend that the national transportation policy is supportive of a highway transportation system. It is supportive of a long-headway diesel bus transportation system. It is not supportive of LRT as a transportation alternative or of transit as a major element of transportation or, for that matter, of efficiency in highway transportation.

The national transportation policy puts social burdens on the transit system without putting those same social burdens on the highway system. At the same time, national policy stimulates suburban sprawl through loans to middle- and upper-income persons subsidized by the Federal Housing Administration and income incentives based on tax deductions for mortgage costs and real estate taxes, while it does not provide tax incentives for redevelopment in the center-city areas. People in the transportation planning profession at all levels of government express platitudes about coordinated planning, development control, growth strategies, and so on, but we have never in the history of transportation in this country constructed a highway or a transit facility only because it encouraged desirable land development rather than because it satisfied an existing need. Hence, while we promote LRT by pointing to the land-use value created, those who weigh the justification for LRT look at the existing ridership, densities, and land consumption in order to determine whether the system can be installed. In essence, one must be able to justify a project on the basis of need, not on the basis of creating a need or shaping land development. This immediately produces a major constraint for all medium-sized and small cities, particularly with regard to LRT.

The federal agencies are properly concerned that, if they were to approve an LRT system for Dayton, many cities throughout the United States could request similar funding, and this would severely tax the capability of the federal government to finance transit projects. Rather than addressing the policy and priority questions that problem presents, the federal government has treated LRT as a system to fall back on, one that would cost less than constructing a commuter rail or heavy-rail system. As long as the federal government, many planners, and some citizens' groups look at LRT as a preliminary step toward commuter rail or as a means of investing less capital than would be required for commuter rail while providing reasonably similar levels of service, we will continue to be faced with the idea that there are not more than a dozen cities in the United States that can expect funding for LRT, as has been stated by past administrations.

If both planners and the federal government truly believe that the concerns of this nation include energy conservation, improvement of air quality, and the provision of transportation for all our population, then we must conclude that the development of major transit facilities is desirable. LRT systems can promote the shaping of land, can promote the reduction of energy consumption and the improvement of air quality, and can satisfy many of our social objectives. We suggest, therefore, that what we need is not a transportation policy but a change in the existing transportation policy so that it will fit all national objectives. The suggestion that one of the criteria for approving funding of an LRT project is the assurance of public and private commitment to redevelopment is merely an excuse for procrastination. Public and private commitment follows transportation decisions or develops unrelated to them, but it does not develop simutaneously. It puts an undue burden on transportation planners to expect them to develop a composite package that includes a total land redevelopment commitment.

It is not suggested here that it is improper for the federal government to have proposed and implemented alternatives analysis regulations but rather that it is unfair to require a literal response to those regulations retroactively. This problem is certainly not unique to UMTA. It exists in all of our federal agencies. If an LRT project has evolved from a transportation planning process, it has gone through an alternatives analysis in the true meaning of that word, whether or not all the specific requirements listed in UMTA's regulations have been fulfilled. We are suggesting here that another federal constraint arises from the length of time it takes to develop a major project, since there is a risk that changes in the rules and regulations will require doubling back to satisfy those regulations, thus adding to the time for development and therefore exposing it to greater risk of changing regulations. This can entail considerable penalties of cost and time.

The vicious circle that develops in terms of the federal requirement to assure that there is financial commitment to a project presents some interesting constraints. It is very difficult to get a local or state commitment without a federal commitment. What evolves is a case of contingent commitments that depend on the commitment of the other levels of government. In essence, it requires a multiple cycling through federal, state, regional, and local jurisdictions before the final funding package is totally committed.

There have been many proposals at the federal level for dealing with some of the transportation funding problems, including both (a) establishing a transit trust fund and (b) breaking up the highway trust fund and creating a single transportation trust fund. The real problem is that we are unable to commit funds for the long periods now required to implement projects and seem unwilling to find ways of shortening that period to fit the time frame available. The commitments that are made for all forms of transit funding are actually invalid, although they are normally lived up to. A present city council cannot bind a future city council; funds cannot be appropriated beyond the current year, and funds not appropriated are not legally committed.

The state transportation department cannot make a commitment beyond the monies appropriated by the legislature. In Ohio the legislature appropriates on a biennial basis. There is no contractual commitment authority beyond that biennium. One-year and 2-year budgets do not fit transportation project schedules except for the purchase of buses. The persistent planner and the persistent local official, however, can overcome these obstacles if the current administration makes clear its position toward funding LRT projects of the type we have defined that have evolved from a proper planning process. It is in fact a waste of federal dollars, state dollars, and local dollars to grant study contracts to evaluate the feasibility of LRT projects in any city if the basic decision has not first been made that LRT projects are an alternative acceptable to the federal government in such a city. In Dayton, we are past the decision point. We want LRT. The alternatives analysis process serves only to satisfy UMTA's requirements, not to provide input to the decision-making process; this somehow makes everything seem backwards.

CONCLUSIONS

Significant constraints to the implementation of LRT service in Dayton obviously still exist; after 12 years nothing is on the ground. However, many barriers to the creation of an LRT system have been overcome, and the remaining problems are fairly well understood by those involved in transportation planning. The problems involve local, regional, state, and federal constraints.

Rail transit is inherently service to a corridor. Corridor choice and staging are crucial issues. Local governments must be involved in cooperative planning at the earliest point, because it is these jurisdictions that must apportion and bear the cost of the area's local share for capital costs and operating subsidies. It is these same jurisdictions that must control and adapt to the land-use impacts that rail service will bring.

LRT is a latecomer to the medium-sized American city. Its rights-of-way must be aligned through existing patterns of land uses and established circulation systems. Adapting existing rail lines for LRT service while acquiring parallel or new facilities will entail extremely high right-of-way costs. In addition, because of LRT's operating characteristics, it is unlikely that the proposed service area for any LRT system will coincide with an existing governmental jurisdiction or district. Designating or establishing a capable and acceptable operating authority is crucial for the success of an LRT project.

Regional transportation planning agencies that propose an LRT system should anticipate difficulties in coordinating state assistance with federal requirements. As always, the level of funding approved may be less than the amount felt to be needed. An additional state constraint on the design and operation of LRT commuter systems may exist in state plans for intercity rail service. This factor may become increasingly significant.

A final constraint, and the one that has proved to be the most significant in Dayton, is the amount and types of federal assistance available and the delays met in processing applications for this aid. UMTA's programs for LRT do not have sufficient priority to provide a workable and timely source of funding. As was previously pointed out, Dayton's regional transportation planning agency is today back at the point reached in 1973—justification of a choice of mode. This is now our most severe constraint to the implementation of LRT.

Analysis of Transit Alternatives

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The planning and implementation of major public works projects require the consideration of many engineering, social, environmental, political, and fiscal issues. In particular, the 1970s have seen nonengineering issues take precedence over engineering considerations in project planning and implementation. These issues are highlighted in a conceptual approach based on six tests of feasibility—physical, operational, institutional, social and environmental, financial, and economic feasibility. This paper describes the application of this approach and the nonengineering issues that were identified as having an effect on the planning of a light-rail transit system in Harrisburg, Pennsylvania. The feasibility tests were found to constitute a valuable approach because they lead to a formal or explicit recognition of several planning issues that are usually only implicitly recognized in planning studies. Once they were explicitly identified, these issues could be analyzed in terms of their impact on the planning process.

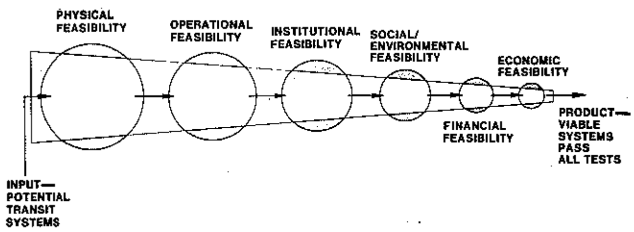
The planning and implementation of major public works projects require the consideration of a number of engineering, social, environmental, political, and fiscal issues. It once was the case that, if the need for the particular public works project was particularly clear, public support was unambivalent, and fiscal resources were adequate, the major thrust of the planning and implementation effort could be limited to the identification and resolution of the engineering issues. The process moved smoothly from planning through preliminary and final engineering studies to construction and operation. The conception, planning, design, and initial decade of implementation of the Interstate highway program (1956 to 1966) illustrates a situation in which only the engineering issues required detailed analysis. But times have changed. The completion of the Interstate system is now often challenged in many communities on social, environmental, and fiscal grounds. Few, if any, major transportation capital projects in the 1970s can be said to have unambivalent public support or adequate fiscal resources and, while the need for a solution to an identified problem may be clear, the best solution is not always self-evident. We believe that social, environmental, political, and fiscal issues are now taking precedence over engineering considerations in project planning and implementation and are generally proving to be far more difficult to resolve.

The attractiveness of light-rail transit (LRT), as evidenced by the success of TRB's conference on LRT in 1975 and many active LRT proposals in cities throughout the United States and Canada, is that it offers some hope of a compromise solution to the conflicting requirements of the nonengineering issues. An LRT alternative falls between a do-nothing alternative, which offends few interests but satisfies few needs, and a very capital-intensive transit alternative such as conventional rapid transit, which has the potential to satisfy many travel needs but carries a high cost in social, environmental, and fiscal resources. For example, LRT at grade or in a shared right-of-way represents a transportation compromise between the inefficient existing automobile and bus transportation system and the very efficient (from a transportation point of view) rapid transit subway operation. At the same time, it offers a fiscal compromise because the cost of building an LRT system at grade or in shared rights-of-way is often less expensive than a completely grade-separated or subway system and hence is more likely to be fundable. Thus, the revival of interest in LRT indicates a growing awareness of the need to address the nonengineering issues involved in the planning and implementation of a major transportation project or program.

We have developed a conceptual approach to the planning of major transportation projects that is intended to explicitly identify and highlight all of the issues involved in the planning and implementation of a new transportation system. The emphasis of this approach is to identify the implementability of a proposed transportation or transit alternative through tests of its physical, operational, institutional, social and environmental, financial, and economic feasibility. An alternative that passes the first five tests and outperforms other alternatives in the test of economic feasibility should have the best chance of being carried through to implementation. These tests are presented schematically in Figure 1.

The tests of feasibility are summarized briefly below in the context of a rail study recently conducted by Tippetts-Abbett-McCarthy-Stratton (TAMS) in Harrisburg, Pennsylvania. The test of physical feasibility addressed the question of whether it was physically possible to construct new rail services in a candidate travel corridor. Physical constraints were identified, engineering design criteria were established, and rough capital cost estimates were prepared. The test of operational feasibility was intended to identify operational conflicts with other transportation modes. If new facilities were required to permit operational feasibility, cost estimates were prepared. The test of institutional feasibility was intended (a) to identify all federal, state, or local agencies; private companies; public or semipublic authorities; and labor organizations and unions whose responsibilities, ownership, legal rights, and so on would affect or be affected by the inauguration of rail transit services and (b) to determine, as required, the agency or agencies that should own, operate, and manage the new transit service. A large part of the maneuvering between the Federal Railroad Administration (FRA), private railroads, and affected labor unions during the recent formation of the Consolidated Rail Corporation (Conrail) illustrates the great influence institutional considerations can have. To a certain extent, institutional issues are more flexible constraints than physical, operational, or fiscal factors because institutional positions or factors can often be modified through negotiation. The test of social and environmental feasibility identified the social and environmental aspects of the project, e.g., disruption, mobility, noise and air pollution, accidents, and energy consumption. The test of financial feasibility was basically a cold, hard look at the magnitude of federal, state, and local financial resources available to meet anticipated capital costs and operating deficits. No matter how favorable the cost/benefit ratio of a transit alternative, if it is not fundable it will not be built, and its benefits will never be realized. An alternative can be dropped from further analysis at any time it proves to be physically, operationally, institutionally, financially, or socially and environmentally infeasible or unimplementable. Surviving alternatives should be compared by using conventional techniques of economic analysis in the test of economic feasibility.

Figure 1. Schematic representation of the tests of feasibility of transit alternatives.



HARRISBURG LONG-RANGE TRANSIT PLAN

TAMS recently completed a 3-year study of the feasibility of various long-range transit options for the Harrisburg area as part of the Harrisburg Area Transportation Study (HATS). The nature of the study performed and the transit alternatives considered are described in this section. In a subsequent section, the application of the tests of feasibility is described.

Harrisburg, the capital of Pennsylvania, is strategically located in a three-county metropolitan area of 300 000 in the south-central area of the state. Harrisburg's location is important as a rail hub, the railroad gateway to the West, and the western terminus of railroad electrification. The rail network in the Harrisburg area is nearly ubiquitous; it extends in six spokes to and beyond the nearby communities of York, Gettysburg, Carlisle, Duncannon, Dauphin, Hershey, Elizabethtown, and Columbia. The location of these rail lines is shown in Figure 2.

Most of the railroad facilities in the Harrisburg area were taken over by Conrail, the quasi-public freight railroad formed by the federal government to take over the bankrupt railroads in the northeastern United States in April 1975. Conrail subsequently passed to the National Railroad Passenger Corporation (Amtrak) the control of the former Penn Central Transportation Company's main line extending from Harrisburg through Elizabethtown to Philadelphia. Amtrak also acquired the railroad stations at Harrisburg, Middletown, and Elizabethtown. In this paper, the railroad lines in the area will be referred to by their pre-Conrail designations.

Most of the rail lines in the region are fairly active. The Penn Central line between Harrisburg and Mechanicsburg serves primarily as a 14.5-km (9-mile) freight siding for the many industries between Harrisburg and Mechanicsburg. The Reading Company's line from

Figure 2. Railroads in the Harrisburg area.

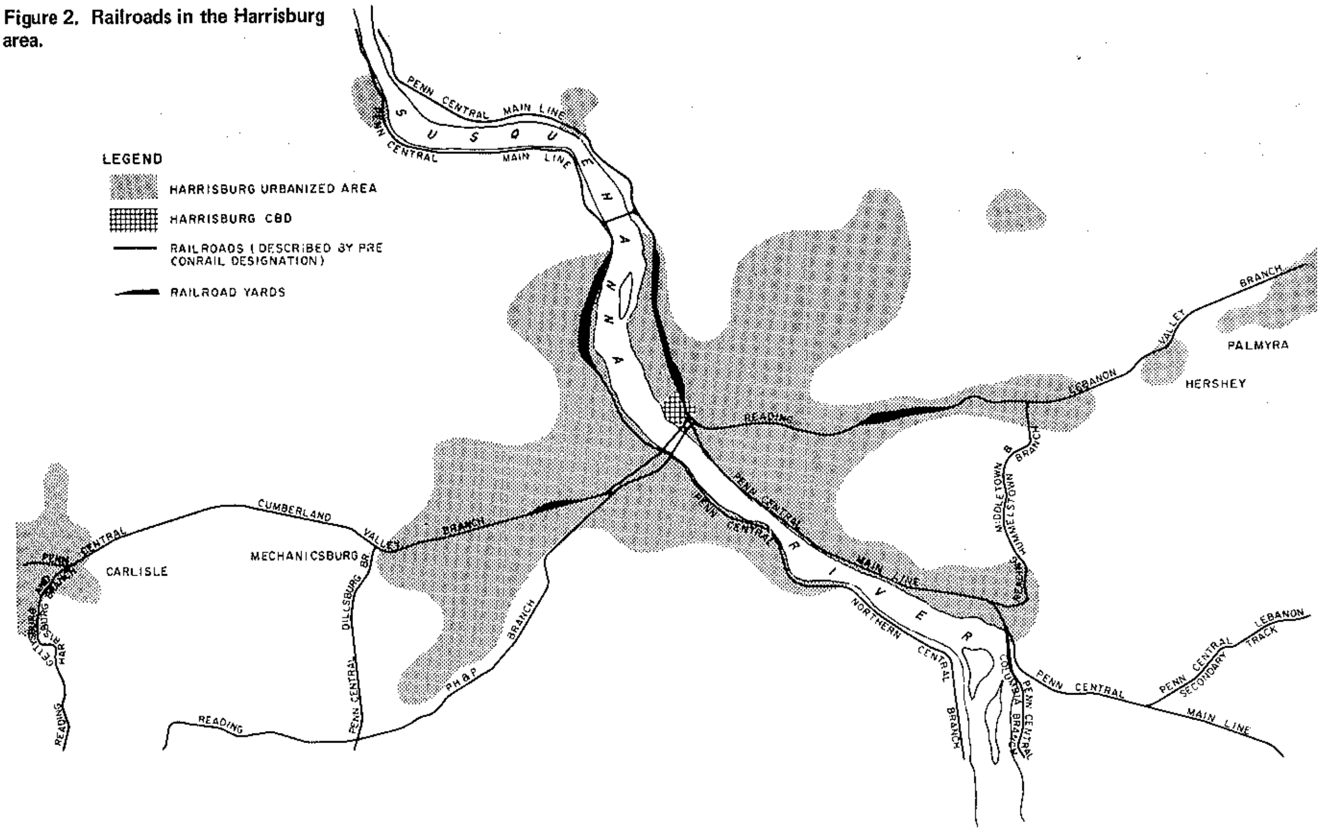
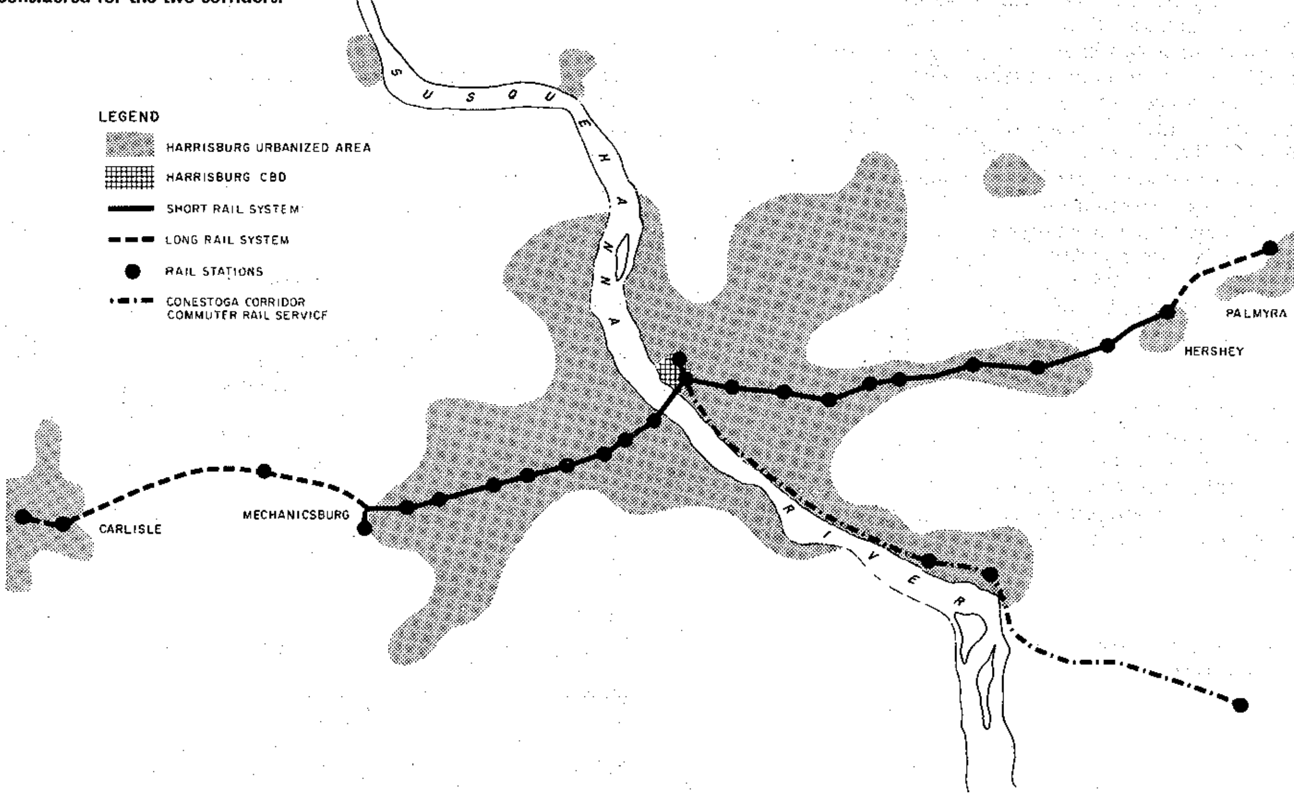


Figure 3. The rail transit alternatives considered for the two corridors.



Harrisburg through Hershey and points east is an important main-line connection to New York that will see increased use under Conrail. The Penn Central main line from Middletown through Harrisburg and north along the Susquehanna to Pittsburgh is the main artery for east-west rail freight traffic and long-distance passenger service in Pennsylvania. Other freight lines in the region are also frequently used.

For a number of years, there have been several groups in the Harrisburg community that promoted capital-intensive transit service improvements. They urged that the existing railroad facilities in the Harrisburg area be examined to determine whether they were suitable for use by rail transit services. As a result of controversy over several highway projects in the adopted highway plan for 1990, the fuel crisis in 1973, and increased public concern about an effective mass transit system, the HATS coordinating committee decided to explore the potential for rail transit services in the Harrisburg area. The long-range transit study was begun in 1973 to explore these possibilities. Its primary focus was the exploration of the feasibility of initiating new low-cost rail transit services within existing railroad rights-of-way. Several options for rail transit services were developed and analyzed in terms of patronage attracted, construction costs, operating and maintenance costs, revenues, operating deficits, and time and cost savings to affected travelers. The scope of the study was expanded in 1974 to include an analysis of long-range improvements to the existing bus system as well.

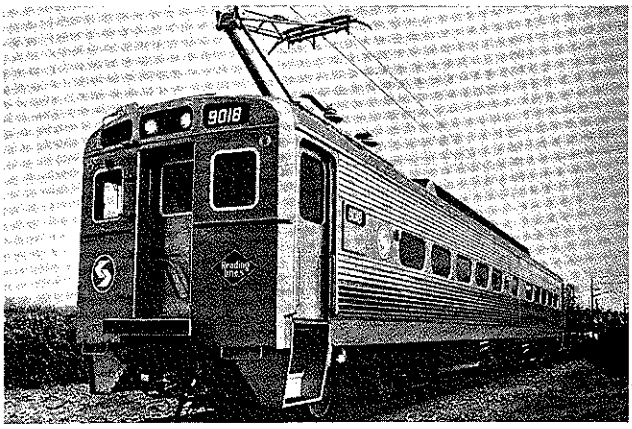
RAIL TRANSIT ALTERNATIVES

The rail transit alternatives developed for the Harrisburg region considered options for both routes and vehicles. There are nine travel corridors or subcorridors that contained railroad rights-of-way and were thus potential corridors for rail transit services. A preliminary evaluation of these corridors in terms of their tributary population and accessibility identified five corridors that were suitable for further analysis. Preliminary estimates of capital and operating costs and transit patronage revealed that only two corridors could justify serious consideration for frequent, all-day transit services. These were the Lebanon Valley corridor, which runs east from Harrisburg to Hershey and beyond and is centered on the former Reading Company's Lebanon Valley branch, and the Cumberland Valley corridor, which runs west from Harrisburg to Mechanicsburg and Carlisle and is centered on the former Penn Central Cumberland Valley branch.

Rail transit alternatives were developed in some detail for these two corridors; see Figure 3. Two options were considered for rail services in these corridors. One, referred to as the rail and bus short system, consisted of a 38-km (23-mile) system between Trindle Spring in the west and Hershey in the east, operating through Harrisburg Station and a new rail station north of the State Street Bridge and serving the Capital Complex, which has 15 000 employees. The second option, the rail and bus long system, consisted of services between Carlisle and Palmyra, operating through the Harrisburg and Capitol Complex stations during peak periods—a distance of 58 km (35 miles)—and between Mechanicsburg and Hershey during off-peak periods. To complement the proposed rail services, several bus routes in both corridors were developed to act as feeders to the rail lines.

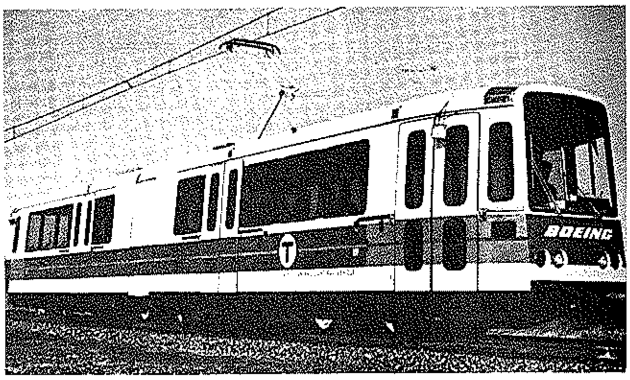
In addition to the tests of feasibility that are the prime topic of this paper, an interesting feature of the long-range transit study was the evaluation of existing transit vehicles for use on the rail transit services. Two types of rail vehicles were considered for service in the Leb-

Figure 4. Examples of rail vehicles considered for service.



SILVERLINER CRV OPERATED BY SEPTA IN PHILADELPHIA

PCC LIGHT-RAIL VEHICLE
REBUILT BY ALLEGHENY TRANSIT-PITTSBURGH



NEW STANDARD LIGHT-RAIL VEHICLE

anon and Cumberland valleys: commuter rail vehicles (CRVs) and light-rail vehicles (LRVs); both types are shown in Figure 4.

CRVs are typically designed for relatively long commuter trips—8 to 50 km (5 to 30 miles)—and for higher operating speeds, lower acceleration rates, and a higher ratio of seats to passengers carried than typical LRVs or rapid transit vehicles. The CRVs under consideration for Harrisburg would be self-propelled electric cars like the Silverliners, which are used by the Southeastern Pennsylvania Transportation Authority (SEPTA) in the suburbs of Philadelphia and on the Philadelphia to Harrisburg services. Although these vehicles are intended primarily for routes whose stations are at least 1.6 km (1 mile) apart, Silverliners are operated successfully on routes in the Philadelphia area that have low-level stations spaced less than 1 km (0.6 mile) apart. This is possible because of their relatively high acceleration rate of 10 m/s^2 (33 ft/s^2). The Silverliner, like a number of the CRVs that operate in the New York area, draws its electrical power from 11-MV alternating current in overhead wires and has on-board rectifiers and transformers to convert this power for its direct-current electric motors. Both new and used Silverliners were considered for service in Harrisburg. New Silverliners currently cost about \$800 000 each. It was estimated that used Silverliners or New Haven 4400s could be purchased and rehabilitated for about \$150 000 each. Since new and used Silverliners have approximately the same number of seats, the capital-cost advantage of used vehicles is readily apparent.

Two LRVs were also considered, the Boeing Vertol Standard Light-Rail Vehicle (SLRV) and the Presidents' Conference Committee (PCC) car. These vehicles differ in two important respects. The SLRV has a greater passenger capacity than the PCC car. It can seat more than 70 passengers and carry a total of more than 100, as opposed to 50 or 60 seated passengers and 80 total passengers for the PCC car. The cost of SLRVs is now more than \$600 000, whereas a PCC car costs \$160 000 including rehabilitation.

The tests of feasibility were applied to these vehicles. Another important factor, besides the differences between CRVs and LRVs in vehicle size and electrification systems, had to be taken into account in system design. FRA regulations state that all rail passenger vehicles that come under its jurisdiction must meet several collision-strength standards. Any rail transit vehicles that operate on active freight trackage come under the FRA's jurisdiction.

Because CRVs meet federal standards for collision strength, they would be allowed to share active freight trackage; CRV services between Harrisburg and Philadelphia do so today. Rail transit alternatives were therefore developed for both the short and long systems that assumed maximum use of existing trackage as a result of track sharing between CRVs and freight cars. On the other hand, LRVs must be operated on separate trackage because there are no LRVs that meet FRA collision standards. Alternatives developed for these vehicles would require less cooperation with Conrail and freight users since scheduling conflicts would be minimized (but not eliminated entirely) because of the required separation of trackage. The construction costs associated with the LRV alternatives represent a reasonable maximum for rail transit services in Harrisburg that use a shared right-of-way.

Headways for all three kinds of vehicles considered (Silverliners, SLRVs, and PCC cars) were sufficiently long to permit some extended single-track operation even though this was not reflected in the alternative track layouts that were developed. The alternatives developed for both LRVs and CRVs were primarily double-track systems. Single-track operation would be used only in several short sections in which construction of an additional track would require expensive earth cuts or fills or a new bridge. This approach left some flexibility in the system concept so that, if detailed engineering analysis revealed that Conrail would not be able to share or yield trackage or right-of-way to permit double-track operation in certain locations, single-track operation would be feasible, even if it were less desirable.

TESTS OF FEASIBILITY

In order to examine each alternative in terms of the tests of feasibility, basic information about each system was developed. Data on the rail system (location of tracks, switchyards, stations, and so on) were collected in field surveys. The field surveys and interviews with railroad employees provided information on existing railroad operations. Requirements for additional facilities were identified, and cost estimates were prepared. Patronage estimates were prepared as a basic input for the tests of financial and economic feasibility. They were used to identify the fleet size required, the level of service to be provided (and hence the operating costs), the fare-box revenues to be generated, and the overall system travel and time costs. The financial feasibility test also required that funding sources and their probable level of support be identified. To this end, existing levels of local, state, and federal transit funding were analyzed. The economic feasibility tests required information on highway travel as well. Estimates of 1990 highway traffic were carried out for this reason. No data base existed or could be developed within the scope of this study to permit more than a general analysis and evaluation of the indirect economic and the environmental considerations.

This study was carried out in a transitional period. Conrail took over the railroads in Harrisburg less than 6 months before the conclusion of the long-range transit study and was in no position to make long-term planning commitments regarding rail transit services and properties it had just acquired and begun to operate. Consequently, a number of important issues identified through the tests of feasibility were not resolvable within the time frame of the study.

Physical and Operational Feasibility

The tests of physical and operational feasibility are treated together here because in this study they largely overlapped. These tests required both the identification of constraints and the development of a design or design approach for overcoming them and an estimation of associated capital and operating costs. The stated intention of the long-range transit study was to develop low-cost rail alternatives for Harrisburg. Thus the tests of physical and operational feasibility were directed toward alternatives that made maximum use of existing facilities.

The test of physical feasibility basically involved whether a rail transit system could be built within available Conrail rights-of-way. To answer this, the rights-of-way in the Cumberland and Lebanon Valley corridors and the railroad facilities they contained were identified. Information was gathered on the extent and boundaries of existing rights-of-way; the location of existing bridges, structures, embankments, and other civil engineering works; the location of existing trackage, yards, stations, electrification, and other railroad facilities; and adjacent land use and topography. The test of operational feasibility dealt with whether existing freight and passenger services could be maintained and whether rail transit services could be successfully integrated with them. Several factors were considered, including present track use, frequency and characteristics of freight and passenger operations, and likely trends in railroad operations.

On the basis of a physical and operational inventory of Conrail facilities and operations in the two travel corridors, a number of constraints and facility requirements were identified. Of primary importance was the conclusion that existing rights-of-way could accommodate both existing freight and new rail transit services. Over much of the length of each corridor, vacant roadbed and unused or little-used trackage could be easily converted to rail transit use, although existing freight operations would impose a number of constraints on rail transit services. These constraints would depend on the type of vehicle, since CRVs would be allowed to share trackage with freight services, while LRVs would not.

The operational challenge entailed in track layout for an LRV system lay in developing a double-track transit system that interfered with a minimum of freight sidings and left sufficient trackage available for existing freight operations. A major rail overpass was found to be required in one location in the Cumberland Valley to switch the LRT alignment from the north to the south side of the main-line freight right-of-way in order to avoid a major yard and several important sidings. Bypassing another freight yard required more than 3.2 km (2 miles) of new roadbed that used, in part, an abandoned interurban right-of-way that had been taken over by the Reading. Fortunately, most of the active sidings are located on the south side of the right-of-way and have adequate track space or vacant right-of-way on the north side for LRT services. Over the 58-km (35-mile) length of the long system, 15 sidings and four through tracks would be crossed at grade. Protective devices would be included as part of the LRT signalling system to prevent LRVs from entering sections of track that have at-grade or flat junctions if the junction were in use by freight trains. The use of these sidings would be limited to night hours when transit services would not operate.

A CRV alignment was developed that made maximum use of existing trackage, a significant portion of which would be in active use by freight trains. New construction was minimized. As a result, construction costs for the CRV system were one-third less than those for the LRV system. However, because much of the trackage would be shared, freight operations on the shared track would be totally restricted during peak periods (4 h) and somewhat curtailed during the remainder of the transit operating day. Such operating restrictions could only be imposed with the consent of Conrail. As noted earlier, it was impossible to resolve this question at the time of the study. Without Conrail's consent, only the LRV alignment is operationally feasible.

Capital-cost estimates for both LRV and CRV alignments were used to develop a range of costs that were carried through the tests of financial and economic feasibility. It was found that the cost of providing facilities for rail transit services could vary by as much as 50 percent depending on the amount of track sharing that would be possible and the type of rail transit vehicle operated.

Institutional Feasibility

The test of institutional feasibility involved the issue of the ownership, operation, and management of new rail transit services. This required an analysis of the interaction between existing institutions and the proposed rail services and the identification of possible institutional arrangements for the new rail services.

The regulatory institutions affected are those public bodies at the federal, state, or local levels of government charged with ensuring that those involved in the transportation of people and goods operate in the public interest, i.e., both with ensuring public safety and ensuring that there is competition between carriers at a level that maximizes public welfare.

At the state level, the Pennsylvania Public Utility Commission (PUC) bears both of these responsibilities. The PUC had several actions under way that affected the proposed rail line because they related to the safety of several crossings. In general, the PUC's concerns for public safety would be the same as those of the rail transit operating authority. Cost estimates included allowances for upgrading the warning devices at the at-grade street crossings along the rail lines of interest. In the area of the regulation of competition, the PUC awards carriers franchises that permit the carriers to offer a defined service to a specified geographic area. With the exception of the terminus of each line, the proposed rail services did not conflict with existing franchises held by transit operators other than the Cumberland, Dauphin, and Harrisburg Transit Authority, generally known as Capital Area Transit (CAT), and its contractor, Capitol Bus Company.

At the federal level, the agencies with the most pertinent regulatory powers are the Urban Mass Transportation Administration (UMTA), FRA, and the National Transportation Safety Board (NTSB), all part of the U.S. Department of Transportation. UMTA's regulatory powers generally stem from the strings that are attached to federal capital and operating assistance grants. Provisions in the Urban Mass Transportation Act of 1964 as amended require that transit projects that receive federal funding assure the protection of affected transit employees (section 13c), prepare an environmental impact analysis, and draw up a program to accommodate the elderly and handicapped. In addition, the act empowers UMTA to investigate the safety conditions of any of the projects it funds. The FRA's regulatory authority has been discussed earlier in this paper. The NTSB has been actively involved in developing system safety plans for rapid transit systems now in the design or construction phase. It would be involved in the planning of any rail transit system in Harrisburg. In addition, the NTSB is responsible for investigating rail transit accidents, except in the case of commuter operations controlled by the Interstate Commerce Commission.

The operating institutions that would be affected by new rail transit services include Conrail, Amtrak, Septa, and other railroads that have trackage rights on the Conrail or Amtrak systems, as well as the intercity bus services that serve Harrisburg and CAT. Amtrak owns Harrisburg Station and the Penn Central main line between Harrisburg and Philadelphia. Conrail owns the remaining lines of interest. There is every possibility that Conrail and Amtrak, the operating organizations most affected by the rail transit proposals, will agree to permit new local rail transit services to use part of their facilities, but no negotiations have taken place at any level with either. This made it impossible within the scope of the study to unequivocably state that rail transit service was institutionally feasible.

There are three operating institutions that could operate or own new rail transit services either singly or jointly with one or more other institutions—Conrail, CAT, or a new rail transit authority that could be formed. Conrail purchased the rail lines of interest from the bankrupt Penn Central and Reading railroads at essentially their scrap value on April 1, 1976. Conrail would apply the "dominant-user" criteria to determine whether Conrail or the rail transit authority should own the facilities to be shared. In this case, it could be argued that the rail transit service would be the dominant user in terms of the number of trains per day. In realistic terms, however, considering the function of the rail lines of interest, there is no question that Conrail would be the dominant user and should own the facilities. Our study assumed Conrail would retain ownership and lease the trackage rights to the rail transit authority. The value of the lease would be negotiated. If Conrail were the operating agency under a purchase-of-service agreement, part of the fees would cover the economic value of the trackage rights. The plan that outlined the structure of Conrail (1) set down guidelines for the lease of rail properties and suggested the lease value should represent a fair return on the value of the property used.

A totally new agency, independent of CAT and Conrail, could be set up to operate rail transit services. The only advantage to this approach is that the new agency would start with a clean slate. It would not have any of the operating biases or political and union commitments that CAT or Conrail have inherited or evolved through time. Administratively, however, it would make little sense to develop a new agency when there are existing agencies that could provide the same services.

An alternative operating institution considered was the local transit authority, CAT. New rail services could be operated under its control either directly or through a purchase-of-service agreement with Conrail. The type of rail vehicle affects this analysis. CAT is the best institutional alternative to operate rail transit services that use LRVs. The union work rules under which LRVs are typically operated are similar to typical union work rules for buses. For example, LRVs are operated in Newark, Pittsburgh, Boston, and New Orleans by locals of the Amalgamated Transit Union, which also represents CAT's employees. CAT would also carry out vehicle maintenance. There is no advantage in this case to having this function performed by Conrail. For administrative reasons, it would be advantageous to form a rail operating division within CAT. This would allow policy decisions to come from a common source while the day-to-day transit operations of the two modes would be carried out independently.

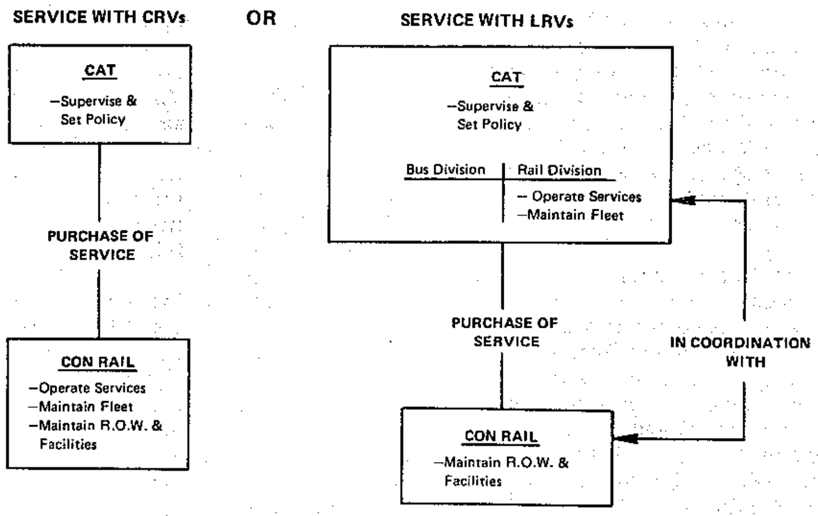
The third alternative is Conrail, which currently performs the operation and maintenance functions for rail transit services in Philadelphia and New York. In realistic terms, it is the only agency able to perform maintenance of facilities and way in Harrisburg, particularly under the track-sharing option that would use CRVs. Conrail would also be the logical agency to operate the services and maintain the vehicles. Conrail now operates and maintains a fleet of several hundred CRVs, including Silverliners, in Philadelphia.

If LRVs are selected, vehicle operation and maintenance would be somewhat more complicated. LRVs are typically operated under transit work rules that are quite unlike those that ordinarily apply to CRV operations. The transit work rules by which CRVs are operated, if applied to LRVs, would make LRV operation particularly uneconomic. It was concluded that Conrail would not be the most suitable operating agency if LRVs were selected.

The operation of rail transit services also requires close coordination with the freight services operated by Conrail. In the case of CRVs that would share tracks with Conrail, Conrail would surely need to have overall dispatching control of all trains moving on the same facilities. It would therefore be logical under these conditions that Conrail operate the rail transit services. If LRVs were used, the need for coordination is less because no track sharing occurs; it would be more reasonable for an agency other than Conrail to operate the transit services.

In summary, practical institutional arrangements for the implementation of rail transit services in Harrisburg were identified. The ownership of rail facilities would remain with Conrail, which would levy annual charges for trackage rights. Rail services would be operated under the general authority of CAT. No matter which type of rail vehicle were selected, Conrail would carry out maintenance of facilities and way under a purchase-of-service contract. If CRVs were selected, Conrail would also carry out vehicle operation and maintenance. If LRVs were selected, CAT would carry out the same functions. Figure 5 shows these relationships schematically.

Figure 5. Options for the operation of rail transit services.



Financial Feasibility

The test of financial feasibility analyzed the amount and availability of funds required to construct and operate transit services in Harrisburg. This test was not intended to determine whether the funds would be well spent on any or all of the various alternatives or whether the funding sources would agree to commit the funds over which they have control. Its purpose was to identify the possible funding sources and their resources and to estimate the level of capital and operating funds required to implement the two rail alternatives under consideration.

At the federal level, UMTA is the primary source of funds. The details of UMTA's funding programs are well known and will not be discussed here. There is an additional source of federal funds. The Federal-Aid Highway Acts of 1970 and 1973 permit the use of federal urban highway system funds for the construction of fringe parking facilities associated with public transportation facilities and for bus lanes, bus priority treatments, and fixed-rail facilities. The HATS coordinating committee could request that some urban highway system funds be diverted to mass transit. This funding source was rejected because, in light of the currently restricted level of highway funds available in Pennsylvania for construction, such a diversion would be the end of most highway improvements in the HATS study area.

The state department of transportation, through its Bureau of Mass Transit Systems, has been providing both capital and operating assistance. Thus, the state share of the total assistance required will vary according to the federal share. If federal funding provides the maximum 50 percent of the operating deficit, the state share could be as much as $33\frac{1}{3}$ percent and the local share as low as $16\frac{2}{3}$ percent. Capital and operating assistance grants are included in the state budget. Their total varies from year to year and has generally increased with time, but there is no regular funding program equivalent to UMTA's section 5 program; funds are approved by the state legislature on an annual basis. Requests for operating assistance now exceed the legislature's level of appropriation. Unless the state legislature increases its level of funding for operating assistance, the department of transportation will be unable to provide a full one-third share of each transit authority's operating deficit.

Cumberland and Dauphin counties and the city of Harrisburg provide the local share of capital and operating assistance funds out of general revenues, splitting it 25, 45, and 30 percent respectively. These local sources now spend about 1 percent of their total budgets on CAT.

Capital costs include all capital expenditures that must be made between 1976 and 2000, including the replacement of the existing bus fleet when it wears out, expansion of the bus fleet, purchase of rail vehicles as required, and purchase or construction of all of the necessary capital facilities. Operating costs include the total cost for operating and maintaining the transit system. Since the operating costs will obviously vary from year to year, the estimate for 1990 was used to indicate the likely level of overall funding required. Total system costs for each alternative are presented in Table 1.

At the federal level, the capital and operating assistance funding requirements can be met within existing levels of funding. At the state level, while capital funding requirements can probably be met, it is unlikely that the state will be able to provide its full share of operating assistance. The local governments that support CAT will probably find that the combined requirements of capital and operating assistance funding will be greater than can be conveniently met from their general budgets. The rail transit alternatives could easily require more than 5 percent of their gross budgets if the state is unable to provide its one-third share of operating assistance funds. For the rail transit alternative to be considered financially feasible, therefore, additional revenue sources at the state and local levels must be developed.

Economic Feasibility

The test of economic feasibility included a complete summary of the costs and benefits of alternatives under consideration in order to determine whether all of the economic, social, and environmental benefits arising from the proposed alternatives outweigh their costs.

For the HATS long-range transit study, the all-bus alternative was selected as the base alternative because it represented a logical evolution of transit services in the Harrisburg area. The economic comparison of alternatives was limited to the travelers affected by the rail transit alternatives proposed for the Cumberland and Lebanon Valley corridors. Approximately 3 800 000 passengers/year would use the rail transit services in the rail and bus long system in 1990. Fewer rail passengers would be attracted by the rail and bus short system; the difference would be attributable to automobile drivers. Under the all-bus system, fewer still would use buses;

the difference would again be made by automobile drivers. In effect, the three alternatives represented different ways of carrying the 3 800 000 passengers and are compared below on that basis.

Mode	All-Bus System	Rail and Bus Short System	Rail and Bus Long System
Automobile	2 090 000	500 000	–
Bus	1 710 000	–	–
Rail	–	3 300 000	3 800 000
Total	3 800 000	3 800 000	3 800 000

Tables 2 and 3 compare the alternatives on the basis of quantifiable (in monetary terms) and nonquantifiable economic factors. The all-bus alternative was found to be the least cost alternative in quantifiable economic terms by a margin of 10 to 15 percent. This alternative would, however, entail higher levels of fuel consumption, accidents, and air pollution. No attempt was made to put a monetary value on these factors. The differences between the three alternatives are small in comparison with the total figures for the area.

This discussion has not dealt with the indirect economic benefits that might follow the construction of a rail transit system. The region as a whole may reap benefits from these induced changes in several ways. Intraregional changes in land use represent a benefit when they lead to increased efficiency in the use of public and private facilities. The shifting of residential growth per se is not a net benefit. The same is true of an intraregional shift in economic growth or vitality. Community values enter this analysis because the community may deem a given land use or economic pattern preferable to all others. Where the transportation improvement supports the preferred pattern, the community will realize a net benefit. A revitalized downtown, as exemplified by the Harristown project in Harrisburg, may be a community goal. In this case, a rail transit system, which would indeed add to downtown vitality, would lead to net beneficial changes in land use and economic activity. Clearly, the indirect intraregional changes resulting from a transportation improvement, e.g., rail transit services, must be evaluated within the context of community goals and values.

At the interregional level, there are several possibilities of economic activity flowing into the Harrisburg region. One form of economic growth that is easily identified is the flow into the area of state and federal funds to construct the rail transit system. A large part of the funds to finance construction of the rail facilities could be expected to remain within the area. Less easily identified is the extent to which industries would be attracted to the region from outside because of the presence of a high-capacity rail system.

This discussion of indirect economic benefits has been a general one because their identification and analysis were outside the scope of the work performed by TAMS for the long-range transit study. The magnitude of indirect benefits is influenced by public policy and community desires. Only when these policies and desires run parallel to the advantages an improved transportation facility offers will the community reap significant indirect economic benefits.

SUMMARY

The six measures of feasibility represent a systematic way of taking into consideration the nonengineering factors that all successful transportation planners consider. The six-test approach is a coherent and explicit way of identifying the important issues. Its intent is to distinguish the most implementable alternative from the most economic alternative (which may not prove to be implementable). During the Harrisburg study, the approach served as a logical framework for conducting an issue-oriented planning approach by identifying the many issues and factors not under the control of the transportation

Table 1. Funding requirements for the three transit alternatives (in 1975 dollars).

Item	Percentage	All-Bus System ($000s)	Rail and Bus Short System ($000s)	Rail and Bus Long System ($000s)
Capital cost				
Federal share	80	3200	28 000	40 000
State share	10	400	3 500	5 000
Local share				
Harrisburg	3	120	1 050	1 500
Dauphin County	4.5	180	1 575	2 250
Cumberland County	2.5	100	875	1 250
Total		4000	35 000	50 000
Total annual operating cost		1550	2 750	3 500
Total annual fare-box revenue		850	1 500	2 000
Annual operating deficit				
Federal share	50	350	625	750
State share	33.3	233	417	500
Local share				
Harrisburg	5	35	63	75
Dauphin County	7.5	52	93	112
Cumberland County	4.2	29	52	63
Total		700	1 250	1 500

Table 2. Comparison of the monetary costs of the three transit alternatives (in 1975 dollars).

Item	All-Bus System ($000s)	Rail and Bus Short System ($000s)	Rail and Bus Long System ($000s)
Annualized capital cost	160	2 470	3 480
Annual operating and maintenance cost			
Transit	1570	2 740	3 640
Automobile (gasoline, oil, parking)	2770	1 020	–
Total	4340	3 760	3 640
Annual cost in passenger time			
Transit	2800	4 200	5 200
Automobile	2600	900	–
Total	5400	5 100	5 200
Total annual cost	9900	11 300	12 320

Table 3. Comparison of nonmonetary economic effects of the three transit alternatives.

Item	Cumberland and Lebanon Valley Corridors Only: All-Bus System	Rail and Bus Short System	Rail and Bus Long System	Whole HATS Study Area
Annual gasoline consumption, L (000s)[a]	3750	2200	1480	303 000
Annual accidents				
Persons killed	1.4	0.6	0.6	50
Persons injured	59	36	28	4 200
Property-damage accidents	308	140	28	26 000
Annual air pollution, Mg[a]				
Carbon monoxide	170	71	3.6	16 960
Hydrocarbons	38	14.5	4.5	2 270

Note: 1 L = 0.26 gal, 1 Mg = 1.1 tons.
[a]These figures reflect an allowance for the improvements that are being made to automobiles.

planning process. When the Harrisburg rail transit study began, it was viewed by elected officials, local planners, and the general public as strictly an engineering exercise of fitting new railroad tracks within an existing right-of-way, turning the power on, and beginning transit service. Through the feasibility test approach, TAMS was able to identify other important factors influencing the construction of new rail transit service, some of which required community action and some of which (particularly institutional issues) were outside the community's control. The attraction of the feasibility-test approach is not that it offers a methodology for resolving planning issues but rather that it leads to their formal or explicit identification.

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Both authors were formerly with Tippetts-Abbett-McCarthy-Stratton, New York.

Joint-Development Potential for Light-Rail Systems

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In recent years, many cities have begun to question the universal application of conventional rapid transit (CRT) systems but have indicated a need for a fixed-guideway solution to their transit problems. During this period of technological reexamination, light-rail transit (LRT) systems are being evaluated in greater detail to determine their capacity to meet operational specifications. This paper isolates for discussion the potential of LRT systems to inspire joint-development opportunities like those that have been attributed to CRT systems. Current incentives are evaluated in terms of the similarities that exist between the development of CRT and LRT systems. LRT's operational flexibility is widely recognized. This flexibility also provides new dimensions for station-area development; the small scale (compared with CRT stations) provides opportunities for initiating development within areas that normally would not be considered to have development potential. The barriers to joint development for LRT systems are essentially the same as those for CRT systems. The most significant barrier to a full realization of joint-development potential is the lack of adequate private capital to realize the full opportunity of the public investment. Under the new policy directives for urban revitalization, several new financial assistance programs have been developed. The urban design action grants appear to have a significant potential for use in expanding the joint-development potential of LRT systems. Value-capture options for stimulating private investment in joint development are currently being given considerable attention in demonstrations of LRT and downtown people movers. Each rapid transit system currently under consideration must conduct an assessment of the value-capture potential as part of the requirements for federal funding. Implementation techniques are discussed in terms of development incentives and the control mechanisms that are necessary to guide development along the lines of community objectives.

Since there is a general professional consensus regarding the physical and economic merits of joint development, one wonders why so few valid examples exist today. Federal agencies have invested millions of dollars in joint-development research, yet the private development community's reaction remains tepid at the hour of implementation. While the number of examples of joint development increases with each kilometer of transit, freeway, or waterway development, there remains a gap between the public and private entrepreneur.

In recent years our nation has refocused on light-rail transit (LRT) as a valuable transportation resource, the infrastructure for which already exists in many urban and suburban environments. Since the cost of conventional rapid transit (CRT) sometimes exceeds $30 million/km ($50 million/mile), both the federal and local governments are looking at existing LRT rights-of-way and considering adding to them for new or expanded systems. No one is suggesting that LRT is a panacea for solving transportation and urban development problems, but LRT is considerably less expensive to construct and operate than CRT and has greater functional flexibility.

This presentation attempts to analyze the joint-development potential that LRT systems offer in a variety of patterns of urban density and land use. The same rationale that has encouraged cities to look more closely at LRT for urban transportation systems is applicable to the joint-development opportunities. Severa_ components of the planning process for LRT and joint development will be isolated for analysis, including (a) current incentives for joint development, (b) current liabilities affecting joint-development potential, (c) federal assistance for joint development, (d) value-capture financing options, and (e) implementation opportunities.

Since very few examples exist in the United States to illustrate the joint-development potential of LRT systems, the case studies presented here will generally be taken from CRT systems. Most of the developmental and financial techniques are transferable and the effects may be quite similar.

INCENTIVES FOR JOINT DEVELOPMENT

A turning point in the recognition of joint-development planning as a workable component in the transportation planning process came in a memorandum on the role and responsibilities of the federal highway system in Baltimore written by the late Charles Abrams in 1967 (1).

The interdisciplinary concept team formed in Baltimore at that time was one of the earliest examples of a planning team set up to integrate the transportation engineering and civic design process.

In 1969 the U.S. Department of Transportation (DOT) commissioned a technical study to develop guidelines for the promulgation of transportation and joint-development planning activities (2). Case studies of five cities were analyzed. At the same time, the National Environmental Policy Act of 1969 emerged as the most powerful piece of environmental legislation of the decade. The act required the preparation of environmental impact statements that covered the analysis of social, economic, and physical impacts of publicly funded projects. This served to further encourage the use of multidisciplinary teams in the evaluation of project impacts.

Other notable joint-development studies followed, including the Boston transportation planning review (begun in 1970) and the 1973 program of the National League of Cities and U.S. Conference of Mayors to set up prototypes for providing financial assistance for joint development. However, most of these studies emphasized the planning rather than the implementation process. Not until the Young amendment to the National Mass Transportation Assistance Act of 1974 was passed were joint-development planning activities directly linked to an implementation process.

The Young amendment permits section 3 funds to be used to assist the establishment and funding of local public or private corporations operating in designated corridors and districts. The Young amendment inspired the reconsideration of tax-increment financing as a workable tool for local governments to use in implementing joint-development projects related to public investments. In addition, "brick-and-mortar" funds are now available through community development block grants from the U.S. Department of Housing and Urban Development (HUD). Other public funds have also been committed to the encouragement of such projects. However, the previous lack of coordination between federal and local agencies and the delayed initiation of joint-development planning in advance of system construction have stymied local project development.

Aside from the fact that joint development tends to make the best use of land and converging activities, joint development is a proven method of obtaining additional financial benefits from the creation of transportation improvements in conjunction with community or urban-area improvements. Therefore, the incentives for developing integrated transportation and urban improvement programs are economic as well as conservational in nature. By using joint-development financing options, which will be examined below, it is possible to recover as much as 20 to 40 percent of the capital cost of transit improvements. This quantifiable incentive, coupled with the better use of land and the concentration of activities, can be a significant factor in the integration of the transportation and urban development planning and implementation processes.

Do these economic, physical, and social incentives apply to LRT systems? They certainly apply to the consideration of new or extended LRT systems, and they have limited application to improvements in existing systems. Beyond lower capital and operating costs, one of the most significant advantages of LRT systems is functional flexibility. This advantage is magnified when joint-development opportunities are explored.

An early misconception about the feasibility of joint development concerned the physical size of the development site. Recent LRT joint-development projects in Toronto have illustrated that, even if station size and the development site are restricted, there can be successful integration of land use and economic activity. There is a tendency to consider joint-development solutions only in conjunction with high-rise air rights development, commercial centers, or high-density residential developments. While the potential economic return from joint-development activities such as these is greater, it should only reflect the proportional public investment in the transit station at these sites.

Since the intensity of use of LRT stations is lower than that for CRT systems, the scale of development can also reflect a lesser impact. This is not to imply that LRT stations do not have the same joint-development potential as CRT stations; it simply accepts that the density patterns that dictate the need for CRT rather than LRT systems will probably prevail in measuring the impact of joint development.

CURRENT LIABILITIES AFFECTING JOINT-DEVELOPMENT POTENTIAL

Several factors may exist in an area that act as disincentives for meeting joint-development objectives. These local liabilities are usually attitudinal rather than functional in nature but are, nonetheless, real barriers to realizing the full potential that can accrue to integrated development. In certain environments, there are institutional barriers to implementation opportunities, but rarely are there barriers to the integration of planning activities. The effort for change must be consistently directed toward the institutional barriers but have an equal focus on the financial disincentives that fester within outdated institutional frameworks.

Several institutional barriers exercise financial, legal, or planning constraints that prevent the full recognition of joint-development potential. A local government must be able to separate those barriers that are entrenched in legal restrictions from those that are attitudes developed over years of using a single-purpose planning and implementation process. The construction of any fixed-guideway system is a large enough financial venture to require a comprehensive approach to planning and implementation activities. It therefore represents an appropriate opportunity to scrutinize existing institutional structures for possible improvements and to direct any creative impulses toward refinement of the process.

Planning Barriers

Several impediments to joint development appear in the early phases of the planning process. One major barrier is the absence of an organizational sponsor or catalyst at any level of local government. Often several agencies, groups, or organizations are suitable and capable of being prime sponsors, but the institutional framework or attitudes of a community may prevent one from emerging. This condition or attitude can produce an approach to transportation and land-use planning that addresses these elements separately rather than in an integrated process. Key decisions are often settled by default rather than through an open decision-making process. The result is that public and private interests—the merger of which is essential to the success of joint development—are in conflict.

In many communities the analytical techniques necessary for defining the level and intensity of interaction between land use and transportation are not developed. The value of perishable data sources is often not defined in a manner that facilitates before-and-after impact monitoring. Similarly, nonperishable data sources are organized for single-purpose use (e.g., analysis of housing supply and demand) rather than accumulated in a comprehensive fashion, thereby facilitating early analysis of the potential benefits of joint development. The impetus for joint development is sometimes lost in the time-consuming feasibility-analysis stage of transit and joint development planning. A comprehensive data base reduces the delays that often erode local interest.

Financial Barriers

The financial constraints on the public and private sectors form the greatest barrier to the potential success of joint development projects. One simple but major constraint is that the economic advantages of joint development are either unknown to or not accepted by local government officials. This is especially true in cities that are considering fixed-guideway systems for the first time. Since the Center City transportation project study on joint development was completed in 1970 (2), considerably more research and development funds have been devoted to providing joint development data to local governments for specialized use. In addition, new funding programs of DOT, HUD, and the Economic Development Administration (EDA) have provided information and encouragement to local governments that are considering joint development activities. HUD's urban development action grants offer still more potential for implementation funds.

Given the growing role of various federal agencies in joint development, the private sector should be more receptive to risking venture capital. To date, this has been the greatest shortcoming of joint development proposals, since real or imagined barriers have discouraged the investment of seed capital by private entrepreneurs. Traditionally, the private market seizes on land development opportunities that are created by the convergence of favorable economic, social, and political conditions. Except for the need to obtain building permits, environmental certifications, or zoning approvals or to fulfill other government-imposed requirements, the private market is virtually free to select the best use of a property.

In joint development all of these factors apply, but the initiating market stimulus is a public decision to invest tax revenues in a capital-improvement project, regardless of the best use of the property. The private market must then adjust to this government-sponsored activity and reestablish the profitability of a transit station in relation to other surrounding land uses. For this reason, joint development often relies on the government to assume a leadership role in initiating the condition for private investment, and the ultimate success of joint development is dependent on the adoption of consistent goals for public and private economic investment.

Legal Barriers

Many states and localities do not have an existing legislative base that encourages joint-development planning or implementation programs. For example, laws governing the exercise of eminent domain are not uniform for all transportation modes in all states. The result is that each joint-development project must be considered as a special legal case, which hinders the transfer of experience between projects. This barrier is gradually being removed as more court decisions have upheld the rights of localities to acquire property in excess of construction rights-of-way to implement projects for the public good.

Many states do not have laws that allow tax-increment financing for public-private joint ventures. Without this financing tool, a valuable catalyst for joint development is lost. The public, generally speaking, remains largely uninformed or uninterested in this financing option; a local bond issue suffered defeat in Dade County in late 1976.

The creation of public development corporations requires state legislative action, which often limits the nature and extent of the charter. Overcoming this barrier can require a substantial commitment by local governments, which are often only marginally convinced of the need at all. The passing of the Young amendment to the National Mass Transportation Assistance Act of 1974 has helped to alleviate some local concerns by providing a financial avenue for establishing public development corporations. Public corporations are not unique in the United States; housing and development authorities have used these concepts for years. However, their use in the past has predominantly been for single-purpose developments rather than for an integrated multidirectional scope, as is required in joint transportation and urban development proposals.

Many of the current liabilities that affect the feasibility of joint development exist because the apparent barriers have never been challenged. Local government officials often walk a tightrope in dealing with acceptance of a transit improvement program by a local community or neighborhood and therefore develop opposition to more creative approaches that may require amending existing laws or ordinances. LRT and CRT systems face similar constraints in relation to such liabilities. Since station locations for LRT systems are much closer together than for CRT systems, the need for a comprehensive public development charter is greater. Unless a comprehensive joint-development program is adopted, a strategy for joint development may become diffused and ineffective.

FEDERAL ASSISTANCE FOR JOINT DEVELOPMENT

Various incentives for joint development have been discussed. The most significant incentives are financial, and in recent years there has been evidence that the federal government, through several agencies and funding vehicles, is willing to accept a larger role in providing the initial financial incentives. Capsule descriptions of these programs follow.

U.S. Department of Transportation

The Young amendment provided the inducement for establishing public development corporations by allowing the use of section 3 funds to defray operating and administrative costs. To qualify for these funds, a public sponsor must prepare a grant application that illustrates the objectives, feasibility, and operating intent of the corporation. Support data concerning the quantity of land assembled, the anticipated costs and benefits and the scope of the corporation must also be provided. The local-participation share in the funding is 20 percent.

The Urban Mass Transit Administration (UMTA) recently began a 2-year demonstration program to provide technical and financial assistance to a select group of cities to evaluate the potential for joint development by using value-capture financing options. Capital grants for site acquisition and station modification will be provided in addition to potential loan guarantees for related infrastructure costs. The cities are asked to include value-capture options. The intended result of this requirement is that joint development will at least be considered as a contributing factor in the reduction of capital costs by returning to the public coffers a portion of the benefits derived from public investments. It requires that joint-development feasibility be explored in a comprehensive manner during the planning of LRT or CRT systems that use section 3 capital funds.

Another new UMTA program involves a demonstration effort oriented toward the testing and evaluation of personal rapid transit (PRT) systems in an urban environment. The downtown people-mover demonstration program will focus on less costly solutions to needs for mobility in major activity sectors of three demonstration cities—St. Paul, Houston, and Los Angeles. These cities are encouraged to use the demonstration funds to define the specific role of joint development in the planning and implementation processes. Since some aspects of PRT systems closely resemble those of LRT systems, an increased resource base should be available and transferable from this demonstration program.

U.S. Department of Housing and Urban Development

In 1973 HUD and DOT jointly financed a study by the National League of Cities and U.S. Conference of Mayors to recommend prototypes for financial assistance in planning joint development projects within a 760-m (2500-ft) radius of a transit station. This study (3) established the criteria for the use of community development block grants to assist in setting up and supporting development corporations. The funds continue to be available for joint-development projects, including the improvement of sidewalks and utility systems at stations in low-income neighborhoods.

The Housing and Community Development Act of 1977 (PL 95-128) adds a new component to the community development block grant program—the urban development action grants. The intent of these grants is to "alleviate physical and economic deterioration through reclamation of neighborhoods having excessive housing abandonment and deterioration [and] through community revitalization in areas with population out-migration or a stagnating or declining tax base." The program is designed to stimulate economic development and revitalization of residential neighborhoods through joint efforts of public and private investment. Approximately $400 million/year has been authorized for expenditure. Guidelines for the grant program have been developed; the Transit and Urban Development Committee of TRB served as a review group. This program represents an important breakthrough for funding transit-station development in neighborhoods that are experiencing economic decline. The funds can provide important seed money for encouraging other public and private financial commitments.

Economic Development Administration

EDA funding has traditionally been used to promote predominantly rural development, tourism, or industrial development activities. However, EDA has recently taken a number of steps to begin developing an urban strategy that includes cooperative agreements between HUD and EDA on urban development action grants. A recently initiated national demonstration program will support the administrative costs of hiring experienced professional staff and managing central-city economic development programs aimed at inducing greater public and private investment in urban settings. Districts in cities that have high levels of unemployment will be given first priority for funds. Joint development projects in such environments should qualify for EDA assistance for areawide revitalization.

Other federal funding programs, such as those under the Bureau of Outdoor Recreation, are suitable for use in joint development projects. The successful projects will use these programs to accumulate the basic functional infrastructure capital and technical assistance funds. However, the success of joint development will depend on the enthusiastic support of private investment. The major issue is still whether adequate private capital can be attracted to a project to ensure its financial feasibility.

PRIVATE INVESTMENT INCENTIVES FOR JOINT DEVELOPMENT

Although federal programs can provide the initial incentive for joint development, these funds are not essential for integrated transportation-related urban development activities. Direct access has been provided from a number of transit stations into office buildings (such as the Pan Am building in New York) or department stores without federal assistance. The private market has consistently responded to investment opportunities created through public investment in capital improvements. However, in recent years a concept has emerged that encourages public stimulation of private-sector investment, yet returns to the public coffers a share of the financial benefits that accrue to the private development. This concept, value capture, warrants closer examination.

Value-Capture Financing Options

Value capture has been defined as "a means whereby land adjacent to transportation facilities (in this case, transit stops) is purchased, managed, or controlled in order for the public to share in potential financial and community development benefits from the facilities that are not otherwise possible" (4). Research work completed by the Rice Center for Community Design and Research team has demonstrated that 20 to 40 percent of the capital costs of transit improvements may be saved by using the value-capture technique in joint development.

At the heart of value capture is a defensible legal basis. Recent court cases have upheld the right of cities to sell property in excess of the necessary construction right-of-way for private development. A history of court cases upholds the ability of a public body to acquire more land than is required for a project to accommodate future expansion needs. However, recent cases have allowed the acquisition of additional land for the purpose of development to ensure its financial success. These cases have established a legal precedent for financing joint development on surplus lands and returning to the public a share of the profits to defray the transit system's capital costs.

Special-benefit districts have been used as a means of sharing in the cost of transit improvements; this is also a form of value capture. This concept, frequently used to finance pedestrian malls, has numerous applications for transit-station development and is particularly appropriate for LRT systems, where the smaller scale of development is more easily defined than for CRT station areas. Legislation exists in many states (Minnesota's joint powers, Wisconsin's benefit district, and South Carolina's special assessment district) to allow an increase in property taxes to be used for financing the cost of improvements. In California this concept has been used by defining concentric districts around certain San Francisco Bay Area Rapid Transit stations and levying different tax rates on private land according to its proximity to the station. Revenues from this differential taxation are then used to defray a portion of the system costs.

Although the influence zones surrounding LRT stations are not generally as broad as those around CRT stations—perhaps 300 m (1000 ft)—the use of benefit districts or

Table 1. Summary and comparison of results of investment analysis.

Station Location	Proposed Development	Value-Capture Technique Applied[a]	Development Capital Cost ($000s)	Net Cash Accumulated from Development ($000s)	Net Present Value ($000s)[b]	Length of Transit Segment (km)	Estimated Cost of Transit Segment ($000s)	Percentage of Costs Defrayed: Net Accumulated Change	Percentage of Costs Defrayed: Net Present Value
Los Angeles									
Watts	Station, parking, commercial	4	1650	2 490	690	3.7	7 900	31.5	8.7
Expo	Station, parking, commercial, office, hotel	3, 4	1590	30 490	11 330	2.4	35 750	85.3	45.3
St. Louis									
Downtown A	Station, parking, commercial, office	4, 7	2510	6 230	1 770	1.9	500	1245.6	354.6
Downtown B	Station, parking, commercial, office	3, 4	2150	7 620	2 290	1.9	500	1524.4	457.0

Note: 1 km = 0.6 mile.
[a] The value-capture techniques are identified in the text.
[b] A discount of 8 percent/year has been applied.

joint-powers districts remains an economically valid technique to encourage LRT joint development. The same potential for air or subsurface rights development that exists for CRT systems is available for LRT systems. LRT has a slight functional disadvantage if an overhead power source is used, but this need not preclude air rights development. The shorter and lower platform of LRT systems can also be a significant feature in air rights development.

Several techniques for applying value capture to station-area joint-development projects were developed by Carl Sharpe and the Rice Center team (5). These techniques are designed to assist a public agency or development corporation in capturing both financial and community design benefits from integrated station-area development programs. These techniques are defined below.

1. Ad valorem taxation: The transit or development entity taxes the assessed market value of land and improvements within the entity's taxing jurisdiction or the city served by the transit system.
2. Special district taxation: An ad valorem tax would be levied by the entity on a district in the city adjacent to a transit station. The district's boundaries are set to include the area that receives special benefits from the facility. The transit or development entity would, through the separate tax on the assessed valuation of the market value of the land and its improvements, receive some of the financial benefits created by its facilities.
3. Incremental value taxation: This instrument also sets up special districts, but no new taxes are introduced. The entity receives by agreement all or part of the ad valorem tax revenues on the incremental difference between the assessed valuation of the land at some future date and the assessed valuation at a point prior to the construction of the transit improvements.
4. Develop and hold real property: The entity constructs transit-related facilities around the transit stop and leases or rents them. Public participation in the development of the facilities enhances the potential for community influence over the design, while generating revenue through lease and rental agreements.
5. Develop and sell real property: The entity acquires land fee simple and develops transit-related improvements and facilities thereon. At completion, the land and facilities are sold. As in the preceding technique, the public participates in the community development process, which yields potential benefits unique to this and the above or last techniques.
6. Hold and sell real property: Fee-simple interest and other development rights (air or subsurface) of transit-related land parcels are acquired by the entity. In the future, when the development of these parcels meets appropriate public purposes, the rights or land is sold subject to specific-use conditions.
7. Lease of real property: After acquiring land related to the transit facility, the entity enters into long-term leases for the ground or air and subsurface rights to the land or related development rights, subject to the terms of specific development programs in regard to community design and public finance benefits.
8. Participation in holding real property: Interest in transit-related land parcels or development rights is ceded to other private or public parties for development around stop locations. Under some circumstances, the transit or development entity may receive a portion of the income thus produced.

To illustrate the application of these techniques and define the financial incentive that value capture can have in reducing the burden of capital development, the Rice Center team applied the value-capture financing approach to several different transit-station situations. Each station has two or three different land-development projects associated with it. Table 1 provides a comparative view of the transit development costs, returns from the value-capture application, and an estimate of the transit development costs that can be defrayed through value capture. The cash flow is accumulated over a 25-year development period and also illustrates the impact of discounting the returns at a rate of 8 percent/year to determine net present value. Although the transit systems are assumed to be CRT, a similar impact might be expected from LRT systems. The scale of the economic development and thus the potential returns might be reduced simply because there would be smaller influence zones surrounding LRT stations; however, the joint-development opportunities remain valid.

The last column in Table 1 illustrates the importance of considering value capture as a financing tool in the development of a comprehensive station-area development plan. In the four examples shown, as much as 450 percent of the development costs of a particular segment or station can be defrayed by use of the value-capture method of financing station-area development. Obviously, in some instances the land use, density pattern, and concomitant market land values may be so well established and the development costs so high that there will be very little value to capture for defraying development costs. If, for example, unrestrained land speculation is allowed to occur prior to actual construction, the opportunity for defraying development costs by capturing the value of the increment achieved through the public improvement will be minimized. The important finding of the Rice Center work, however, is that value capture should be considered along with other economic incentives as a method to accrue income from public improvements that can, in turn, be used to offset the cost of improvements.

Value capture is one tool for financing integrated development opportunities, but it is not a substitute for joint development. It is a means to achieve an end but not the end itself. Joint development can accommodate many financing combinations, both public and private, to accomplish the desired results. The work of the Rice Center team and others has substantially advanced the resource base that must be available if cities and private entrepreneurs are to be encouraged to enter into a union for the express purpose of improving the social quality and economic vitality of urban centers.

Integrating Implementation Techniques in the Planning Process

It should not be assumed that joint development, even on a small scale, will automatically occur because a transit station has been absorbed into an area. Earlier research evaluating the impact of development along the Philadelphia-Lindenwold high-speed rail line illustrated that minimal land-use conversions occurred as a result of the implementation of the two new systems. In addition, not every transit stop is a candidate for private capital beyond the actual investment in the station itself. The joint-development projects that have the best potential in an overall system plan should be the result of a comprehensive urban design and economic development program that links planning goals to implementation strategy. Although development can occur after a station has been constructed, the maximum joint-development potential can be gained if the urban and transit development planning processes are conducted simultaneously. Concurrent implementation does not necessarily have to occur, although important functional linkages should be accommodated during the construction of the station.

A major consideration in the joint-development planning process is gaining an understanding of the cycle of impacts that will follow the development activities. The impact zone for LRT systems is generally smaller than that for CRT stations, but a definable ripple effect can be expected to begin in the immediate station environment and extend to related developments within an estimated 300-m (1000-ft) radius of the station. The planning process for the station area must identify a coordinated development program for the entire influence zone, but implementation phasing must consider the likely cycle of economic impacts. The planners must also consider the effects phased implementation will have on traffic circulation, pedestrian movement, extreme changes in density patterns, and the inducement of strip developments between stations. Anticipating these impacts is possible only if the planning and implementation processes have common development goals.

One potential problem in urban design related to joint development of LRT stations that has economic implications is that stops on an LRT system are more closely spaced than those on a CRT system. Zones may overlap, and a diffusion of joint-development activities can occur. This makes financing techniques such as value capture more difficult, since development sites may overlap to the point of making it impossible to identify boundaries for the purpose of establishing assessment districts or other jurisdictional limits. A coordinated program of corridor development goals and station-area development plans can eliminate this potential erosion of the LRT joint-development opportunities.

The planning process for LRT joint development must include (a) a recognition of the need for a coordinated station-planning framework; (b) a resource base that allows the measurement of the potential ripple effect that station development can have on other functions within the urban setting; (c) a full grasp of the tools available to induce development, such as bonus zoning, transfer rights, and special districts, that will encourage and coordinate joint development; and (d) a complete awareness of the aesthetic impact a joint development project can have on community revitalization.

The final important ingredient in a comprehensive joint-development planning process is the vital linkage between station-area planning and implementation procedures. Without this well-defined linkage, examination of joint development will remain a paper exercise to satisfy federal grant application requirements that consistently falls short of actually achieving the commitment of private investment. To achieve this linkage requires a very detailed understanding of the unique design aspects of CRT and LRT systems, especially in relation to accommodation of power source, platform size and height, and the definition of influence zones.

At the present time, a variety of development incentives and controls are being tested in various transit construction programs. The downtown people-mover demonstration programs are also providing a valuable opportunity to evaluate public and private joint-development activities. During the next 2 years, our resource base for identifying successful development incentives and control models will expand, primarily because of the downtown people-mover demonstrations and the Miami and Baltimore transit programs. In addition to these larger examples, many medium-sized cities are evaluating the benefits of forming public development corporations and using tax increment financing as an incentive to encourage the public-private joint venture. All of these efforts will substantially improve the data base for evaluating the joint-development potential of LRT systems.

CONCLUSIONS

The following general conclusions have been drawn concerning the potential that LRT systems have for joint development opportunities.

1. The same basic urban design opportunities that exist for CRT systems are available in the development of LRT systems.
2. Functional differences between LRT and CRT systems that affect joint-development opportunities will generally involve reduced volumes of riders at LRT stations and the smaller platform size and lower platform height of LRT systems.
3. The functional feasibility of LRT systems presents an important joint-development potential. Caution should be exercised in locating joint-development programs between stations since LRT stations tend to be closer together than CRT stations; the impact of a station may be lost if it overlaps with an adjacent station.
4. The financial incentives that apply to joint-development solutions for CRT are transferable to LRT systems.

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Fort Worth's Privately Owned Subway System

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For the past 14 years a small subway system has been carrying passengers into and out of the central business district (CBD) of Fort Worth, Texas. It has two unique features: It is privately owned, and passengers ride it for free. In the early 1960s, two merchants in Fort Worth hit on the idea of providing subway service to their downtown department store from a large parking lot on the banks of the nearby Trinity River. They bought second-hand electric trolley cars from Capitol Transit Company of Washington, D.C., modified them extensively, dug a tunnel from the edge of the parking lot to the lower level of their store, and began operating the subway in February 1963. Tandy Corporation bought the department store in 1967 and continued to operate the subway, which carried nearly 15 000 passengers/d. Tandy is now rebuilding the subway cars to give them a squared-off configuration and many refinements. Introduction of these refurbished cars will coincide with the opening of Tandy Center—an eight-block complex of office buildings and shopping malls in downtown Fort Worth that the subway system will serve. There has been some preliminary exploration of the feasibility of extending the subway system several blocks south through the CBD. This short-haul do-it-yourself subway system has proved that shoppers and downtown workers can be induced to leave their automobiles in a fringe parking lot and ride into the heart of the city by light-rail transit.

For the past 14 years a small subway system has been quietly and steadily carrying passengers into and out of the central business district (CBD) in Fort Worth, Texas. The subway is owned by Tandy Corporation, which was founded in Fort Worth and is headquartered there. Charles Tandy, chairman of the board and chief executive officer of the corporation, says, "We may have the only subway system in town, but we try not to act like it." As proof of this, he points out that passengers ride the subway system free. They also park their automobiles free on a riverbank lot before boarding the subway for the 3-min ride into downtown Fort Worth on the 100-passenger electric cars.

Many of the passengers are unaware that they are riding on what is probably the only privately owned subway system in the world. Most of them are aware that the 1.6-km (1-mile) subway line and all of its equipment and stations are currently undergoing extensive updating and renovation. Later this year, when full service is restored, the subway system will boast a fleet of 10 modernized cars, all air-conditioned, colorfully painted, newly upholstered and carpeted, and equipped with stereo music. The introduction of these completely refurbished cars will coincide with the formal opening of Tandy Center—an eight-block development in downtown Fort Worth that the subway system is primarily intended to serve.

The first phase of Tandy Center, which is now nearing completion, consists of a 19-story office tower, which will house Tandy Corporation's international headquarters; a three-level shopping galleria surrounding an ice-skating rink; and a three-level parking garage. The second phase of construction, now well under way, includes a 20-story office tower and a new Dillard Department Store—the first new department store to be built in the CBD in 40 years. The third phase of Tandy Center, which is still on the drawing boards, calls for a 500-room hotel or a 45-story office tower or, perhaps, both. The subway cars that will begin carrying passengers into the new Tandy Center will bear little resemblance to the old trolley cars purchased from Capitol Transit Company of Washington, D.C., in 1962.

BACKGROUND

The subway is now and always has been a small-scale operation. What makes it interesting to transportation engineers and planners is that it represents a low-cost, do-it-yourself approach to public transit. The Fort Worth subway system contrasts markedly with transit operations in many urban areas throughout the world, some of which are characterized by high costs, high deficits, and high subsidies. Fort Worth's trolley subway system was constructed by a department store and for most of its life has been operated by department store personnel without financial assistance from any level of government—local, state, or federal.

In the early 1960s, Marvin and Obie Leonard, pioneer merchants in Fort Worth, hit on the idea of providing subway service to their downtown store from a large parking lot on the banks of the nearby Trinity River. They figured that free subway service and free parking for automobiles would keep customers coming into their store rather than making their purchases in the suburban shopping malls that were being built around Fort Worth and throughout the nation.

The Leonard brothers bought five electric trolley cars from Capitol Transit Company of Washington, D.C., where the public transit system had just switched over to buses. Since the demand for second-hand trolley cars was limited, the Leonards acquired their small fleet for a total of only $10 000. These were Presidents' Conference Committee (PCC) streetcars, manufactured by the St. Louis Car Company. They were extremely modern in design and are among the finest transit vehicles ever manufactured; many of them are still in operation in several of our nation's cities. The cars are 2.5 m (8.2 ft) wide, 13.4 m (44 ft) long, and 3.4 m (11.2 ft) high. Each car weighs about 21 Mg (24 tons). All doors are installed on one side; there are double doors in the middle for exit and single doors at the front and the back for rapid entry. Seats for 60 passengers face the center along the length of the cars; the maximum capacity is about 100 passengers (40 standing). Operating speed is about 48 km/h (30 mph).

Employees of Leonards Department Store modernized and customized the five cars, installed several thousand fittings and other items made by hand, refitted the doors so that they would open onto the high-level station platforms, reshaped the cars to make them more modern looking and attractive, and painted them in a combination of blue, white, and silver. Several additional cars were bought later and kept in storage for some years.

The Leonards had previously leased a 3000-space parking lot on the bank of the Trinity River about 1.6 km (1 mile) from their downtown store. In fact, before pursuing the subway idea, they had been using a fleet of buses to haul customers (and others) from the 9.3 hm^2 (23-acre) lot to their store. They had also hired a contractor to dig, by the cut-and-fill method, a tunnel 430 m (1400 ft) from the parking lot to the lower level of Leonards downtown store. Part of the tunnel had to be blasted through solid rock to a depth of 13 m (42 ft). Workers laid a double standard-gauge railroad track through the 6.4-m (21-ft) wide tunnel so that cars could pass each other coming and going. The overall length of the double track was approximately 1220 m (4000 ft)—430 m inside the tunnel and 790 m (2600 ft) outside, on the parking lot.

When construction of the tunnel was completed on February 15, 1963, the M and O Subway—named after Marvin and Obie Leonard—went into operation. Instead of a ribbon-cutting ceremony to mark the occasion, the first subway car arriving at the downtown terminal crashed through a simulated brick wall constructed across the tunnel. By this time the Leonards had an investment of about $1 million in their subway system. About half had gone into constructing the tunnel and buying and laying the track; the other half had been used to buy and modify the trolley cars, build the stations, pave the parking area, and supply such things as fencing and landscaping.

The parking area along the riverbank was offered free to everyone, customer or noncustomer, together with a free subway ride into downtown Fort Worth; there was service every few minutes between three stations on the parking lot and a station in the basement of Leonards Department Store. The service was used not only by the store's customers but also by its employees, other workers in the CBD, shoppers in general, visitors to the CBD, and tourists. As a matter of fact, the subway began operating on rush-hour frequencies at 7:30 a.m. in order to carry commuters from their free parking spaces to their downtown jobs, even though Leonards Department Store did not open its doors for business until 10:00 a.m.

Ridership on the subway has always been fairly high, averaging 10 000 to 15 000 passengers/d. At peak periods, the five cars were delivering 500 passengers to the store and parking lot every 8 min. A survey taken in a week in December in the early 1970s indicated that approximately 12 000 people rode to the store on a Tuesday, 24 000 on a Thursday, and 50 000 on a Saturday.

Leonards bore the entire cost of operation as well as the cost of buying and modifying the trolley cars, constructing the tunnel and the four stations, and leasing and maintaining the parking lot; the M and O Subway was considered public-service advertising. Operating costs during peak years were about $118 000/yr. This figure included salaries of drivers and maintenance people, costs of replacement parts for the cars, track repairs, ground maintenance, overhead trolley wire, the generator system, and electrical service.

In 1967 Leonards Department Store was sold to Tandy Corporation. The subway system came with the store. Tandy Corporation retained the Leonards name, continued to operate the store and the subway system on practically the same basis, and expanded Leonards into three suburban shopping malls.

In 1974 Tandy Corporation sold Leonards Department Stores—downtown and suburban—to Dillard Department Stores, which is headquartered in Little Rock, Arkansas. By contractual agreement with Dillard, Tandy continued to operate the subway system into downtown Fort Worth. Tandy was willing to do this because, by this time, it was proceeding with its plan to develop an eight-block area in downtown Fort Worth to be known as Tandy Center. Tandy had already bought outright or had obtained long-term leases on eight contiguous blocks including and surrounding the department store. The subway system, which features free parking and free rides, is likely to be a major factor in the success of this downtown revitalization, which, like the subway operation, is being carried out without any financial support from federal, state, or local governments.

PRESENT OPERATION

The subway system is now in a period of transformation. The current fleet of 10 trolley cars is once again undergoing a metamorphosis, this one even more complete than when the cars were purchased 15 years ago. Some of the caterpillars have already turned into butterflies. The finished products no longer look much like trolley cars. Gone is their bullet shape, with curving windshields on each end and small windows topped by transom panes along the sides. The sleek new cars, modeled along the lines of the cars used in San Francisco's rapid transit system, have a squared-off configuration that features broad expanses of tinted window glass. The exteriors of the cars are being completely covered with 14-gauge welded steel.

Tandy has continued the do-it-yourself approach of this transit operation. Redesign of the cars was handled in house. A subway crew of 18 drivers, maintenance men, and mechanics is doing all of the work on the cars, tearing them down to their frames and rebuilding them to the new design. Each member of the crew has worked at times as painter, welder, upholsterer, and electrician (and even paperhanger) and has still handled his regular shift as driver or maintenance man for the old cars still in daily operation.

The interior and exterior color schemes of the rebuilt cars will vary. Each car will be carpeted with artificial turf, will have walls and ceiling covered with textured vinyl, and will be fitted with new seats upholstered in either textured vinyl or velvet. Tandy Corporation's Radio Shack Division is installing stereo equipment in the air-conditioned cars. Other refinements include special fluorescent lighting, climate-controlled cooling and heating, and operating controls at each end of the cars to permit change in direction at each end of the track. The cost of converting the prototype car to the new configuration was about $60 000. The cost of converting the next three or four cars was slightly less; the cost is expected to drop very little for later cars because no two cars will be exactly alike.

Workers are also busy renovating the track and roadbed for the subway, creating a base for a smoother ride. The tunnel is being widened as it approaches Tandy Center so that three loading platforms can be built there; new floodlights have been installed on the parking lot; and the entire parking area is being resurfaced. While all of this is going on, 40-passenger buses are being used to carry passengers from the parking lot to Dillard's downtown store and bring them back. Rides on these temporary buses, of course, are free. These buses now run from 7:15 a.m. to 9:30 p.m. on Monday, Friday, and Saturday, and until 6:30 p.m. on Tuesday, Wednesday, and Thursday.

FUTURE OPERATIONS

The goal is to have most of the cars modernized and the work on the parking lot and loading stations completed by the time the first phase of Tandy Center formally opens in late 1977. At that time, load factors on the subway system are expected to rise somewhat because there will be additional shoppers and workers going into and out of the downtown area. The three-level shopping mall in Tandy Center will lure shoppers; the ice-skating rink around which the galleria is built will attract both skaters and spectators; and the 19-story office tower will attract hundreds of employees who will daily park their cars on the riverbank lot and ride the subway to work. The subway system will probably extend its hours of operation to accommodate the extra traffic.

Business on the short-haul subway will get another boost when the second phase of Tandy Center is completed in 1978. This phase entails a 20-story office tower and a new Dillard Department Store. An estimated 3000 persons will ultimately work in the center's first two office buildings and there will be more workers and more shoppers interested in free parking and free subway rides. Approximately 12 000 other people work within two blocks of Tandy Center.

The third phase, which is still in the planning stage, will include a 500-room hotel. In between the second and third phases of Tandy Center will come the completion of a new public library building on a two-block site adjacent to Tandy Center, in fact connected to it by means of an underground passageway. Like Tandy Center, the library will have much of its activity below ground level, and shoppers and library patrons can move freely from one activity to the other. It will be only a short walk from the library to the subway platform on the same level, which means that the subway system is likely to be carrying many more library patrons than is now the case. The subway traffic will probably also include the employees of a large insurance firm, which is building its home office near the public library building and Tandy Center.

At this rate, the 3000-space parking lot on the riverbank may have more business than it can handle. This is not considered a problem. A second deck will be erected on the lot that will double the lot's capacity. Some preliminary planning has already been done.

There has been some discussion and some preliminary planning about the possibility of extending the subway system several blocks farther south through the CBD to a parking lot on the south side of downtown Fort Worth; the city government and the federal government would foot the construction bill on some kind of matching basis. A preliminary engineering plan and report on the Fort Worth CBD subway, conducted under technical study grants from the Urban Mass Transportation Administration, was completed in 1974. This report concluded that construction of a 1.7-km (5600-ft) extension of the existing subway through the CBD is, from an engineering standpoint, practical and feasible. The report estimated the cost of such a new line at approximately $54 million and the time required to design and construct it at approximately 5 years.

It is evident that this interesting adventure in small-scale rail transit deep in the heart of Texas is turning out quite well. Its future is even brighter than its 14-year past.

OBSERVATIONS ON THE SUBWAY SYSTEM

This short-haul subway system, with its free rides and its free parking, is a happy blend of a private interest and the public interest. The department-store owners who installed the subway system felt that it would be good for their business and good for their city. Tandy Corporation, the present owner and operator of the subway system, feels the same way. The subway system—because it puts private automobiles on a riverbank parking lot rather than into the CBD—cuts down on street congestion, particularly during peak periods. It also reduces, at least modestly, the need for downtown parking facilities.

Tandy Center, which will eventually cover eight blocks and be served by the free subway system, is certain to be a strong rejuvenating influence on downtown Fort Worth. Like other large and medium-sized cities across the country, Fort Worth has seen its CBD lose ground in recent years to suburban shopping malls. But it has moved forward more than most cities in the past decade or so. A new convention center was built in 1968, and a municipal building was opened in 1971. There are also a 37-story bank building opened in 1974 and the public library building, insurance building, and eight-block Tandy Center described above.

In addition, the whole Dallas-Fort Worth area (part of the so-called sun belt) is steadily growing in population and attractiveness to industry. Among the major factors in the future growth of the area is the new Dallas-Fort Worth airport, the second largest airport in the world. This airport, midway between Dallas and Fort Worth, is likely to be more of a boon to Fort Worth than to Dallas because, until the airport opened 3 years ago, Fort Worth passengers had to land and take off at Love Field in Dallas. The Dallas-Fort Worth airport also includes a small automated fixed-route transit system that interconnects all parts of the gigantic airport, but that is another story.

It is difficult, if not impossible, to pin down the value capture involved in Tandy Corporation's subway system in Fort Worth. We bought a department store, and the subway came with it. The price paid for the department store was unquestionably somewhat higher because of the subway. Later, we bought or leased eight contiguous blocks in downtown Fort Worth surrounding the downtown terminal of the subway system in order to build Tandy Center. By this time, however, the subway system had already been operating for a decade, and any appreciation in land values of the eight blocks was captured by somebody else—those who sold the land to Tandy. This appreciation, however, was probably modest, because there was only one downtown subway station, and it was in the department store.

In summary, the subway situation in Fort Worth is short on theory and long on practice. What we have done is perhaps not entirely in keeping with some of the theories held by transit authorities and transportation experts. It has involved no expensive computer-controlled equipment. It has required no federal, state, or municipal funds. What Tandy Corporation has done in Fort Worth, using its own funds and its own personnel and tried-and-true equipment, is to build, operate, and continually update a short-distance, low-cost subway system and parking lot, offering both of them free to all comers.

In return—and it may be a bigger return than you think—all passengers must leave the subway at Tandy Center and board it there for the return trip to the parking lot. Very few downtown shopping malls and office towers can offer as inducements to prospective tenants a free subway system and parking lot for the customers and the employees of tenants. This privately owned and operated subway system has successfully proved during its 14-year history that it can induce shoppers and downtown workers to leave their beloved automobiles in a fringe parking lot and ride into the heart of the city by light-rail transit.

Part 4
Hardware and Technology

Evaluations of Operating Light-Rail Transit and Streetcar Systems in the United States

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The goal of the research presented in this paper is to evaluate how closely each of the light-rail transit (LRT) and streetcar systems in the United States approaches the LRT concept. Both LRT and streetcar systems are evaluated because the usual pattern of development, here as in Europe, has been for streetcar systems to be upgraded gradually to LRT standards. Of the surviving networks, several run largely on reserved rights-of-way and closely approach the LRT concept; others are clearly street-car operations that possess few true LRT characteristics. Highlighting the strengths and weaknesses of existing systems should be helpful to those planning new LRT installations. The paper also stresses two of the most important qualities of LRT systems: (a) flexibility in right-of-way location and its concomitant, the ability to improve segments of systems on an incremental basis, and (b) ability of systems constructed in a trunk-and-branches pattern to provide both line-haul and collection and distribution functions, thus giving most patrons a single-vehicle ride.

There were 72 100 km (44 800 miles) of electric railway trackage in the United States in 1917 (1). Despite the current popular impression, this vast network was not located entirely in city streets. In many cities, portions of one or more streetcar lines were located in boulevard medians. The Dundalk Avenue line in Baltimore, now abandoned, was a good example. Many suburban lines operated on private rights-of-way. In addition, there was a network of intercity light electric railways that were called interurbans.

Rochester, New York, had a streetcar subway that ran into its central business district (CBD), as did the Pacific Electric Railway in Los Angeles, which operated a large network of suburban and short-haul intercity lines over more than 800 route km (500 route miles). This system included one of the first transit-freeway joint rights-of-way. Instead of building transit in an expressway median, as is now commonly suggested, the Hollywood Freeway was constructed through Cahuenga Pass in 1939 and 1940 on either side of the Pacific Electric's Hollywood Boulevard line.

Why did all these lines fail? Essentially, their demise was brought about by a combination of growing automobile ownership and improved roads. During this era of decline, roughly from the late 1920s through the 1950s, transit service continued to be provided by private companies. These operators were justifiably concerned with maintaining their profitability; it was not surprising that, in the face of declining ridership and revenues, they turned to less capital-intensive means of providing basic transit service or discontinued operations altogether.

The massive switch to buses generally resulted in avoidance of maintenance costs for right-of-way, track, and power distribution systems. Abandonment of these facilities and streetcars brought income tax write-offs, as well as substantial sums realized from the sale of salvaged materials. Finally, buses were relatively inexpensive to acquire and were short-lived vehicles that could be depreciated rapidly, so that they would not outlast the expected disappearance of the need for public transit service.

Now, since most major metropolitan transit systems are operated by public agencies as essential community services and since the specter of dwindling petroleum supplies confronts us, it is time to reexamine the potential of the electric railway. Although most cities that want to build light-rail transit (LRT) systems will have to start from scratch, there are a few places in which streetcars and suburban light electric railways survive.

OPERATING LRT AND STREETCAR SYSTEMS IN THE UNITED STATES

LRT and streetcar systems in the United States have dwindled to 35 routes totaling about 320 km (200 miles) of line and using a fleet of 1035 cars. They carry about 560 000 passengers on a typical weekday. There are 13 definable systems providing regular service in nine U.S. cities.

1. Boston—Green Line: Four routes link the CBD with residential areas in the southern and western parts of the city and in the western suburbs of Brookline and Newton. One line is the 15.1-m (9.4-mile) Riverside extension, which in 1959 replaced a commuter railroad (2).
2. Boston—Mattapan-Ashmont: This is an LRT feeder to rapid transit that was built in a former commuter railroad right-of-way (3).
3. Newark—City subway: This remainder of the former subway-surface system, built in an abandoned canal bed, extends from the CBD to northern residential areas of the city.
4. Philadelphia—City streetcars: There are seven routes, each 4.7 to 20.1 km (2.9 to 12.5 miles) long; they are the remnant, along with the subway-surface lines, of a much larger network.
5. Philadelphia—Subway-surface: Five routes share a 4.0-km (2.5-mile) subway west from the CBD, then fan out to run as streetcars in residential areas.
6. Philadelphia—Media-Sharon Hill: Two lines of four remain; they link the Delaware County suburbs with rapid transit lines to the CBD through the 69th Street Terminal at the city's western edge (4).
7. Philadelphia—Norristown High-Speed Line: This completely grade-separated line has high-platform stations, runs single cars with on-board fare collection, and feeds suburban patrons to rapid transit at 69th Street.
8. Pittsburgh—South Hills: Four physically distinct routes link the CBD with suburbs to the south of the Monongahela River. The Library and Drake lines are remnants of once-longer runs to Charleroi and Washington, Pennsylvania.
9. Cleveland—Shaker Heights Rapid Transit: Two lines were built in 1913 and 1920 by real estate developers to link their new, planned town of Shaker Heights with the CBD; the line shares 4.0 km (2.5 miles) of track with rapid transit trains (5).
10. Detroit—Downtown trolley: This short 1.3-km (0.8-mile) shuttle line through the CBD was opened in September 1976 (6).
11. New Orleans—St. Charles: The last U.S. line to use the double-truck streetcars built in the 1920s connects the CBD and a gracious residential area; it also

Table 1. General characteristics of U.S. LRT and streetcar systems.

System	One-Way Line (km)	Types of Service Offered: Line Haul to CBD	Feeder to Line-Haul Transit	Local Urban or Suburban Transit	CBD Distribution	Through Service Routes: Number	Length (km)	Revenue Service Cars	Annual Car Kilometers of Revenue Service (000s)	Passengers Carried (000s): Annually	Avg Weekday	Avg System Operating Speed (km/h)
Boston									10 100			
Green Line	43.8	Yes	No	Yes	Yes	4	58.1	276		41 100	151	20.0
Mattapan-Ashmont	4.2	No	Yes	Yes	No	1	4.2	15		3 900	14	19.3
Newark City Subway	6.7	Yes	No	Yes	Yes	1	6.7	26	1 000	2 450	8	32.2
Philadelphia									40 100			
Streetcars	82.4	Yes	Yes	Yes	No	7	83.4	350		40 000	130	14.5
Subway-surface	35.9	Yes	Yes	Yes	No	5	52.4			20 000	65	18.0
Media-Sharon Hill	19.1	No	Yes	Yes	No	2	22.4	32		4 000	14	25.8
Norristown Line	21.9	No	Yes	Yes	No	1	21.9	21		2 750	10	49.9
Pittsburgh: South Hills	39.9	Yes	No	Yes	Yes	4	54.9	95	3 100	7 000	24	22.0
Cleveland: Shaker Heights	21.1	Yes	No	Yes	No	2	30.7	57	1 800	4 720	18	37.0
Detroit: Downtown shuttle	1.3	No	No	No	Yes	1	1.3	6	—	—	—	7.7
New Orleans: St. Charles Line	10.5	Yes	No	Yes	No	1	10.4	35	1 300	7 830	25	15.0
Fort Worth: Tandy Center Subway	1.9	No	No	No	Yes	1	1.9	6	—	1 200	4	25.8
San Francisco Muni	29.3	Yes	No	Yes	Yes	5	54.4	115	—	30 000	98	15.3
Total	318.0					35	402.7	1034		164 950	561	21.9

Note: 1 km = 0.6 mile.

Table 2. Intensity of use of LRT and streetcar systems.

System	Weekday Passengers	Line Length (km)	Avg Weekday Passengers per Kilometer of Line
Boston			
Green Line	151 000	43.8	3400
Mattapan-Ashmont	14 000	4.2	3300
Newark City Subway	8 000	6.7	1200
Philadelphia			
Streetcars	130 000	82.4	1600
Subway-surface	65 000	35.9	1800
Media-Sharon Hill	14 000	19.1	700
Norristown Line	10 000	21.9	500
Pittsburgh: South Hills	24 000	39.9	600
Cleveland: Shaker Heights	18 000	21.1	900
New Orleans: St. Charles Line	25 000	10.4	2400
Fort Worth: Tandy Center Subway	4 000	1.9	2100
San Francisco Muni	98 000	29.3	3300

Note: 1 km = 0.6 mile.

serves as a tourist attraction. It is operated by a private company.

12. Fort Worth—Tandy Center Subway: This line, opened in 1963 as Leonards M and O Subway to link their department store in the CBD and its periperal parking lots, now also serves the Tandy Corporation's headquarters office towers (7).

13. San Francisco—Municipal Railway (Muni): Five routes provide service from western and southern residential areas within the city to the CBD; it is now undergoing upgrading from streetcar to LRT operation (8).

Some general characteristics of these systems (2, 9, 10, 11, 12, 13, 14) are presented in Table 1. The newest and shortest line, Detroit's downtown shuttle, is actually the imaginative use of antique four-wheel trolley cars to provide both a useful service and an attraction in its own right. It is included in Table 1 because it is operated by the Detroit Department of Transportation as part of its citywide transit system. Since it is so short and has no LRT characteristics, it is omitted from further consideration in this paper.

Even though they form a unified physical entity, Philadelphia's 118.3 km (73.5 miles) of streetcar and subway-surface lines provide two distinct levels of service. Streetcar routes run at an overall system average operating speed ($\bar{V}$) of 14.5 km/h (9.0 mph) and serve primarily as feeders to rapid transit and as local area transportation. Line-haul ridership to the CBD is secondary, since only two of the seven routes enter that area. The opposite is true for the five subway-surface lines, all of which penetrate the heart of the CBD and, operating at a $\bar{V}$ of 18.0 km/h (11.2 mph), offer somewhat faster service (although the same types of cars are used on both parts of the city system). Wherever possible, these two groups of routes are treated as separate systems.

There are substantial variations among the several systems. Some, such as the Tandy Center Subway in Fort Worth, are quite small; others are much longer and larger in terms of number and length of routes, fleet size, and typical weekday patronage. Length, however, does not govern intensity of use as measured by the number of passengers per day per kilometer of line. As Table 2 shows, the Fort Worth line is exceeded in this statistic only by the Boston, San Francisco, and New Orleans lines. Among the many causes of the variation in intensity of use among systems are the service-area population, park-and-ride opportunities, integration with other modes of transit, level of CBD development, existence of other trip generators, types of services offered, and service quality (frequency, speed, reliability, comfort, and safety).

It must also be considered that most of these systems have been in existence for many years. The newest—Fort Worth—opened in 1963. The oldest—New Orleans—traces its history to the New Orleans and Carrollton Rail Road Company, which began operating horse-drawn cars in 1834. Steam locomotives were used for some years; the line was electrified in 1893 (15). Changing patterns of urban development during the intervening years have robbed some lines of their patronage bases. Some lines have survived simply because they were the most substantially built segments or trunks of once-larger networks.

The Newark City Subway is a good example. It was completed in 1935 by the city of Newark and operated for the next 15 years (under lease to a private company) as the downtown end of a subway-surface system of several routes that had formerly run all the way downtown in the streets. These routes left the City Subway—the name that applies to the whole 6.7-km (4.2-mile) line, even though only 2.1 km (1.3 miles) are underground—at Central Avenue, Orange Street, Bloomfield Avenue, and Franklin Avenue. All of these streetcar routes were converted to bus operation about 1950, but the city insisted that the subway continue in operation. It serves only its immediate catchment area, since most of the buses run all the way downtown. This, combined with the gradual decline of the Newark CBD as a working and shopping area and the fact the line parallels a large park for most of its above-ground run, has resulted in the underuse indicated in the tables.

Similar problems of urban change have hurt ridership on Cleveland's Shaker Heights system, particularly the stagnation of that part of the CBD adjacent to the line's downtown terminal (16). As a result, morning peak-hour riding in 1973 was down to 4200 from a high of 5500 between 7:00 and 9:00 a.m. However, a large degree of recovery has been achieved since then by halving the fare and providing free transfers under the new Greater Cleveland Regional Transit Authority.

LRT lines that feed rapid transit also appear to be used at a lower level of intensity than line-haul routes. Passengers using Philadelphia's Media, Sharon Hill, and Norristown lines must change to a rapid transit line to complete their trips to the CBD. Not only are they inconvenienced by having to walk through the 69th Street Terminal to make the change, they also must pay an additional full fare because the Southeastern Pennsylvania Transportation Authority (SEPTA) has not integrated the fare structures of its several operating divisions. These two factors have always hampered ridership development on these lines.

This has not been the case in Boston. The world's first streetcar subway opened in Boston in 1897; most of it is still in service today as part of the Green Line (3). It has been extended over the years and, in the last decade, most of its stations have been modernized. However, it no longer provides streetcar service. Rather, the four lines radiating from the tunnels run largely on reserved tracks in boulevard medians; the Riverside line is completely grade separated. This line operates at a V of 25.4 km/h (15.8 mph) overall or 36.2 km/h (22.5 mph) in the section west of the subway. It competes effectively with other modes for commuter traffic to Boston from the western suburbs. Other Boston LRT lines serve heavily built-up areas, including at least four colleges and universities. Major cultural and entertainment facilities—Symphony Hall, the Museum of Fine Arts, the Museum of Science, the Municipal Auditorium, Fenway Park (baseball), and the Boston Garden (hockey and basketball)—all are served by the Green Line.

The subway portion of the Green Line is the only rail transit facility that follows the spine of Boston's elongated CBD, which stretches from Government Center around the Boston Common to Back Bay (2). The Green Line also has direct interchange stations in the CBD with all three of Boston's rail rapid transit lines and, at North Station, with Boston and Maine commuter rail services to the northern suburbs. In addition, it also intersects many bus routes throughout its service area. All of this results in outstanding system connectivity. These factors help explain why the Green Line is the most heavily used of Boston's four line-haul rail transit routes and carries more passengers daily than any of the others, as well as why it is the most intensely used U.S. LRT system (Table 2).

COMMUNITY CHARACTERISTICS OF THE SERVICE AREAS

Boston's example clearly demonstrates that transit systems exist successfully only as useful parts of the total urban fabric. To understand and evaluate existing LRT and streetcar systems, it is necessary to describe the kinds of populations and communities they serve.

Several socioeconomic indicators were developed by using data from the 1970 U.S. Census at the census-tract level to show how LRT service areas in different cities compare with one another. Tracts through which LRT or streetcar lines pass have been analyzed and are assumed to be synonymous with the service area; i.e., most park-and-ride and feeder-bus patrons are ignored. Data have not been assembled for the shortest systems: Detroit, Fort Worth (which serves no resident population), and Mattapan-Ashmont (the shorter of Boston's two systems). Table 3 presents the results of the census-data investigation. The various LRT and streetcar systems can be seen to serve populations ranging from 47 000 to nearly 760 000, or from roughly 1 to 15 percent of the population of the total metropolitan area, depending on their location, length, number of routes, and so on.

The mean income levels and income distributions shown for the several service areas indicate that LRT, although it accommodates substantial numbers of poor people, is a vehicle for all classes. The Shaker Heights Rapid Transit System provides an example. While it serves several tracts in Cleveland in which the mean annual income was about $5500 in 1970, its main rider pool comes from Shaker Heights, where the 1970 mean income was $26 674. Similar variations from tract to tract may be observed in other LRT service areas, although they are not always so pronounced.

For Boston's Green Line, the mean income in 1970 was $11 250 for LRT tracts in the city of Boston, $17 693 in Brookline, and $22 896 in Newton, compared with $10 272 for the city of Boston as a whole. This shows that LRT, in some of its present applications, serves markets made up largely of riders who could, if they wished, choose to use other transportation.

Age composition is rather stable. Where the group of riders under 18 is smaller (Boston, New Orleans, San Francisco), the difference is shared relatively evenly by the groups of those 18 to 64 and those 65 and over. LRT serves areas of cities that have large black populations (e.g., Newark, Philadelphia, Cleveland, and New Orleans); in the San Francisco service area, a substantial non-black minority population (mostly Asian-Americans and some Mexican-Americans) is included. The sex groupings confirm only that females slightly outnumber males generally.

Variations in the density of development of the service areas may be more important to system development. Table 4 lists the total population, number of housing units, and land area for each service area and then uses these data to calculate the population per square kilometer, the number of housing units per square hectometer, and the number of people per housing unit. The last, as expected, is generally smaller in the CBDs than in the residential areas of core cities, which in turn show smaller values than suburban areas. Densities of population and housing units are also relatively low in the CBDs, since these are principally areas of work rather than residence (San Francisco is an exception). However, both peak for residential areas within city boundaries, then trail off in the typically newer, more spread-out suburban areas. It may be noted for reference that building plots of 15.2 by 30.5 m (50 by 100 ft) represent a density of 20 housing units/hm^2 (8 housing units/acre), assuming single-family houses and allowing for street right-of-way.

Some interesting inferences can be drawn by evaluating these indicators in light of the figures on system use developed in Table 2. This is done in Table 5. Only CBD-oriented systems are included, since the rapid transit feeder lines (Media-Sharon Hill and Norristown) and Philadelphia's streetcar network do not exhibit similar patterns. The two indicators of the intensity of use of the systems decline together. This would seem to indicate larger pools of regular riders on the more intensely used systems. In San Francisco, some trips to the CBD may be made on other modes: automobiles or the Bay Area Rapid Transit (BART) line that begins in Daly City. Both this line and a freeway parallel each other along the southeastern edge of the streetcar service area. The Muni streetcars operate at relatively low average speeds, as the table indicates. This problem has been recognized, and a current program to upgrade the system (described in a later section of this

Table 3. Summary of socioeconomic indicators for the service areas of LRT and streetcar systems.

System	Population (000s)			Mean Family Income ($)	Percentage of Families With Income					Percentage of Population			Race (%)			Sex (%)	
	Service Area	Metropolitan Area	Core City		Under $5000	$5000 to $9999	$10 000 to $14 999	$15 000 to $24 999	$25 000 and Over	Under 18	18 to 64	65 and Over	White	Black	Other	Female	Male
Boston Green Line	282	2899	641	15 102	16	27	23	20	14	18	67	15	92	5	3	56	44
Newark City Subway	47	2055	382	8 902	27	37	23	11	2	32	63	5	63	35	2	51	49
Philadelphia		4818	1950														
Streetcars	758			8 647	24	37	25	12	2	32	56	12	60	39	1	53	47
Subway-surface	254			8 778	22	37	26	13	2	31	58	11	47	52	1	53	47
Media-Sharon Hill	110			13 519	8	27	33	25	7	32	57	11	99	1	—	53	47
Norristown Line	66			17 005	8	23	27	28	14	30	60	10	96	4	—	51	49
Pittsburgh:																	
South Hills	157	2401	520	12 822	11	30	32	21	6	34	56	10	97	3	—	53	47
Cleveland:																	
Shaker Heights	91	2064	751	16 589	20	25	20	18	17	30	56	14	65	34	1	54	46
New Orleans:																	
St. Charles Line	77	1046	593	12 291	32	30	16	12	10	25	60	15	64	35	1	54	46
San Francisco Muni	275	3110	716	12 732	16	28	27	22	7	21	64	15	80	11	9	51	49

Table 4. Density of development in the service areas of LRT and streetcar systems.

System	Population	Housing Units	Area (km^2)	Persons per Square Kilometer	Housing Units per Square Hectometer	Persons per Housing Unit
Boston Green Line						
CBD	8 570	5 021	4.9	1 700	10.2	1.7
Brookline	52 659	20 968	10.6	5 000	19.8	2.5
Newton	45 057	12 779	26.2	1 700	4.9	3.5
Other Boston city	175 871	71 561	14.2	12 400	50.4	2.5
Overall	282 157	110 329	55.9	5 000	19.7	2.6
Newark City Subway						
CBD	9 296	3 771	1.8	5 200	21.0	2.5
Other	37 186	13 070	5.4	6 900	24.2	2.8
Overall	46 482	16 841	7.2	6 500	23.4	2.8
Philadelphia						
Streetcars						
CBD	16 484	10 108	3.1	5 300	32.6	1.6
Other	741 546	242 333	85.5	8 700	28.3	3.1
Overall	758 030	252 441	88.6	8 600	28.5	3.0
Subway-surface						
CBD	5 590	3 561	0.8	7 000	44.5	1.6
Other	248 536	83 430	25.1	9 901	33.2	3.0
Overall	254 126	86 991	25.9	9 800	33.6	2.9
Media-Sharon Hill	110 210	36 275	36.0	3 100	10.1	3.0
Norristown Line	65 682	20 277	36.5	1 800	5.6	3.2
Pittsburgh: South Hills						
CBD	2 944	1 401	1.0	2 900	14.0	2.1
Other	154 307	46 968	62.9	2 500	7.5	3.3
Overall	157 251	48 369	63.9	2 500	7.6	3.2
Cleveland: Shaker Heights						
CBD	1 201	419	4.4	300	1.0	2.9
Shaker Heights	36 306	12 885	16.1	2 300	8.0	2.8
Other Cleveland city	53 646	21 877	13.7	3 900	16.0	2.4
Overall	91 153	35 181	34.2	2 700	10.3	2.6
New Orleans: St. Charles Line						
CBD	2 604	1 933	3.1	800	6.2	1.4
Other	74 026	30 020	16.1	4 600	18.6	2.5
Overall	76 630	31 953	19.2	4 000	16.6	2.4
San Francisco Muni						
CBD	23 509	19 275	2.8	8 400	68.8	1.2
East of Twin Peaks	87 520	38 456	8.3	10 500	46.3	2.3
West of Twin Peaks	164 237	63 552	31.1	5 300	20.4	2.6
Overall	275 266	121 733	42.2	6 500	28.8	2.3

Note: 1 km^2 = 0.4 $mile^2$ and 1 hm^2 = 2.5 acres.

paper) should raise the system speed substantially.

Philadelphia's subway-surface system must compete with rail rapid and commuter rail services in some portions of its service area. Four commuter rail stations—49th Street, Angora, 52nd Street, and Overbrook—serve portions of West Philadelphia that are within the catchment areas for subway-surface routes 10, 11, 13, and 34; they may be taking some riders who otherwise would use the trolley, especially at peak commuting hours. Darby, at the outer end of route 13, is also served by commuter rail. North-south bus routes crisscrossing West Philadelphia act as feeders to the Market-Frankford subway-elevated system and may provide faster trips downtown (in either real or perceived terms) for some subway-surface service-area residents.

The Newark City Subway, as noted earlier, has the smallest total service-area population of any of the LRT and streetcar systems studied. While several of the former rail routes that have been converted to bus routes run through to the CBD, there still are some routes that feed the City Subway at Franklin Avenue, Park Avenue, and Norfolk Street. It may be that riders from these feeder lines and from commuter trains who use LRT to reach CBD offices from Pennsylvania Station are swelling the number of subway users; this would inflate the figure for the number of rides per person residing in the service area.

On the basis of the limited data and statistics presented in this section, the following conclusions appear to have at least some validity, although the small number of systems makes generalization difficult.

1. Existing LRT and streetcar systems usually are located in areas of moderate to high population and housing-unit density.

2. LRT and streetcar systems serve financially and ethnically diverse populations. Systems that serve CBDs or feed rapid transit lines are able to attract large numbers of riders who could use other modes of transportation but find LRT to be convenient.

3. Although the data are not conclusive, it does appear that systems operating in areas of relatively high

Table 5. Comparison of intensity of use and trip characteristics of CBD-oriented systems.

System	Avg Weekday Passengers per Kilometer of Line	Annual Rides per Capita in Service Area	Average Operating Speed (km/h)	Estimated Typical Trip Length (km)	Estimated Typical Trip Time (min)
Boston Green Line	3400	146	20.0	7.2	22
San Francisco Muni	3300	109	15.3	5.5	21
New Orleans: St. Charles Line	2400	102	15.0	5.2	21
Philadelphia subway-surface	1800	79	18.0	5.0	17
Newark City Subway	1200	52	32.2	4.5	8
Cleveland: Shaker Heights	900	52	37.0	12.6	20
Pittsburgh: South Hills	600	45	22.0	11.3	31

Note: 1 km = 0.6 mile.

Table 6. Type of right-of-way occupied by LRT and streetcar systems.

System	Location of Line (km)							Percentage of Line			Avg Operating Speed (km·h)
	Subway or Tunnel	Surface: Grade Separated	Surface: Private Right-of-Way	Surface: Median	Surface: Reserved Lane	Surface: Mixed Traffic	Total	Grade Separated	Reserved	Mixed Traffic	
Boston											
Green Line	7.2	17.1	0	15.3	0	4.2	43.8	55	35	10	20.0
Mattapan-Ashmont	0	4.2	0	0	0	0	4.2	99	—	—	19.3
Newark City Subway	2.1	4.6	0	0	0	0	6.7	99	—	—	32.2
Philadelphia											
Streetcars	0	0	0	0	4.2	78.2	82.4	—	5	95	14.5
Subway-surface	4.0	0	0	1.6	0	30.3	35.9	11	5	84	18.0
Media-Sharon Hill	0	0	16.2	0	0.3	2.6	19.1	—	87	13	25.8
Norristown Line	0	21.9	0	0	0	0	21.9	100	—	—	49.9
Pittsburgh: South Hills	1.1	0	28.2	0.8	0	9.8	39.9	3	73	24	22.0
Cleveland: Shaker Heights	0	11.3	0	9.8	0	0	21.1	53	47	0	37.0
New Orleans: St. Charles Line	0	0	0	9.0	0.2	1.3	10.5	—	88	12	15.0
Fort Worth: Tandy Center Subway	0.8	1.1	0	0	0	0	1.9	100	—	—	25.8
San Francisco Muni	5.2	0	1.6	*4.2	0	18.3	29.3	17	20	63	15.3
All systems	20.4	60.2	46.0	40.7	4.7	144.6	316.7	25	29	46	21.9

Note: 1 km = 0.6 mile.

population density are used more intensively than lines in lower density areas, even though the latter may offer higher average operating speeds.

EVALUATION CRITERIA

As Table 1 indicates, the average operating speeds of the various LRT and streetcar systems have a broad range: 15 to 50 km/h (9 to 31 mph). The remainder of this paper examines the sources of these variations and attempts to classify each operating system as an LRT or streetcar system. The concise definition adopted by TRB's Committee on Light-Rail Transit in spring 1976 (17) is the yardstick against which each existing system was evaluated. The prime consideration in this definition is right-of-way location.

Light-rail transit is a mode of urban transportation utilizing predominantly reserved but not necessarily grade-separated rights-of-way. Electrically propelled rail vehicles operate singly or in trains. LRT provides a wide range of passenger capabilities and performance characteristics at moderate costs.

Relevant information on each LRT and streetcar system was assembled to permit evaluation (2, 4, 7, 14, 16). Table 6 describes the types of right-of-way occupied by each system, listing the types in descending order of protection of interference from other traffic. The percentages of the lines that operate on grade-separated or reserved rights-of-way are also shown in Table 6.

Right-of-way location is a principal factor affecting overall average speed ($\overline{V}$). Higher $\overline{V}$s generally coincide with greater degrees of reservation and lesser interference from other traffic. The aptly named Norristown High-Speed Line is completely grade separated and achieves a $\overline{V}$ of 50 km/h (31 mph); the Philadelphia streetcar system, which has a $\overline{V}$ of 14.5 km/h (9 mph), has only 5 percent of its lines located on the lowest quality right-of-way reservation. There are exceptions however. Boston's Mattapan-Ashmont Line has only one crossing at grade but averages only 19.3 km/h (12.0 mph). The St. Charles Line in New Orleans is 88 percent reserved yet averages only 15.0 km/h (9.3 mph), while the Media-Sharon Hill lines, which are 87 percent reserved, average 25.7 km/h (16.0 mph).

Other factors must be examined. These include frequency of passenger stops, frequency of at-grade crossings, track traffic patterns, signal systems, and vehicle performance (4, 7, 9, 10, 14, 16, 18, 19, 20, 21). Indicators for these system elements are presented in Tables 7, 8, and 9.

Boston Green Line

The Green Line, 43.8 km (27.2 miles) of line and four routes totaling 58.1 service route km (36.1 service route miles), is the larger of the Boston area's two physically separate systems. Only one of its routes has any unreserved street trackage: 4.2 km (2.6 miles) or 10 percent of the system total at the southern end of the Huntington Avenue line. The remainder of this line and the surface portions of the Beacon Street and Commonwealth Avenue routes are located in reserved boulevard medians. The line to Riverside was converted from commuter rail to LRT operation in 1959 and is completely grade separated. All lines, as described earlier, pass under the CBD in subway.

Despite having 90 percent reserved right-of-way, the system $\overline{V}$ is only 20.0 km/h (12.4 mph). The Riverside line has a $\overline{V}$ of 25.4 km/h (15.8 mph), Commonwealth has a $\overline{V}$ of 16.1 km/h (10.0 mph), Beacon has a $\overline{V}$ of 16.4 km/h (10.2 mph), and Huntington has a $\overline{V}$ of 17.4 km/h (10.8 mph). Perhaps the major reason these $\overline{V}$s are so low is the intensity with which the system is used. It is not uncommon for cars to carry standees in the subway even during base periods, and crowding occurs during rush hours, even though two- and three-car trains are operated. As a result, loading and unloading are slow, especially when the left-hand sides of Presidents' Conference Committee (PCC) cars (which have only a single set of doors) are at center-island station platforms. On the surface portions of outbound trips, $\overline{V}$ is further restrained by a pay-as-you-leave fare collection system that requires each alighting patron to use the car's front door. Other factors affecting performance may be noted in Tables 7, 8, and 9. Although stations have typical LRT spacing, the reserved, at-grade portions of the system average an at-grade crossing every 0.32 km (0.2 mile). Most of these crossings are controlled by street traffic signals. Some of those along Commonwealth

Table 7. Frequency of stations and at-grade crossings.

Item	Boston: Green Line	Boston: Mattapan-Ashmont	Newark City Subway	Philadelphia: Streetcars	Philadelphia: Subway-Surface	Philadelphia: Media-Sharon Hill	Philadelphia: Norristown Line	Pittsburgh: South Hills	Cleveland: Shaker Heights	New Orleans: St. Charles Line	Fort Worth: Tandy Center Subway	San Francisco Muni	All Systems
Stations or car stops													
Grade separated	15	7	10	0	8	1	22	0	9	0	4	2	78
Reserved	54	1	1	29	11	38	0	80	19	45	0	45	323
Street	25	0	0	434	147	11	0	8	0	5	0	136	766
Total	94	8	11	463	166	50	22	88	28	50	4	183	1167
At-grade crossings (in reserved right-of-way)													
Railroad flashers or preemptive traffic signals		1	0	0	1	31	0	7	0	0	0	0	
Nonpreemptive traffic signals	48	0	1	10	3	11	0	0	20	16	0	39	
Warning signs		0	0	14	0	3	0	36	0	1	0		
No protection	0	0	0	0	0	0	0	0	0	81	0	0	
Total	48	1	1	24	4	45	0	43	20	98	0	39	323
Grade separations (overpasses and underpasses)	26	8	8	0	0	2	36	14	26	1	0	2	145
Avg spacing, km													
Stations (separated and reserved)	0.58	0.6	0.68	0	0.29	0.42	1.05	0.37	0.76	0.19	0.64	0.23	0.43
Car stops (lines in streets)	0.16	0	0	0.18	0.21	0.24	0	0.31	0	0.26	0	0.13	0.19
Stations or car stops (entire system)	0.47	0.60	0.68	0.18	0.21	0.39	1.05	0.37	0.76	0.21	0.64	0.16	0.27
Grade crossings (reserved right-of-way only)	0.32	2.09	3.38	0.19	0.53	0.37	0	0.66	0.50	0.10	0	0.14	0.29

Note: 1 km = 0.6 mile.

Table 8. Track traffic patterns and signal systems.

System	Track Traffic Patterns: Double Track: Kilometers	Double Track: Percent	Single Track: Two-Way Running: Kilometers	Two-Way Running: Percent	Single Track: One-Way Running: Kilometers	One-Way Running: Percent	Total (km)	Control of Train Operations: Automatic Block Signals: Kilometers	Automatic Block Signals: Percent	Street Traffic Signals: Kilometers	Street Traffic Signals: Percent	Unsignalled: Kilometers	Unsignalled: Percent	Total (km)
Boston														
Green Line	43.8	100	0	–	0	–	43.8	24.3	56	19.5	44	0	–	43.8
Mattapan-Ashmont	4.2	100	0	–	0	–	4.2	4.2	100	0	–	0	–	4.2
Newark City Subway	6.7	100	0	–	0	–	6.7	6.7	100	0	–	0	–	6.7
Philadelphia														
Streetcars	61.3	74	0	–	21.1	26	82.4	0	–	82.4	100	0	–	82.4
Subway-surface	35.1	98	0	–	0.8	2	35.9	3.4	9	32.5	91	0	–	35.9
Media-Sharon Hill	13.7	71	5.4	29	0	–	19.1	5.4	29	4.8	25	8.9	46	19.1
Norristown Line	20.8	95	1.1	5	0	–	21.9	21.9	100	0	–	0	–	21.9
Pittsburgh: South Hills	27.0	68	10.6	26	2.3	6	39.9	26.4	66	10.6	27	2.9	7	39.9
Cleveland: Shaker Heights	21.1	100	0	–	0	–	21.1	17.9	85	0	–	3.2	15	21.1
New Orleans: St. Charles Line	9.0	86	0	–	1.5	14	10.5	0	–	10.5	100	0	–	10.5
Fort Worth: Tandy Center Subway	1.9	100	0	–	0	–	1.9	0	–	0	–	1.9	100	1.9
San Francisco Muni	29.3	100	0	–	0	–	29.3	0.8	3	24.2	82	4.3	15	29.3
All systems	273.9	87	17.1	5	25.7	8	316.7	111.0	36	184.5	58	21.2	6	316.7

Note: 1 km = 0.6 mile.

Table 9. Characteristics of revenue service vehicles.

System	Fleet: Type	Fleet: Number	Mechanical Data: Axles	Motors	Kilowatts per Motor	Acceleration (m/s^2)	Balancing Speed (km/h)	Car Body: Type of Unit[a]	Avg Weight (Mg)	Operability in Trains: Percentage of Fleet Equipped	Staff per Car	Age of Fleet (years)	Seats	Power Collector[b]
Boston														
Green Line	Boeing Vertol	32	6	2	157	1.2	80	A: DE	31	100	1	1	52	P
Mattapan-Ashmont	PCC	276	4	4	41	1.8	72	S: SE	17	83	1	26 to 36	52	T
Newark City Subway	PCC	15	4	4	41	1.8	72	S: SE	17	0	–	26 to 36	52	T
Philadelphia	PCC	26	4	4	41	1.8	72	S: SE	16	0	–	28 to 31	54	T
Streetcars and subway-surface	PCC	350	4	4	41	1.8	72	S: SE	16	0	–	29 to 36	45 to 53	T
Media-Sharon Hill	Suburban	32	4	4	41	1.6	97	S: DE	19 to 22	41	1	28 to 45	59	T
Norristown Line	High speed	21	4 to 10	4 to 8	75 to 93	0.7	145	S(19), A(2): DE	24 to 95	90	1	36 to 53	52 to 141	S
Pittsburgh: South Hills	PCC	95	4	4	41	1.8	72	S: SE	16	0	–	28 to 32	50 to 54	T
Cleveland: Shaker Heights	PCC	57	4	4	41	1.8	72	S: SE	17 to 20	91	1	29 to 31	60 to 62	T
New Orleans: St. Charles Line	City streetcar	35	4	2	48	0.8	43	S: DE	20	0	–	53 to 54	52	T
Fort Worth: Tandy Center Subway	PCC	10	4	4	41	1.8	72	S: DE	–	0	–	32	30	T
San Francisco Muni	PCC	115	4	4	41	1.8	72	S: SE	17	0	–	26 to 30	53 to 60	T

Note: 1 kW = 1.3 hp, 1 m = 3.3 ft, 1 km = 0.6 mile, and 1 Mg = 1.1 ton.

[a] A = articulated, S = single unit, DE = double ended, SE = single ended.

[b] P = pantograph, T = trolley pole, S = third rail shoe.

Avenue are known to be preemptive, but exact information was not available.

As of August 1977, most of the cars in use were PCC cars, but 32 new Boeing Vertol light-rail vehicles (LRVs) have been accepted for service. Fully 83 percent of the PCC fleet is equipped for multicar operation, as are all of the LRVs. PCC acceleration is adequate, as is maximum speed, given the system's physical restrictions (grade crossings, sharp curves in the subway, proximity to traffic when operating in streets and on some narrow medians). The somewhat higher balancing speeds of the new LRVs will be beneficial principally on the Riverside line, where station spacings outside the subway are a relatively long 1.37 km (0.85 mile) and there are no grade crossings. The Green Line clearly meets the criteria of the definition of an LRT system.

Mattapan-Ashmont Line

The Mattapan-Ashmont Line, 4.2 km (2.6 miles) long, feeds the rapid transit Red Line (Harvard-Ashmont) at its south end. It is virtually all grade separated; there is one at-grade crossing. Average station spacing is 0.60 km (0.37 mile) but, because there is little deviation from the average—0.16 km (0.1 mile) or less—there are no long runs at balancing speed. Only single cars are run, but peak-hour headways are as close as 2 min. This line also clearly fits the LRT definition.

Newark City Subway

The Newark City Subway, 6.7 km (4.2 miles) long, also has only one street crossing at grade. This crossing, at Orange Street, is controlled by a nonpreemptive traffic signal, the only significant impedance to speed on the line. This, combined with somewhat longer station spacings than on the two Boston systems, as well as much lighter patronage, results in a substantially higher $\overline{V}$ of 32 km/h (20 mph). Single PCC cars are operated; the line has double tracks and is block signaled throughout. This system, too, is correctly classified as LRT.

Philadelphia Streetcars

The city streetcars of Philadelphia do not now form a system that meets LRT criteria. Only 5 percent of trackage is reserved, and that is only reserved by having lines painted on paved streets to mark off the lanes containing the tracks. Although the initial costs for such reservations are low, their effectiveness depends on enforcement. This does not seem to have been adequate so far, and the lanes have not increased streetcar speeds enough to lure many people out of their automobiles, as had been hoped by the U.S. Environmental Protection Agency, which ordered their installation. Route 6, which has about 2.7 km (1.7 miles) of reserved lanes, still runs at a $\overline{V}$ of 14.5 km/h (9.0 mph); Route 15 continues to be the slowest in the system at a $\overline{V}$ of 11.7 km/h (7.3 mph), although it has not quite 1.5 km (1 mile) of reserved lane in a total length of 13.4 km (8.3 miles).

Opportunities for increasing $\overline{V}$ appear to be minimal. If stops were made every other block instead of every block and if the traffic signals at intersections between stops were made preemptive, the number of stops could be halved. However, this might not be practical on many portions of the streetcar lines.

Philadelphia Subway-Surface Lines

The five subway-surface lines link West Philadelphia residential areas with the CBD. Just to the west of the CBD, they pass through University City, home of two major universities: the University of Pennsylvania and Drexel University. Because they run in a 4.0-km (2.5-mile) subway under University City into the heart of the CBD at City Hall, their $\overline{V}$ is somewhat higher; it ranges from 15.1 km/h (9.4 mph) for Route 10, which leaves the tunnel after only 3.2 km (2.0 miles) of its 9.3 route km (5.8 route miles), to 19.8 km/h (12.3 mph) for Route 36, which in addition to a full 4.0 km (2.5 miles) in the subway includes 1.6 km (1.0 miles) of median trackage. The $\overline{V}$ for all five routes is 18.0 km/h (11.2 mph), which puts it at the lower end of the 16 to 32-km/h (10 to 20-mph) range usually quoted as typical of LRT.

Single PCC cars are used. Headways in the subway shrink to as little as 30 s during peak periods, about as close as is physically possible. Any further increase in car throughput would require consideration of multicar operation during rush hours.

The subway was opened in two stages. The eastern portion was completed in 1905 as part of the Market-Frankford subway-elevated line construction. In this segment, express subway trains use the center pair of tracks in a four-track tunnel, while streetcars use the outer pair and provide local service at three stations not served by rapid transit. The West Philadelphia section of the tunnel opened in 1955. It was built entirely within street lines and thus includes three 90° curves that have 20-m (100-ft) radii around which cars must creep. This routing, which was chosen to reduce construction costs, has resulted in long-term operating inconvenience.

Like the Green Line, the subway-surface lines provide a good illustration of LRT's branching capabilities. There are at least two happy results of having a group of branches joined to a trunk that is planted firmly in the CBD. First, the branches act as distributors in the residential areas so that patrons may board and alight within walking distance of their homes yet have a single-vehicle, no-transfer ride downtown. Second, service on the trunk can be very good, even during nonpeak hours. The subway-surface lines run at 12 to 20-min intervals at these times, and four of the five routes pass under the University of Pennsylvania. Average base headways between the university and the CBD are about 3 to 5 min. Despite the deficiencies noted above (much street running and sharp curves in the subway), the subway-surface lines offer a quality of service that, although it lacks high speed, must be considered to be within the spirit of the LRT concept.

Media-Sharon Hill Lines

The Media-Sharon Hill lines serving Philadelphia's southwestern suburbs constitute a nearly perfect example of the LRT concept. They are located predominantly (87 percent) on reserved right-of-way but include some street running where this could not be economically avoided. Stations are spaced on average 0.42 km (0.26 mile) apart. At-grade crossings occur every 0.37 km (0.23 mile), and there are two areas of grade separation. The track traffic pattern combines double-track (71 percent) and single-track (29 percent) operation, all with two-way running. Single-track segments are protected by block signals, but double-track portions are largely unsignaled except for blind curves. In peak hours, both local and zone express services are run.

The cars used truly fit the LRT concept, even though they antedate the use of the term by many years. Three series of cars are operated in regular service; they were built in 1932 (10 cars), 1941 (9 cars), and 1949 (13 cars). The newest group is equipped for operation in two-car trains. All of the cars can reach nearly 100 km/h (60 mph) but rarely exceed 80 km/h (50 mph) on the lines now operating (one of two abandoned routes had 100-km/h track). Even so, the $\overline{V}$ is 25.8 km/h (16 mph) to 27 km/h (17 mph) for Media and 23 km/h (14.5 mph) for Sharon Hill.

Recent events on the Media-Sharon Hill lines serve to illustrate how the concept of incremental improvements can be applied on a small scale. Two short segments of second track that together total less than 1.6 km (1 mile) were installed on the Media line within the last 5 years to eliminate the single-track running that had caused operating delays while cars waited in sidings for opposing traffic to clear. Operations were thus improved at moderate cost. Other work included the reconstruction of old passenger shelters and the placement of additional shelters at stops.

Norristown High-Speed Line

The Norristown High-Speed Line, which is completely grade separated, is one of only two LRT systems operating in the United States that has high-platform stations, and it is the only one that has a third-rail power distribution system. Although these characteristics may make it seem more like rapid transit than LRT, the line's use of on-board fare collection at all times and mostly single-car trains allows it to be classified as LRT.

In addition to being free of grade crossings, the line has the longest average interstation spacing of any system discussed: 1.05 km (0.65 mile). Effective station spacing is further increased through use of a unique flag-stop indicator system that allows trains to skip stops if there are neither boarding nor alighting passengers. Each intermediate station platform has a cord that passengers pull to light a white signal located far enough in advance of the station to allow car operators to stop safely. If the signal is lit, the car stops; otherwise it runs past at full speed.

These factors permit the fleet of truly high-speed cars to attain a $\overline{V}$ of 50 km/h (31 mph), which is fast for rapid transit, let alone LRT. Changes in motor field taps now limit the maximum speed to about 110 km/h (70 mph), but the cars were capable of 145 km/h (90 mph) for two decades. Between 1950 and 1952, before these changes were made, rush-hour expresses that made only two intermediate stops covered the 21.9 km (13.6 miles) to Norristown in 17 min, a $\overline{V}$ of 77 km/h (48 mph).

Three distinct classes of cars are used. There are 9 cars dating from 1924 to 1929, 10 cars—the wind-tunnel-tested Bullets—from 1931, and two 4-car, triple-articulated trains originally built in 1941 for express Chicago-Milwaukee service—the Liberty Liners—that were acquired secondhand.

Pittsburgh South Hills Lines

The South Hills lines in Pittsburgh are CBD oriented but do not have a downtown subway. They circulate through the business district on unreserved tracks in city streets. The question of these lines' survival has been debated for the last decade, but the decision now has been made to retain and improve them (22).

In its heyday, the Pittsburgh Railways—private predecessor of the public Port Authority Transit—ran city streetcars, suburban car routes, and interurban lines to smaller cities around Pittsburgh. All used the same tracks in the city; the interurbans used suburban lines to the fringes of the urbanized area. As noted earlier, the Library and Drake lines are remnants of once-longer interurban routes. The Mt. Lebanon line is a suburban operation. One streetcar line remains, the route that runs up and over Mt. Washington.

The two interurban lines, which run on private right-of-way outside the CBD, are the longest and fastest routes; the Library line is 20.4 km (12.7 miles) long and has a $\overline{V}$ of 25.7 km/h (16 mph), while the Drake line is 17.4 km (10.8 miles) long and has a $\overline{V}$ of 24.9 km/h (15.5 mph). The Mt. Lebanon line, 11.7 km (7.3 miles) long, includes the only median trackage, a stretch of 0.8 km (0.5 mile). Despite its considerable length of reserved right-of-way, it operates at a $\overline{V}$ of 13.8 km/h (8.6 mph) because it has closer stop spacing—0.29 km (0.18 mile)—and more frequent grade crossings—0.50 km (0.31 miles)—than are found on the interurbans. The streetcar line, which runs on narrow streets and up steep grades over Mt. Washington, averages only 11.3 km/h (7 mph). The overall system $\overline{V}$ is 22.0 km/h (13.7 mph); station spacings follow typical LRT practice. On average, street crossings on the reserved portions of the system occur every 0.66 km (0.41 mile). There are 14 grade separations.

Standard PCC cars run singly on all lines. Fully two-thirds of the line length is protected by block signals, including three sections of single track that have passing sidings. This is the last operating example in the country of what was once typical light-density electric railway practice, i.e., sidings long enough for only three or four cars and equipped with equilateral turnouts so that both tracks diverged instead of having a through route and a siding as is usual in railroad practice.

New track standards adopted by Port Authority Transit—45-kg (100-lb) rail, 61-cm (24-in) tie spacing, and 30.5-cm (12-in) slag ballast section—should, when fully implemented, result in better ride quality than now exists on much of the system. In addition to improving its open track, a portion of the right-of-way north of Castle Shannon is being rebuilt with track embedded in concrete for joint use by buses and rail cars. The Mt. Washington tunnel has been paved for the same reason. This construction, when completed, will result in one of the more unusual examples of joint right-of-way use.

In its present state, Pittsburgh's system must be categorized as a hybrid. The two interurban lines clearly fall into the LRT classification; the Arlington-Warrington line over Mt. Washington is just as clearly a streetcar. Finally, the Mt. Lebanon route, because of its frequent stations and grade crossings, can best be described as a streetcar line that has incipient LRT right-of-way qualities.

Shaker Heights Rapid Transit

Shaker Heights Rapid Transit, which is now part of the Greater Cleveland Regional Transit Authority (RTA), is a second example that seems to epitomize the LRT concept. Its two branches operate in broad suburban boulevard medians in Shaker Heights, then join to run on a 9.6-km (6-mile) grade-separated trunk line to downtown Cleveland. The last 4.0 km (2.5 miles) into Cleveland Union Terminal are run on tracks shared with the rapid transit trains of the RTA's east-west line to the airport. This is another example of joint use: different types of electric rail vehicles use the same tracks.

As originally conceived, the Shaker Heights Rapid Transit was to have used heavy multiple-unit cars like those used until recently by the Illinois Central Railroad in Chicago. This concept was carried through into the construction phase and is evident in the heavy-duty line between downtown and Shaker Square, the junction of the two branches. Even though three- and four-car trains are run during peak hours, the system resulting from the use of light-rail technology is much more compatible with its surroundings in Shaker Heights than railroad commuter cars would have been.

Table 10. Classification of systems as LRT or streetcar operations.

Category	System	Avg System Operating Speed (km/h)
Light-rail rapid transit	Norristown High-Speed Line	49.9
Light-rail transit group 1	Cleveland: Shaker Heights	37.0
	Newark City Subway	32.2
	Philadelphia: Media-Sharon Hill lines	25.8
	Fort Worth: Tandy Center Subway	25.8
Light-rail transit group 2	Pittsburgh: South Hills	22.0
	Boston	
	Green Line	20.0
	Mattapan-Ashmont	19.3
	Philadelphia subway-surface	18.0
Streetcar	San Francisco Muni	15.3
	New Orleans: St. Charles Line	15.0
	Philadelphia streetcar	14.5

Note: 1 km = 0.6 mile.

The average station-spacing figure shown in Table 7 may be somewhat misleading. On the branches, stations are typically 0.5 km (0.3 mile) apart; west of Shaker Square the average distance between stops is 1.6 km (1 mile). Virtually the only impediments to operation are 20 nonpreemptive traffic signals for at-grade crossings on the branches. Despite these, Shaker Heights Rapid Transit is the country's second fastest LRT system. Trains are protected by block signals except at the far outer ends of the branches, and all but five of the PCC cars are equipped for multi-car operation.

St. Charles Streetcar Line

The St. Charles streetcar line, part of one of the few large transit systems still operated by a privately held utility company, is prized almost as highly by New Orleanians as are the cable cars of San Francisco by their local supporters. It is called a streetcar because the last regularly used pre-PCC city cars in the country serve the line. Although 88 percent of the route is reserved in the median of St. Charles Avenue, operating speeds are at streetcar levels because of the short distances between car stops—0.19 km (0.12 mile) on average—and the high frequency of grade crossings—about every 0.10 km (0.06 mile). Because of these conditions, faster cars would be of little use, and there appears to be no special pressure to make the line speedier.

Patronage is sufficient to require short headways all day: 3.5 to 4.5 min during peaks and 5 to 5.5 min during midday. The reasons for this high ridership lie in the areas served by the line. For most of its length, it passes through a gracious, tree-shaded, but rather thickly developed residential area. Low- and mid-rise apartments are interspersed among the single-family homes. A thriving subregional shopping area is located at the turn from St. Charles Avenue to Carrollton Avenue. Both Loyola and Tulane universities are served. At its inner end, the line circulates through the CBD on street track and reaches the edge of the French Quarter. It serves both residents and tourists. Although the reserved right-of-way gives the line the appearance of LRT, it functions as a local streetcar.

Tandy Center Subway

The Tandy Center Subway in Fort Worth is unique in two ways: It is the only U.S. LRT line that serves as a shuttle between a CBD and peripheral parking lots, and it is privately owned and operated without public subsidy. The line was opened in 1963 by Leonards Department Store. Both the store, actually a complex of several buildings, and the LRT line have changed ownership twice since then. The present owner has embarked on an improvement program for the line, which had been allowed to deteriorate under the previous management. Although the cars used by this system are secondhand PCCs from the abandoned Washington, D.C., streetcar network, they do not look it. All have been air-conditioned and modified for high-platform passenger loading. Constructed for single-end running, they have been reworked for double-end operation. Under the latest refurbishing project, the cars are being stripped to the frames and fitted with new car bodies that have contemporary styling. The propulsion equipment is also being overhauled but not significantly altered.

San Francisco's Municipal Railway

San Francisco's Muni operates one of the most diverse surface transit fleets in the country: streetcars, trackless trolleys, buses, and—of course—cable cars. The streetcar system is now in a transitional period during which it is being upgraded to LRT standards. Like other systems described previously, this one has the basic strength of five branches tied to a central trunk line leading to a vital CBD. This basic characteristic is enhanced by the dense development of the system's service area—a result of its location on a peninsula and the fact that two tunnels built to overcome steep grades also provide grade separation for portions of four of the five routes. Despite long-standing track reservations amounting to 29 percent of the total line length, operating speeds have been low because of frequent passenger stops and cross streets.

The improvement program is geared to alleviate some of these problems. As part of the BART construction project, a tunnel for Muni rail cars was provided under Market Street from Embarcadero to the east portal of the Twin Peaks Tunnel. Not only will this eliminate traffic congestion, but the number of stops along Market Street will be reduced by about 75 percent, to seven underground stations (18).

Less dramatic, but already in service, is 2.6 km (1.6 miles) of track in Judah Street converted from unreserved street trackage to reserved median. This was accomplished by building up the area around the tracks to a height of 7.6 cm (3 in) above the street paving and surfacing it with rough, exposed aggregate concrete (23). This increases the amount of reserved line to 37 percent of the total, as shown in Table 6. Emergency vehicles are allowed to use the median paving, as are drivers making left turns into their own driveways. Thus, the right-of-way is not exclusive, but it is reserved. Some cross streets are reported to have been cut off, but the exact number affected has not been obtained.

As mentioned earlier, the improvement program—which also includes new LRVs, reconstruction of tracks and power distribution systems, and new maintenance facilities—is expected to allow running time to be reduced. The L Line, which is 12.6 km (7.8 miles) long, will be covered in 34 instead of 52 min. This will increase $\overline{V}$ from 14.5 to 22.2 km/h (9.0 to 13.8 mph). Similarly, the one-way running time for the N Line, 11.3 km (7.0 miles) long, is expected to drop from 50 to 35 min, increasing $\overline{V}$ from 13.5 to 19.3 km/h (8.4 to 12.0 mph). This will bring the Muni lines into the same range of average operating speeds as Boston's Green Line.

SUMMARY

When all is said and done, the systemwide $\overline{V}$ rather accurately summarizes all the factors that determine whether a system should be classified as essentially LRT or as a streetcar operation (Table 10). Even though the Muni is becoming an LRT system and the St. Charles line appears on the surface to have an LRT right-of-way, both now provide streetcar service. The only anomaly is Pittsburgh, in which there are two LRT lines, a slow but largely off-street route (Mt. Lebanon), and a true streetcar line. It does not appear coincidental that the Pittsburgh system in its present state and at its typical trip time of 31 min has the smallest daily ridership of any CBD-oriented system except Newark and Shaker Heights, which pose special problems of urban and transit system development.

Some systems, such as the Shaker Heights Rapid Transit and the lines in Philadelphia's western suburbs, must be fast so that typical trip times are not unduly long. Speed, however, is not everything. The four systems in the group that have a $\overline{V}$ between 18 and 22 km/h (11 and 14 mph) include two heavily used CBD-oriented operations—Boston's Green Line and Philadelphia's subway-surface lines. Typical trip times for these systems are about 20 min. More importantly, these lines connect vital elements of the urban core with each other and with residential areas. For the latter, the trunk-and-branches configuration allows most riders to have a single-vehicle ride.

The currently operating LRT systems serve the kinds of medium- to high-density urban and suburban areas that future development may well have to emulate as decreasing amounts of fossil fuels, especially petroleum, make it more and more expensive to sustain the automobile-oriented spread-out style of life. This process might be called the Europeanization of American cities. Given the role that LRT plays in many areas of Europe and the vitality of the cities thus served, such a trend might be more acceptable than we now think. Certainly, the quality of life along Boston's Green Line supports this notion.

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Operational Idiosyncrasies of a Subway-Surface System

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The objectives of this paper are to acquaint the reader with the behind-the-scenes activities that constitute the day-to-day operations of Philadelphia's subway-surface system and to pinpoint techniques and methods that new systems could adopt to avoid some of the problems SEPTA faces. The paper discusses daily operations, service interruptions, training, accident prevention, and support activities. The problems discussed are accompanied by a discussion of the solutions adopted or those that would be adopted if there were adequate funds and local cooperation. Specific recommendations for new systems are summarized.

A daily rider of Philadelphia's subway-surface system might describe a typical journey as follows:

I live close enough to the car line to walk to the stop, and I usually only wait a short time before a streetcar arrives. I get on board with the other people and, if I'm lucky, I find a seat. During the 20-minute ride I usually either read the paper or just watch the signals in the tunnel flash by. At 15th Street I get off and make my way to my job; normally I arrive before my next-door neighbor, who drives to work.

Our passengers probably never give a thought to the many behind-the-scenes activities that make their safe arrival possible. I wish to describe these activities here and provide an introduction to one of the most efficient ways of moving people—the surface-subway operation of the Southeastern Pennsylvania Transportation Authority (SEPTA). I will first review the history of the system and then discuss daily operations and service interruptions, considerations for training and for accident prevention, and support activities.

HISTORY OF THE SYSTEM

Some historical background will place today's operation in perspective. Subway construction fever gripped Philadelphia at the turn of the century, and numerous companies were chartered. One of these, the Market Street Elevated Railway Company, advanced a plan for a route to connect the western suburbs with the center city. The track was to be elevated from 69th Street to the Schuylkill River, cross that river on a new bridge, and then go underground to the Delaware River via City Hall.

An interesting feature of the scheme was that West Philadelphia streetcars would climb up on the bridge to join the El before both trains and trolleys began the underground trip to and around City Hall. El trains were to operate as expresses in the two center tracks from the Schuylkill River to City Hall. The trolleys were to operate on the two outer tracks and make local station stops at 24th and 19th Streets.

The surface-car subway, operated by the Philadelphia Rapid Transit Company (PRTC), was opened in December 1905, before the El's completion. Trolleys crossed over at 19th Street to use the El tracks and temporarily stub ended at 15th Street. In early 1907 the streetcars were shifted onto their own tracks entirely and routed around City Hall, looping under the newly opened El. The eastern terminus was and is Juniper Street Station.

Almost as soon as the subway opened, PRTC advanced plans to extend it. One such idea called for a surface-subway distribution loop in the center city. It was to run from City Hall via Broad, Walnut, Fifth, and Arch streets and back to City Hall. Some of the stations on Arch Street were actually started. Also proposed was a tunnel to replace the Schuylkill Bridge, and an extension of the subway into West Philadelphia. The tunnel under the river was actually dug in the 1930s but, like the distribution loop, fell prey to the constant bickering between the city and PRTC.

It was not until 1955 that a joint extension underground of the El to 44th Street and the trolleys to portals at 36th and 40th streets opened, replacing the bridge at last. Unfortunately, the surface-subway alignment was dictated by urban renewal, University of Pennsylvania expansion, and cost considerations. The initial cost savings have been negated many times over because the twisting tunnel alignment reduces schedule speeds, causes rail and wheel wear, requires more signaling, and results in an ever-present potential for car collisions. Where possible, new systems should minimize curves.

DAILY OPERATIONS

Today five routes originating in the western fringes of Philadelphia make up the system (Figure 1). These routes operate 90 cars and carry an average of 60 000 passengers each way daily. The headway in the subway during peak hours is a very close 30 s. Route 10 operates out of 64-year-old Callowhill Depot and enters the subway at 36th Street near Market. The other four lines operate from Woodland Depot, which dates from the horsecar era of the 1860s.

The surface portion of the system has conventional street running with its attendant hazards of traffic congestion and service delays (Figure 2). Traffic signal preemption for streetcars has been suggested to the city by SEPTA but to date has not been implemented. There is one section of private right-of-way on the outer end of Route 36, but it is subject to interference from cross traffic. The final unprotected turn into traffic to reach the terminal gives the operator quite a challenge. This is one of the places where preemptive signals, such as those commonly used in Europe, would speed service and provide safer operation. Loops at the ends of lines should always include bypass capability for scheduling flexibility and for passing disabled cars.

The four lines that enter the 40th Street Portal activate a preemptive traffic signal that stops automobiles crossing in front of the tunnel. The automobile traffic presents a serious accident hazard and delay potential, so the city plans to reroute traffic and restrict the area around the portal to transit only.

When the car enters the subway, the operator faces an abrupt change in light levels that affects his or her vision. We are exploring the possibility of installing yellow transitional lighting just inside the portals of both the surface-car and rapid transit tunnels. New tunnels should be designed to minimize the impact on operators of such changes in light level.

Most of the tunnel is lighted only by widely spaced incandescent bulbs, but the stations are bright. This poses another vision problem for operators entering and leaving stations. Some sections of the tunnel have been modernized with fluorescent lighting, and we are studying the feasibility of installing roof-mounted car headlights for better visibility in the tunnel. Light levels should be uniform throughout the tunnel.

A three-aspect block signal system regulates car progress everywhere in the tunnel except in the old section between 22nd and 15th streets. In this area, safety depends on the operator's vision and alertness. Techniques used to maintain this alertness are discussed later. To increase station capacity, a call-on system is used that enables the following car to move into the station while the first car is still loading or unloading. This practice does increase the likelihood of car collisions, and we closely monitor its use.

The signals are numbered to help the operator quickly identify his location. All eastbound signals are even numbered, and westbound signals have odd numbers. By mentally adding a zero to the signal number, the operator also knows the house number on the street above him. Thus, MS 211 is located at 2110 Market Street. This system greatly aids the Radio Room personnel who dispatch help to an operator.

Since the majority of passengers disembark and load at Juniper Street Station, we use a sliding gate to increase car capacity there. In the morning rush, a supervisor positions the gate so that four cars can unload simultaneously before each moves beyond the gate to the paid area to load. In the evening rush, the gate is positioned to allow four cars to load at once in the paid area.

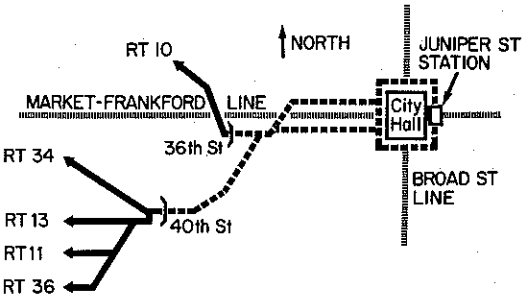
Lighted signs at 15th Street West Plaza Station and automatic ones at Juniper Street Station direct passengers to the berth at which cars on a given route will stop. A sign in the tunnel outside the entering end of the station tells the operator at which berth to stop.

Before these two stations were modernized, the berthing positions were changed from moment to moment according to which car was next due in. Standard berthing positions were introduced to eliminate the accident hazards of people darting into the track area or shoving their way through the limited waiting space to reach the proper berth. I can recommend constantly changing berthing only if the station is properly designed to safely handle passenger ebb and flow.

Passengers normally pay fares to the operator when they enter the trolley, but at the two busiest stations, Juniper and 15th Street West Plaza, cashiers are used. Cashiers collect fares for a few hours at Sansom Street Station during the heavy influx of school children from that area. The 30th Street Station cashier handles both local (subway-surface) and rapid transit (Market-Frankford) traffic. Once he or she is inside the cashier controls, the passenger is directed by means of color-coded turnstiles to the correct line. Because the surface-subway is integrated with the subway-elevated lines, certain joint operational techniques are employed. At 15th Street West Plaza Station, the cashier admits passengers for both the surface-subway and the Broad Street subway lines.

At Juniper Street Station, a blue train-arrival light comes on during the very late hours to alert a trolley operator that an El train has arrived at the adjacent 13th Street Station and that the operator must give passengers enough time to descend the stairs to reach their cars. Stationmen are assigned to the Juniper and the 15th street stations in the evening peak hours to provide center-door loading. This lessens station dwell time.

Figure 1. Schematic map of Philadelphia subway-surface system.

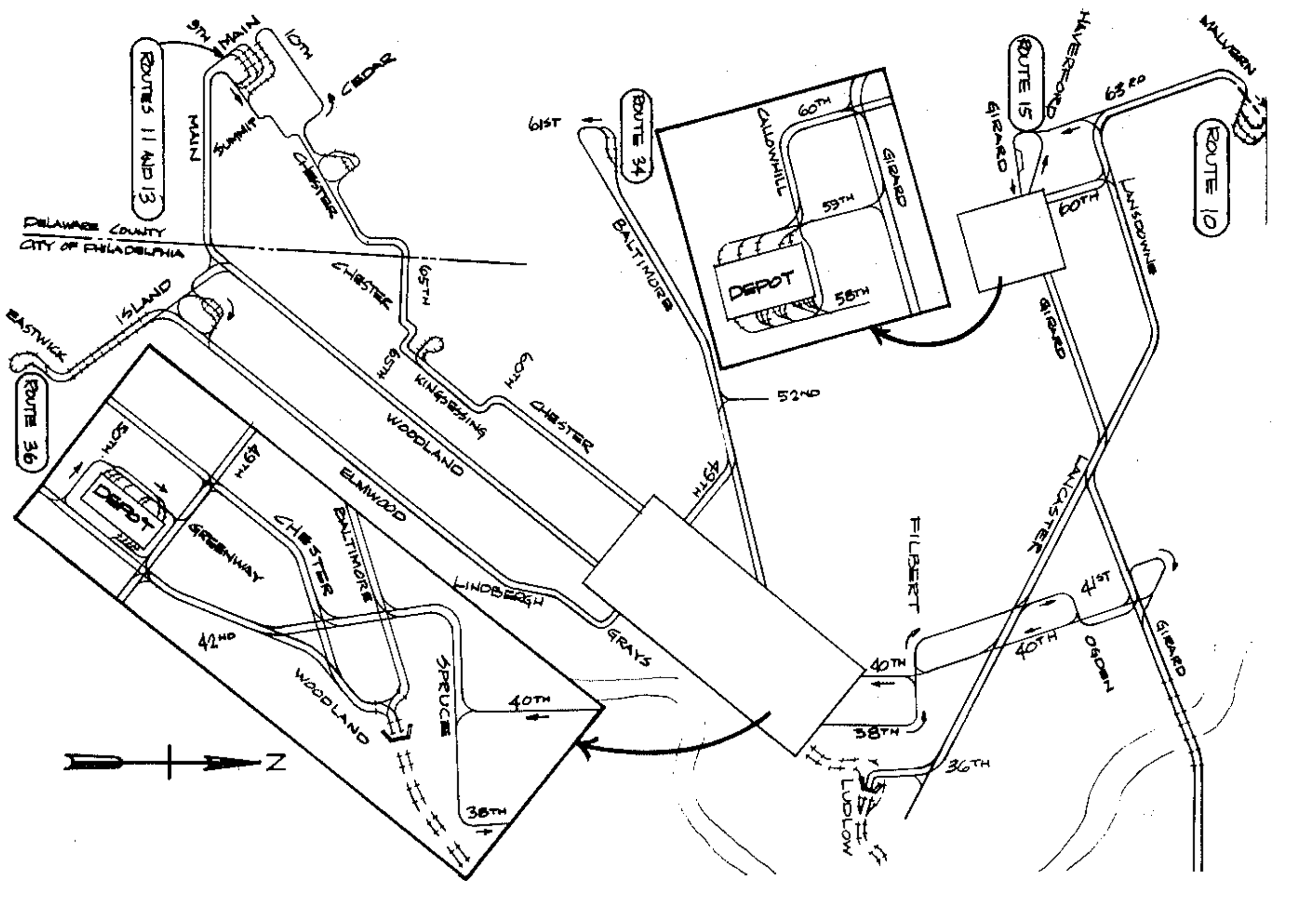


SERVICE INTERRUPTIONS

Since our streetcars are not equipped with radios or train telephones, an operator faced with a delay, mechanical breakdown, or other problem must call the control center, Radio Room, from the nearest telephone and then follow instructions. In the tunnel, telephones are located on the walls. A grant request is being prepared for funds to enable us to equip the cars with radios.

Radio Room personnel pass on to the operator instructions from the street supervisor or, if the delay is in the tunnel and is of major consequence, turn jurisdiction over to the subway-elevated train dispatcher. Street supervisors use radio-equipped automobiles but can conserve air time by calling in on telephones strategically placed at the portals. During delays, instructors who are not engaged in the training of students frequently join supervisors to clear the track as quickly as possible. Both aim to minimize the impact on passengers riding

Figure 2. Surface trackage of subway-surface routes.



trolleys that are immediately behind the crippled car or that must be cut to restore the operating schedule.

Today's social problems unfortunately have a direct impact on transit operations. Fare disputes sometimes necessitate police intervention, and certain cashier booths have switches to turn on a police-request light located at the street entrance to the station. At times, the streetcar operators are faced with the dangerous problem of unruly and perhaps violent passengers. To assist the operator in alerting police along the route, some trolleys have been equipped with a revolving amber help-needed light. These lights are, however, difficult to see in the daylight and have not been in operation long enough to provide a final evaluation of their worth. The help-needed light does serve another function in the subway. If the car breaks down, the operator turns on the amber light before leaving for the nearest telephone, and the reflection off the walls makes the light even more visible. Operators of trolleys going in the opposite direction can then alert the first instructor or supervisor they encounter. In the joint-operation section of the tunnel, Market-Frankford subway-elevated operators who spot the amber light call the train dispatcher immediately on their train telephones.

Fire boxes, fire extinguishers, and emergency exits are located together throughout the subway. Most are placed adjacent to the telephones. Telephones are kept locked to prevent vandalism, and operators carry a special key. We hope to place arrows on the walls, so that when an operator leaves the car to find a telephone he or she will immediately know which direction to take to reach the nearest telephone. The present private telephone system will shortly be replaced by Bell System telephones whose locations will be standardized to facilitate finding them in an emergency.

The use of trolley poles rather than pantographs results in all-too-frequent dewiring and torn overhead wires. Emergency crews are on call and are directed into the subway through the nearest station.

Each operator is issued a flashlight for his or her own and the passengers' safety in the tunnel. Supervisory personnel have flashlights equipped with fuse testers to facilitate trouble shooting. Although the all-electric Presidents' Conference Committee (PCC) cars have interior emergency lights that are powered by the battery, PCC cars with air brakes do not. A disabled, dark car can produce a panic situation. All new cars, whether they have air brakes or are all electric, will be equipped with adequate emergency lighting.

The normal procedure for handling breakdowns in the subway during rush hours is to immediately hook up and push the disabled car out. During off-peak hours and on the street, a trouble-shooting sequence is followed, and many times the problem is corrected by replacement of a fuse. Since delays in the subway cannot always be immediately cleared by pushing, we have emergency tools placed throughout the subway. These are periodically checked to ensure they are present and in working condition. In addition, great care must always be taken while making repairs in the joint-operation area because elevated trains may strike personnel who are engrossed in fixing the trolleycar.

Operator initiative plays an important part in keeping delays to a minimum, and often the disabled car is being pushed out before supervisory personnel reach the scene. SEPTA also has special hydraulic rerailing equipment that greatly assists in getting a trolley back on the track in minimal time.

Since the subway is a continuous loop with no cutbacks or crossovers, a car that breaks down eastbound would have to be pushed all the way out if it were not for a two-car spur adjacent to Juniper Street Station. This spur allows us to place the disabled car out of the way and fix or retrieve it during off-peak hours. Of course, a better solution would call for double-ended cars and frequent crossovers.

Procedures designed to clear the line as quickly as possible specify that all pushed cars go to Woodland Depot because it is closer than Callowhill. We use the Route 13 trackage on Chester Avenue instead of the more direct Woodland Avenue to avoid runaways on Route 11's steep hills.

Major accidents or derailments in the subway can make continued operation below ground impossible. When this happens, instructors or supervisors turn on pole-mounted amber lights located at the track switches for diversion routes. When operators see these lights they know they are not to enter the subway but instead take their passengers over a normally unused diversion routing to the 40th and Market El station. There the people can transfer to the trains to complete their trip to the center city. These diversion routes are also used for a few hours in the early morning each Thursday to let us close the subway to make uninterrupted repairs in the tunnel.

Unfortunately, we do not have a loop at the entrance to the 40th Street Portal, but an operator whose car has mechanical problems can, with the assistance of a supervisor or instructor, use the y-shaped track there to turn the car and return to the depot. This is not an ideal situation, since such an operation ties up the entrance. The city's plan to close 40th Street to all but transit will provide an opportunity to redesign the entrance trackage to include a loop.

The heavy ridership on the subway-surface lines makes it necessary to operate even while surface track is being reconstructed and roads are being paved. Temporary crossovers, temporary signals, and workers using walkie-talkies make this a safe, smooth operation and ensure minimum delays to our passengers. Major subway reconstruction, such as the shifting of the 15th Street Station platform, included provisions for cars to continue in service with only brief interruptions druing track tie-ins.

TRAINING PROGRAMS AND ACCIDENT PREVENTION

Delays occasioned by equipment breakdowns are serious but not as costly as those resulting from accidents. At SEPTA, the instructors in the Operational Training and Safety Division teach and follow up employees in both operation and accident prevention.

The initial 14-d training program stresses not only car operation, trouble shooting, and courtesy but techniques of accident avoidance. On-vehicle and classroom instruction are augmented by teaching aids, such as model boards, signal flash cards, and written examinations. Training stresses the operator's responsibility to anticipate such hazards as slippery rails where there are falling leaves. Follow-up training in defensive driving techniques is given to both new operators and experienced employees by instructors certified by the National Safety Council.

We keep employees informed about specific current problems through periodic distribution of handouts and the monthly issues of the four- to six-page Safety Sense Newspaper, which is specifically designed to provoke employee reaction and thought.

When they are not engaged in actual training, instructors function in many other roles. Follow-up rides are periodically taken with each operator to identify bad operating habits or poor performance. These rides also provide the opportunity to commend an operator for a job well done. Instructors must spend 15 min/d walking between stations in the subway. This serves several functions. The likelihood that an instructor may appear anytime and anywhere helps keep operators on their toes. In addition, instructors assist the Facilities Department by spotting and reporting out-of-order equipment, evidence of vandalism, and other problems. Finally, many breakdowns or delays are quickly cleared because an instructor was handy.

Besides working to assist operators, instructors run various checks of compliance with operating rules. The subway's block signals do not have trips, since an arrangement such as that used on the Shaker Heights PCC cars cannot be employed on street-running trolleys. Operators are sometimes tempted to lose respect for red signals, especially on time-zone lights. To minimize safety violations of this type, instructors periodically conduct signal checks during which the signal is held at red until the operator comes to a complete stop. Violators are suspended for a day for the first offense, and progressively stricter discipline is exercised thereafter. The possibility is being discussed of equipping new cars and the tunnel with an inductive-coil trip system such as that used in Belgium.

Our rules require operators to come to a complete stop at all facing point switches (except the air-brake-operated double-point switch in the subway) and to ensure that the switch is properly set before proceeding. Instructors conduct frequent switch checks. Interlocking switch and signal plants are possible accident sites, and operator adherence to safety rules at our one such location is reinforced by the use of a graphic recorder that can pinpoint signal or switch violations. This recorder in the 34th Street Tower is monitored by a signal maintainer.

The subway-surface system has only one railroad crossing; this is also frequently checked by instructors to see that operators stop and look before proceeding. The overhead wire at the crossing has a conductive net guard to catch the pole if a dewirement occurs. This allows the car to clear the crossing before the pole is rewired. Other safety aids are installed where needed, such as signs to warn of slippery rail. There is also a mirror at the portal so that an inbound trolley operator can watch in the mirror for automobiles behind outbound cars.

None of these efforts in itself will ensure accident-free operation but together they are very effective. SEPTA's greatly improved safety record attests to this.

SUPPORT ACTIVITIES

There are many activities and facilities necessary to support a subway-surface system, so I will mention only a few. Because our private right-of-way precludes the use of automotive vehicles to string or repair overhead wire, a tower car is employed. This car is also essential for repairs in the subway. Trash removal from the tunnel is facilitated by use of a work car. Other maintenance and repair functions dictate the need for crane and flatbed work motors. Car maintenance itself is accomplished at Callowhill Depot for Route 10 and at Woodland Depot for the other routes. A disastrous fire in late 1975 destroyed the Woodland Shop; we must now make do with a temporary prefabricated structure.

The future of the five subway-surface lines is assured. Specifications are being prepared for new light-rail vehicles to replace the tired fleet of PCC cars. A new depot and major maintenance facility have been designed to replace the antiquated Woodland Shop. Together these efforts will begin a new era in efficient transportation for the people of West Philadelphia. By then the joint efforts of the city and SEPTA to provide better security on the system for passengers and operators, eliminate graffitti, and in general raise the quality of service will have gone far forward.

RECOMMENDATIONS FOR NEW SYSTEMS

1. Use preemptive signals liberally for street running or private right-of-way with cross traffic, especially where turns are involved.
2. Plan the subway alignment to exclude or minimize curves; unavoidable curves should be made as gradual as possible.
3. Provide for transitional lighting where operators enter and leave the tunnel.
4. Provide uniform lighting levels throughout both stations and tunnel sections.
5. At terminal stations use sliding gates to increase loading and unloading capacity during peak hours.
6. Plan for the strategic, uniform placement in the tunnel of such items as telephones, extinguishers, fire alarms, and emergency tools.
7. Use arrows to indicate the shortest distance to such emergency equipment and make sure the tunnel has a concrete walkway for operator use and emergency evacuation of passengers.
8. Buy double-ended cars or cars with back-up controllers and place crossovers at frequent intervals in the trackage.
9. Provide for diversion of routes since even the most well-designed system will suffer blockages; it would be especially wise to include a loop at tunnel entrances if cars are single ended.
10. Ensure safety with simple block signals and car trips.

Traffic Engineering for Light-Rail Transit

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The development of safe and operationally effective designs for at-grade intersections and crossings for light-rail transit (LRT) is an issue central to the future deployment of the mode. This paper describes a design approach based on the performance characteristics of light-rail vehicles (LRVs) and the application of conventional traffic engineering hardware and design practice. At-grade operation of LRT introduces potential conflicts with motor vehicles and pedestrians at intersections, in streets between intersections, and at mid-block crossings. These conflicts are a source of delay and accidents for LRVs. Application of the appropriate conflict-control techniques must consider that modern LRVs have performance characteristics essentially similar to those of transit buses. There are four strategies available to the traffic engineer to eliminate or

control points of conflict among LRVs, motor vehicles, and pedestrians: at-grade separation of traffic flows in space, vertical separation of traffic flows in space, separation of traffic flows in time, and reduction in the number of traffic approaches.

A rail transit system is classified as light-rail transit (LRT) if it has the capability to operate safely and effectively through at-grade conflict points. LRT is being increasingly considered as a mass transit alternative in many medium- to large-sized cities all over the world. While LRT has many of the characteristics of heavy-rail transit (HRT) systems, such as the ability to operate at high speeds on exclusive right-of-way or to couple vehicles into trains, it has the additional capability to operate on steeper grades and negotiate sharper curves than conventional HRT systems. Most importantly, it has the capability to operate at grade. The development of safe, simple, and operationally effective designs for at-grade intersections and crossings for LRT is an issue central to the future deployment of the mode.

At-grade operation of LRT introduces potential conflicts with vehicles and pedestrians at intersections, at mid-block crossings, and in street operations between intersections. Various traffic engineering techniques exist for reducing delay to LRT and controlling conflict between light-rail vehicles (LRVs) and other vehicles and pedestrians. Vast improvements to LRVs, primarily in braking, enable them to operate more like modern transit buses than like railroad vehicles (Figure 1).

The level of sophistication of traffic-control methods should be commensurate with the level of activity at the conflict point. In areas where LRV headways are long and conflicting motor vehicle volumes are low, only limited measures need be taken to control conflict. Where LRV headways are short and conflicting motor vehicle or pedestrian volumes are high, sophisticated measures (such as traffic signals with LRT priority, channelization, and turn prohibitions) may be appropriate.

CONFLICT CONTROL

In improving the traffic flow and safety of existing LRT systems and in designing new LRT systems, the traffic engineer should consider the LRV in relation to traffic movement and not treat it as if it were a railroad. This traffic movement, when accommodated on an at-grade alignment, will introduce new conflicts with motor vehicles and with pedestrians. These conflicts can be a safety hazard as well as a source of delay to LRT. The number of persons carried by the LRV must be considered in determining priorities between conflicting movements.

These conflicts will occur both at intersections and at mid-block locations. The highest number of conflicts among vehicles, pedestrians, and LRVs occurs at a multileg intersection that has branching LRT lines. The number of potential conflicts is lowered if the number of intersection approaches or LRT lines is reduced or if one or more traffic movements is prohibited. The lowest number of conflicts occurs at an LRT mid-block crossing.

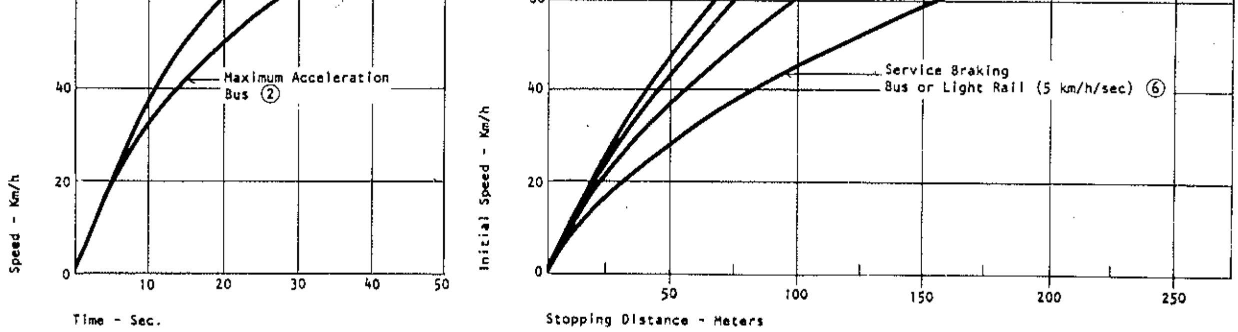
CONTROL STRATEGIES

There are four strategies available to the traffic engineer to eliminate or reduce LRT conflict points at intersections or mid-block crossings: at-grade separation of traffic flows in space, vertical separation of traffic flows in space, separation of traffic flows in time, and reduction in the number of traffic approaches. Within each of these strategies many different techniques are available.

At-Grade Separation of Traffic Flows in Space

Traffic flows can be separated at grade by developing separate traffic lanes for each movement, by developing medians, or by prohibiting or diverting certain movements. Development of special lanes, such as through lanes or right-turn lanes serves to compartmentalize

Figure 1. Comparison of performance in acceleration and braking.



Note: 1 km = 0.6 mile; 1 m = 3.3 ft.

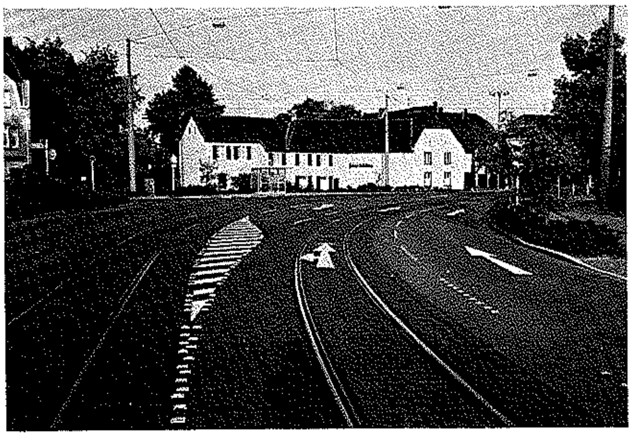
1. 1975 Boston test data for Boeing Vertol LRV with 102-passenger equivalent load.
2. 12-m (40-ft) General Motors transit bus with V8 engine (model T8H 5307), 66-passenger load, and air-conditioning on.
3. Dry pavement, including 2.5 s reaction time.
4. Based on Federal Motor Vehicle Safety Standard No. 121 for dry pavement, skid number 75, including 2.5 s reaction time.
5. Based on the German federal standard for LRVs on dry rail, including 2.5 s reaction time.
6. Limited by considerations of passenger safety and comfort.

the traffic movements, and this reduces potential conflicts at a given intersection approach. Figure 2 illustrates the use of a left-turn lane between the LRT tracks to improve traffic flow. A more positive means of separating LRT from motor vehicle traffic would be to separate the two movements by using a median. Such a treatment, which is found in most LRT systems, would restrict crossings to specific locations, and special design measures can be undertaken at these locations to safely separate the movements. Such a median would provide opportunities for landscaping, placement of traffic signs and signals, platforms, a refuge area for crossing pedestrians, and space for left-turn lanes.

Prohibition of certain traffic movements can also result in a reduction of the number of conflicts. Examples of this would be prohibition of left turns or through movements from a cross street. Such a prohibition could also apply to a pedestrian crossing.

Diversion of conflicting motor vehicle movements to parallel routes would reduce conflicts and the delay to LRT. This could be done by reducing the progression speed along the arterial that carries the LRT to the average travel speed of the LRV, including stops. Parallel arterials may then become more attractive for the motorist to travel on. Such an approach is being considered in Philadelphia.

Figure 2. Use of left-turn lane with LRT in mixed traffic (Krefeld, West Germany).



Vertical Separation of Traffic Flows in Space

Traffic flows can be separated vertically so that conflicts are totally eliminated. Examples of this treatment are pedestrian overpasses and underpasses and railroad or highway grade separations. When the LRT is separated from all motor vehicle and pedestrian conflict, it becomes a rapid transit system. Capital cost considerations usually dictate that this form of conflict control for LRT should only be used when all other traffic engineering measures have failed. Grade separations of critical conflict points are often a last step in an overall improvement program of a portion of an LRT line. A good example of such a program in the United States is the coming LRT subway in downtown San Francisco.

Separation of Traffic Flows in Time

The separation of traffic flows in time is one of the most heavily used traffic engineering techniques; it is usually accomplished by the use of traffic-control signs or traffic signals.

At locations with a relatively low volume of traffic, stop or yield signs are used to define the right-of-way of specific movements. This technique may be adequate at the outer ends of LRT lines, where cross-street traffic may be low (less than 5000 vehicles/d) and the LRT headway high (greater than 5 min).

At higher volume intersections or crossings, traffic signal control can be used to positively assign right-of-way to conflicting movements. Standard traffic-signal warrants must be met before installation of such a device is considered. Figure 3 illustrates the use of traffic signals to control conflicts between LRVs, motor vehicles, and pedestrians. Two-phase signal control would

Figure 3. Typical use of traffic signals at intersection.

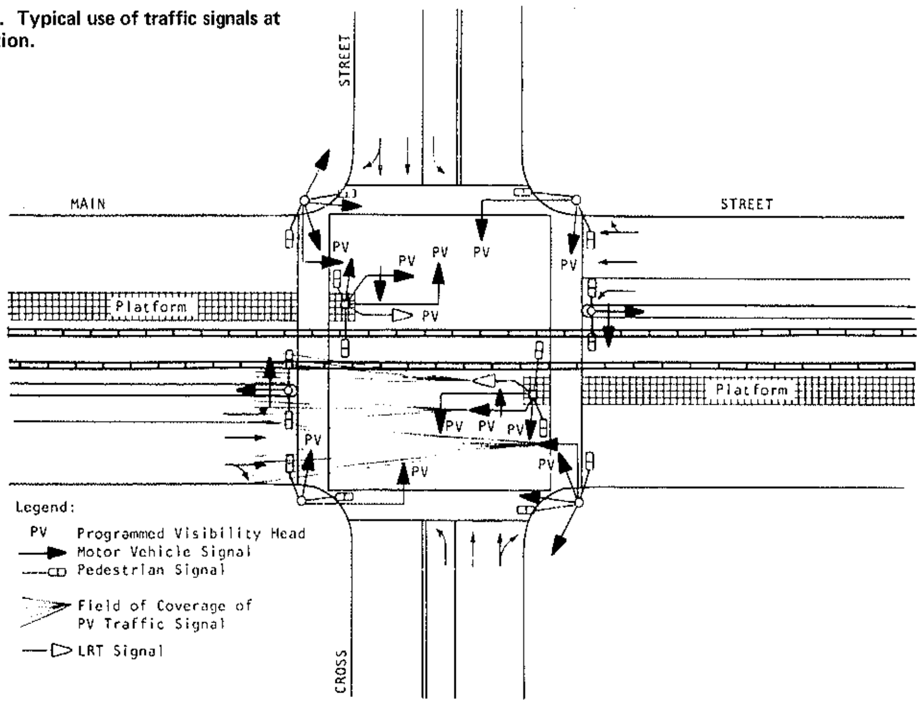
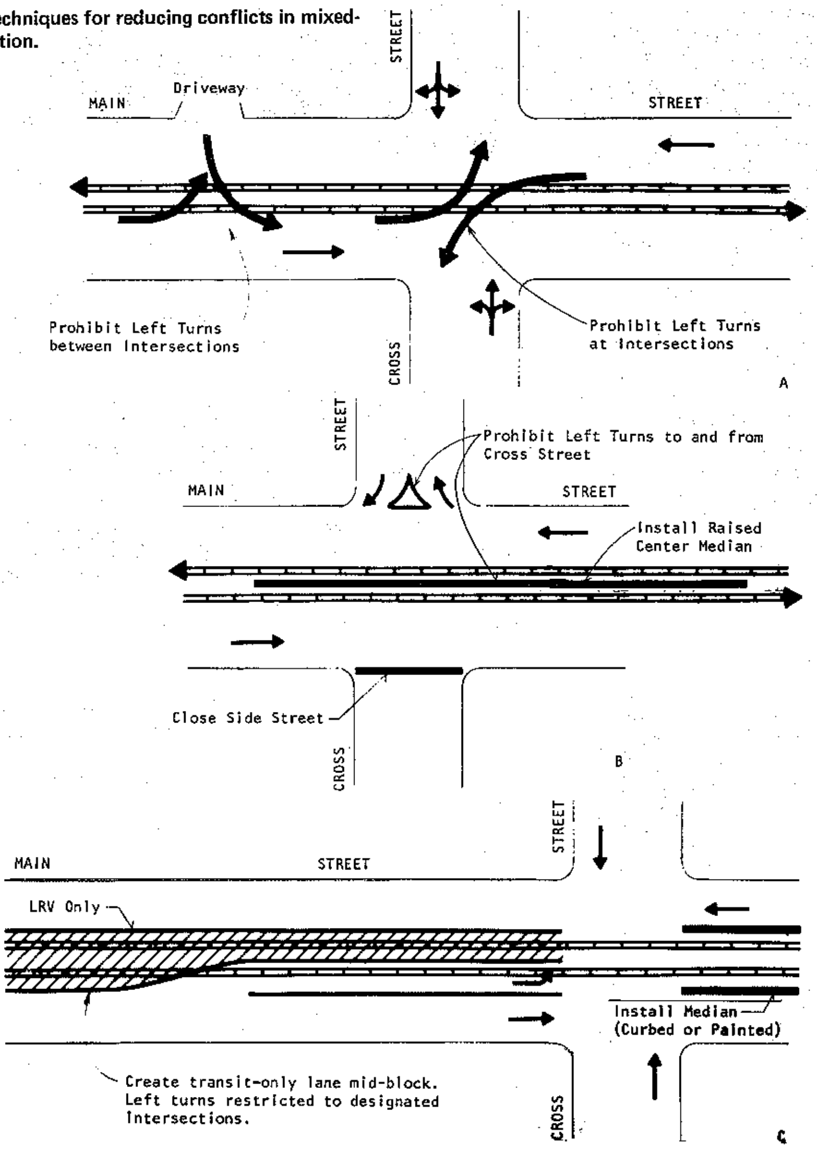


Figure 4. Techniques for reducing conflicts in mixed-traffic operation.



create a potential for conflicts between left-turning motor vehicles and LRT during the green phase for the main street. This conflict can be eliminated by prohibiting left turns or adding a left-turn phase. Programmed visibility traffic-signal heads allow each movement at a multiphase intersection to be controlled independently of all other movements. They are frequently used to control left-turn phases. As the use of these devices has increased and drivers gain familiarity with their use, acceptance by the public has been quite good.

Reduction of the Number of Traffic Approaches

A reduction of the number of approaches to an intersection or mid-block crossing can be achieved by converting one or both of the crossing streets to one-way operation or by closing one or more of the approach legs. For example, conversion of a two-way cross street to one-way operation cuts the number of potential conflicts at the intersection almost in half. Conversion of two-way streets to one-way operation is easiest to accomplish where there is a grid street pattern. In such locations, one-way couplets can be established, and access to private property is usually not seriously affected.

Another significant benefit of converting to one-way operation is that the traffic-signal phasing at such intersections is simplified. The smaller the number of phases used to control a given intersection, the greater the throughput capacity of that intersection.

Application

One or more of the above conflict-control techniques can be applied to provide fast and safe operation of LRT. The operation of LRT in mixed-traffic flow will be used to illustrate the application of some of these conflict-control techniques.

In mixed traffic, conflicts between LRT, motor vehicles, and pedestrians occur all along the street. The sharing of a common travel lane by LRT and motor vehicles creates the potential for rear-end and side-swipe collisions. Motor vehicle queues at approaches to intersections, vehicles waiting to make left turns, and vehicles double parked or too closely parked could cause significant delays for LRT.

Possible methods of reducing conflicts between motor vehicles and LRT are illustrated in Figure 4. Left turns between intersections can be prohibited through signing, traffic bars, median islands, or creation of a mid-block transit-only lane. Any of these prohibitions would eliminate most mid-block LRT delay. Alternate access routes to adjacent properties must be available if this technique is to be used. In San Francisco, such a design is planned for the outer ends of the N Line and is in operation on Market Street. Left turns at intersections can be prohibited by installing signs or channelization islands. The sign prohibition could be in force during peak periods or all day, depending on the accident history and the nature of the delay. Installation of center channelization islands on the cross-street approaches or between the LRT tracks would eliminate cross-street through and left-turn movements and main-street left turns. An example of this treatment can be found on Huntington Avenue in Boston. This technique would be highly effective in increasing safety and reducing delay to LRT, but it would impair local circulation. This treatment is most appropriate for low-volume local streets and collector cross streets. Elimination of the cross-street through movement would cause diversion of traffic to other streets. Residents along the streets that attract diverted traffic may oppose such a treatment.

An outgrowth of the previous step could be to close the side street to motor vehicle traffic as shown in Figure 4B. This treatment would primarily benefit pedestrians, since the pedestrian-vehicle conflicts would also be eliminated.

The most positive means of reducing mid-block vehicle-LRT conflicts and controlling pedestrian-LRT conflicts would be to convert the inside lane from mixed-flow operation to transit only and separate the two lanes with a painted or raised median (Figure 4C). It could mean loss of a travel lane on the arterial, and this could significantly reduce its traffic-carrying capacity. On narrow streets such a median could have mountable curbs to allow emergency vehicles or turning vehicles to use the median. An example of such a treatment can be found on a portion of the N Line in San Francisco.

On arterials carrying large amounts of automobile traffic, this treatment could result in serious congestion or significant diversions of traffic to other routes. For this reason, this treatment is best used where parallel routes are available to handle the diverted traffic or where traffic demands are low enough that they can be satisfied by the remaining traffic lanes. Alternatively, the street could be widened to provide equivalent automobile capacity. A study of Vermont Avenue in Los Angeles (1) revealed that the conversion of a portion of that street from two travel lanes in each direction to one travel lane and one LRT lane in each direction could result in significant congestion on Vermont Avenue and diversion of at least 30 percent of the 19 000 vehicles/d that use that street to parallel streets.

Placing transit stops in areas of mixed flow creates potential vehicle-LRT conflicts. These conflicts can be mitigated by a variety of traffic engineering techniques. If LRT platforms are installed in mixed-flow operations, motor vehicle traffic must pass on either side of them. This introduces a potentially serious vehicle conflict between the automobiles and the platforms. Designs that require a change in the direction of the travel lane contribute to collisions with the platforms by automobiles. On a section of the K Line on Ocean Avenue in San Francisco, as many as 10 vehicle collisions/platform were recorded in a single year. Most occurred at night, and none involved waiting passengers. This could indicate that the poor visibility of the platforms, which are 15 cm (6 in) high, was a significant causal factor. Gentle transition areas, a median with far-side platforms and near-side left-turn lanes, crash barriers on the upstream side of the platform, or left-hand loading from a platform located in the median between the LRT tracks (as is used in Mexico City) can mitigate this potential safety problem. The use of center-platform loading allows use of a narrower median and avoids the need for widening the intersection approach to provide space for platforms. In addition, if the median is confined to the area between the tracks, left turns can be allowed from the track lane at selected locations. The use of leading green arrows will minimize delay of LRT.

TRANSIT PRIORITY

The success of the LRT system in attracting patronage is to a large degree a function of its travel time in relation to that of other modes. Shorter travel time can be achieved either by extensive use of grade separation (a costly alternative) or by use of traffic engineering strategies to control conflicts and reduce delay. At traffic signals this involves granting LRT priority over conflicting movements. This discussion will focus on median operation of LRT at intersections and on mid-block crossings by LRT. Most of the alternative control strategies apply equally well, sometimes with minor modifications, to alternate LRT alignments.

For the purposes of this discussion, the terms priority and preemption both refer to preferential treatment given to LRT at traffic signals to minimize delays to LRT caused by the traffic signals or by other vehicles in the traffic stream. Preemption is intended to imply as immediate a response as is consistent with safety, whereas priority is intended to imply that, in addition to safety considerations, the needs of other movements, primarily vehicular, will be evaluated before deciding whether to grant preference to LRT. There are four types of preferential treatments that could be used to control the LRT crossings at intersections.

Progression Speed Favoring LRT

In an interconnecting traffic-signal system, the signal timing can be adjusted to favor transit. This usually means reducing the progression speed along a given street, e.g., from 40 to 48 km/h (25 to 30 mph) or about 24 km/h (15 mph). The lower progression speed would include average dwell time at passenger stops (see Figure 5). Such a change in travel speed would favor transit by reducing the number of times that an LRV would get caught at a red light, but at the same time it would increase delay to motor vehicles. Such increased delay usually has the added benefit of diverting some of the motor vehicle trips to parallel routes. This diversion will reduce motor vehicle-LRT conflicts and thereby could improve the safety aspects of that LRT line.

As an alternative, or in combination with the above, travel speed of LRT can be increased by selective placement of the platforms. Alternating platforms from near-side to far-side locations achieves a more desirable progression speed. The end of the LRV's dwell time would then nearly coincide with the arrival of the next motor vehicle platoon traveling in the green band. The progression speed can then be set to more closely coincide with automobile travel speed. A good example of this treatment, shown in Figure 6, can be found in Dusseldorf, West Germany.

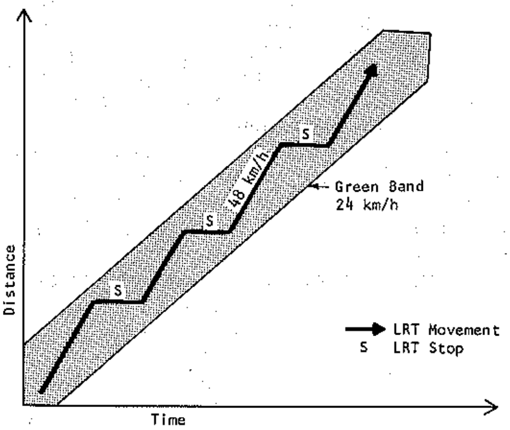
Since this treatment provides higher progression speeds for motor vehicles, it would not achieve the same degree of traffic diversion as that achieved with low progression speeds that favor transit. During periods of light patronage demand, e.g., midday or evening hours, the LRV may travel with the normal vehicle platoon for considerable distances if it is able to skip station stops.

Special Signal Phases for LRT

A second method of intersection control features the use of a special phase to control the movement of an LRV. This special phase may appear during every signal cycle on a fixed basis, or it may be actuated by an approaching LRV, which places a call to the controller and waits for the phase to appear. This would involve no preferential treatment for LRT, and therefore an LRV would suffer delay.

This treatment is most useful where an LRV comes into unusual conflict with motor vehicles to create the potential for collisions. Such cases exist where light-rail tracks leave the center of the street and turn into a cross street or enter a separate right-of-way. Figure 7 illustrates this situation in Mannheim.

Figure 5. Alteration of progression speed to favor LRT.



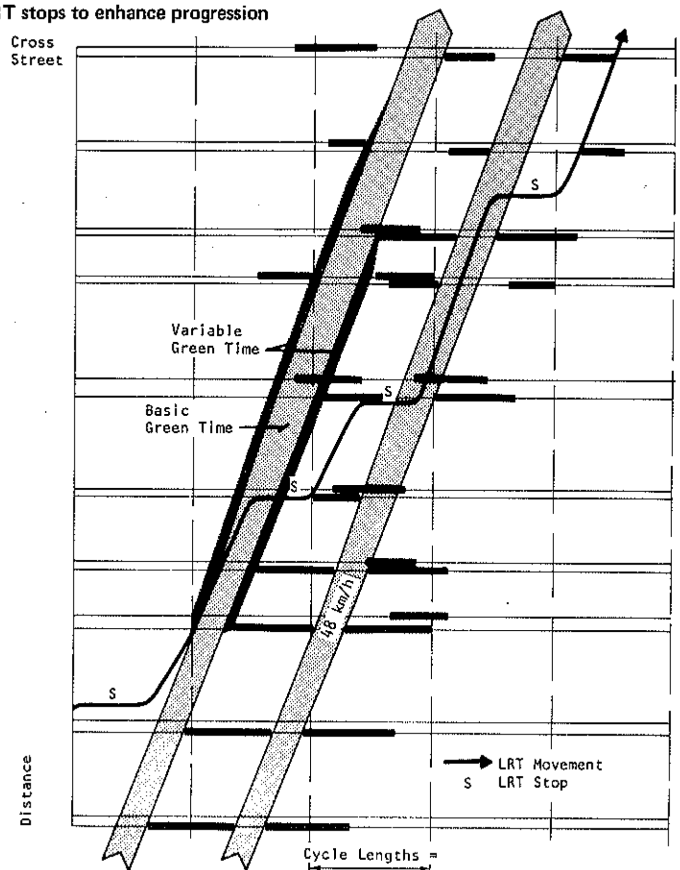
Preemption of Traffic Signals

A third form of intersection control would provide unconditional preemption for LRVs at conflict points. This means that the crossing-control signals will display a green LRT indication by the time an LRV arrives at the preempted intersection. This method most closely resembles the operating speeds and operating characteristics of grade separation. If far-side platforms are also used, an LRV will always clear the crossing and avoid a double stop. Because the preemption is unconditional, vehicular demands are not used to establish the exact traffic-signal timing. After an arriving LRV is detected, only the minimum intersection-clearance intervals are timed out before the signal switches to the LRT preemption phase. Clearance intervals are usually set by the safe-crossing requirements for pedestrian rather than vehicular demand.

Use of the unconditional preempt will result in some loss in intersection capacity. This loss is proportional to the LRT headway and is also a function of upstream intersections and the particular preemption strategy used. For example, at a standard intersection where all other traffic must stop to let the LRV pass, as shown in Figure 8, about 10 percent of the available signal time would be lost if preemption occurred every 3 min.

To illustrate the effect of LRT preemption at a standard intersection, I calculated intersection capacity for a range of vehicular and LRT demand. The main-street traffic volume was assumed to be constant at 20 000 vehicles/d and the cross-street volume was varied from 10 000 to 20 000 vehicles/d. The intersection configura-

Figure 6. Selective placement of LRT stops to enhance progression speed.



tion is that shown in Figure 3. It was found that a multiphase traffic signal makes LRT preemption feasible in every third signal cycle. If simple two-phase signals are used and left turns are prohibited, LRT preemption in every second signal cycle is feasible.

Similar capacity calculations performed for a mid-block crossing of a four-lane arterial by LRT showed that preemption is feasible as often as every 2 min for traffic volumes as high as 25 000 vehicles/d. In both cases the Highway Capacity Manual's level of service D (2) was used to determine the maximum congestion level.

Figure 7. LRV entering private right-of-way (Mannheim, West Germany).

Figure 8. Preemption of all traffic for crossing by LRV (the Hague, the Netherlands).

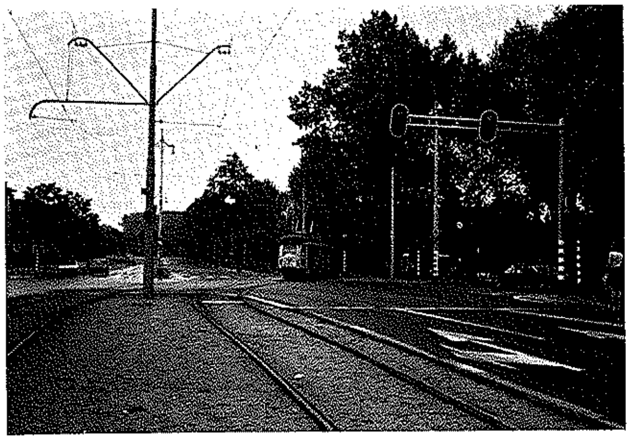
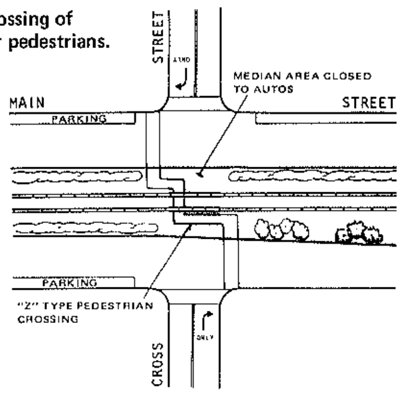


Figure 9. Z-crossing of LRT tracks for pedestrians.



In a dense traffic-signal network, frequent preemptions could disrupt vehicular traffic flows, result in unused green time at downstream intersections, and result in increased incidence of rear-end accidents if a vehicle platoon is preempted just as it arrives at a given intersection. For these reasons this method is best applied in less busy locations. This treatment should be combined with far-side LRT stops, since the accurate prediction of the arrival time of an LRV at a given intersection, which is impossible in the case of near-side stops, is important to the efficient timing of the preemption phase.

Priority

When the needs of conflicting vehicular or transit demands must also be met, then conditional preemption or priority techniques should be used. This would call for detectors to measure the conflicting traffic demand and locate arriving vehicle platoons and LRVs. A master controller would then predict the arrival time of those platoons and the LRV at the intersections in question and assign green signal time to the movement predicted to arrive first. If both are to arrive simultaneously, then the signal may be set to favor the movement carrying the greatest number of people.

This type of control would involve an extensive feedback between the controller (probably a computer) and vehicle detectors located in the street system. A number of control parameters could be fed into the computer to set the degree of priority treatment that LRT should receive. The flexibility of this approach is limited to the requirements of pedestrians, the amount of disruptions tolerable at adjacent intersections as signal adjustments are made to favor LRT movements, and the needs of conflicting transit movements. The degree of priority afforded conflicting transit movements must be a function of relative delay to people. Such a system is currently being installed along Commonwealth Avenue in Boston.

PEDESTRIAN CONFLICTS

Pedestrian conflict occurs when a pedestrian must cross LRT tracks, either at an intersection or mid-block, or when a pedestrian is boarding or alighting from an LRV. Crossings of LRT tracks at intersections are treated like crossings of a street that does not carry LRT. If possible, pedestrian signals should be used. Streets that have wide medians can carry supplementary indications in the median to aid pedestrians in crossing and to allow shorter pedestrian crossing time. This allows a shorter signal cycle and, where vehicular green-time demand is less than pedestrian demand, increases the level of service (capacity) of an intersection.

At mid-block crossings, the pedestrian-LRT conflict is relatively simple to control. Since LRT movements are usually fewer than vehicular movements, the primary problem a traffic engineer faces is to make sure the pedestrian is aware of the arriving LRV. Provision of good sight distance all along the LRT right-of-way is a key to solving this problem.

On median or private right-of-way operation, fencing should be used to establish specific crossing locations. These locations must be chosen on the basis of both pedestrian demand and such safety considerations as adequate sight distance. To increase the pedestrian's awareness of an approaching LRV, a Z-barrier can be installed. Such a barrier, illustrated in Figure 9, makes sure the crossing pedestrian faces toward the nearest approaching LRV and prevents him or her from blindly dashing straight across the tracks.

Figure 10. Signal island to protect pedestrians.

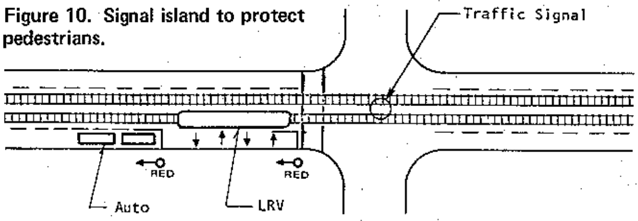
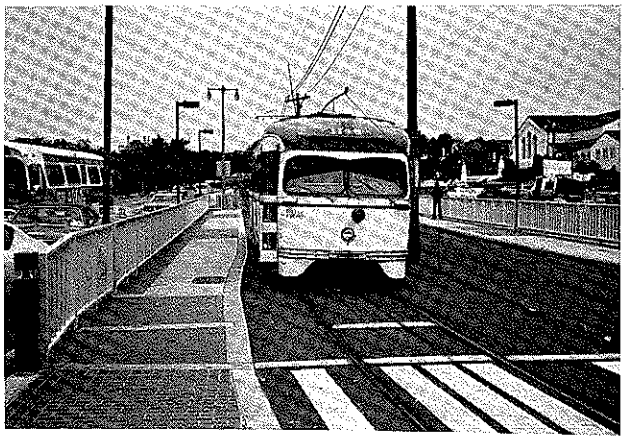


Figure 11. Fenced platform for passenger boarding (San Francisco).



At transit stops the problem gets more complicated because queuing space must be provided to handle boarding and alighting passengers. In mixed-flow center operation without platforms, passengers must enter the roadway to board a vehicle. This is acceptable only when the street is narrow and automobiles cannot pass the LRV on the right. On wider streets, a signal island can be provided. Such a treatment, illustrated in Figure 10, is used in Dusseldorf. An arriving LRV actuates a traffic signal located at the programmed stop. When this signal turns red, it stops approaching motor vehicle traffic upstream of this transit stop. Such a signal must be coordinated with a nearby downstream traffic signal to avoid blockage of the LRT tracks by motor vehicles stopped at the next intersection.

Alternatively, a raised platform can be provided in the street. If motor vehicle traffic is allowed to pass on either side of the platform or must change direction of travel in order to avoid striking the platform, the potential for accidents exists. Experience with such island platforms on Ocean Avenue in San Francisco shows that motor vehicles strike them an average of 10 times/year. Luckily these accidents usually occur when no passengers are waiting on the platform. To protect waiting passengers, transit systems have installed crash barriers on the upstream side of the raised platforms.

To prevent passengers from crossing behind waiting LRVs and from dashing into adjacent automobile lanes, fencing between the tracks as well as between the platform and the automobile lane can be quite effective, as illustrated in Figure 11. Alternatively, the platform can be located on a median between the tracks. If the LRVs have left-hand doors, the passengers can board from the median. This technique, used in Mexico City, has the added benefit of not forcing a change in direction by the motorist; this reduces the likelihood of a collision with the median.

BUS OPERATION ON LRT RIGHT-OF-WAY

Generally speaking, it is feasible to operate buses on the LRT right-of-way. This operation can be undertaken either to supplement scheduled service or to act as a backup in case of outages on the LRT system due to power failures or accidents. Joint operation of buses and LRT in a separate median, which is used in such cities as New Orleans, Chicago, and Hamburg, should result in an increase in bus operating speed since median operation is generally faster than mixed-flow curbside operation because there are fewer conflicts. These benefits could accrue as long as headways were long enough so that transit vehicles would not interfere with each other.

If bus operation on LRT right-of-way is to be implemented, all sections of the LRT right-of-way must be paved to full strength. This means no open trackage of ballast or other unpaved or thinly paved sections can be allowed. The general design criteria regarding grades and horizontal and vertical curvatures apply equally well to both modes; therefore no special alignment modifications would have to be made during the design of an LRT system to permit bus operation. However, the inability of a bus to track entails greater lateral clearances for a bus than for an LRV. Buses should have at least a 3.7-m (12-ft) lane to provide adequate side clearance. Less clearance would inhibit their use and would lead to slower operating speeds and increased potential for collisions. A good example of low-speed operation is found in the Mount Washington tunnel in Pittsburgh, which was designed for LRVs and is now shared by buses. The buses operate at about 16 km/h (10 mph) because of the narrowness of the travel lanes. Generally, the minimum width for LRT is 0.3 to 1.0 m (1 to 3 ft) narrower than is satisfactory for bus operations. In addition, center poles could present a potential safety hazard to the buses. If an LRT system is being designed for joint operation, center poles should not be used.

Basically, the same traffic engineering principles that govern control of LRT movements apply to buses. However, the detection equipment for traffic-signal actuation or traffic-signal priority treatments would have to be modified to respond to bus actuation and bus operating characteristics.

Joint operation could result in several operational and safety problems. Paved trackage looks more like a street to the automobile driver than does unpaved track. Since buses would be operating on the LRT right-of-way, automobile drivers, thinking that the buses are traveling in an automobile lane, might enter the LRT right-of-way. Care must be exercised in placing proper signing and other warning devices at openings to the right-of-way to prevent trespassing by automobiles.

Joint median operation for buses and LRT would increase the concentration of passengers loading and unloading in the middle of the street on the platform. This could increase the hazard of accidents to pedestrians who have to cross traffic lanes. Fencing of the traffic side of the platform and proper vehicle and pedestrian signaling could mitigate this problem. The greater concentration of passengers on the platforms may also require that these platforms be wider and possibly longer to accommodate more than one transit vehicle at a time.

SUMMARY

Modern LRT can be an attractive transit alternative to heavy-rail transit. The key to a successfully operating LRT system is optimum control of at-grade conflicts. It requires very little imagination but a lot of dollars to build a grade separation for LRT. On the other hand, it requires a lot of imagination to build and operate a fast, efficient, safe, and inexpensive at-grade LRT system. To achieve optimum operation a community must be willing to sacrifice some of the conveniences of the automobile for the benefit of LRT. Most importantly, the various jurisdictions governing transportation, such as transit planning, operations, design, traffic engineering, and police, must work together in designing, operating, and maintaining the traffic-control system for an at-grade LRT system.

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Control of Light-Rail Transit Operations in Edmonton

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The first line of Edmonton's light-rail transit (LRT) system is currently being completed. The underground portion of the line in the downtown area connects to a surface portion that shares its corridor with a major railway line. Interactions between the railway, LRT, and other transportation modes have created problems in the areas of safety, roadway capacity, and regularity of service. This paper describes the approach taken in Edmonton to overcome these problems. The new transportation management system, which is in its initial stages of implementation, is a major tool in minimizing the negative impacts of LRT. The system focuses on the establishment of LRT controls that, in addition to the categoric requirements of safety, must guarantee optimum use of the LRT tunnel, which in turn depends greatly on the regularity of service on surface portions of the LRT line, and integration with other transportation modes in terms of safety, coordination of scheduling between LRT and buses, and minimization of disruption to all modes at the nine grade crossings. In general, the flexibility of LRT operations and the implementation of an integrated transportation management system has enabled cost-effective solutions to be developed.

In 1974, the city of Edmonton formally adopted a transportation philosophy that had as a basic objective an increased reliance on public transportation and the development of techniques to use more fully the capacity of the existing transportation network. This led to the development of a new transit concept plan for Edmonton and the development of a transportation management system (TMS).

The transit concept relies on the new light-rail transit (LRT) system and a restructured bus system for provision of improved public transit service. The TMS will integrate the management of all transportation resources of the city and will use advanced surveillance and monitoring techniques to provide better utilization of the transportation infrastructure. Both systems are now in a first stage of implementation. The implementation of the Northeast LRT line provided the first opportunity to apply some of the TMS features to a real-life situation.

PUBLIC TRANSIT IN EDMONTON

Public transit in Edmonton is an important component of the urban transportation system. It carries about 20 percent of all daily work trips and about 35 percent of the peak-period trips to the central area of Edmonton. During the past 15 years the proportion of central-area trips made by transit has been increasing steadily. A second major function of the transit system is the provision of transportation services for people who cannot use an automobile for travel.

An overall public transit plan for Edmonton is set out conceptually in Part 1 of the city's Transportation Plan (1). Figure 1 illustrates the general pattern of transit service proposed in this plan. A main feature of this concept is the development of transit centers in the outlying sectors of the city. Local feeder-bus routes serving the surrounding areas meet at the transit centers, and then most routes continue to the downtown area. This plan provides direct service to the downtown area, and passenger transfers between different bus routes are provided at the transit centers; this permits reasonably direct trips between outlying origins and destinations.

In the northeast sector of the city, the first LRT line is now in the last stage of construction. This facility will provide a high-capacity transit line to the downtown. The three outlying stations will serve as transit centers for LRT, buses, and private vehicles (Figure 2). At these transit centers, off-street bus stations and parking areas will be provided, along with pedestrian connections to the station. An example of a typical outlying station is shown in Figure 3. These stations will also offer transit services during special events along the corridor. Near the middle of the Northeast Line, a new stadium with a capacity of 40 000 is being built for the 1978 Commonwealth Games. Further to the northeast, the Edmonton Coliseum attracts regular audiences of more than 15 000 people. Finally, in the same neighborhood, the Northlands horse-racing track and Edmonton Exhibition Grounds draw very large daily crowds during major events, such as Klondike Days. Since all of these facilities are in developed areas, parking space is limited.

The other two stations on the Northeast Line are in the downtown area. One of these stations is a through station; the other will serve as a temporary terminus until the line is extended through the downtown.

The line is 7.2 km long; about 1.6 km are in the downtown tunnel, and 5.6 km are at grade along the Canadian National Railways (CNR) right-of-way. While this corridor provided a readily available route for LRT, it required addressing specific problems related to operational aspects of LRT and other modes, as will be discussed later. The table below examines the daily work-trip travel demand in the northeast corridor.

Mode	1971 Number	1971 Percent	1981 Number	1981 Percent
Automobile	8 656	59	10 380	55
Transit	3 860	26	5 705	31
Other	2 035	15	2 607	14
Total	14 551		18 692	

The typical travel demand for a special event at the new stadium in 1978 is expected to be handled as follows:

Mode	Number	Percent
Park-and-ride	25 000	68
LRT	4 500	12
Private automobile	3 000	8
Chartered bus	2 500	7
Other	2 000	6

A more detailed description of Edmonton's LRT system is presented by MacDonald and Bakker elsewhere in this Report.

Figure 1. Principal features of the Edmonton transit plan.

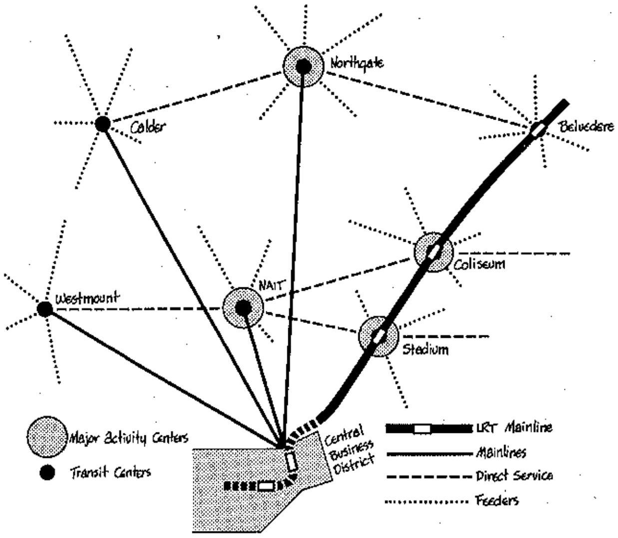
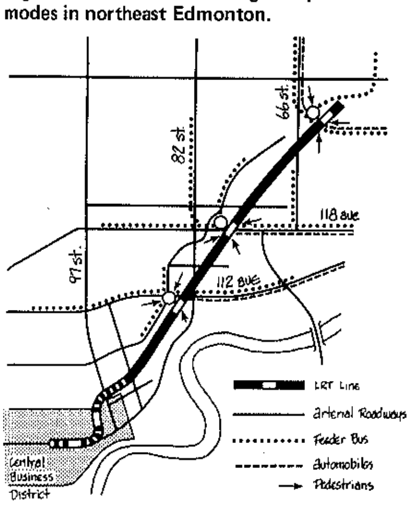


Figure 2. Interactions among transportation modes in northeast Edmonton.



TRANSPORTATION MANAGEMENT SYSTEM

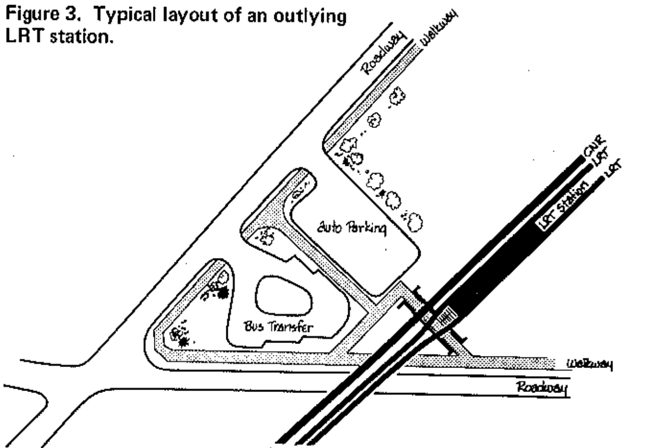
In 1977 the city of Edmonton completed a study that detailed a 10-year implementation plan for a TMS (2). This study encompassed all city agencies involved in the provision of transportation services. The study's objective was to identify measures that were available to maintain and to improve the operation of the transportation infrastructure. The objectives of individual agencies were identified and used as the basis for the definition of the overall system requirements. Improved services, dissemination of public information, and a better data base for planning and management purposes were the main TMS objectives related to the transit system. The major goals of the traffic operations group are increased safety, maintenance of acceptable levels of service in the downtown, and increased network efficiency. The police, on the other hand, are concerned with surveillance of various areas, control of special or emergency events, and the ability to monitor signal performance. The remaining goals were related to the activities of the fire department and to the maintenance and planning bodies.

Formulation of goals provided the basis for definition of the functional attributes of the system. The study identified a number of system characteristics related to transit, such as ability to integrate traffic and transit strategies and tactics, ability to accommodate both repetitive and unpredictable events, ability to monitor and analyze network performance in real time, ability to maintain a management and planning data base, ability to communicate with and supervise transit units in service, and rapid provision of information on performance of networks to both the system management group and the general public.

The various agencies connected with the Transportation Management Center agreed to place it under the control of the City Traffic Engineer. The center will perform two vital functions. One will be the provision of overall control of the street network operation of all transportation modes falling within its jurisdiction. The other will be the provision of information exchange mechanisms and integrating mechanisms between participating agencies, schematically illustrated in Figure 4. The system will use advanced computing technology and a communication network. Although the use of complex hardware is required, the system still relies heavily on human involvement.

Implementation of the system will occur in two phases, the basic and the advanced. In principle, both phases use identical measures, but they differ in the extent of

Figure 3. Typical layout of an outlying LRT station.



their features in terms of complexity and geographic application. Major elements of the system are shown in Figure 5.

LRT AND TRANSPORTATION MANAGEMENT

The operation of the LRT system will resemble in part a subway operation and in part a modernized streetcar system; it will have both grade-separated and surface sections. The trains (up to four cars) will be operated by one motorman who will maintain the schedule by consulting an instruction board similar to that used by the bus fleet. The vehicle chosen is a six-axle, two-section articulated double-ended light-rail vehicle (LRV) manufactured by Duwag. It is 24.3 m long, 2.7 m wide, and 3.3 m high. It weighs 31 Mg and has adhesion of 23 Mg. Its capacity is 64 seated and 97 standing (4 passengers/m^2). It has an electronically controlled motor-driven camshaft controller. The system will operate on 1.435-m (standard gauge) track at a maximum speed of 80 km/h and an average speed of 20 km/h; the rate of acceleration is 1 m/s^2 and that of deceleration, using dynamic braking, is 1.3 m/s^2. The minimum turning radius is 35 m for loaded cars and 25 m for empty cars.

The performance of the system depends greatly on the optimum use of the tunnel portion, which in turn depends on the regularity of headways on surface portions.

Figure 4. Concept of Edmonton's transportation management system.

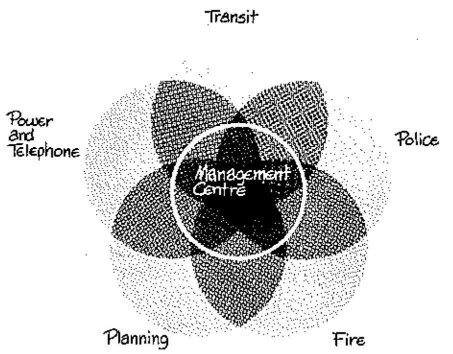
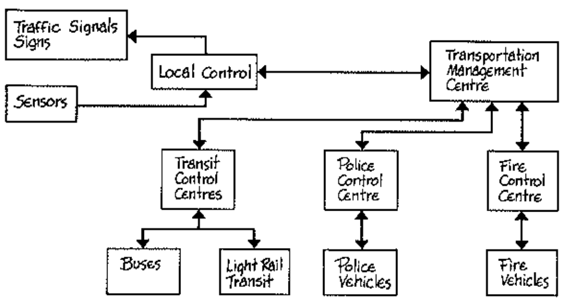


Figure 5. Elements of the transportation management system.



Since in the future the tunnel portion will become a trunk line for more surface lines, any disturbance of service on the surface may result in a complete disruption of the system. For that reason, great emphasis was placed on system controls. The control functions will be centralized; computing facilities and personnel will be located in the city's Transit Control Center, which will be an integral part of the TMS.

For control purposes the LRT line is divided into six blocks whose average length is 1 km. Each block includes one station. A red or green wayside signal advises the motorman of the occupancy of the block ahead. At the beginning of each block there is an overlay circuit approximately 230 m long, a distance sufficient for safe train stopping. The operation of the block system is illustrated in Figure 6. For a train at station C, signal C remains red until the train ahead clears the overlay circuit of block B. At this point, signal C turns green, permitting the train to proceed to station B. As this train enters block C, signal C returns to its red aspect. In this way, the minimum possible separation between successive trains is the length of the overlay circuit. Normally, however, since a train would not stop just beyond the overlay circuit, the separation of trains would be much longer. Any violation of a red signal will trigger automatic braking of the train to a complete stop. This is an additional safety feature that ensures a stop in the event that a motorman ignores a signal.

At the downtown end of the line, single-track operation for reversing the trains has been temporarily adopted. A train is permitted to enter only if this track portion is clear. Initially, only one direction of travel is automated. When the system is expanded, crossover maneuvers in both directions will be under computer control. The outlying end of the line will maintain a single-crossover movement from northbound to southbound track only.

A special problem was encountered near the middle of the line, where LRT trains entering the line from the maintenance yard or heading into the yard have to cross the parallel CNR line. This maneuver is facilitated by a diamond crossover that will have fully interlocked switches on the LRT tracks. Crossing maneuvers will require detection of an LRV entering or leaving the depot by means of a catenary sensor. If the railway tracks are clear, CNR signals will display red, switches will be set and locked, and LRT signals will turn to green. After the LRT train has left the conflict area, all signals and switches will be automatically reset to allow normal railway operation again.

LRT red and green signals will also be used in front of the nine at-grade crossings of roadways (3). These signals will ordinarily display red and will change to green only after an LRT train activates a demand for road closure and the gates have started their closing action. The gates will lift immediately after the train leaves the conflict area. If the gates fail to operate, the signal will remain red. Should the motorman fail to obey the red signal, automatic braking will be initiated so that the train will be stopped in front of the grade crossing.

The instruction board, supplemented by wayside signals, would not suffice under unusual circumstances.

Figure 6. Operation of the LRT block system.

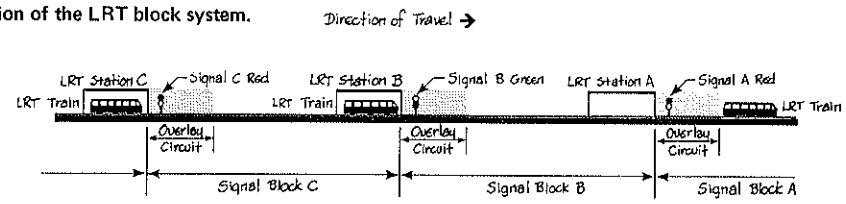


Figure 7. Typical peak-hour conditions at one of the at-grade crossings.

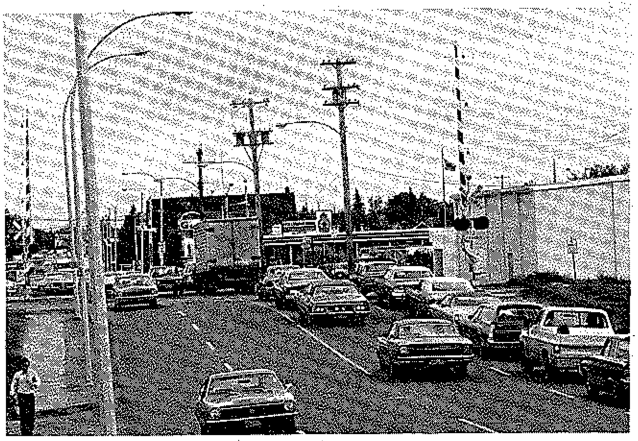
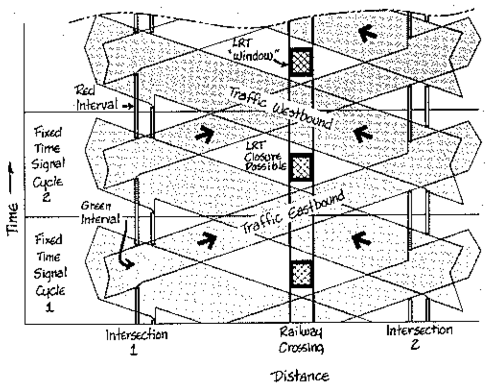


Figure 8. Time-space diagram of the LRT window principle of traffic signal coordination.



For special conditions, such as difficulties in maintaining schedules, breakdowns, or crossing of the railway main line, two-way radio communication between the motorman and the central control will be used. For track maintenance or train emergencies, a system of wayside telephones can also be used if these measures prove to be insufficient. A digital data communication system can easily be incorporated as an integral part of the system if it is required in the future. All stations will be equipped with closed-circuit television cameras, both for communication and for security purposes; the transmissions will go to the Transit Control Center.

Another option that will be evaluated after some experience with the system is the application of either wayside or in-cab speed signals. They may be especially useful in the control of train arrivals at grade crossings.

INTEGRATION WITH OTHER MODES

Three major concerns were identified with respect to interaction between LRT and other modes of transportation: (a) safety of grade-crossing operations, (b) regularity of service of both LRT and feeder buses, and (c) minimum disruption to traffic at grade crossings.

In addition to LRT trains and CNR trains, the grade crossings are used by private vehicles, LRT feeder buses, express buses, and pedestrians. Figure 7 illustrates the typical peak-hour condition at one of the crossings. Concerns about the safety of operation of grade crossings that carry 15 000 to 30 000 vehicles/d were determining factors in the selection of protection devices and their timing (to allow one LRT train to pass, the gates have to be closed for about 40 s). One solution to all of these problems would have been the construction of structural grade separations; these would have cost \$3 million to \$4 million each and required 2 years of construction time. A more cost-effective solution, in the short term at least, has been found in the development of integrated controls for LRT and other modes of transportation (3). In order to implement such a scheme, three major principles for the design of grade-crossing controls were adopted.

1. The first principle was coordination of traffic signals so that extensive queuing of vehicles across the railway crossing would be eliminated. This is achieved by controlling the capacity of upstream road signals that feed this link and reducing the queuing in front of the downstream intersections to an acceptable length. Subsequently arriving vehicles can then move through the downstream intersection without stops. This measure reduces the number of stops and delays in the system. In most cases, vehicles will be stopped only on the approaches to the upstream intersection and will move through the system in a green wave.
2. The second principle was integration of the operation of traffic signals with LRT controls. The objective was to use the periods of time provided by the shadow of the red signals at adjacent intersections for LRT crossings of the road link (Figure 8). Ideally, the time provided by this window should exceed the closure timing required for the crossing. This is difficult to achieve because of the number of other constraints, such as LRT scheduling and operation.
3. The third principle was use of special features in intersection control, preemption of downstream signals, warning of drivers, and changing of signal sequence in the case of excessive queuing.

These principles, which satisfy all three of the concerns noted above, require some adjustments to both LRT and traffic controls. For example, in addition to a set of LRT scheduling requirements to meet the window principle, a special LRT signal at the middle station will be tied to the traffic-control system. This signal will release the trains from the station at the most suitable period of time. On the other hand, traffic signals in the adjacent network possess enough flexibility so that the period during which the LRT station signal blocks the train's departure is minimized. The potential to adjust the operating speeds of LRT trains is not currently used but may be used in the future. The crossing-control logic also takes into account simultaneous or almost simultaneous arrivals of LRT and CNR trains in opposite directions; it extends the closure time of the crossing rather than allowing two successive closures without a safe interval between them.

Another service TMS provides to transit in northeast Edmonton is assistance in achieving regularity in feeder-bus operation. Bus schedules are designed to connect to LRT at specific intervals to achieve convenient and reliable transfers between routes.

Traffic signals along the route are therefore programmed in such a way that the variations in bus running times are minimal. The principle applied here is coordination of traffic signals for buses. In special cases, other types of bus priority measures may be applied. Adjustments in bus stop locations and bus schedules, as well as changes in the street geometry and parking and other regulations are required to achieve this principle at various points on the street network. The assistance to bus operations is especially important in front of bus terminals at LRT stations. These off-street locations have a large number of bus movements on and off major arterial roads, and traffic signals with bus priority measures will be used in some cases.

The Transit Control Center will have direct contact with the bus fleet. In the first stage of development, this monitoring and supervision will be based on voice communication. It will, therefore, be limited to the most logical locations, such as LRT-bus transfer stations. Radio communication will also be used to minimize disruptions in service caused by breakdowns or other incidents. Since there is a connection to the overall TMS, corrective measures can then be taken in areas not under the Transit Control Center's jurisdiction. More advanced monitoring and supervision options, including digital radio transmission of such data as bus location and passenger volumes, will be evaluated and may be incorporated into the system.

CONCLUSIONS

Introduction of LRT in Edmonton would have been difficult if costs had not been kept within a reasonable range. Keeping the costs down required a certain amount of compromise between minimum and maximum operational requirements. These trade-offs tax the management abilities of LRT. Its control system and the TMS together, however, provide sufficient tools to guarantee satisfactory standards of operational safety and the desired regularity of service, both of which are necessary for any transit operation. Moreover, by integrating transportation modes, this combined system offers several additional features that can improve the overall transit performance in northeast Edmonton. The design of the system and the negotiations leading to integration of its individual portions were not easy. It appears at this stage, however, that operational problems have been effectively solved because of the streetcarlike features of LRT and the flexibility of the TMS.

The TMS provides an opportunity to closely monitor the operation of all components of the LRT line. The data supplied by the system will be evaluated and assessed regularly. Operating experience will be the base for making adjustments to the system and to the design of future phases of both LRT and TMS.

Since the accepted transportation philosophy in Edmonton concentrates on full utilization of available facilities before new ones are built, the control of transportation operations will become even more important as new LRT lines are introduced. It is realized, of course, that in the future more complex and in some cases more capital-intensive solutions may be required. Notwithstanding the introduction of more complex methods and technology, it is a certainty that the effective management of transportation resources will be the key to resolving Edmonton's urban transportation problems.

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2. A Transportation Management System for the City of Edmonton. Edmonton, Alberta, 1977.
3. J. Schnablegger and S. Teply. Traffic-Control Measures at Highway-Railway Grade Crossings With Provisions for Light-Rail Transit. TRB, Transportation Research Record 628, 1977, pp. 6-11.

Light-Rail Transit Signaling

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This paper presents considerations regarding conventional signal systems that should be helpful to people planning a light-rail system. Attention is first directed to establishing the need for a signal system, including a discussion of its advantages and disadvantages on the basis of the technical, operational, economic, labor, and regulatory elements involved. A definition of conventional signal systems is provided, and the various types of systems are explained on the basis of their capabilities. Safety and failure modes are addressed as the key issues in any signal-system design. To illustrate the importance of all these factors, a comprehensive description of the new San Francisco Municipal Railway's subway signal system is presented, and conclusions are then drawn as to the general design concepts required for other future light-rail systems.

Any transit planner, regardless of his or her particular area of interest, is confronted by many questions in considering light-rail transit (LRT): Is a signal system necessary? If so, what type of signal system will meet the need? What kind of equipment should the signal system employ? What systems are available, and what are their relative merits? This paper will address these questions.

Whether to install a signal system on an LRT facility is a very important issue and involves a trade-off between economy on one hand and safety and efficiency on the other hand. A signal system adds to the initial cost of a facility, increases maintenance expense, and presents operational and administrative problems. From the standpoints of both safety and uninterrupted service, a poorly maintained signal system is worse than no signal system, and a competent maintenance force must be recruited, trained, and maintained by the operating authority. In the case of small signal systems, it is necessary to train and keep a larger force of people familiar with the signal system than is actually necessary to carry the work load; qualified people will thus be available at all times and the force will not be completely depleted by resignations, retirements, sickness, vacations, and so on. Ordinarily, training is part of the construction contract, and the original trainees train others as vacancies occur and are filled. Every signal system must have its set of operating rules to govern employees, both the car operators and others. The employees must be capable of understanding the rules and be willing to abide by them; this fact may force a change in hiring practices and involve special measures to enforce compliance with the rules. It may even involve changes in labor contracts to permit the discharge of employees who violate the operating rules.

In contrast to the expense and complications involved in a signal system are the disadvantages of operating without one. Without a signal system, full responsibility for safety rests with the car operators and their reactions to what they can see by looking ahead. Consequently, operators must limit their speed to a rate from which they can bring their cars to a stop within their range of vision. When topography or weather conditions create short sight lines, very low speeds result. Running times are also increased if cars must slow down or stop for drivers to operate track switches. For these reasons, a facility that lacks a signal system has less capacity, less operating flexibility, and probably less safety.

If, in spite of the costs and complications, it is necessary to install a signal system, a compromise must be reached between economy on one hand and, on the other hand, the need to ensure safety, attain the full potential efficiency of light-rail vehicles (LRVs), and meet both the requirements of legal responsibility and the pressures of public opinion. At this time, as in the past, the most attractive compromise is to select one of the several variations of conventional signal systems that have been in service for many years on the nation's long-haul railroads and metropolitan heavy-rail transit (HRT) facilities. The alternative choice is to assume the expense of experimenting with a newly conceived system and run the risk of operating with a patched-up one-of-a-kind system. A review of the reports presented at the 1975 Light Rail Transit Conference reveals that many of the speakers felt that the acceptance of LRT depends to a great extent on (a) keeping the costs down and (b) the development of new systems through accelerated research. Excessive cost may very well block a proposed LRT project, and there is no need to burden a project with expenditures for signal research. There are suitable systems proven in extended service immediately available that can be adapted to meet the features and operational requirements of any proposed LRT facility. These proven systems employ relay logic extensively, whereas other systems make much more use of either hard-wired, solid-state logic or computer logic and have had much shorter demonstration periods. Relay logic has some important advantages:

1. It is largely free of the bad effects of electrical transients.
2. It is easily understood, the operation can be readily determined from a circuit plan, and the operation of the component relays can be observed visually.
3. Only a few simple instruments are required to maintain relay logic and correct faults.
4. The components are rugged and, to a very great extent, free of deterioration from aging, humidity, heat, and so on.
5. Relay logic is not finely tuned; very few adjustments are necessary.

CONVENTIONAL SIGNAL SYSTEMS

1. Automatic block signal system: The track is divided into sections (blocks), and a trackside signal is located at the entrance to each block. These signals convey information to car operators concerning the presence or absence of cars in one or more (usually two) of the blocks immediately ahead. Safety depends on whether the signal system operates as intended and on whether the operators remain alert, observe the signals, and control their cars in accordance with the information conveyed by the signals. This system can be employed for two-direction operation on the same track, in which case signals are provided at each end of each block. This system does not require any car-borne signal equipment.
2. Automatic block signal system with train stop: This system reduces the degree of responsibility vested in the car operators. HRT systems generally use mechanical trip-stop arrangements in which a trackside device engages a lever on a car that passes a STOP signal and causes the brakes to be applied. Another version that has been employed by long-haul railroads consists of an electrical trackside device that inductively couples with a car-carried device and applies the brakes unless the operator manually acknowledges each restrictive signal as he or she passes it. Automatic train stop greatly reduces the hazard of an incapacitated or inattentive operator. This system requires only a moderate amount of additional car-borne equipment.
3. Cab signal system: Signals in the car operator's control cab can supplement or take the place of trackside signals and provide the car operators with signals that are not only clearly visible in all weather conditions but are also in view continuously. Cab signals advise car operators of changed conditions ahead (whether better or worse) as they occur; this enables the operator to increase or decrease speed immediately, that is, without waiting for the next trackside signal to come into view. Most cab signal systems require the car operator to manually acknowledge a restrictive cab signal indication to prevent a brake application. This also reduces the hazard of an incapacitated or inattentive operator.
4. Cab signal system with automatic speed control: This system requires the operator to take steps immediately to reduce the speed of the car when the cab signal calls for a speed lower than that at which the car is currently traveling. If this is not done, the brakes will be applied and cannot then be released until the car comes to a stop. A limit to the highest speed permitted is also imposed.
5. Automatic train operation system: This system leaves the car operator little to do except watch the operation and take control of the car in an emergency. In some but not all installations, the operators control the doors or depress a button to start a car in motion. In a fully automated system, the speed of the train is automatically controlled in accordance with conditions ahead, and the cars stop in their proper berths at stations automatically.

Highway grade-crossing protection consists of flashing lights that warn highway traffic of approaching rail vehicles. In many cases the flashing lights are augmented by crossing gates, which provide a physical barrier to highway traffic on both sides of the tracks. Highway crossing protection is usually controlled automatically by approaching trains, but manual control may be provided either as the primary control or as a supplement to automatic control. The automatic control can effectively take care of special situations, such as avoiding delay to highway traffic when a rail car makes a station stop near a highway crossing. The train-detection system employed in conventional signal systems can be used to preempt street traffic lights either independently or in a way that coordinates the operation of street traffic lights with the operation of highway grade-crossing protection gates and flashing lights.

Interlockings are power-operated track switches protected by trackside signals whose controls of switches and signals are interlocked so that the signals cannot be displayed to authorize car movements unless the switches are properly set and so that switches cannot be operated while PROCEED signals are displayed. Interlockings can be controlled manually from local control panels, remote control panels, or push buttons located at the signals, or they can be controlled automatically by approaching cars. Conventional interlockings may have two different sections—one that is not involved with safety and one that is. The generation and transmission of commands from a central (remote) control panel, a local control panel, or an automatic route-selection or dispatching arrangement are not safety functions and, while failure of the equipment that performs these functions may interrupt service, such failures will not affect safety. Therefore, cheaper relays, multiplex techniques, and other techniques in which failure modes are unpredictable can be used. The section that executes the commands, however, is very much concerned with safety, and that section, as well as the automatic block system between interlockings, must be designed with safety as the prime consideration.

FAILURE MODES

Failure modes are an important consideration in securing safety. Most devices have two or more failure modes, and some devices can be designed to have one failure mode that occurs extremely infrequently. For instance, when it is operating normally, a relay has its prime contacts closed when its coil is energized and its prime contacts open when its coil is deenergized. Therefore, this relay has two failure modes: the prime contacts may be open when they should be closed, or they may be closed when they should be open. By designing the relay so that the prime contacts are opened by gravity (plus spring bias in some relays) and carefully avoiding anything that would impede the movement of the contacts, one failure mode (prime contacts closed when they should be open) has been rendered highly unlikely at the expense of the other failure mode. It then remains to design the circuit that supplies power to the relay coil so that there is little chance of the relay coil being energized when circumstances require that vehicle movements be restricted and to arrange the circuits controlled by the relay so that restrictions will be imposed when the prime contacts of the relay are open and removed when they are closed. The relay provides a simple example of a device that has one failure mode that is extremely rare and shows how this fact can be used to advantage in relay logic. Some electronic devices can be designed to have one very rare failure mode, but this is more difficult to achieve.

The safety sections of either a simple or a complex conventional signal system are created by assembling proven components and proven methods into a system that is adapted to fit the physical features and operating requirements of a particular facility. The failure modes of all the components must be predictable, and the circuitry must be such that the more frequent failure modes do not affect safety. This has led some people to refer to the conventional signal system as a fail-safe system. This is unfortunate, however, because no system can be entirely free from unsafe failures, and the proponents of recently conceived substitute systems often denigrate the fail-safe (conventional) system on the basis that it is obviously not 100 percent fail-safe. The conventional signal system is really a highly acceptable compromise between economy and safety that has been developed and improved through decades of extensive use. It is now the standard of safety and reliability by which all proposed substitute systems must be judged. It is interesting to note that the evolution that has made conventional signal-system components extremely safe has, coincidentally, made them very reliable.

If a conventional signal system includes some type of remote or centralized control of interlockings, the link between the control console and the interlockings may employ electronic devices, and the maintenance of this link may require the services of an electronic technician. On the other hand, the safety portion of a conventional signal system does not require the services of this type of technician. A person needs only a slight familiarity with the elements of electricity and a little patience to understand the relay logic and the rather simple components used in conventional signal systems. While the circuitry for a large interlocking can be very intricate, there are no truth tables, no formulas, no equations, and no complex theories involved. Even the circuit plans by which the approved components are assembled into a system can be prepared by people who have no other specialized training, provided they are familiar with the standard principles and practices of conventional signaling, which are nothing more than the lessons learned through decades of experience.

ADVANTAGES AND DISADVANTAGES

The advantages of a conventional signal system include the following.

1. It has all the advantages of relay logic mentioned above except, of course, in those portions where relay logic is not used.
2. If the electronic components included in the system can be considered black boxes that have specific outputs corresponding to specific inputs and represented on the circuit plans as empty squares, then the design is relatively straightforward, and the operation can be easily understood by people without training in electronics or other specialized fields.
3. The standard components of conventional signal systems have been perfected by long use, and the suppliers have continued to supply replacement components and repair parts for long periods.
4. The components are small and easily rearranged in different configurations when this is necessary to adjust the signal system to altered operational features, an increase in patronage, or an enlarged service area.
5. The components are distributed over the facility; that is, there is no large component or large concentration of components in which trouble will shut down or endanger the entire facility. The things that provide safety are located in the area they protect and transmission problems are largely avoided by keeping communication lines short.
6. Long experience has developed a fine balance between economy and safety in regard to details of how standard components are combined into a system to fit a particular facility.
7. Long experience has produced an accurate understanding of how much preventive maintenance is required to keep a conventional signal system operating safely.

There are some problems connected with conventional signal systems, including the following.

1. Most knowledgeable engineers, technicians, and mechanics are employed by signal-supply companies, railroads, or HRT systems in which they have learned the business from their predecessors. It is therefore difficult to recruit experienced people.
2. There are very few contracting firms that have signal experience.
3. Signaling appears so simple from the outside, like street traffic signals, that firms looking for jobs or anxious to diversify may enter into signal contracts they are ill fitted to carry out.
4. All signal work (design, installation, and maintenance) requires painstaking adherence to accepted principles and practices, but not everyone has the needed patience.

5. There is very little literature available on this subject. The signal-supply companies publish information regarding their products and the Communication and Signal Section of the Association of American Railroads has published considerable material, but none of this material is of much use to a person who does not already have a grounding in signaling.

6. The railroad industry has never recognized a need to compile statistics on railroad signal-system performance.

The fixed portion of a signal system for an LRT facility, either single or double track, should not cost more than $187 500/route km ($300 000/route mile), including impedance bonds, power supply, and all other signal costs, except system-length conduit runs or duct lines. Car-borne cab signal equipment may cost $10 000/car; automatic speed control may cost $1500/car. These are very rough average figures, and they are quoted here only to present a very general idea of signal costs, which are affected by many variables, including the fact that unit costs are higher for small quantities than for larger quantities.

SAN FRANCISCO'S SIGNAL SYSTEM

A conventional signal system is now being installed on the Market Street underground portion of the San Francisco Municipal Railway (Muni). It will include cab signals, automatic speed control, and five small interlockings. There will be no trackside signals except at the interlockings. It will be a double-track system in which both tracks are signaled for movements in both directions, but cars will normally move on the right-hand track only, and the interlocking signals will clear automatically for all normal car movements including normal turnback movements. At two locations where it is necessary to determine the identity of cars in order to set up the correct interlocking route automatically, that information will be fed to the signal system by an independent and separate destination-sign system to be described later. If the interlocking route automatically selected is not the correct route, the operator of a car may stop the car at the interlocking signal and correct the route selection by reaching through the window of the cab and depressing trackside push buttons.

At the downtown terminal the tracks are stub ended. Arriving inbound cars will be automatically routed to whichever station track is vacant or, if both are vacant, to the left-hand track as viewed from the front of inbound cars. Outbound cars beginning their outbound trip will be routed to the normal outbound (right-hand) track automatically after the operator has indicated his or her readiness to depart by reaching through the cab window and depressing a trackside push button. There are two portals; one that is 8.8 km (5.5 miles) from the downtown terminal is used by three surface lines. Two turnouts in the main tracks about 4 km (2.5 miles) from the downtown terminal lead to the other portal, which is used by two other surface lines. Cars being placed in service or being taken out of service will move directly from one portal to the other without traveling to the downtown terminal. These cars will stop, reverse their direction and cross over at an interlocking approximately 3.2 km (2 miles) from the downtown terminal. Such movements are considered normal; that is, the track switches will be positioned and the signals cleared automatically in advance of each movement.

Each interlocking is provided with a local control panel in the local relay room. The interlocking at the downtown terminal has an additional control panel located on the station platform. None of these control panels will be staffed in normal circumstances, but they provide the means for changing over from automatic to manual control at will. In addition, there will be at each interlocking signal a set of push buttons that can be actuated by the operator of a car stopped at the signal. By reaching through the window of the cab, the operator can select any one of the several routes available to that car or cancel a previous route selection. It will not be necessary to make use of these push buttons in normal circumstances.

The cab signals display three aspects: 10 MPH [16 km/h], 27 MPH [43 km/h], and 50 MPH [80 km/h]; the automatic speed control enforces these speeds by requiring positive action by the operator to avoid a penalty stop when the actual speed exceeds the speed indicated by the cab signal by more than 3.2 km/h (2 mph). The cab signals are cut in automatically on all cars of a train when that train enters a portal and cut out automatically when a train leaves a portal. The automatic speed control enforces a top speed limit of 80 km/h—actually 83 km/h (52 mph)—regardless of whether the cab signals are cut in or cut out. The cab signals or the automatic speed control can be cut in or cut out manually by breaking a seal and operating a switch in the electric locker.

Interlocking signals will display stop aspects and aspects authorizing a car to proceed in accordance with cab signal indication. The operator of a car that does not have cab signals or whose cab signals are out of order and stopped at an interlocking signal will be able to change a "proceed in accordance with cab signal indication" aspect to a "track clear to next signal" aspect (when conditions permit) by reaching through the cab window and depressing a push button. All PROCEED aspects will include information concerning whether the interlocking route is straight.

The Muni signal system will include electronic amplifiers and demodulators on the cars and electronic demodulators as part of the train-detection system, but it is primarily a relay logic system.

A central computer will track the cars and control the display of destination signs at each of the nine stations. The operator of each signal car or the operator of the lead car of each train will be required to describe his or her car or train before entering a portal and before beginning an outbound trip. This will be done by means of input devices connected to the computer that can be reached from the cab. As indicated above, the destination-sign system will feed train-identity information to the signal system at two locations; otherwise, the signal and destination-sign systems are entirely independent.

The selection of the system being installed was dictated by cost considerations and current patronage, and it is expected that this system will suffice for many years. However, if conditions change, the system can readily be upgraded as needed without any major loss of the original capital investment. For example, centralized control can be conveniently added, and an automatic car-identification arrangement can be easily substituted for the present manual computer inputs. In fact, the wayside and car-carried equipment could be augmented to provide full automatic train operation in the subway if that becomes desirable.

OBJECTIONS TO CONVENTIONAL SYSTEMS

Proponents of actual or proposed systems to supersede conventional signal systems often advance objections to the conventional systems, including the following.

1. Relay logic is old-fashioned and out of date, and

relays require more space and consume more power than electronic devices.

This is true. There is nothing new or novel about relay logic, and relays do require more space and use more power than electronic devices. However, the space and power requirements of relays are not large, and the savings that can be made by substituting electronic devices is therefore limited.

2. Conventional signal systems are designed to stop vehicles when component failure occurs.

This is true, but it is entirely justified by the alternatives. No matter how serious an interruption to service may be, allowing a car to proceed when it may not be safe for it to proceed is more serious. If a component failure must cause neither a false PROCEED signal nor a stop, then redundant systems must be provided. As will be explained later, redundant systems are very expensive.

3. Conventional signal systems depend on appropriate human performance for safety.

As was explained in the descriptions of the various forms of conventional signal systems, the cheaper forms depend on appropriate human performance to a greater degree than do the more sophisticated forms. Thus, a reduction in dependence on human performance entails increased cost, and the complete elimination of vulnerability to human error entails very great cost. A typical cab signal and automatic speed control system requires dependence on the car operator in two situations. When it is approaching another car or a stop-interlocking signal, a car is automatically restricted to a low speed, such as 16 km/h (10 mph), but the operator is responsible for bringing the car to a stop. When a car is stopped by the failure of a signal, the car operator may obtain oral permission to override or cut out the devices that prevent the car from moving and then operate the car with no restrictions other than the usual operating rules. To eliminate the dependence on operators to bring a car to a stop after its speed has been reduced automatically but still permit closing up in stations and other areas, it is necessary to establish very short blocks and to control the speed of cars in very small increments. Although this can be done, the cost is high. To eliminate standby manual operation as a means of moving cars after a component in a signal system has failed, it is necessary to provide standby or redundant signal and automatic speed control systems to prevent a component failure from bringing operations to a stop. In this connection, it is important to note that simple duplication does not suffice. When duplicate systems produce conflicting outputs, e.g., GO from one and STOP from the other, it is difficult to determine which system is in error; a minimum of three redundant systems is thus required to minimize delays resulting from failures in a system that does not have standby manual operation. The cost of a signal system that neither requires nor permits human intervention would be prohibitive for any but the most highly congested facility.

Most proposed replacements for conventional signal systems are electronic—either hard-wired solid-state or digital computer systems. It is claimed that simple hard-wired solid-state devices like those currently employed in the safety portion of conventional signal systems can be designed to have predictable failure modes. However, systems able to handle more complicated logic can be made safe only by resorting to redundancy, closed-loop arrangements, or other expensive techniques. These techniques increase both the cost and the number of components that may fail. Designers of electronic signal systems must guard against the temptation to compromise safety in order to keep costs down and the temptation to avoid the increased exposure to component failure in redundant systems by accepting a GO from either system instead of requiring a GO from both systems before permitting a car movement.

The first application of electronics to the safety portion of a signal system took place in 1923 in connection with the original cab signal system. Since that time, electronics has been used extensively in the nonsafety portions of conventional signal systems, and there has been a limited use of electronics in the safety portions: amplifiers and decoders in car-borne cab signal equipment, decoders with coded track circuits, high-frequency track circuits, overlay track circuits, motion detectors, and so on. More general use of electronics in signal systems has been retarded by the difficulties and the expense involved in producing electronic devices or systems that have predictable failure modes. Safe and reliable electronic signal systems will be available eventually, but they will be available first in a form more suited to HRT than to LRT. This is because their high cost will be justified only by the demands of highly patronized and highly congested systems in which the need for full automation, high speeds, small headways, no interruptions, automatic dispatching, automatic adjustment of schedules when trains fall behind schedule, and so on is urgent. At the present time, the electronic devices used in the safety portion of conventional signal systems are used principally to drive relays, the contacts of which are then used in the conventional relay logic.

CONCLUSION

In this paper I have tried to present some facts and ideas about signal systems that will be helpful to people planning an LRT facility. Most important among these are that a signal system should not be installed unless its proper maintenance is assured and that the distinction between the section of the signal system that is not involved with safety and the section that is so involved should not be overlooked. Safety must be the prime consideration, and it must not be entrusted to unproven equipment or methods. If for some reason an exotic arrangement for generating and transmitting commands must be installed, it should be ensured that the commands will be executed by a time-proven system of the type generally referred to as fail-safe. The type and form of the signal system selected should be those that are best suited to the needs of the facility; the temptation to be ultramodern or to build a showpiece should be resisted.

Use of Railroad Rights-of-Way for Light-Rail Transit Systems

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This paper describes the conditions that are required for railroad rights-of-way to be usable for light-rail transit. Some of the locational characteristics of desirable rights-of-way are described. A method for analyzing railroad use and physical characteristics is presented. Several solutions to problems in using railroad rights-of-way are outlined. The design parameters for joint use of rights-of-way are explored.

There are many potential locations for construction of low-cost light-rail transit (LRT) systems that use railroad rights-of-way. Recent railroad mergers and the decline in railroad passenger service have led to the downgrading or partial abandonment of many once important urban rail lines. In addition, shifts in the characteristics of freight handling have changed the manner in which the urban rail network is used. Such factors as the increased use of piggyback shipping and containers and the relocation of industries to outlying facilities have increased the number of rail lines available in urban areas.

Obtaining railroad rights-of-way may require one or more of the following: (a) relocation of through movements to other routes, (b) abandonment of railroad service, (c) provision of separate trackage within the same right-of-way, (d) joint use of trackage, and (e) provision of rail freight service by the LRT system. The applicability of each of the solutions depends on individual circumstances. Factors that must be considered in analyzing various solutions include the density of rail freight traffic, the number and rail-use levels of on-line industries, and the availability of other routes.

The locational characteristics of a railroad right-of-way that are most generally desirable are (a) access to a central business district (CBD) and (b) penetration of an area of sufficient population to provide an adequate level of use. Access to a CBD does not necessarily require a right-of-way that goes into the center of the commercial area. It is more likely that the right-of-way will reach the edge of the CBD, and only a short section of subway construction or street operation is needed to reach the commercial center. In many cities, this distance is less than 1.6 km (1 mile).

While it is not within the scope of this paper to address the issue of the level of use necessary to support LRT operations, it must be pointed out that many rail corridors that have access to a CBD are not suitable for LRT development because they largely serve industrial areas or undeveloped parts of an urban area or are isolated from residential development by terrain or natural barriers. For example, a right-of-way may lie along the edge of a river in a relatively narrow valley. Often access to one side is blocked by the river, and access to the other side is made difficult along much of the tributary area because of the slope of the terrain.

Feeder service, using either buses or park-and-ride lots, can sometimes be used to overcome locational disadvantages if the length and speed of the line (and thus the amount of time advantage that the line provides) are sufficient to offset the circuitous routing. Travel distances must be of sufficient length that a somewhat circuitous route is still competitive with other modes in total travel time. This condition is likely to occur only in the largest urban areas.

In addition to providing direct access to a CBD, railroad rights-of-way may be useful for LRT service in the largest urban areas in two other ways. LRT may serve as a feeder to an existing rail transit service, as on the Ashmont-Mattapan line in Boston. This type of feeder may, in some situations, be less costly to construct and operate than an extension of heavy-rail transit (HRT) service. In a very few situations, nonradial or crosstown routes may be desirable in the largest cities. However, these routes are likely to be useful only where they serve as feeders to other rail lines as well as provide crosstown service.

To sum up, a railroad right-of-way is valuable for LRT service if it serves a corridor with a high volume of current or potential transit use. In many situations, the existence of high-volume bus routes will indicate the presence of such a corridor. Railroad rights-of-way that are not located in potential high-volume corridors will not be useful for successful LRT routes. The temptation to regard a right-of-way as suitable simply because it is easily available should be strongly resisted.

RAILROAD USE AND TRACK REQUIREMENTS

Use

Analysis of rail-line use requires a thorough knowledge of the type of train movements that travel the line, the volume of train movements, and the magnitude and frequency of car spottings on individual sidings along the line. Gathering data at this level of detail is a necessary first step in determining the feasibility of using a particular railroad right-of-way.

Several types of train movements may be used on a given line, e.g., through freight and passenger train movements between points remote from the line under consideration, local or way freight movements that traverse the line but may also set out and pick up cars along the line or switch cars for major customers, switching movements that operate exclusively to pick up and set out cars on a given line or within a given switching district, and transfer movements to exchange freight cars between railroads or between nearby yards on the same railroad. Knowing which movements are used permits categorization according to which simply traverse the line and which use the line to switch cars to on-line rail facilities or customer sidings. It should also be determined whether these movements are attributable to one or several carriers. The owning road may grant access to other roads. The line might also represent joint trackage, i.e., it may be owned by several roads.

Field observations may be a useful source of this data if a sufficient number of observations are made. Rail activities can fluctuate enough that it could be misleading if only one or two observations are made. Rail records are the best source of use data once the type of movement is known. Some common sources include the following.

1. A timetable for employees provides a list of all scheduled trains. Generally only a portion of the total freight movements will be shown. Within the timetable is a section (special instructions) that details the type of signal rules governing the line, speed limits, and other operational features.
2. Train sheets are kept by a dispatcher and log all through train movements over the line. If the line is totally or partially within area switching (yard) limits, these sheets will not constitute a log of all train movements.
3. Block office records detail all train movements that have passed an office by a given time of day.
4. A yardmaster controls movements within a specified territory, subject to the railroads' operating rules. Most railroads require that a log of these operations be maintained, but through movements are not likely to be shown.

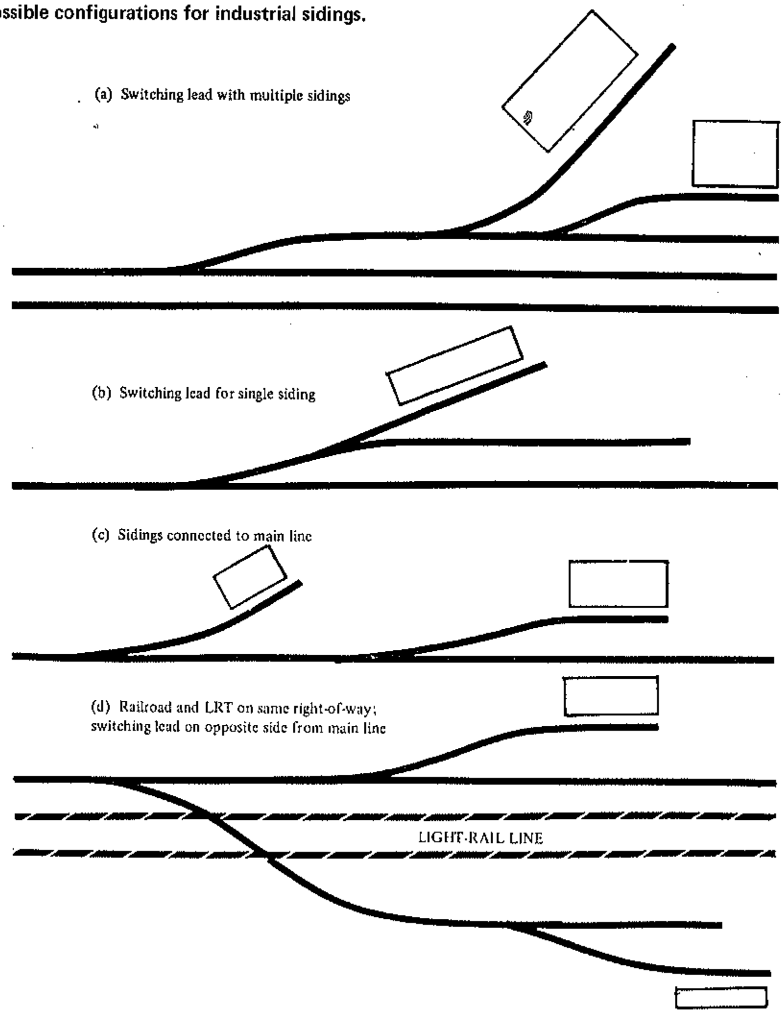
Railroads also maintain records from which the frequency and number of railroad cars that use a given siding or group of sidings can be determined. Sources of this information include the car accounting records, which are maintained primarily to support per diem and demurrage charges but can also be used to determine the magnitude and frequency of use of sidings, and waybills, since an analysis of waybills for customers on a given line specifies rail use and when it occurred. At least two sources of information, one on movements information and the other on siding use should be employed.

Track Requirements

The review of use will provide a preliminary indication of the current track requirements and which track facilities may be classified as excess. Through movements that are either frequent or random in occurrence will require retention of main-line tracks or relocation of the movement to another line. These movements must be able to traverse the line at any time without delay and generally require that tracks for on-line switching activity be segregated. For example, switching tracks should be designed to allow switching activities that do not foul main tracks. In areas where there are numerous rail customers, a parallel switching lead is often a practical solution, as is shown in Figure 1A. A switching lead intended to serve one customer should have two stub tracks of sufficient capacity to avoid fouling the main tracks during switching movements, as in Figure 1B. The absence of through movements or minimal siding activity will allow switching to be accomplished by using the main track, as in Figure 1C.

The number of main tracks that must be retained is generally a function of the volume of through train movements and the type of signalization that is used. For example, if there is no signalization or if the existing signal system is unidirectional, a railroad may chose to retain two main tracks, even in traffic of moderate density. The LRT project may be able to reduce the railroad's track need by improving the signal and control system and thereby increasing the capacity of the remaining tracks.

Figure 1. Possible configurations for industrial sidings.



The location and number of sidings that must be retained will be determined by the waybill analysis or car accounting records. If sidings are randomly located on both sides of the right-of-way, it will be necessary for the LRT line to be crossed. The track arrangements must be such that railroad switching activity does not take place on the crossing. A possible configuration is shown in Figure 1D. The operational aspects of such a crossing are further discussed in a following section.

CONSTRAINTS ON THE USE OF RAILROAD RIGHT-OF-WAY

The level of use is the major determinant of the availability of a railroad right-of-way for an LRT system, but there are other areas of consideration that are also important, particularly the issues of whether the physical characteristics of the line are suitable to accommodate an LRT operation, what institutional constraints might be encountered, and how they will affect operation of the line.

Physical Characteristics

The physical characteristics of a railroad right-of-way that are important for potential LRT use include width of the right-of-way, number and location of rail customers, number and type of highway and railroad crossings, and barriers to right-of-way expansion.

Right-of-Way Width

An inventory of right-of-way widths can be compiled by obtaining Interstate Commerce Commission (ICC) evaluation maps from the railroad engineering department or tax maps from the local government body. A simple field check is recommended as part of the preliminary planning to determine whether there are incursions of nonrailroad buildings or structures and to check the locations of railroad structures, such as bridges, fills, and cuts.

The right-of-way must at least accommodate two tracks and be approximately 9.14 m (30 ft) wide. The need to provide for continued railroad operation will require a wider right-of-way. The exact width will depend on the number of tracks and the use to which they are put. The maximum number of tracks a railroad is likely to require is four, two main tracks and two parallel sidings that will accommodate switching activity without fouling the main tracks. The railroad may need only one track to accommodate switching activity. The nature of track use also has an effect on the required width. Main tracks designed for high-speed operation may require greater width to accommodate perimeter fencing.

The right-of-way width in areas of cuts or fills is also important if additional tracks are required to segregate railroad operations. The need to increase the size of these structures to accommodate segregated trackage can also require wider rights-of-way. Since railroads use a great deal of off-rail maintenance equipment, vehicle access roads may be required if the rail line is a major route. Right-of-way width is also critical in areas where it may be advantageous now, or in the future, to have grade separations.

Number and Location of Rail Customers

The use survey will provide a list of all active customers. The likelihood that inactive sidings will become active in the future may also need to be investigated. Some sidings may be inactive because the facilities they serve are temporarily vacant. Others may be inactive because users switched from rail service to truck or piggyback service. A survey of the owners or tenants of inactive sidings is recommended to permit estimation of the future use of these facilities.

Barriers to Right-of-Way Expansion

The railroad right-of-way cannot be expected to supply all the land needs associated with the LRT line. Stations may require land outside the right-of-way to accommodate parking and in certain cases to facilitate access. Platform areas can usually be accommodated within the right-of-way, but the need for continued railroad operations may require additional width at stations.

Grade-separation structures can have two effects. Additional land may be required for the structure approaches, particularly where a street grade is changed and the railroad grade remains the same. Also, land may be needed for both rail and highway traffic detours during construction.

The ability to expand the right-of-way can be estimated by taking an inventory of all structures that border or are near the existing rail line. This is especially important near proposed station sites or where grade-separation structures are required.

Number and Type of Highway and Railroad Crossings

LRT operations have the flexibility to tolerate grade crossings as long as they do not present severe operating impediments. Traffic volumes by time of day should be obtained for all highway crossings to determine possible trouble spots. The presence of a large number of heavily used highway crossings that would require grade separations could push costs up to the level of rail rapid transit. Heavily used highway crossings that are not grade separated will probably require the installation of traffic signals that are tied into the street signal system. Such signals would reduce interference with street traffic but would lower the quality of LRT service by increasing running time. If railroad grade-crossing signals are acceptable from the point of view of traffic control, then LRT service would be relatively unimpeded. The interconnection of grade-crossing signals with traffic signals at nearby intersections to minimize both LRT and street traffic delay has been proposed for Edmonton, as noted by O'Brien, Schnablegger, and Teply in their paper elsewhere in this Report.

Railroad crossings can pose similar problems. Crossings of railroad main and branch lines can create service-delay problems because of the randomness of train operation. This situation is even more acute if it is the railroad that controls the crossing, since the controlling party has the right to hold or stop any movement on the other line in order to protect movement on its own line. If control is exercised from a remote location, waiting time will be even greater. Such situations could not be tolerated, and a grade separation would be required. Crossings that have railroad switching leads can be tolerated if they are infrequently used and activity can be confined to nonpeak periods. In addition, all switching would have to be done outside the limits of the crossing.

Operating Issues

The need for continued rail access to all or a portion of the right-of-way requires either operational or physical separation of railroad and LRT activity.

Operational Separation

Railroad and LRT operations can use the same track if railroad operation is restricted to periods that would not interfere with LRT operation. Railroad operation would typically be restricted to the late evening hours, during which its impact would be negligible or nonexistent. In most instances, railroads would not tolerate such restrictions on through freight movements but might be inclined to accept them on switching movements. The feasibility of restricting switching movements depends largely on the needs of the rail shippers affected. If the shipper requires early morning delivery at some destination, the siding will have to be switched in the late afternoon, and a restriction could not be tolerated. In this instance, physically separate rail facilities would have to be provided.

The joint use of tracks without this form of separation would present a variety of problems, not the least of which could be the effects on LRT service reliability. Other problems would include incompatibility of signal and other train-control systems used for railroad and LRT operation and the incompatibility of operating rules of the two systems. Joint use without operational separation is not recommended.

Physical Separation

Railroad and LRT operations may use separate track facilities within the same right-of-way, scheduling movements so that they have minimal impact on each other. It is quite likely that situations will arise in which the railroad will require access to both sides of the right-of-way (Figure 1D), necessitating one or more crossings at grade. Such crossings will require interlocking facilities that protect movements on both lines. Understandings will have to be reached as to the hours that the railroad can use the crossing and the length of time the crossing can be held by the railroad.

Institutional Constraints

It is impossible to list all institutional problems that might arise, since many are based solely on local considerations. However, federal agencies or regulations will have significant impact on LRT operation; this is discussed below.

The Federal Railroad Administration (FRA) exercises control over railroad safety matters, including track standards and equipment design. The FRA has no jurisdiction over rail transit operations that do not provide interchange freight service. An LRT line would have to adhere to FRA track standards in areas of joint use. However, those standards are generally less stringent than normal LRT operating practice. If joint operations did not have positive time separation, the FRA might insist on compatible car-design specifications. These specifications would rule out the use of light-rail vehicles (LRVs) because of the differences in floor and coupler height. There have been numerous examples of mixed railroad and LRT operations in the past, but unfortunately no examples have survived to form a precedent today.

LRT operations linking two states would fall under the jurisdiction of the ICC in matters of rates and service. Lines that handle short-haul passenger traffic exclusively are classified as suburban electric railways and are thus now subject to ICC control only in regard to rates.

If an LRT line were to assume direct responsibility for freight operation over its lines and participate in joint tariffs, the ICC would have jurisdiction over the freight service and could possibly claim jurisdiction over passenger service on the basis of some rather ancient precedents (1). The one transit operation that also provides rail freight service, the New York City Transit Authority, has used a subsidiary company, the South Brooklyn Railway, for its freight operations in order to avoid the problems of ICC jurisdiction. Operation of freight service by an LRT system under contract to a railroad would most likely remove the LRT system from ICC jurisdiction, since there would be no participation in freight tariffs. This was true for the freight service that the Chicago Transit Authority operated for many years for the Chicago, Milwaukee, St. Paul and Pacific Railroad Company.

RELOCATION OR ABANDONMENT OF RAILROAD SERVICE

Relocation or abandonment of railroad service is often a means for making a right-of-way available for LRT use. As mentioned previously, many rail lines in urban areas have become surplus as a result of railroad mergers and changes in patterns of use.

Relocation of Railroad Service

Relocation of transiting movement to other routes is often possible in areas that have a high density of railroad facilities. Relocation of transiting movements may be used to permit total abandonment of a line that does not have significant local traffic, to permit reduction in the number of railroad tracks required for freight operation so that right-of-way is available for LRT use, or to reduce the level of use so that joint use is possible. Figure 2 shows how the relocation of through movements to an alternate route could be arranged. The connections required for the relocation of service are indicated. In many situations, new connections will be required. In some of these situations, lines belonging to more than one railroad will be used, and agreements on trackage rights will be needed. In other situations, the lines to be used will belong to one railroad. However, new connections will still be required, particularly if common ownership of parallel routes is the result of a fairly recent merger.

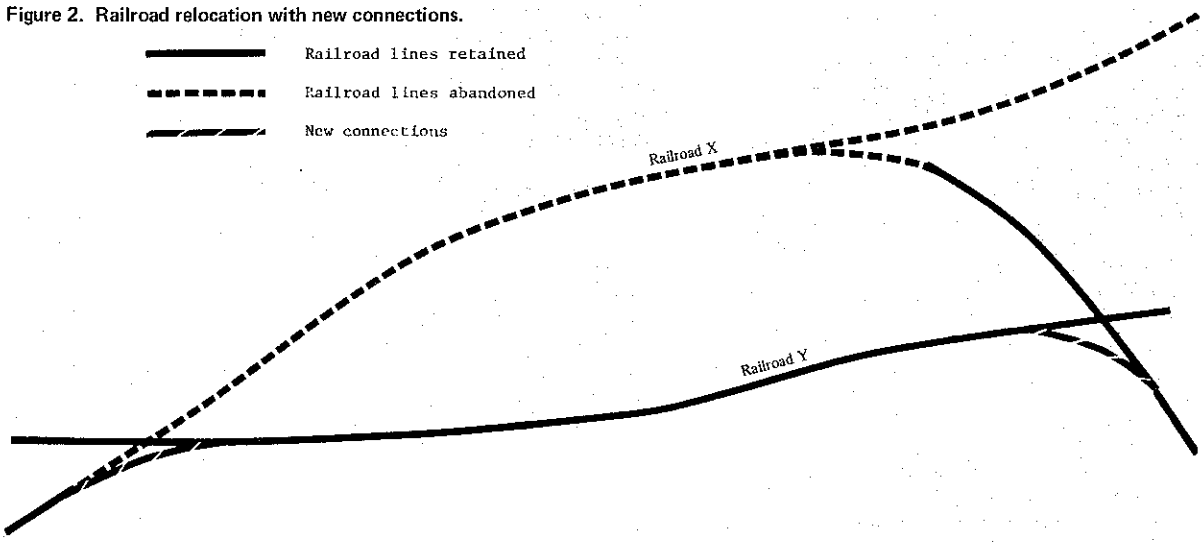
Abandonment of Railroad Operations

Abandonment of railroad freight service is possible where a route is not required for through movement and there is insufficient on-line traffic to justify its retention. Abandonment of a railroad line requires ICC approval. The ICC has established minimum use criteria for abandonment at 54 car movements/route km/year (34 car movements/route mile/year). In many cases, however, abandonments of significantly more heavily used lines have been permitted; each abandonment case may require a unique decision. Alternative uses for rights-of-way are given consideration in abandonment decisions. Most such decisions, however, have resulted from the need to provide an expensive grade separation between an interstate highway and a little-used railroad.

In abandonment procedures there is no requirement for compensation to affected industries. However, the relocation of on-line industry may be a means of reducing the level of use of a rail line so that abandonment is feasible. Such a policy has never, to our knowledge, been formally developed. Thus, the legal requirements of publicly financed industrial relocation, where rail access is being discontinued but there is no condemnation of property, remain unexplored.

The discontinuance or reduction of railroad operations

Figure 2. Railroad relocation with new connections.



to accommodate a federally-funded LRT operation could give rise to labor protection claims under section 13c, which is designed to give job protection to workers affected by federally supported mass transit projects. However, ICC decisions in railroad abandonments usually require employee protection as a condition of abandonment where only a portion of a railroad is affected.

Most railroad abandonment situations would involve only a small number of employees, and thus could probably be resolved by the normal railroad employee protection procedures at low cost. However, where a large number of employees would be affected, such as in the discontinuance of a railroad commuter service, there could be substantial costs that would have to be assumed by the LRT operating agency. It is suggested that, if possible, railroad abandonment procedures be completed substantially in advance of the acquisition of railroad property, in order to minimize the employee protection liability of the LRT operator.

Another possible claim by railroad labor unions is for jurisdiction over the employees of a new service on the grounds that it replaces the railroad service. This claim has been advanced in a few cases in which commuter service has been replaced by rail transit service, but it has never been successful.

DESIGN CONSIDERATIONS FOR JOINT USE OR JOINT OPERATION

Clearances

Sufficient horizontal and vertical clearance for freight equipment must be provided in all cases in which rights-of-way are shared or trackage is jointly used for freight and LRT operation. The source for all data on railroad equipment referred to in this section is the Car and Locomotive Cyclopedia (2).

Substantial differences exist between recommended railroad practice for new construction and clearances on existing railroad lines. Recommended practice calls for 6.7 m (22 ft) of vertical clearance and 2.4 m (8 ft) of horizontal clearance for fixed structures as measured from the track centerline at the top of the rail. However, the standard clearance diagram for rail freight equipment, as is shown in Figure 3, is significantly more restrictive: maximum height of 4.8 m (15.5 ft) and maximum width of 3.3 m (10.7 ft), 1.6 m (5.3 ft) from track centerline. Cars built to this standard are acceptable for operation on more than 95 percent of the railroad trackage in the United States.

However, although this is the nominal standard, much of the railroad equipment in service exceeds the vertical clearances of this standard. Car heights of 5.2 m (17 ft) are not uncommon. Loaded trilevel automobile carriers are almost 5.8 m (19 ft) high. A few special cars for aircraft assembly shipment have been built with a maximum height of 6.0 m (19.7 ft). Table 1 gives the typical dimensions of various types of rail freight equipment.

The clearance requirements affect the design of LRT systems that have joint use of right-of-way or shared trackage in three areas. Vertical clearance requirements may present problems in relation to wire height. Horizontal clearances are a problem if platforms at the car-floor level are to be used in joint operation. Clearance requirements for railroad operation may require that the clear height of grade separations be increased.

Vertical clearance for jointly used trackage or for crossings of railroad lines at grade may increase the wire height beyond the 5.8-m (19-ft) maximum operating height of the pantograph specified for the standard LRV (3). However, for most industrial trackage a wire height of 5.5 m (18 ft) is acceptable. This height will allow a 0.3-m (1-ft) clearance for high-cube boxcars. Railroads will generally insist on 6.7 m (22 ft) of vertical clearance on main lines, on trackage that serves automobile-loading facilities, and for access to industries that are likely to originate or receive oversized loads. In these situations, two solutions are possible. Where a 4.6-m (15-ft) minimum wire clearance on the LRT line is practical, the pantograph base can be elevated to provide a 6.7-m (22-ft) maximum wire height. If the problem exists only at a small number of railroad crossings at grade, wire bridges may be used, as is done in Cleveland (a wire bridge is a lift mechanism that raises a section of wire from the normal operating height to a height sufficient for railroad clearance requirements).

Horizontal clearances present a significant problem only if platforms at the level of the car floor are desired. Although a railroad freight car is significantly wider than the standard LRV, the standard design practice of using 3.7-m (12-ft) or 4.0-m (13-ft) track centers and 2.1-m (7-ft) side clearance is sufficient for almost all freight movements. Three means are available to provide for freight operation on LRT lines that have high-level platforms: gauntlet tracks, car-door sill extensions, and hinged platform edges. However, none of these meets the test of being both operationally simple and low in cost. If extensive joint use of an LRT line is under consideration, it is probably better to avoid platforms at car-floor level entirely.

Gauntlet tracks are relatively expensive, since they require a switch at each end of the gauntlet. In addition, remote-controlled power switches are necessary if freight trains are not to stop at each end of the gauntlet for a crew member to manually operate the switches, which increases costs substantially. Car-door sill extensions are feasible only if all stations have high platforms, since the extension must be below the bottom of the door. In addition, a gap of approximately 0.3 m (1 ft) would exist between the car side and the platform except at the doors; this would create a hazard for passengers, particularly during boarding. Hinged platform edges are time consuming for a freight-train crew to operate, since they must be hinged in short sections to be lifted manually. Gauntlet tracks have been the most commonly used and are probably the most satisfactory solution.

Vertical clearance requirements for grade separations are similar to those for wire height. The 6.7-m (22-ft) clearance standard should be adhered to if practical. An examination of the individual railroad line is necessary to determine existing clearance restrictions and thus to determine acceptable vertical clearances. As was pointed out above, a 5.5-m (18-ft) clearance is often sufficient.

Figure 3. Outline of standard LRV and standard clearance diagram for rail freight equipment.

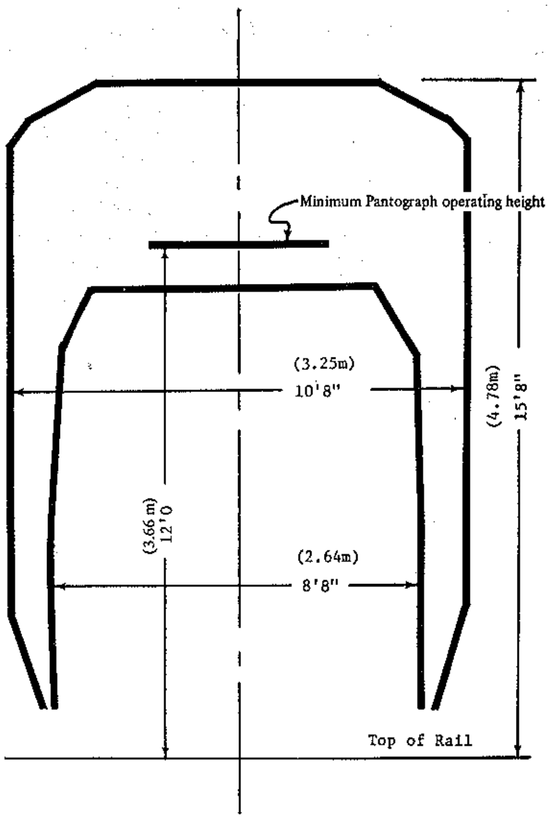


Table 1. Critical weights and dimensions of rail freight equipment.

Equipment	Gross Weight (Mg)	Truck Centers: Individual Cars (m)	Truck Centers: Adjacent Coupled Cars (m)	Car Height (m)
Locomotive				
Four-axle (EMD-GP38)	113.4	10.37	7.62	4.65
Six-axle (GE-U36C)	190.5[a]	12.5	8.08	4.73
Standard box car	99.8	12.5	4.42	4.75
High-cube box car	99.8	19.51	8.99	5.18[b]
Covered hopper car	119.3	12.15	4.12	4.57
Flat car with automobile rack	99.8	20.12	8.69	5.72[b,c]
Open hopper car	119.3	10.98	3.81	3.73
Ore car	119.3	6.1	3.81	3.51
Piggyback flat car	99.8	20.12	8.69	5.18[b,c]

Note: 1 Mg = 1.1 tons and 1 m = 3.3 ft.
[a] Maximum ballasted weight.
[b] Exceeds standard clearance.
[c] Estimated height of loaded car.

Weights

Table 1 also shows the weights of representative types of rail freight equipment, which are substantially greater than the typical weights of both LRT and HRT equipment. A fully loaded standard LRV weighs approximately 47 Mg (51.5 tons). As a result, track and structures designed for joint operation or for use of a common right-of-way will need to be capable of accommodating much higher loads than those found in LRT operation only. While it is unlikely that track design standards would change significantly, structural designs would be affected.

To illustrate the differences in carrying capacity required, the weights that would occupy a 30.5-m (100-ft) bridge span in varying operational situations are presented below (1 Mg = 1.1 tons). Among cars with a nominal capacity of 63.5 Mg (70 tons) and a gross weight of 99.8 Mg (110 tons), locomotives impose the greatest loading. Among cars with a nominal capacity of 90.7 Mg (100 tons) and a gross weight of 119.3 Mg (131.5 tons), car weight is greater than locomotive weight, except where cars with a relatively long wheelbase are used in conjunction with six-axle locomotives.

Equipment	Gross Loading (Mg)
LRVs in trains	65
Light-rail maintenance-of-way equipment	91
Freight trains	
63.5-Mg cars (four-axle locomotives)	227
90.7-Mg cars	239 to 298
Six-axle locomotives	345 to 381
Ore cars	417

Most railroad facilities should be designed to permit the operation of 90.7-Mg cars. The operation of six-axle locomotives should be allowed for on main-line trackage, but it is not a requirement for industrial lead tracks. The extremely concentrated loads imposed by 90.7-Mg open hopper cars, ore cars, and other short-wheelbase cars are present most commonly on lines that serve steel mills and coal-burning power plants.

Grade Separations and Crossings

Joint operation or use of a common right-of-way will require substantially different design criteria for grade-separation structures than those required for LRT use only. The difference in vehicle weights has already been described. Approach gradients will be a greater constraint where the grade level of the rail line has to be changed to accommodate a grade separation. Generally, grades of more than 1 percent are undesirable for main-line freight operation and those of more than 2 percent are undesirable for switching leads. An LRT line may commonly have long grades of up to 6 percent; short grades of up to 10 percent are feasible.

If use of a common right-of-way is planned, it may be desirable at some locations to have grade separations for the LRT line but not for the rail freight trackage. This solution is attractive if the rail freight track is used relatively infrequently and the cost of the grade separation would be substantially increased by including it. A more elaborate example of this type of design would have the rail transit route built on an elevated structure over a non-grade-separated railroad right-of-way, as was done in portions of the San Francisco rapid transit system.

The use of railroad rights-of-way for LRT routes will often require crossings of remaining railroad trackage. In designing rapid rail systems, it has usually been thought desirable to have grade separation for all such crossings. For LRT operation, crossings of railroad lines at grade are acceptable in many situations.

The design of signal protection for a crossing depends on the degree of central control that is required on both the LRT line and the railroad. The most common crossing has no signal control on the railroad and automatic block signals without central control on the LRT line. In this situation, a key-operated time-delay interlocking is sufficient protection. Normally the interlocking is cleared for the LRT route and is activated manually by a railroad crewman. A time-delay circuit prevents the signals from clearing for the railroad line until a sufficient time has passed after the LRT signals indicate STOP so that any car that has already passed the signals will clear the crossing. A short track circuit is provided on the railroad line to restore the interlocking to its normal state after the railroad train has cleared the circuit.

A somewhat more sophisticated version of this type of crossing protection is provided by the automatic interlocking, which is controlled by approach track circuits on each line. This type of interlocking has the circuit logic of the two systems interconnected so that the crossing is cleared for the vehicle or train that arrives first at the approach section. This type of protection can be used for branch lines and secondary main lines where a mandatory stop for railroad movements over a crossing is undesirable. It is also suited to railroad operation in automatic block signal territory.

CONCLUSIONS

Railroad rights-of-way have been used for transit purposes in several cities, e.g., Boston and Edmonton. HRT lines have been built on railroad rights-of-way in Boston, Chicago, Cleveland, New York, Philadelphia, San Francisco, and Washington. A hybrid system that has characteristics of both LRT and HRT also exists in Chicago.

The use of railroad rights-of-way for LRT has differed significantly from their use for HRT because both rail-highway and LRT-railroad grade crossings are acceptable. Thus, substantial reductions in construction costs are possible. Railroad rights-of-way usually provide horizontal and vertical alignment characteristics that exceed the requirements for both LRT and HRT systems. In using railroad rights-of-way, the less restrictive alignment requirements of LRT are an advantage only in transition sections.

Joint use of trackage does not present any difficult design problems, but it does present some operational problems that are inherent in mixing LRT and railroad freight service, as well as several institutional problems. These make joint use unfeasible except where positive operational separation can be provided without degrading passenger service. Such situations exist only for low-volume switching activities.

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The Design of Light-Rail Track in Pavement

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Many existing light-rail transit (LRT) networks and parts of some new ones require the construction of track in pavement. Sometimes this track is intended for joint use with street traffic or buses; in other places paved track is used in pedestrian areas or on medians. This paper describes the types of LRT track used in pavement in North America and Europe and suggests that the standards now in use in the United States may be in need of revision. There has been very little construction of LRT track in pavement in North America in the last 40 years. What little has been built has followed the traditional standards of the industry, which date from the earliest streetcar days, and has generally used girder rail, ties, and ballast set in concrete pavement. By contrast, most European LRT systems have adopted a basically different type of track for use in pavement. It is built without conventional ties and is mechanically separated from the street pavement structure. Such track is quieter and may also be less costly; it appears to warrant serious consideration for new U.S. installations.

There has been very little construction of light-rail transit (LRT) track in street pavement in North America in the last 40 years. What little has been built, for realignment or rerailing, has been constructed to standards first developed in the earliest days of streetcars; these standards are straightforward and have stood the test of time. During the recent bleak period of transit history, there was little need for better designs and no resources available to research them. Now that several existing LRT systems in North America are engaged in refurbishing their physical plants and new systems are under design, it is appropriate to pay some attention to the progress that has been made in the search for a track design that offers potentially lower costs and environmental benefits in countries in which LRT has been the beneficiary of continuing development.

NORTH AMERICAN PAVED-TRACK DESIGN PRACTICE

The most common form of LRT track in pavement used in North America consists of girder rails spiked directly to wooden ties that rest on ballast as is done in conventional railroad construction. The track is then paved by covering it with concrete up to pavement level (Figure 1). In some designs, an asphalt concrete surface is used instead of a full concrete section. Sometimes girder rails are bolted directly to a concrete base slab without the use of wooden ties. Here too, the track is paved by covering it with concrete up to the railhead. Occasionally, the rails are set directly into the paving slab.

The distinguishing characteristic of all of these forms of track is that the rails are rigidly set in the pavement. This rigid type of track has long been used successfully throughout North America and in many other countries. It has a long life and suffers few problems of settlement or misalignment, provided that it is built on a firm foundation. However, because the rails are rigidly encased in the pavement, vibrations are readily transmitted from the rails to the surrounding street pavement; this amplifies the noise of rolling wheels.

The need for wooden ties in paved track is also far from clear, and the practice may be a holdover from the days when street pavement was intermittent or nonexistent. Ties increase the depth of the track section and often decay long before the rails are worn out. The resilience afforded by a tie-and-ballast rail support appears to be in conflict with the ridigity of rails cast in concrete. The usual practice of placing ties at the spacing required for railroads ignores the fact that LRT axle loads are generally less than one third those of conventional railroad axle loads. Finally, changing or resurfacing the rails requires breaking out and removing the concrete pavement, as well as disturbing the underlying ties.

Figure 1. Construction of rigid track in San Francisco in 1975 (ballast, ties, concrete pavement).

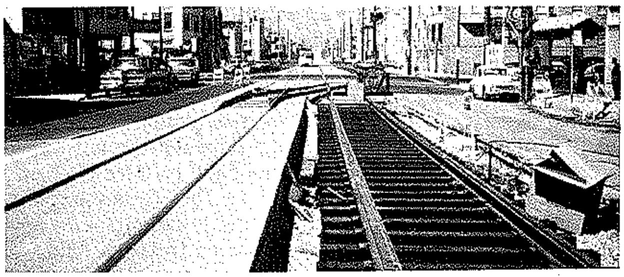
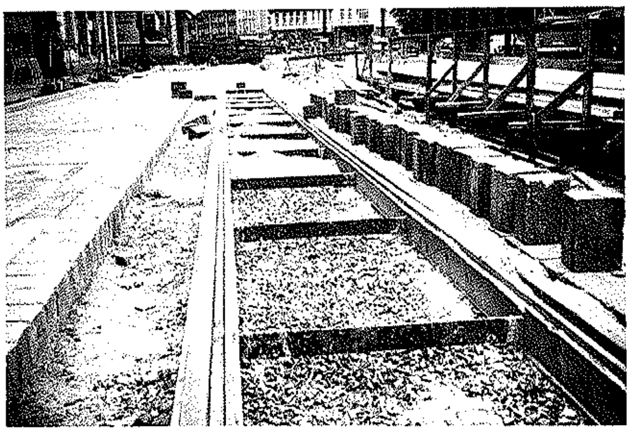


Figure 2. Construction of resilient track in Heissen in 1975 (ballast base, block pavement).

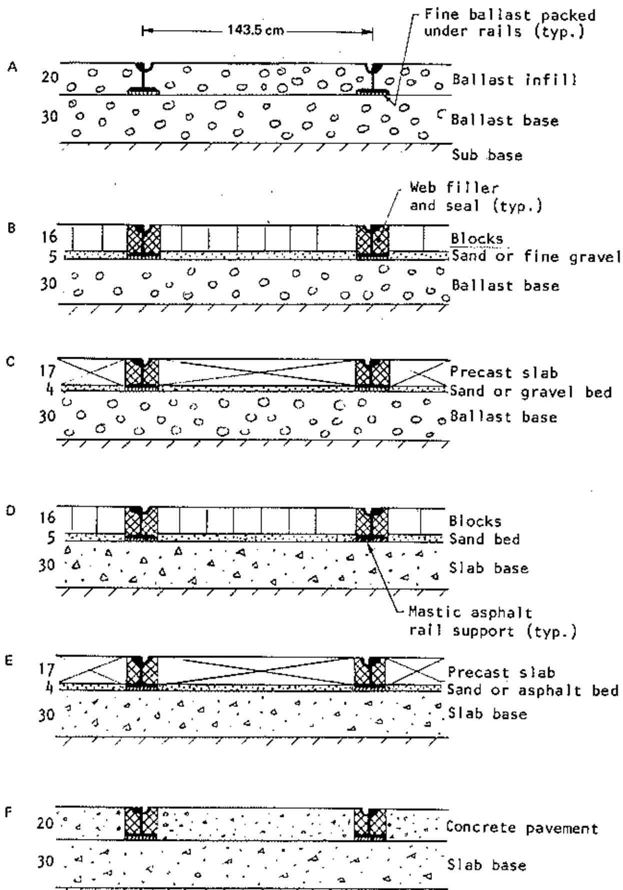


EUROPEAN PAVED-TRACK DESIGN PRACTICE

By contrast, many European LRT systems have adopted a form of resilient track for use in pavement; it is distinguished by the lack of conventional ties and by the mechanical insulation of the rails from the pavement by means of flexible joints beside and beneath the rails (Figure 2). Resilient track represents a compromise between the need for rigidity, which is necessary for a stable and long-lasting pavement, and the need for track flexibility to cut down on vibration and noise.

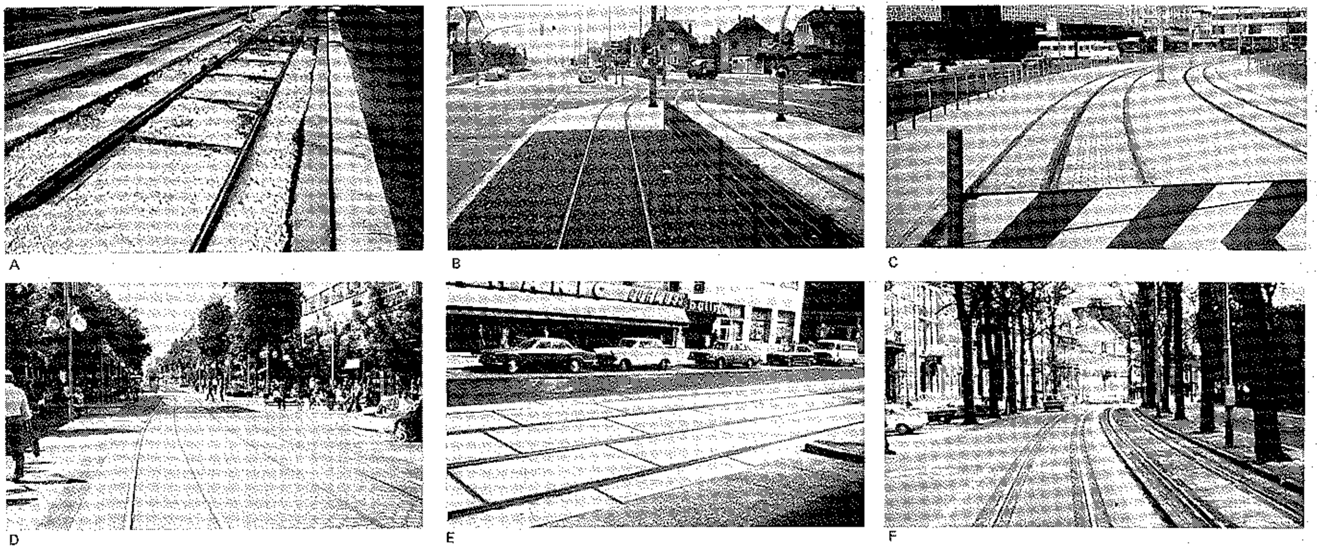
The great variety of resilient track designs used in Europe reflects the experience and preferences of the individual track engineers, funding priorities, and the continuing evolution of design theories and construction techniques. The research for this paper entailed reviewing more than 50 different track standards, most of them for resilient track. Although there are so many designs, there are only two basic types of resilient track, distinguished by the method used to support the rails: ballast-based track and slab-based track. Several permutations of track base and paving methods are used; the most

Figure 3. Types of resilient track.



Notes: 1 cm = 0.39 in.
A = full-depth ballast; B = ballast base, block pavement; C = ballast base, precast slab pavement; D = slab base, block pavement; E = slab base, precast slab pavement; F = slab base, concrete pavement.

Figure 4. Examples of types of resilient track in use.



Note: A = full-depth ballast with asphalt overlay (Gothenburg); B = transition from full-depth ballast to slab-based track with block paving (Braunschweig); C = slab-based track with block paving (Braunschweig); D = ballast-based, block-paved track in LRT pedestrian mall (Mannheim); E = precast slabs on slab base (Vienna); and F = Hannover track in center lane (Amsterdam).

common are illustrated diagrammatically in Figure 3 and in photographs in Figure 4.

Ballast-Based Track

The ballast-based track group offers the least costly approach to paved-track construction. At one time many systems even dispensed with the ballast; the rails were laid directly on the street-pavement base material. However, the higher axle loads of light-rail vehicles (LRVs) and tighter pavement specifications necessary for modern traffic have led to the general adoption of better quality material. The three most common ways in which ballast-based track is constructed are described below.

1. Full-depth ballast: In this design, the track ballast comes up to the railhead. This is necessary to keep the track in alignment and to prevent the rails from shifting laterally under thermal or dynamic stresses. Since this type of track is not actually paved, it can only be used on sections of trackway, such as on street medians or midblock in pedestrian streets where a paved finish is not required. Several line extensions constructed in Braunschweig in recent years have been built to this track standard. One variation uses a sand or gravel base under the rails and fills the track to the railhead with earth; this permits grass to be grown around the rails. It should be noted that ballast-surfaced track tends to accumulate dirt and trash, or the ballast may get displaced onto adjacent roadways; it is therefore not suitable for many urban applications. Where hard rock ballast is used with girder rail, ballast in the flangeway may result in damage to LRV wheels. In Gothenburg, full-depth ballast track is used with graded ballast (macadam) and a thin asphalt overlay of 3 to 5 cm (1.2 to 2 in) to avoid these problems. Where the track is grassed, train adhesion will be reduced whenever grass cuttings get on the rails, and the design should therefore recognize potentially reduced performance. On systems that use multiaxle cars, the lead trucks perform a rail-cleaning function, and performance may be expected to deteriorate less.

2. Block paving: The space between the ballast base and the pavement is paved with blocks made of precast concrete, industrial slag, or stone. Web fillers of cast-in-place concrete or clay tile are used to fill the web cavities (between the base and head of the rail), and the joints between the blocks and between the rails and the blocks are sealed with mastic asphalt. This is the most widely used form of paved track in Europe; it is discussed in more detail later.

3. Precast slab pavement: This track form uses large precast concrete slabs as paving elements. The slabs are manufactured off site and are placed in position by cranes. In some designs, an asphalt concrete overlay is used over the precast concrete slabs to provide a wearing surface for traffic. Again, web fillers are used against the rails, and mastic asphalt is used to seal the joints in the pavement and between the rails and the pavement. This track form appears to have been in use experimentally for several years, but it has not been widely adopted, apparently because it is sensitive to any settlement and is therefore more suited to track on a slab base.

Slab-Based Track

Slab-based track uses a concrete slab to support the rails and can be paved in a variety of ways. To separate the rails from the slab supporting them, a mastic asphalt cushion, usually 3 to 4 cm (1.2 to 1.6 in) thick, is poured beneath the rails after they have been set to alignment and level. This technique provides for the accurate alignment of the track without the need to cast the base slab to close tolerances. Several types of slab-based track are in use; they are distinguished mainly by the method used to complete the pavement, as in the following examples.

1. Paving blocks: Web fillers are placed against the rails, and the pavement is completed with precast concrete, stone, or industrial slag blocks bedded in sand or weak concrete. The joints between the blocks and between the blocks and the railheads are sealed with mastic asphalt. This form of track is used in special loca-

Figure 5. Cross section of track with ballast base and block pavement.

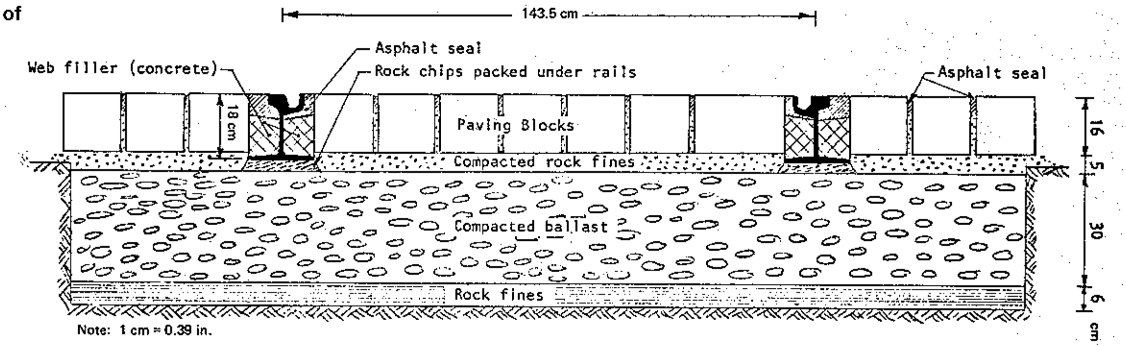
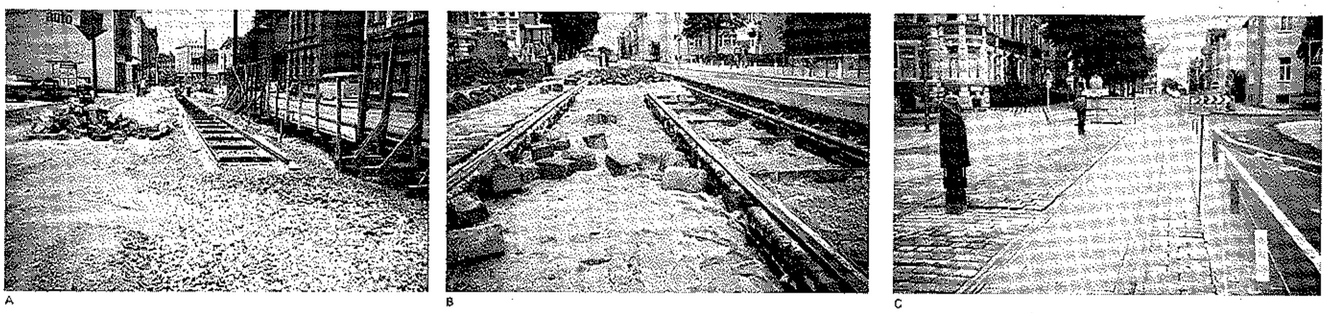


Figure 6. Construction of ballast-based, block-paved track.



Note: A = preparation of base and assembly, welding, and alignment of track; B = placement of web fillers (hollow clay tile) and sand bed for blocks; and C = placement of blocks and cleaning and sealing of pavement.

tions and is relatively uncommon, since it is both slightly more costly than other methods and may require some maintenance.

2. Precast pavement: In this design, the pavement is completed with precast concrete slab elements. These may be bedded on a layer of sand or asphalt, and they may extend the full depth or be covered with an asphalt concrete overlay. Several cities have experiemented with this type of track in recent years, and it appears to have potential for further development.

3. Concrete pavement: After the web fillers have been laid, the pavement is completed with a cast-in-place concrete slab. In some designs, an asphalt concrete overlay is used. The space between the rails and the slab is sealed with mastic asphalt. This track form is widely used and appears to be a preferred design where subbase conditions are poor and rubber-tired traffic is heavy.

SELECTION OF TRACK TYPE

The selection of track type for European LRT systems appears to reflect primarily the experience and preferences of the track engineers responsible. The most prevalent track type uses a ballast base and block pavement (Figure 5). This type is the least costly to construct, can be readily opened up for repair, and is apparently used wherever foundation conditions permit. It is used both on the major systems that have large heavy cars, such as Rhein-Ruhr, Frankfurt, and Hannover, and on the systems that operate equipment with lighter axle loads.

The construction of this type of track is straightforward (Figure 6). A track trench is excavated approximately 2.6 m (8 ft 6 in) wide and 60 m (2 ft) deep. The depth required depends on the condition of the street subbase. Where subbase conditions are good, less ballast is required beneath the rails. The ballast base is placed to within about 20 cm (8 in) of the finished pavement level, and on this base the track structure of rails and tie bars is assembled and welded. The finished track structure is then lined and leveled, and the space beneath the rails is packed with rock chips.

The next stage is to place the web fillers (which normally consist of concrete cast in place) against the rail. Finally the area between and outside the rails is filled with coarse sand or rock fines as bedding for the paving blocks. The paving blocks are especially manufactured in four basic sizes for track paving. The blocks are hand placed, a task that is greatly speeded by the use of only four standard block sizes, and then compacted to grade with a mechanical block tamper. The final task is to seal all joints with mastic asphalt to protect against water and to provide some flexibility in the pavement. Figure 7 shows the paving schedule for a typical section of standard-gauge double track paved by this method; it illustrates the regular and simple block-placement sequence.

A fairly common alternative form of track is the slab-based track with a concrete pavement (Figure 8). This type of track is approximately 20 percent more costly to construct and is accordingly used only where necessary. It is used when foundation conditions are not quite satisfactory or where maintenance is difficult, such as in a major traffic lane, because (a) it is less likely to settle and (b) it can better resist traffic damage. Its method of construction calls for the excavation of a track trench approximately 2.6 m (8.5 ft) wide and 60 cm (24 in) deep, in the bottom of which the slab base approximately 25 to 30 cm (10 to 12 in) thick is poured. On this base, the track structure consisting of rails and tie bars is assembled and welded and then aligned by using folding wedges beneath the rails to achieve accurate adjustment. Hot asphalt filler is then poured beneath the rails to fill the space between the underside of the rails and the base slab. The web fillers, consisting of either cast-in-place concrete, blocks, or hollow clay tile, are then placed in position, after which the concrete pavement slab is completed to final grade. Finally, the joints between the pavement slab and the rail web fillers are sealed with mastic asphalt. In Figure 8, an asphalt concrete overlay is used, but the sequence is essentially the same. This form of track is considered long lasting, but it suffers from the disadvantage of being difficult to repair when adjustment is needed to the line or level of the rails since the concrete pavement must be broken out before any work can be performed on the track. Figure 9 shows a slab-base track under construction, but for the block-paved variant.

In recent years, several cities have experimented with a slab-based track in which the cast-in-place concrete pavement is replaced by precast concrete pavement units (Figure 10). These units are factory made; they are brought to the site and placed in position by crane. The paving units are bedded either in gravel or in an accurately leveled asphalt layer. As for the other track forms, the final stage consists of sealing all the joints in the track structure with mastic asphalt.

The underlying design concept for each of these three track types, and indeed for almost all of the types used in Europe, is the separation of the track rails from the rest of the pavement structure through the use of some kind of nonrigid material and the provision of continuous support to the rails. One of the reasons that blocks are often preferred is that they tolerate vibration and minor settlement without damage. If settlement occurs under a slab pavement, the pavement will crack, and projecting edges will develop.

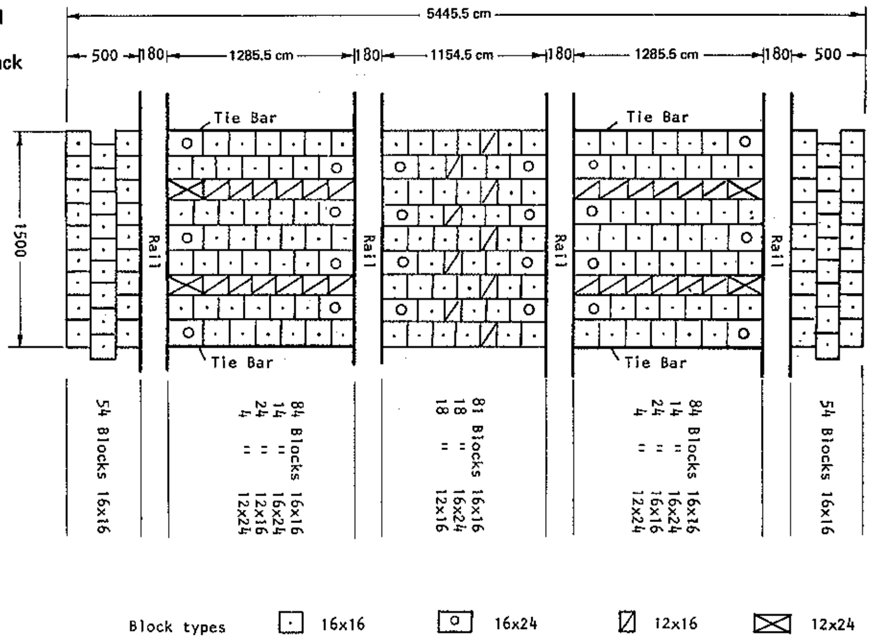
Track Components

The varieties of resilient track discussed in this paper are assembled from a range of basically standard components. The rails are normally 18-cm (7-in) girder rails, which have approximately the same depth as the standard U.S. 7-in girder rail. However, the European or metric rail has an 18-cm (7-in) base, while the U.S. rail has a base of 15.25 cm (6 in). Extra rail-base width helps to distribute the load from the rail to its supporting material. There are no data on the use of U.S. rail with all types of resilient track, since all European track is constructed with metric rail and no resilient track has been constructed in the United States. However, since the cost of rail is based on weight, the cost of the U.S. or metric sections is virtually identical, and it is probably unimportant to resolve this issue. None of the standards reviewed used T-rail in pavement. T-rail is, of course, widely used in open track for LRT.

Rail welding is widely used in new LRT track construction. Where track goes from paved to open track (ties, ballast, and no pavement), a tapered expansion joint is sometimes installed.

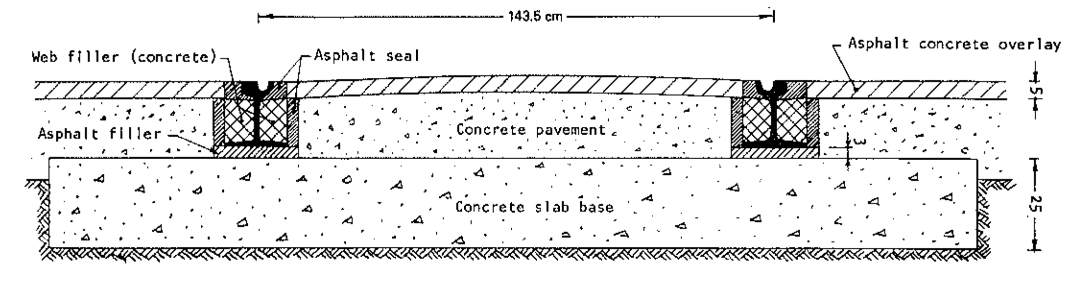
The tie bars consist of 10 by 80-mm (0.4 by 3.2-in) bar steel bolted to the rail webs (the larger dimension is the vertical). They are spaced at intervals of 1.5 m (5 ft) in Hannover to 2.02 m (6.6 ft) in the Hague.

Figure 7. Paving plan and materials schedule for standard-gauge double track with 2.8-m (9.2-ft) track centers.



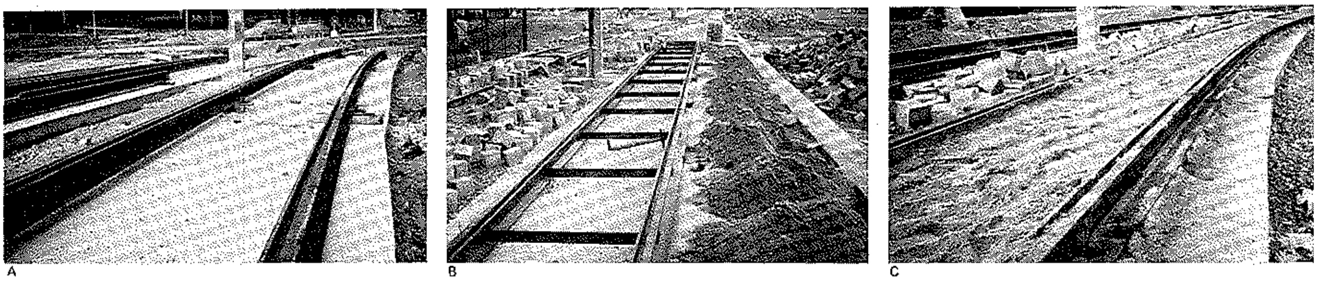
Note: 1 cm = 0.39 in.

Figure 8. Cross section of track with slab base and concrete pavement.



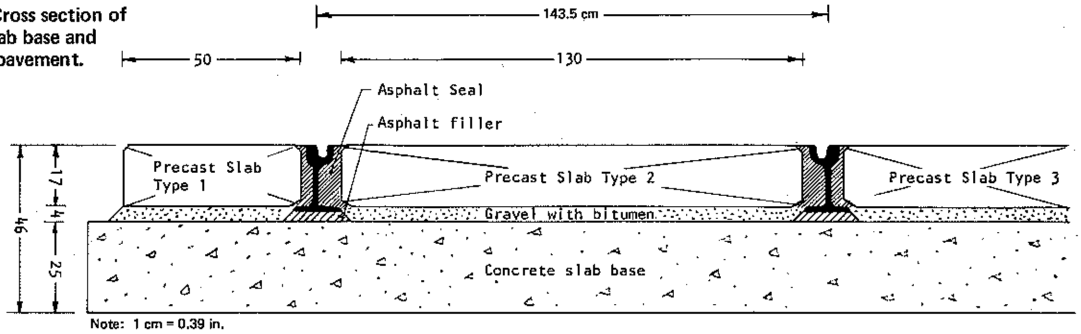
Note: 1 cm = 0.39 in.

Figure 9. Construction of slab-based-block paved track.



Note: A = construction of slab and placement and welding of rails; B = installation of tie bars and lining and leveling of track (note pins that hold track in line and folding wedges that support the rails); and C = pouring of mastic asphalt under rails and placing of sand bed for paving blocks.

Figure 10. Cross section of track with slab base and precast slab pavement.



The preferred material for paving blocks is slag from copper smelters, which has a distinctive black color and high friction qualities. Other materials are often used, including other slags, concrete, and stone blocks. If the track is part of a landscaped area, such as in a pedestrian mall, patterns of blocks of different colors may be used. The use of colored blocks to denote the LRT clearance lines in such areas is a particularly practical technique.

For the most part, the types of resilient track used on tangent sections are also used on curves and for special work. On some systems, short-radius curves are constructed using rigid track, which is encased in concrete, but this practice is not very common; it leads to increased noise levels, as is discussed below.

COMPARISON WITH U.S. PRACTICE

There is little direct comparative data concerning U.S. and European track standards. This is due in part to the lack of activity in this field in the United States and in part to the European tendency to place less emphasis on studies and data accumulation and to rely more on experience. Nevertheless, sufficient material is available to permit certain of the more significant indicators to be compared.

Cost

Enough European cost data are available to permit comparative costs to be developed for the different types of resilient track. As part of a recent study (1), comparative cost estimates were developed for track construction to typical U.S. standards and for resilient track of the ballast-based, block-paved type. The estimated costs of various forms of resilient track, referenced to the cost of U.S. rigid track (ties, ballast, and concrete pavement) are shown below. Note that these costs include base material, ties and rails, and pavement to 60 cm (24 in) outside the rails.

Track Type	Indexed Cost
Rigid track, with wood ties and concrete pavement	100
Resilient track	
Ballast base and block pavement	95
Slab base and concrete pavement	114
Slab base and block pavement	124

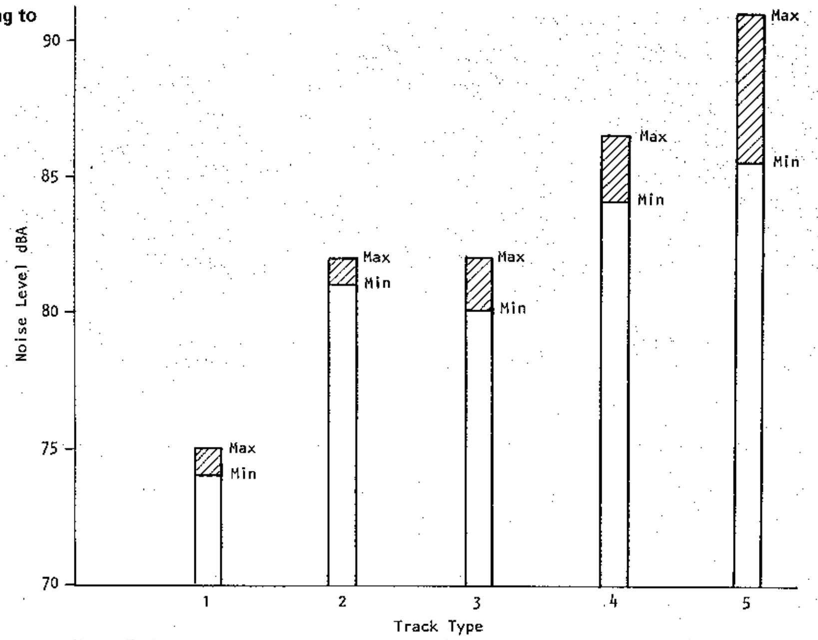
Noise

A major advantage of resilient track is its potential for reducing LRT noise. In 1974, a series of tests was carried out in the Hague to compare sections of the rigid and resilient track used on that system (2). The cars tested were modern Presidents' Conference Committee (PCC) cars, one of them equipped with Bochum wheels, which are commonly used on European LRT systems, and the other equipped with SAAB wheels, which are similar to the superresilient wheels used on U.S. PCC cars. The rigid track tested consisted of girder rail encased in concrete with an asphalt concrete overlay. The resilient track consisted of slab-based track with a cast-in-place concrete pavement and an asphalt concrete overlay. This type of track is widely used in the Netherlands, where it is called Hannover track. Ballast-based track consisting of a sandy track base with earth infill was also tested.

Almost identical tests were performed in San Francisco in 1971 (3) on rigid track only. These tests also used PCC cars, one with Bochum wheels and the other with superresilient PCC wheels. Figure 11 illustrates the data from these two tests; the tests were run at 40 km/h (25 mph), and the noise levels were measured 7.5 m (25 ft) from the track centerline. In both the Dutch and San Francisco tests, the Bochum wheel was found to be slightly noisier than the PCC wheel, except when the tests were performed on curves, where the Bochum wheel proved to be considerably quieter.

In 1973, noise tests were performed on the tracks of the Helsinki LRT system (4). These tests used a variety of vehicles, ranging from modern articulated cars to two-

Figure 11. Comparison of LRV noise level according to track type.



Notes: Track type 1 = sand base, earth infill; 2 = open track (wood ties, no infill); 3 = slab base, concrete pavement (Hannover track); 4 = rigid track (the Hague); and 5 = rigid track (San Francisco).
The range of values reflects the difference in car wheels, test sites (for 5 only), and condition of test cars.

axle cars that were more than 50 years old, on both rigid and resilient track. At the test speed of 40 km/h (25 mph), it was found that the sections of resilient track were approximately 5 dB(A) quieter than sections of rigid track, which seems generally consistent with the findings of the more detailed Dutch tests.

Maintenance

The maintenance of both the track and pavement within 60 cm (24 in) of the rails is generally the responsibility of the transit agency. The life span and maintenance costs for both track and pavement are thus relevant factors. While rail life in excess of 40 years may be achieved, at certain locations (such as passenger stops and curves) rails wear out considerably faster. A significant advantage of track paved with blocks or precast slabs is that the paving material can be removed without the use of an air compressor (and hence less noise); the paving materials can also be reused. Where ballast-based track is used, the track is ready for instant use when it is completed, and it requires no time for concrete to set.

Even if the full rail life of 40 years is achieved, the settlement of the street subbase may require attention to the pavement before the rails are worn out. In such instances, the track and pavement can be readily opened up and repaired without disrupting service, and the paving materials can be reused. By contrast, if wooden ties are used, any significant disturbance of the track often results in the need to replace wooden ties.

Urban Design Treatments

Future applications of LRT are likely to place increasing emphasis on such features as LRT pedestrian malls, which are now widely used in Europe. Resilient track is environmentally well suited to such applications and also offers the opportunity to develop designs that are visually appropriate to such situations. For instance, the paving of the track zone with rounded cobbles in a flush-paved pedestrian zone provides an excellent and unobtrusive reminder to pedestrians not to wander onto the tracks outside the designated crosswalk areas.

CONCLUSIONS

There is a basic difference between paved-track construction practice in North America and in Europe. A variety of track standards are used in Europe. The manufactured components (rails, tie bars, and so on) are generally standardized, but the experience and preferences of the track engineer appear to play a significant role in selecting track design standards.

Consideration should be given to testing some of the more relevant European designs in the United States to determine whether they have any advantages over our present practice and are suitable for U.S. conditions. Because of the lead time required, such tests should be initiated without delay in order that the conclusions may be applied before major investment decisions in this field are made.

ACKNOWLEDGMENTS

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Application of Light-Rail Transit Vehicles

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Flexibility is the primary concept associated with light-rail transit (LRT). This flexibility includes its application, implementation, operation, and capacity and has clear implications for light-rail vehicle (LRV) design, since the capabilities of a vehicle selected for a specific system must meet the requirements of that system. The thesis of this paper is that all such LRT requirements can be met by a family of vehicle designs based on standardized subsystem componentry. System requirements are dealt with in four categories—capacity, geometry, performance, and impact; the vehicle components include the car-body, propulsion, suspension, and command and control subsystems. The alternatives and options within each category are identified, and the matching process is examined. Particular attention is devoted to car-body alternatives; it is shown that the use of single-ended LRVs is desirable whenever system characteristics permit and that articulation is properly used to solve clearance rather than capacity problems. The Toronto Transit Commission's ordering of new LRVs is used to illustrate the process of selecting vehicle attributes that meet the system requirements and the process of moving from a definition of desirable vehicle characteristics through development and testing to car delivery. The ability to derive several vehicle designs from the basic design is discussed in the context of ongoing development activities in order to prove the feasibility of the family-of-vehicles idea.

Numerous definitions of light-rail transit (LRT) have been advanced in recent years to describe the electrically powered, medium-capacity, steel-wheel-on-steel-rail transit mode that is in the midst of a renaissance in North America. At the TRB conference on LRT held in Philadelphia in 1975, LRT was defined as "an urban electric railway having a largely segregated but not necessarily grade-separated right-of-way . . . that provides a medium-speed service for a medium volume of passengers" (1) and as "[encompassing] a wide range of electrically propelled, steel-wheel vehicles" (2). In these and most other descriptions, the key concept is the mode's inherent flexibility with respect to

1. Application—a wide variety of appropriate rights-of-way in urban environments;
2. Implementation—staged upgrading of a minimum system in conjunction with the development of passenger demand;
3. Operation—a range of services, passenger handling techniques, and operating policies; and
4. Capacity—ability to handle passenger volumes ranging from a few thousand to approximately 20 000 passengers/h/direction.

This flexibility also has implications for system costs, since it enables LRT planners to choose from a range of design standards and a variety of techniques for coping with right-of-way and operations problems and thereby to match their system costs to the economic objectives of the transit facility. This discussion is concerned with the implications of this flexibility for LRT equipment and infrastructure, in particular for light-rail vehicles (LRVs).

The thesis of this paper is that the flexibility that is inherent in the LRV concept demands a degree of vehicle flexibility that can best be provided through a family of complementary designs offering a range of capacity and performance but commonality in major components. Producing such a family of vehicle designs depends on major componentry—propulsion, suspension, car body, command and control—that can be efficiently integrated to form the specific vehicles required to meet differing operating requirements. This thesis is in many respects an extension of the approach to vehicle design embodied in the Presidents' Conference Committee (PCC) car. Thousands of streetcars, including many in Europe, were produced by using the same basic PCC body design with modifications, such as increased width and double ending, to suit individual operator's needs. In this paper, commonality is extended beyond vehicle body design to include the major subsystems.

For LRT to be most effective, the specific componentry combination and the resulting vehicle characteristics selected for any application must correspond closely to the characteristics of the LRT right-of-way: stations, geometrics, desired type and level of service, and planned operation. To the extent that operators are able to define similar requirements for transit applications, vehicle standardization is possible. However, if operational circumstances vary, as has occurred in the past and will apparently continue in the future, then a family of vehicles will be required to provide the necessary service. An examination of the nature of operating requirements typically prescribed for LRT systems is instructive in defining the requirements for rolling stock.

OPERATING REQUIREMENTS

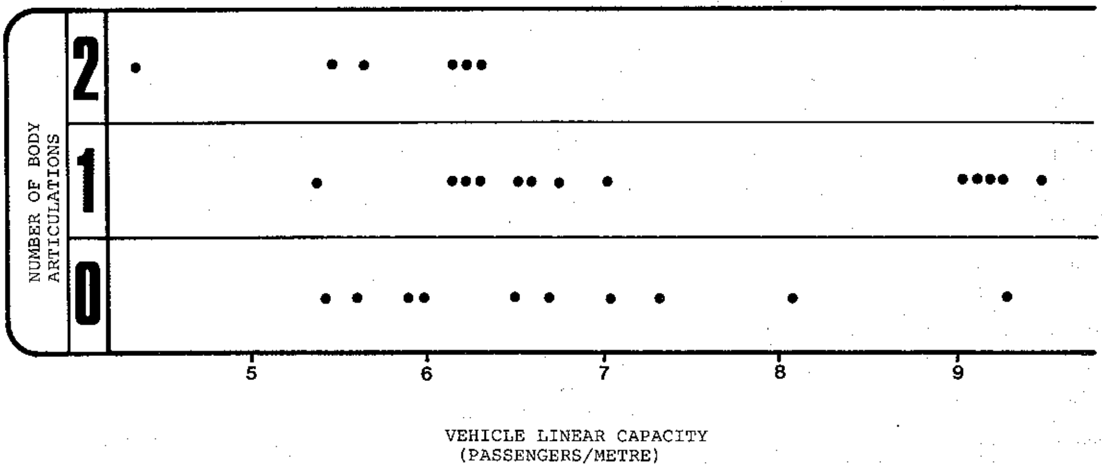
A set of operating requirements or desired characteristics must be established to describe the various circumstances in which LRT systems might operate. The factors that affect the basic LRV design and componentry may be divided into four areas: capacity, geometry, performance, and impact.

The importance of the capacity requirement is clear. Typically, LRT facilities, particularly those with a large percentage of separated right-of-way, are installed to assist the development of economic corridors that have a forecast passenger demand of 5000 to 20 000 passengers/h/direction. Traffic volumes below 5000 passengers/h/direction are usually more economically served in the long run by mixed-traffic modes. Conversely, concentrated loadings above 20 000 passengers/h/direction that cannot be distributed over two or more transit facilities are sufficiently great to require and justify full-scale heavy-rail transit (HRT) systems. A major difference between LRT and HRT may be found in the issue of flexibility; HRT can be thought of as an ultimate development of LRT—a very high-capacity rail system employing large-capacity vehicles, prepaid passenger and high-platform station design, fully exclusive rights-of-way, and high performance standards. By definition, rail systems designed to serve 5000 to 20 000 passengers/h/direction fall within the LRT range. The breadth of this service range is indicative of the flexibility of the concept and technology. The capacity requirements of individual applications affect the selection of car-body size and configuration and the command and control vehicle equipment options.

System geometry requirements include the right-of-way characteristics that distinguish each application—the available right-of-way width, the length and severity of grades, the minimum radii of curves on the line and in yard and storage areas, the permissible overhang and clearances, the design of terminal and turnback areas, and the degree of right-of-way separation and protection from other traffic and pedestrians. These influence car-body, command and control, and propulsion componentry.

The performance requirements of interest are the

Figure 1. Relationship of linear LRV capacity to body articulation.



rates of acceleration and deceleration, cruise speed, limitations on ride comfort, and the ability of the vehicle to maintain prescribed levels of service under a variety of conditions. These performance requirements define the capabilities demanded of the vehicle's suspension, propulsion, and command and control systems.

Environmental and community impacts are important elements of transit system design, particularly at a time when citizen involvement in the planning process is common. Control of noise, vibration, visual impact, community disruption, and intrusion are facets of this problem. Requirements associated with alleviation of impacts can affect all four categories of vehicle componentry.

VEHICLE COMPONENTS

Selection of vehicle configuration, performance standards, and component subsystems depends on the operating requirements of the system in which the vehicle will be used. In addition, the selection process must include consideration of the cost associated with each potential design. Cost trade-offs occur both in the areas of capital and operating costs and in the determination of overall life-cycle cost. In most circumstances, costs accurately reflect the suitability of the match between system requirements and vehicle characteristics; they are thus excellent arbiters of vehicle design. With this type of selection process in mind, it is instructive to examine the design options within each component group. This will illustrate the process of matching vehicle attributes to system requirements.

Car-Body Configuration

The selection of a car body includes decisions about dimensions, frame configuration, directionality, and passenger access and egress. In general, the vehicle dimensions in both length and width will be as large as possible in order to increase the productivity of equipment and labor. Upper limits on vehicle width depend on the available clearances in tunnels and other constricted zones and the distances required between vehicles on curves and in normal roadway traffic lanes. With respect to minimum width, the North American habit has been to strive for a vehicle width that will permit 2 + 2 transverse seating with an appropriate aisle space. This leads to minimum exterior car-body widths of slightly more than 2.5 m. By comparison, many European LRVs have been designed for 2 + 1 transverse seating with a side aisle for circulation and standees; this leads to a vehicle width of 2.1 to 2.3 m. Maximum car-body length is determined by clearances on curves and by vehicle structure limitations. Truck centers on the order of 7.5 to 12.0 m, corresponding to rigid body lengths of 15 to 20 m, have proved to be acceptable for the clearances found in most applications.

If greater vehicle capacity is desired for a given system than that available in the longest permissible single-unit rigid car, then a third truck and articulation joint can be added to effectively reduce the spacing of truck centers. Articulation arose in Europe, where the narrow streets and tight corners precluded the use of long, wide, rigid cars. In most instances, the additional capacity (primarily standee space) offered by articulated body designs is only marginally greater than that of the longest rigid car designs; the complexity of articulation therefore need only be added to overcome clearance constraints rather than to increase capacity. This characteristic is illustrated in Figure 1, which plots LRV passenger capacity per unit of car length. The graph, based on 29 European and North American LRV designs (3), indicates that linear capacity does not depend on the addition of body articulations.

Car directionality is determined by the availability of right-of-way for construction of turnback facilities. In most LRT applications, it is desirable to use single-ended vehicles, since the loss of capacity associated with double-ended cars is substantial. There is typically a 10 to 20 percent increase in fleet capital cost for equal capacity operations. Double-ended vehicles are economical only for applications in which the amortized cost of loops at all regular service and emergency turnback points exceeds the annualized equivalent of the substantial capital and operating costs for the vehicles. The table below presents the results of a comparison of costs for an LRT operation designed to provide service for 10 000 passengers/h/direction over a 16-km reserved right-of-way line.

Item	Single-Ended LRVs	Double-Ended LRVs
Vehicle capacity	157	150
Fleet size	88	93
Annual vehicle kilometers	8 190 000	9 720 000
Annual vehicle hours	250 000	300 000
Annual fleet operating cost, $	4 090 000	4 690 000
Annualized fleet capital cost, $	6 520 000	7 150 000
Total annual cost, $	10 610 000	11 840 000

The annual difference in costs associated with the purchase and operation of single-ended and double-ended versions of the same articulated LRV under identical operating rules, including schedule speed of 32 km/h and station fare collection, in this example is $1 230 000. The capital cost equivalent of this sum (at 8 percent/year over 20 years) is $13 000 000. This is the value of the capital expenditure that could be devoted to loops for a single-ended LRT facility, over and above the value of turnbacks and crossovers, at no additional total expense over that for a double-ended system. Each LRT facility will have a substantial cost penalty of this type associated with double-ended cars; in many cases loops will offer an attractive financial alternative.

The car-body options for passenger access relate to doorway design, height of stepwells, and fare-collection procedures. The selection of alternatives here must take into account the station infrastructure (platform heights throughout the system and the fare-collection procedures) and the passenger volumes expected. To reduce dwell times, it is always desirable to use honor-system, self-service, or station fare collection in conjunction with high-level platform loading. However, this is not always practical for on-street operations, and the reduction in dwell times (and thus operating cost) then can be realized from reducing the service time per passenger is so small that the capital cost of such options can usually only be justified for systems that have passenger volumes at the upper end of the LRT range. Provision of mixed-height platforms to meet special circumstances, e.g., high-low loading, will add to vehicle and station costs and will undoubtedly create operational and maintenance complexity.

Propulsion

The primary propulsion componentry choices that are sensitive to system operating requirements relate to the motor and control package, braking techniques, and power collection. The direct-current rotary electric motor with mechanically driven wheels has been the standard propulsion system in the LRT industry. Recently, alternative motor control hardware that provides a choice among mechanical, partially electronic, or totally electronic technology has become widely available. The primary differences among these systems are found in the potential energy savings possible with the totally electronic system. As a result of both reduced power draw during acceleration and the ability to return power to a receptive line during deceleration, energy savings as large as 30 percent (in comparison with PCC technology) may be realized. The opportunities for savings of this magnitude occur where there is a dense network, frequent service, and downtown street operations equipped with appropriate power distribution facilities, such as in Toronto. Smaller savings would be achieved on isolated individual LRT lines, especially during off-peak hours.

Braking requirements are much more sensitive to system performance requirements than is the propulsion package. Electrodynamic motor braking, friction shoe and disc braking, and magnetic track brakes are among the alternatives. In general, brake reliability and power must increase with increasing vehicle frequency. This relationship arises from the need for greater braking confidence when operating at close vehicle spacings and is manifested in the increased use of backup systems. Furthermore, braking power requirements increase as the degree of right-of-way protection decreases, particularly if such decreases result in mixed-traffic operation. These requirements typically lead to the provision of simple, reliable emergency service brakes.

The power collection technique is directly related to the right-of-way characteristics. Third-rail power collection eliminates the need for trolley-wire support structures and reduces the visual impact, but it is usually only feasible when the entire system right-of-way is fully exclusive and protected. Otherwise, overhead collection by trolley or pantograph must be employed. Generally, pantographs have superior tracking and current characteristics and are suitable for most new systems. The overheads of existing systems may be designed around the trolley shoe and may therefore have to retain this equipment.

Suspension

Suspension options relate primarily to truck design and, while most suspension design decisions are based on ride comfort, stability, maintenance, and propulsion integration factors, measures are available to minimize interior and exterior noise and vibration. In response to increasing concerns about environmental noise, urban rail vehicles are now being fitted with wheels, axles, and trucks that are designed to reduce noise and emissions. In particularly restrictive situations, further improvements are necessary in the suspension design and in its interface with the guideway. These improvements include superior wheel and rail standards and, potentially, the use of steerable trucks to reduce wear and squeal in curves. The choice of hardware for specific applications is clearly dependent on the acceptable impact level in the environment in which the vehicles are to be used.

Command and Control

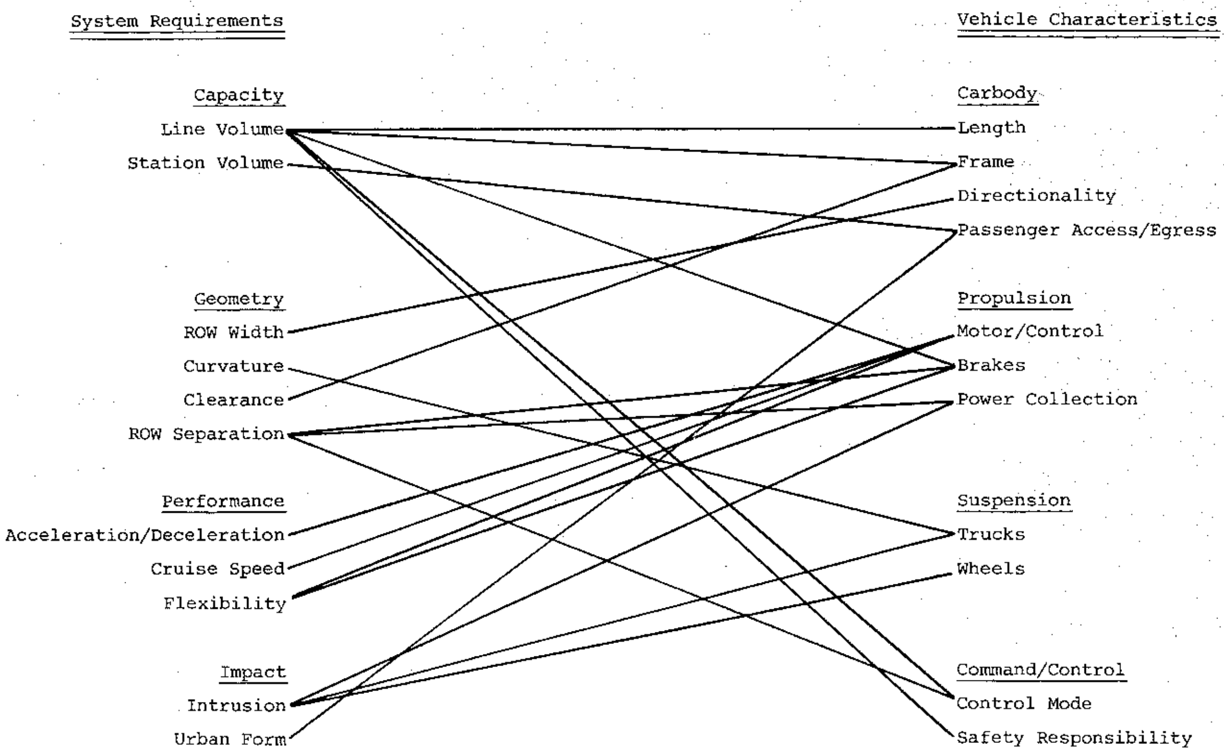
Vehicle or train control alternatives range between fully manual and fully automatic vehicle operation and protection. If the right-of-way is not protected from pedestrians and vehicular traffic, then a manual control capability must be provided. If sight lines are poor or headways are sufficiently short to raise safety concerns, then automatic train protection may be needed. If headways are shorter than human operators can deal with, then automatic train operation may also be necessary. Conversely, if the required capacity is low so that headways may be relatively long, there is generally no need for more than strictly manual command and control. A command and control choice that appears to be finding increasing use in unprotected rights-of-way designed for operations at moderate headways is the use of cab-signal command displays with manual vehicle control, complemented by automatic train protection vested in the system. For most LRT facilities, command and control and safety requirements are fixed by the nature of the application and are not subject to cost trade-offs.

Summary

The major elements of LRT system requirements and vehicle characteristics are shown in Figure 2. Several of the important interactions are indicated on this chart; many more occur at the more detailed levels of vehicle design and selection.

The above overview is representative of the range of LRT options within which LRV designs must be formulated. One effective technique for achieving a range of vehicle designs responsive to varying requirements is to develop a family of designs based on common componentry. The process required to implement this technique, moving from the definition of system requirements to hardware development and testing, illustrates

Figure 2. Interactions between system requirements and vehicle characteristics.



the matching of requirements and equipment. The process entails several sequential steps:

1. Define system characteristics and resulting vehicle requirements;
2. Formalize design criteria and specifications;
3. Evaluate and procure subsystem componentry consistent with the specifications;
4. Finalize the design and produce and test prototypes; and
5. Manufacture, test, and deliver production vehicles.

Each of these steps must be pursued for each vehicle design, but obvious economies can be realized through component commonality and design flexibility. Separation of the steps permits selection and application of skills and resources in the most effective and efficient manner.

TORONTO'S NEW LRV

In November 1972, the Toronto Transit Commission (TTC) decided to retain, and possibly expand, its streetcar and LRT operation. This decision created a requirement for a new fleet of LRVs to provide the base service on TTC's system through the 1980s and 1990s. System characteristics that affect vehicle design were well defined by the features of the existing Toronto operation. Thus the baseline clearances, geometrics, passenger capacities, performance capabilities, comfort levels, maintenance standards, and noise requirements were determined for the new fleet. In addition, it was considered desirable to improve on the performance of the existing PCC cars wherever possible, particularly in the key areas of energy use, passenger amenities, and maintenance and reliability standards, as well as to build into the fleet sufficient performance flexibility to be able to operate over any new territory and to new service standards that might arise as a result of system expansion into the metropolitan Toronto suburbs. These concerns resulted in a clearly defined set of requirements for a fleet of new LRVs.

Formalization of the vehicle requirements into a technical performance specification was a key element of the process. It was essential that the specifications be an effective marriage between the requirements of the system and the operator and the capabilities of proven state-of-the-art transit technology. In a yearlong undertaking similar in many ways to the Urban Mass Transportation Administration's LRV design process of the early 1970s, design criteria were established to reflect the evolution of expectations and technologies that has occurred since production of the PCC cars. On the basis of these criteria and in close cooperation with the TTC, initial vehicle and component specifications were developed and reviewed.

When the required vehicle capabilities and performance levels were well defined, component manufacturers were asked to indicate their ability to supply the necessary vehicle equipment. This was done before the detailed design was established, in order that the widest selection and greatest flexibility of componentry would be possible. This equipment flexibility is essential to the concept of a family of vehicles. Equipment that meets the Toronto fleet requirements has been selected and will be furnished as free issue to the car builders.

The process of converting general specifications and subcomponent characteristics into the specific details of vehicle design with all its interfaces was identified as a separate task from the actual production of the vehicle. An experienced European LRV designer was selected in competitive bidding to assist in design, detailed specification, and proving of prototypes. The design has now been finalized, and the first vehicles are in the testing stage. Six prototypes are scheduled to have completed European testing and to be delivered to Toronto in late 1977 and early 1978. These six prototypes are the forerunners of 190 cars to be produced by a Canadian car builder. The car builder's responsibility will be to fabricate the body and trucks and to integrate the subsystem componentry by using production tooling designs developed for the prototypes wherever possible. Production and delivery of the 190 cars will be effected from 1978 to 1980.

The LRV that is emerging from this process is 15.4 m long and 2.6 m wide over the rub rails. The interior layout selected by TTC provides 47 seats, with standee space sufficient for 43 to 78 additional passengers, depending on comfort level. The maximum number of seats that can be provided is 58. It is a rigid, four-axle single-ended car geared in the TTC configuration for a maximum speed of 80 km/h. In private right-of-way operation, the propulsion system is capable of higher speeds. Acceleration levels allow the car to reach 80 km/h in 30 s, while deceleration is 1.5 m/s^2 in service and twice that in the emergency mode. In order to conserve energy and reduce the vehicle's life-cycle cost, the car is equipped with an electronic chopper motor control and a regenerative braking system. Regenerative and rheostatic electrodynamic braking is supplemented by a friction disc system that is capable of handling all braking requirements on a continuing basis. The propulsion and brake systems have plug-in diagnostic features to aid preventive and line maintenance.

Passenger comfort is enhanced by an outboard frame truck that has steel and rubber primary suspension and load weighing. A forced-air ventilation system provides interior comfort with or without a full air-conditioning package. Interior noise reduction is accomplished by the use of extensive acoustical insulation throughout the car, and both interior and exterior noise are controlled through the use of resilient wheels.

The vehicle represents an improvement in light-rail safety standards. Specific safety features to benefit both the driver and the passengers include system indicator displays, a raised control platform, provision for cab signaling, a bottom step 25 cm high, emergency escape windows, and obstruction-sensing doors.

FAMILY OF LRVS

An awareness of possible future LRV needs has resulted in the inherent flexibility and potential for growth that were built into the design. The additional propulsion capability, for example, can be used to increase either the maximum service speed or the vehicle weight and payload. The greatest flexibility is that afforded by modular design and fabrication of the car shell. Because the entire body structure is formed by joining a set of door, end, and body shell modules, the vehicle can be lengthened, widened, or otherwise reconfigured very easily. This flexibility permitted the design and construction of two six-axle articulated cars based on the shells, trucks, motors, and other components of the basic Toronto car.

These articulated prototypes will be 23.5 m long and single ended, and they will carry, in an interior layout similar to that of the TTC car, 63 seated passengers and 78 to 141 standees. They will be delivered to the Transit Test and Development Centre near Kingston for testing and analysis in the third quarter of 1978. The design capability being demonstrated in this prototyping program is the ability to provide vehicles, based on the same set of components, that are suited to different operating requirements. These particular prototypes represent vehicles that would find application on LRT systems that are required to carry substantial passenger volumes but are subject to restrictive horizontal clearances (e.g., older systems originally designed for short cars or new facilities constrained by existing urban infrastructure).

For LRT systems in which relatively large volumes of passengers must be carried but clearance is not a problem, a long rigid car presents the most economical alternative. Based again on the car-body modularity and the propulsion capabilities of the 164-MW monomotor truck, it is possible to stretch the vehicle length to approximately 20 m. This obviously enhances capacity and productivity in a high-density application. Apart from different under-floor equipment layouts and minor changes associated with the details of specific operator and operating requirements, there are few hardware differences among the vehicles developed in this family concept. They can all make use of the same shell components and truck, suspension, propulsion, door, and ventilation subsystem componentry. In different configurations these components yield a variety of designs, each suited for a different specific subset of LRT operating conditions. While it is not realistic to expect operators to abandon the operational and maintenance advantages of a single-vehicle fleet in favor of fleets of different vehicles corresponding to each different route circumstance, it is possible with a family of designs to provide alternatives from which the operators can select the one or two vehicles best suited to their needs.

It is the ability to design and deliver a variety of vehicles such as these, based on the same components and each responsive to a specific need, that leads to the conclusion that a family of complementary LRV designs is feasible and provides the flexibility necessary to meet the varied requirements of LRT without incurring diseconomies of small production scale. The family-of-vehicles design approach can provide a high standard of vehicle types for a variety of LRT applications.

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Power Supply for Light-Rail and Rapid Transit Systems in Germany

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The purpose of this paper is to define the present state of the art in the design of the power supply for light-rail and rapid transit systems in Germany. The scope includes the incoming alternating-current switchgear, rectifier direct-current switchgear, catenary, and third-rail systems, as well as the breaker on the light-rail vehicle. Attention is paid to the problems of coordinating the various components of standard design and of dealing with corrosion due to the leakage of current from the power supply. Experiences with various catenary designs and their interconnections in Germany are also described. This paper is limited to experience in Germany, and the underlying design criteria are based on German electrical regulations. Since the implementation and reliability of power supply for light-rail and rapid transit systems in Germany are considered to be highly successful, the data, views, and experience presented in this paper should be of interest in North America.

The long years of development in light-rail transit (LRT) and rapid transit systems have led to definite and proven system parameters. This paper covers the latest power-supply system concepts in Germany.

LRT systems generally use 600-V or 750-V direct current, although in the development of more modern, attractive, and powerful systems, there is a trend toward using 750-V direct current. The allowable voltage tolerances according to the German regulations for electrical transportation (VDE 0115) are 70 to 120 percent of the rated voltage. In order to allow as high a voltage drop on the catenary system as possible (to permit the maximum distance between rectifier stations), the full-load terminal voltage rating of the rectifier should be 10 percent higher than the rated voltage of the vehicle.

The transformation of the three-phase high voltages of the utility network is carried out by rectifier substations equipped with specially designed modern silicon rectifiers. These are strategically located along the LRT line; the intervals are based on energy distribution criteria and economic calculations. The electrical connection between the rectifier substations and the light-rail vehicle (LRV) is made through a catenary system.

SHORT-CIRCUIT PROTECTION

Short-circuit protection of each section of the line is provided by properly dimensioned direct-current high-speed breakers located in each of the rectifier substations.

Catenary Systems Energized From One End Only

If such technical parameters as the power demand, speed limits, and substation intervals permit, single overhead wires are used, even in today's densely populated areas. These wires have, in most cases, a maximum cross section of 120 mm^2 in order to keep the architectural environmental pollution to a minimum. The actual resistance of the overhead wire is usually reduced through parallel connections for both directions of travel on double track. Interconnections at regular intervals along the line serve to provide equal current distribution in both overhead wires. Both of these overhead wires can then be switched and protected by only one direct-current high-speed breaker. The simplicity of this electrical constellation is, however, coupled with the disadvantage that the two directions are interconnected, which necessitates their total isolation in cases of short circuits or other interference. If a sufficient cross-sectional area per direction can be provided by an additional wire, as in a compound catenary, or if the third rail, which has a relatively large cross-sectional area can be used, both directions can be electrically separated, so that in cases of disturbance, such as a short circuit, only one direction is affected.

Short-circuit protection is relatively simple to accomplish on catenary systems that are energized from one end only. If a voltage drop of 70 percent of the rated voltage occurs under the rated LRV load at the most distant point on the line from the rectifier substation (where the terminal voltage is set at 1.1 times the rated voltage), then the short-circuit current at the end of the line would be 2.75 times the normal operating current. Even if this factor is not reached because of the characteristic impedance of the power supply, a trip-current setting on the breaker can be set to trip at a current approximately 20 percent higher than the maximum operating current, which would still lie well below the lowest short-circuit current.

Catenary Systems Energized From Both Ends

To improve the voltage stability along the line, especially when high traction power is required, double-ended energization may be installed. In this case, the line catenary between two rectifier substations is simultaneously energized from both substations, which are connected by one high-speed breaker at each station. If, for example, the cross-sectional area of the catenary wire and the substation intervals are the same as those for a catenary system that has single-end feed, double-ended energization both reduces the voltage drop along the line and diminishes the catenary power losses. Furthermore, it permits equalized loading of the rectifier substation.

The optimum design length for double-fed catenary is not determined by the maximum voltage drop that can be tolerated for an LRV's current load but rather by the short-circuit protection that is needed, as is shown in Figure 1. A symmetrical catenary with homogeneous line resistance between two stabilized rectifier substations that feed at a voltage 10 percent higher than the rated vehicle voltage is shown in a schematic diagram. The curve I_{S1} represents the short-circuit current fed from the left rectifier substation and limited by the line resistance. The trip setting of the direct-current high-speed breaker S1 is set so that the level of the short-circuit current at the right end of the line is more than 20 percent over the set value; this will provide sufficient protection. If this maximum load is allowed by the breaker trip setting to move along the catenary, the partial current supplied through breaker S1 is represented by the line I_{S1}. The voltage drop due to this current load is depicted by the curve U. The lowest level in the middle of the line is 87 percent of the rated voltage. The limit of 70 percent of the rated voltage, allowable under normal operation, has not been encroached on. A similar load relationship exists for the right rectifier substation.

Tie-Breaker Application

By applying a direct-current high-speed breaker as a tie breaker in the middle of the catenary system, a tighter layout with respect to short-circuit protection and stable voltage conditions can be achieved. Again, assuming a symmetrically designed network, a homogeneous line resistance, and a stabilized substation voltage of 110 percent of the LRV-rated voltage, the curves shown in Figure 2 would apply. With full use of the allowable voltage tolerances and double-ended catenary energization, the maximum allowable operating current (I_{max}) can be extracted at the midpoint. This current can be assumed to be a wandering load along the length of the complete catenary. The resulting partial current flowing through breaker S1 and the voltage drop caused by the load are represented by the straight line I_{S1} and the curve U. The overcurrent trip of the breaker S1 is set at the maximum permissible current (I_{max}) and the overcurrent trip of the tie breaker S2 is set at one-half this value. The curve I_k shows the short-circuit current flowing through the breaker S1; its location depends on the location of the short circuit. A comparison of the trip settings and the short-circuit current, which is situated at the critical short-circuit distances (catenary middle for S1 and catenary end for S2), shows that the

Figure 1. Short-circuit protection and voltage regulation in section that has power supplied from both ends.

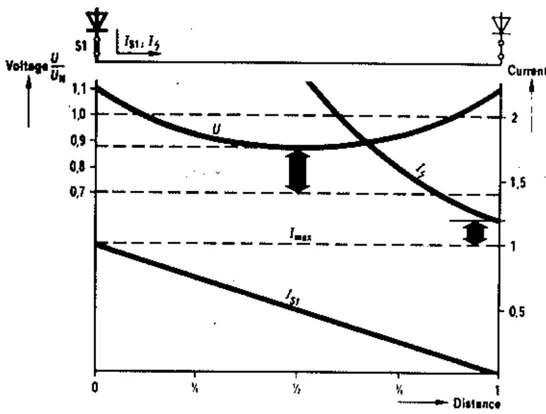
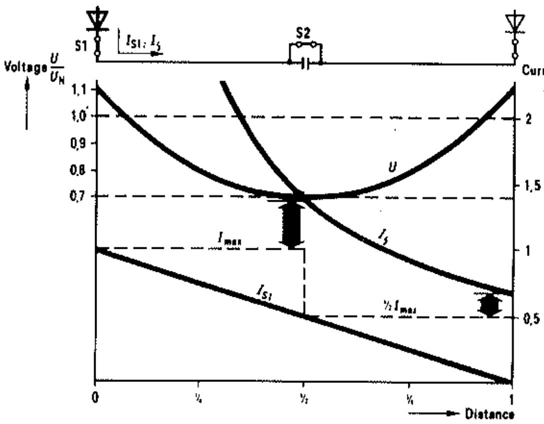


Figure 2. Short-circuit protection and voltage regulation in section that has power supplied from both ends and a tie breaker.



final value of the short circuit still exceeds the tripping value by 37.5 percent. Short-circuit protection is therefore fully guaranteed even with allowances for the rectifier characteristics, the tolerances, and slight asymmetry. The same conditions apply for the high-speed breaker of the right substation.

Cross-Tie Positions

If the catenaries are separated with respect to direction and are fed from both ends, then ties for both cross connection and longitudinal connection can be located in the middle of the catenary system. Such complicated ties are usually made up of four direct-current high-speed breakers and one disconnect switch. Practical experience has shown, however, that there are more advantages to a simple network constellation that has good overview and reduced distances between substations rather than cross ties. The conditions shown in Figure 1 then prevail and result in lower transmission losses, better voltage stability, and reduced danger of leakage current than for tightly interconnected networks. A reduction in voltage drop for LRV operation can be accomplished by the use of chopper control with regenerative braking.

REDUCTION OF CORROSION DUE TO LEAKAGE CURRENT

The traction current of the LRV causes a voltage drop not only in the overhead wires but also in the rails being used as conductors for the return current. Although the relative voltage drops in the rails are considerably lower because of the cross-sectional area available, leakage currents and the danger of resultant corrosion nevertheless exist. Because of the negative direct-current polarity to the rails, leakage currents stray into the surrounding earth, buried metal pipes, and metal construction reinforcements, and they then return to the rails or the connecting conductors in the area of the rectifier substation. After years of operation, destructive corrosion may occur at the points of current discharge; the amount depends on the current's density and duration. Decades of effort on the part of authorities operating direct-current traction systems and corrosion-endangered utility systems and support from various research institutes and commissions led to the issuance in August 1975 of DIN regulation 57150 and VDE 0150. These regulations apply to all operations of direct-current systems that allow leakage or stray currents. In addition to this, the new regulation VDE 0115a on the reduction of danger caused by return currents in direct-current rail traction systems summarizes the protective requirements and regulations specified for rail systems. All technically and economically feasible protective steps and upper measurement values are listed; these are recognized as the maximum justifiable precautions that should be used to combat corrosion danger. Planning teams for new rail systems are required to carry out a preliminary calculation of the leakage current conditions. Guidelines for these calculations are published and are available for the planning engineers.

After completion of construction and commissioning, the potential differences that appeared to be critical in the calculations must be measured. If the actual values deviate too widely from the calculated values, the cause of deviation must be ascertained. The combination of preliminary calculations and actual measurement will reveal that, for example, if high discharge currents in the track network occur because the resistance of the track ballast is too low, only small differences in the potential will be measured. The regulations list 20 points, proposing a wide variety of corrective procedures and limitations. A list of some of these regulations and recommendations follows.

1. The resistance of the track ballast (the quasi-isolating superstructure of clean ballast, wooden ties, isolating barriers, and so on) should be high.
2. The rails may not be directly connected to ground structures.
3. The rectifier substation intervals should be small.
4. All conductors and cables connected to the rails must be insulated for at least 0.6 kV.
5. The return-current busbars of the rectifier substations must be insulated against the ground.
6. If the negative polarity of the rectifier voltage is connected to the rails, the amount of corrosion protection may be reduced.
7. The portion of resistance caused by the rail bonds must not exceed 15 percent of the total resistance. The resistance of one bond may not exceed the resistance value of 5 m of track.
8. The use of salt or brines for treating snow and ice conditions should be avoided.
9. A distance of at least 1 m must be maintained between track and conductive civil works structures.
10. The longitudinal resistance of tunnel structures must be minimized and the track-bed resistance maximized so that the difference in potential within the tunnel structure is kept to a minimum. If the maximum operating current is flowing in the rails, a maximum difference in potential of 0.1 V is allowed throughout the complete tunnel length and the connection-point area.

Since these regulations have been in effect, all lines and tunnels have been planned and built accordingly. Such features as easily accessible track bonds at the tunnel entrances and multiconductor cables to measure the potential are being included to facilitate measurement of current after periods of revenue service. The problem of corrosion from current leakage in rail systems cannot be declared solved; it is still undergoing progress and investigation. It is necessary to follow the continuing addenda to these regulations and recommendations to keep abreast of developments in this area.

CATENARY SYSTEMS

Various catenary systems have been designed to cope with different maximum speeds, current loads, and structural conditions.

Single Overhead Conductor

The use of a single overhead conductor for speeds up to 50 km/h has proven sufficient in most cases. The simplest design uses a simple catenary with drop-wire suspension approximately every 15 m; both ends are anchored. Temperature expansion leads to an increase in the sag of the conductor, which must be compensated for by the vertical travel range of the pantograph. A catenary system that uses fixed tensioning allows a longer distance between poles or structure supports. A network of this type of suspension provides an elastic overhead conductor suspension.

Under moderate traffic density, it is possible to use an automatically tensioned weight-and-pulley overhead conductor suspension for speeds of up to 70 km/h. Automatic tensioning guarantees a constant sag. The relative longitudinal movements of the conductor are not hindered in this design. The elasticity of the system is improved through the distribution of weight by angular drop wires. The horizontal positioning of the overhead is carried out in a zigzag formation from support to support on straight stretches; it is positioned on curves by the addition of curve-tensioning guy wires as shown in Figure 3 to ensure even wear on the pantograph collector.

Compound Catenary Design

A compound catenary system (Figure 4) is installed on lines that have speeds of more than 70 km/h. The full-length messenger wire serves to support the actual overhead conductor, as well as to increase the electrical conductivity by offering a higher cross-sectional area. Vertical drop wires between the horizontal supporting catenary and the overhead conductor are placed at relatively short intervals—10 to 12 m—in order to practically eliminate sag of the contact conductor; this ensures good contact between pantograph and conductor even at high speeds.

It is possible to use two supporting catenary wires for higher current loads. If a heavy power demand is required by a stopped LRV (because of the needs of its heating or air-conditioning systems, for example), it is recommended that two overhead conductors be installed. The overhead conductors are normally automatically tensioned, whereas the supporting wires can be either fix anchored or automatically tensioned.

The compound catenary system offers the best capacity with respect to current-carrying capacity and dynamic transmission. It is preferred for heavily loaded lines that use high speeds and is recognized as today's standard equipment for modern urban and LRT systems.

OVERHEAD CONDUCTOR IN TUNNELS

Overhead conductors were designed for use in tunnels where the available height made it impossible to use a catenary system such as those previously discussed. The design shown in Figure 5 can be applied in tunnels and under bridge girders, for example. The design of the elastic cantilever support shown in Figure 6 allows automatic tensioning through the cantilever arm's capability for horizontal movement. The height of the overhead conductor can be adjusted at the base of the arm. A pretensioned cylindrical rubber insert absorbs the forces exerted by the conductor and also offers the required elasticity. If additional current-carrying capacity is required, further parallel conductors can be mounted on the tunnel roof or wall and crossconnected every 30 to 50 m.

THIRD RAIL

The third-rail is usually selected to supply the current for the heavy power demand of subways (Figure 7). Its cross section is much larger than that of an overhead conductor. Its design is simple, robust, and dependable in operation. The third rail is located adjacent to the rails (Figure 8) and is supported approximately every 6 m. The LRV current collector can operate on any face of the third rail, but in Germany collection from the bottom surface is preferred. A cover of polyvinyl chloride is installed in order to provide protection against accidental contact.

The standard steel third rail (according to DIN regulation 43156) has a current-carrying capacity of up to 300 A, and a cross-sectional area of 5100 mm^2. The higher power demand of future rail vehicles will require the use of alloys (steel and copper or steel and aluminum) in rail manufacture to improve the conductivity. The third rail is manufactured in sections 180 m and 90 m long and welded together on site. Separations and transitions are required at switches and crossovers. Expansion joints (to compensate for temperature changes) are incorporated at appropriate intervals along the rail. Isolating insertions permit electrical sectioning. The length of the isolating pieces depends on the dimensions of the LRV collector.

The cable from the substation is connected to the

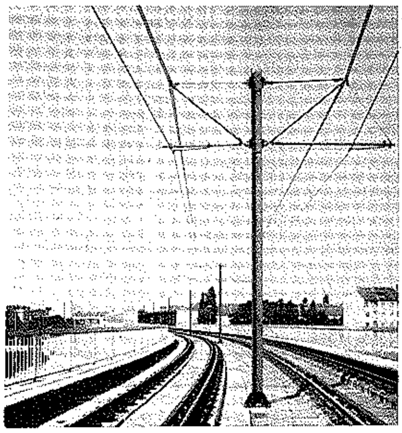


Figure 3. Simple catenary with two messenger wires and fiberglass cantilevers.

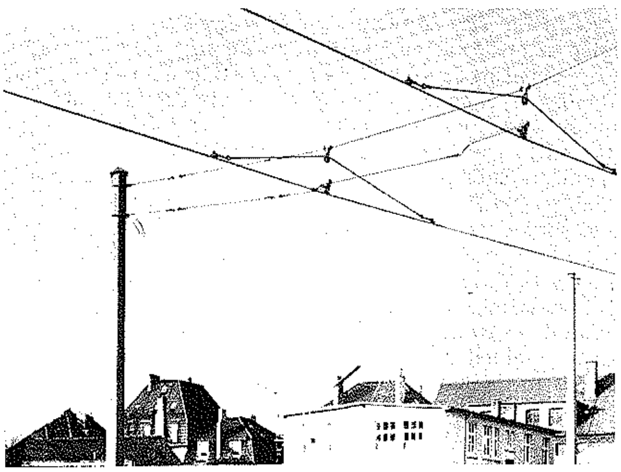


Figure 4. Automatically tensioned trolley wire with bridle and pulley.

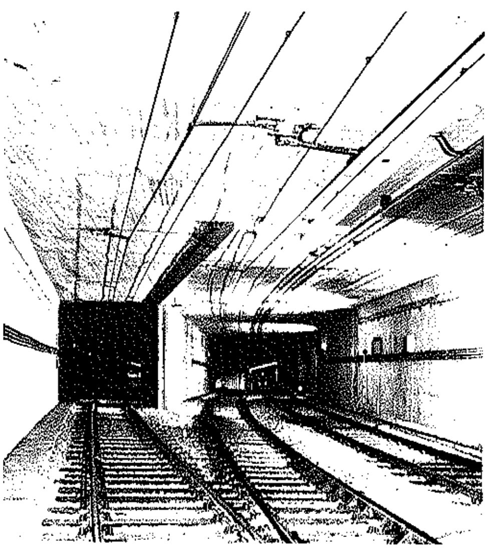


Figure 5. Overhead current supply in a tunnel.

Figure 6. Elastic cantilever support.

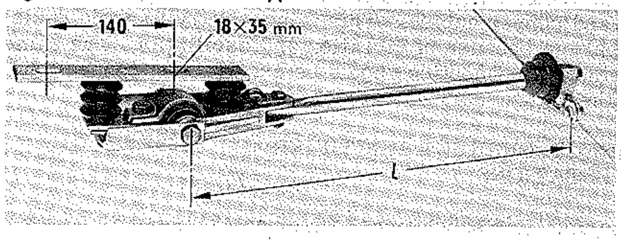


Figure 7. Third-rail power supply system with polyvinyl chloride protection.

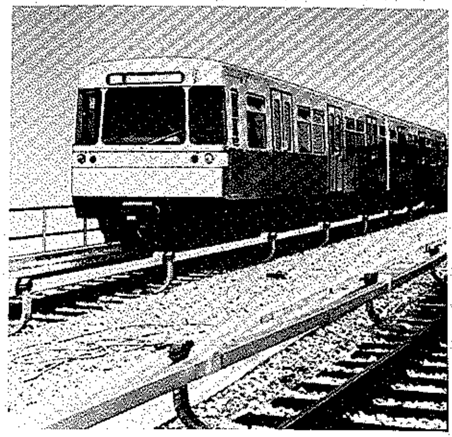


Figure 8. Third-rail systems with top contact, side contact, and bottom contact respectively.

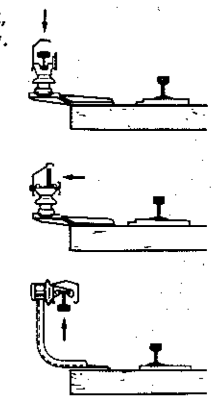
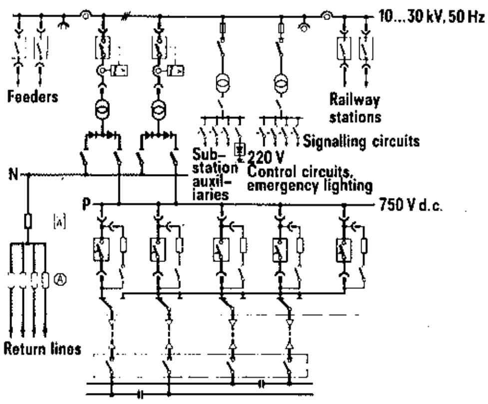


Figure 9. Basic circuit diagram of a rectifier substation.



rail by a bushing, which divides into several many-strand copper cables. This is necessary to avoid cable breakage because of vibration and oscillation. The same method of connection should be used for the connection of the return-current cable.

DIRECT-CURRENT RECTIFIER SUBSTATIONS

The rectifier substations, which are situated along the rail line, are either enclosed in their own housings or integrated with other facilities. When they are located in tunnels, it has proven advantageous to use the space available at the end of the passenger loading platforms. If the stations are located on the surface, the utilities may use prefabricated station housings. Space requirements, accessibility, ease of maintenance, operating safety, and the safety of personnel should be taken into account in the design of stations. The basic design of a standard rectifier substation is shown in Figure 9. The principal electrical components can be grouped as follows:

1. Incoming high-voltage alternating-current switchgear;
2. The rectifier unit, consisting of a rectifier transformer and the rectifier;
3. Load-side switchgear with direct-current high-speed breakers to provide direct-current short-circuit protection;
4. An auxiliary station supply, backed by an emergency battery supply for underground stations; and
5. High-voltage switchgear to supply station equipment.

RECTIFIER UNIT

The heart of the direct-current power supply system is the rectifier transformer and the rectifier, which together constitute the rectifier unit (1). Each unit is switched by a high-voltage breaker equipped with an overload time delay and a bimetal relay to protect the rectifier against short circuits in the network. Several rectifiers can be located side by side and connected in parallel should the power demand require this. Three-phase bridge connections like that shown in Figure 10 are most commonly used. Modern diodes, which have peak inverse voltages of 4 kV, permit rectifiers designed to handle up to 1.8 kV direct current with only one diode in the reverse direction. The diodes are connected in parallel and their quantity is determined by the individual current ratings and class. For rail operation, classes for up to 10 kA are used. A fuse is connected in front of each diode so that, in case of dielectric breakdown, only the faulty diode is disconnected and the total operation is not interrupted. Reverse current transformers register the current flowing up to the point at which the fuse melts; this provides a record of the breakdown of a diode. The rectifiers are protected against high-frequency overvoltages by means of a resistance-capacitance filter on the direct-current load side.

The design of a self-cooled rectifier (Figure 11) should incorporate only a few supporting insulators to provide ease of maintenance, dependability, and lack of sensitivity to dirt. A standard sheet-metal enclosure is recommended to protect operating personnel from making accidental contact with parts that are carrying current. The specially designed heat sinks for these self-cooled rectifiers are made out of diagonally cut extruded aluminum. The 45° diagonal cut of the cooling ribs, as shown in Figure 11, provides an excellent chimney effect and proper channeling of the cooling air. The stacked rectifiers all belong to one branch of the rectifier arm, which is connected in parallel to the vertical busbar. In the illustrated rectifier cubicle, the alternating-current connections are at the top and the direct-current connections at the bottom.

Figure 12 shows the rectifier cubicle for the Munich subway, which is rated at 3 kA. The vertical buses, which have diode fuses, are recognized very easily. The measurements of this cubicle are width = 900 mm, depth = 800 mm, and height = 2200 mm. The rectifier transformers in the substation should be specially designed to ensure long life and dependability. There is a tendency to use dry resin transformers for up to 3 MV·A. These do not require a drip pan and are especially preferred in underground installations because they are inflammable and self-extinguishing. In addition, they are no noisier than liquid-insulated transformers. The rectifier units are designed to withstand a short circuit on the direct-current load side without the diode fuses blowing or the transformer or rectifier being damaged until the alternating-current breaker switches the power off. Overcurrent protection and a bimetal relay are connected in the alternating-current circuit and provide continuous protection, as is shown in Figure 13. The bimetal relay provides tripping in the range of minutes, whereas the overcurrent relay provides tripping in the range of seconds in its delayed function and in the range of milliseconds in its instantaneous function.

Rectifier circuits exert reactive effects on the energizing alternating-current power supply. The intensity of the coupling is reduced as there is an increase in the harmonic frequency. The three-phase rectifier bridge in a six-pulse connection has a reactive effect on the alternating-current network that feeds the substation, especially with respect to the fifth and seventh harmonic, which is 420 Hz in 60-Hz networks. Past investigations have shown that these reactive effects are tolerable as long as the rectifier's power capacity is lower than 20 percent of the network's capacity, as is the case in all LRT installations in Germany. If the rectifier rating is higher than 20 percent, the fifth and seventh harmonic can be avoided if a 12-pulse connection is used. A reduction in the harmonic content can be achieved if the secondary windings of the transformers of every second rectifier unit are shifted 30 electrical degrees. The rectifier units as a whole then react under heavy power demand as they would in a 12-pulse connection. The alternating-current switchgear is of standard design; it is preferred that it be withdrawable and have short-circuit switching capacities of up to 50 kA.

DIRECT-CURRENT SWITCHGEAR

The short-circuit protection of the catenary system is provided by the direct-current high-speed breaker, which is directly coupled to the direct-current busbar system. Siemens, for example, manufactures direct-current breakers that have current ratings of 2 kA, 3.15 kA, 4 kA, and 6.3 kA. These breakers have an overload capacity of 1.5 times the rated current for 1 min and 4 to 5 times the rated current for 20 s, which can easily accommodate load peaks and rapid changes of direct-current traction systems. The inherent response time of only 3 ms between the moment the tripping value is reached and the contact opening of the breaker classifies it as a high-speed breaker. It ensures that the short-circuit current is tripped before it reaches its peak. This speed permits practically unlimited short-circuit capacities. The breaker is equipped with a magnetic overcurrent trip that is directly coupled to the switching linkage. The trip functions independent of current direction and rate of rise when the current reaches the set value.

By using an electronic rate-of-rise current trip in addition, a short circuit can be recognized before the magnetic trip is activated, and the short circuit can be switched off in less time than 3 ms. Calibrated potentiometers of the electronic monitor can select tripping values for near and distant short circuits; this optimizes the protection for the catenary system and the LRVs, reduces the short-circuit damage, and also more adequately protects the power supply system. High-voltage switching peaks also represent danger to the catenary system and the LRVs. Alteration of the arc chamber design criteria makes it possible to limit the arc voltage during switching to a relatively low voltage, e.g., 750 V plus 20 percent for the switchgear limits the switching peak to approximately 1.5 kV. Current designs do not require blow-out coils; this in turn allows the switching of low-value direct currents, which normally poses a problem. Since the breaker is mechanically latched, continuous energization of the holding coil is not necessary.

Figure 10. Traction rectifier in three-phase bridge connection.

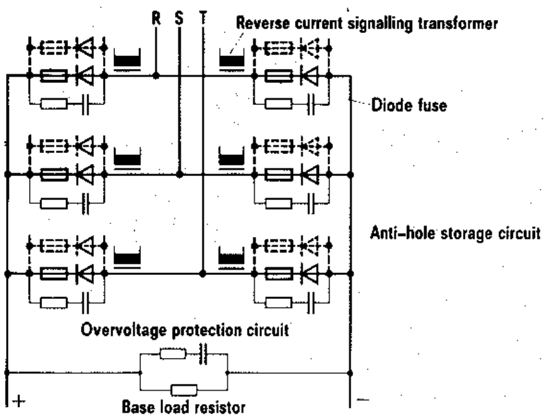


Figure 11. Design of a self-cooled rectifier.

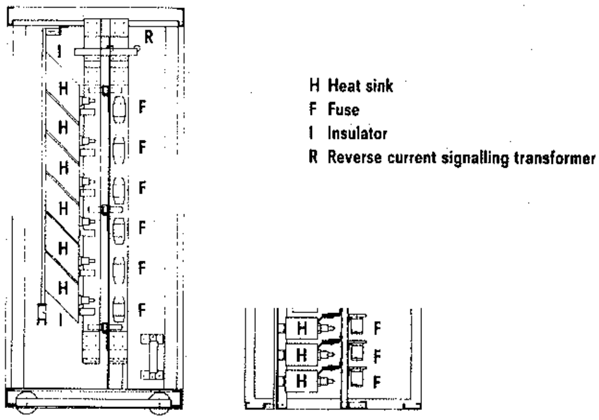


Figure 12. Rectifier cubicle for the Munich underground railway.

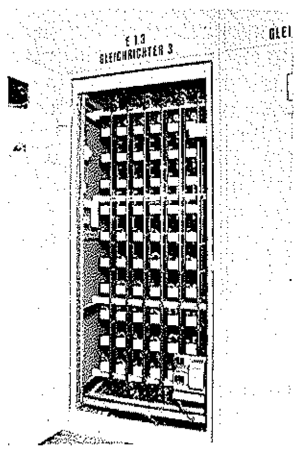


Figure 13. Means of protection of the rectifier.

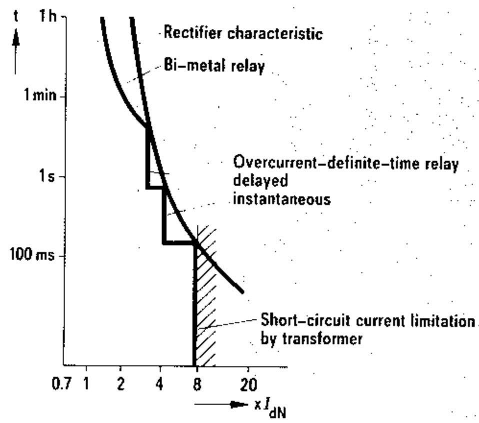


Figure 14. Cross section of a high-speed direct-current circuit breaker.

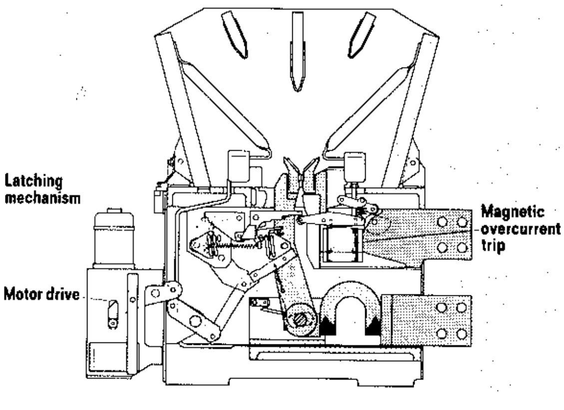


Figure 15. Switchgear cubicle with withdrawable breaker.

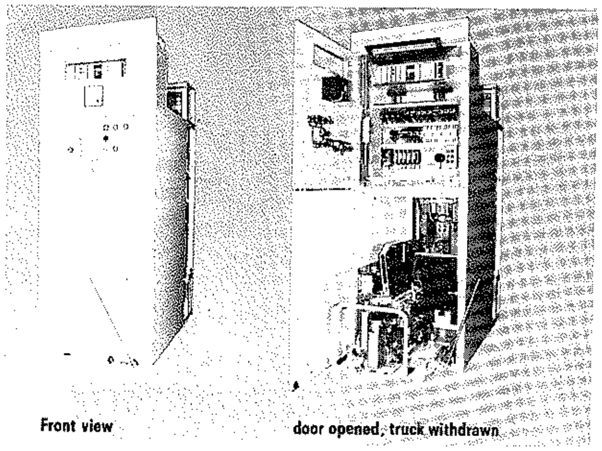


Figure 14 shows a cross-sectional view of a high-speed breaker with a 750-V arc chute. The main current path is illustrated. Its fixed and movable contacts show: on the left, the mechanical linkage; on the right, the magnetic overcurrent trip mechanism; and, on the far left, the motor drive. The main connections are on the side, which aids in making it withdrawable. The direct-current high-speed breakers, in their switching function, govern separate line sections and are located in individual cells—either fixed and mounted or, preferably, withdrawable. Withdrawability provides a visible and positive means of disconnection, which avoids the cost of an additional disconnect and provides quick exchangeability and a high level of safety for operation and maintenance personnel. An interlocking between the breaker and the operation of the withdrawal mechanism removes any danger of malfunction.

The switchgear cubicles also provide a place for mounting the necessary auxiliary controls and protection equipment, such as the rate-of-current-rise monitor and test and reclosing controls. These electronic testing and reclosing controls make remote and automatic operation of the line power supply possible. After a trip of the breaker, the electronic circuiting will check, by sending out limited current according to a timed program, whether an actual short circuit still exists. If, for example, no short circuit is registered after a flashover or if the breaker on the LRV has tripped, the direct-current high-speed breaker will automatically switch back on. The adjustable test circuit can differentiate between test current flowing from auxiliary equipment on the LRV and test current flowing because of a line short circuit. If a preselected number of tests are unsuccessful during the total test period, a continuous short-circuit condition will be registered, and the high-speed breaker will be electrically interlocked in the off position. A line inspection would then be necessary to locate the fault.

Switchgear cubicles that have withdrawable breakers are available in widths of 1250 mm and 800 mm or even 500 mm (compact design). Figure 15 shows an 800-mm cubicle with a withdrawable breaker. Good overview of each component is provided, even with an inserted breaker. Only the breaker itself is mounted on the withdrawable frame. Figure 16 shows a compact 500-mm cubicle on which the auxiliary and monitoring equipment are mounted on the withdrawable frame; good overview and accessibility are available only when the truck is out.

In addition to the direct-current high-speed breakers for each line section, an additional bypass breaker is often installed. This breaker, which consists of a busbar and a changeover disconnect (often remote controlled), can be switched in to replace any line breaker, thereby making maintenance easier and reducing downtime.

A combination of no-load or load disconnects is usually inserted between the direct-current switchgear and the line in order to facilitate coupling, disconnecting, or changeover of the various catenary sections.

Figure 16. Compact switchgear cubicle and its truck.

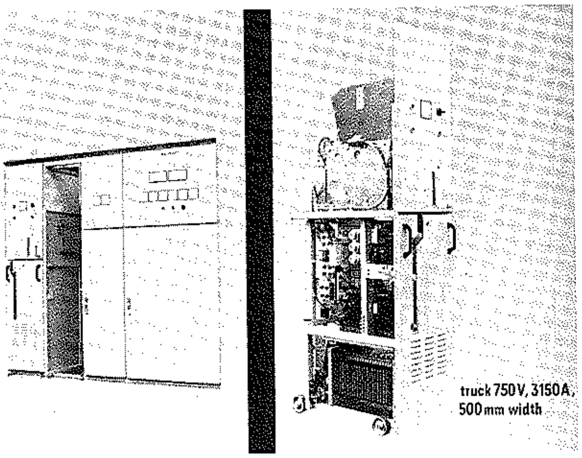


Figure 17. System section on monitor screen.

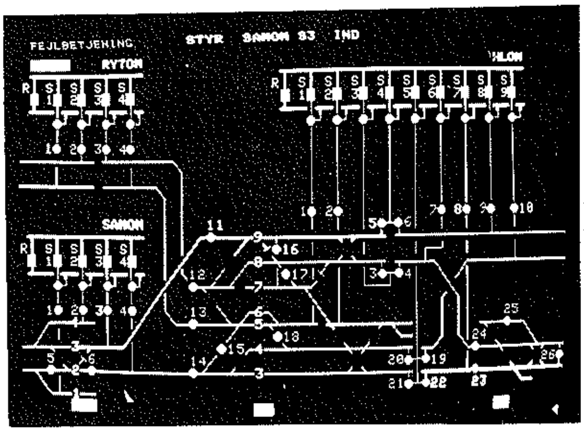
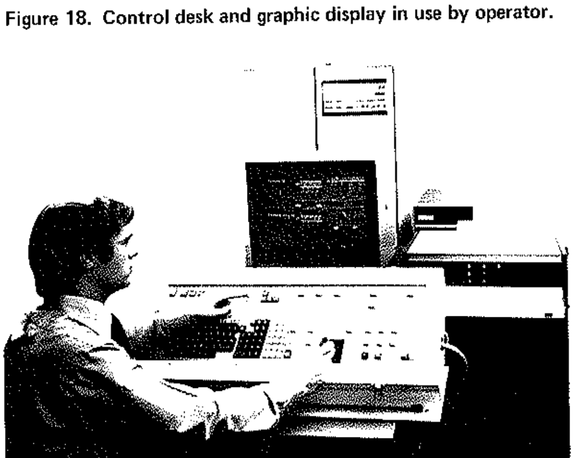


Figure 18. Control desk and graphic display in use by operator.



GROUND PROTECTION OF EQUIPMENT

To protect a substation against damage from faulty currents flowing through the metal frame of the system, ground protection for equipment should be incorporated into the design. The cells must be set on insulation pads, and the cell frames should be connected by a low-ohm current relay to the protective ground of the substation. Relatively low faulty currents will be picked up by this current relay and evaluated; this will lead to the tripping of the alternating-current and direct-current breakers. The current relay is laid out to handle current up to the tripping level of the breakers without being damaged. In addition, a voltage relay can be inserted between the equipment ground and the rail ground in order to monitor voltages of more than 90 V and to initiate the trip.

The size of an LRT network increases the operational problems and responsibility. In order to solve these problems and, at the same time, to rationalize and improve the operational dependability, centralization is becoming more and more popular for controlling and monitoring the power supply system. Remote control and measurement are carried out by using standard, proven telemetering components. By adding specific components, the problem of the automatization of the traction power supply can be solved. Integrated circuits provide a high level of dependability, high transmission speed, simple expansion, and simple programming. The signals, commands, and measurements to be transmitted are coded into impulses that are transmitted over a single pair of wires. The receiver then decodes these impulses.

The central control can be simplified by using mosaic block systems in which the push buttons, control switches, pilot lights, and so on are inserted. Mosaic boards have the advantage that future changes of the network can be incorporated very easily. Although the mosaic technique maximizes the number of control functions that can fit in a small space, some regional control centers require a control board that would be too long for efficient operation. Large control rooms and long control panels debase the overview and reaction time. Such large regional control centers have selective graphic displays and use computers. The network is represented on the mosaic display board to give a general overview. The illumination of the mosaic board, which depicts the actual switching conditions, is governed by a process computer. The complete and detailed display of stations or network sections (as selected by the operator) is shown on the graphic display board (Figures 17 and 18). The switch to be operated is located on the graphic display and can then be switched by a single push button. If a faulty operational signal has been given, the process computer will so indicate in written form, giving the correct operating instructions. All signals and operations will be recorded; this permits accurate reconstruction of the situation in case this is needed.

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Technology and Economics of Regeneration for Light-Rail Applications

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Regeneration is one method of recycling a vehicle's surplus kinetic energy during braking. Regeneration is recuperative braking in which the recycled energy goes back to the vehicles' power supply system for use by other vehicles. Several propulsion systems that use regenerative braking have been applied and operated on direct-current electrified rail systems. The fundamental limitations on effectiveness that are beyond the propulsion designer's control are considered. The performance of an alternating-current induction motor system with an inverter and a direct-current series motor system with a chopper are explored to illustrate the present state of technology. Comparison is made with two other types of recuperative braking—flywheel energy storage and height changes in the route profile. The inefficiency of the former and the difficulty of construction of the latter are noted. The industry's present interest in regeneration is questioned since it would have minimal economic impact but require complex propulsion hardware and extra maintenance costs.

Regenerative braking is one method of recycling a vehicle's surplus kinetic energy during deceleration. It is recuperative braking in which the recycled energy goes back to the supply system for use by other vehicles. In transit operation, acceleration and deceleration are the predominant vehicle activities. Because of this, the duty cycle that determines the required rating of a vehicle's propulsion system and brake system equipment depends primarily on the acceleration and deceleration needs for that vehicle. For example, on the Norristown Line of the Southeastern Pennsylvania Transportation Authority (SEPTA) local cars go through 21 acceleration-deceleration cycles in a 26-min run that covers 20.9 km (13 miles). That averages out to just more than 74 s/cycle. Of this, approximately 50 to 55 s are spent accelerating and decelerating, which leaves from 19 to 24 s for coasting and station dwells.

The propulsion and brake equipment on these cars is from an era when the virtues of simplicity and serviceability were considered as well as the costs of power. The motors and motor controls have only one task, i.e., accelerating the car. The friction brake has only one task, i.e., decelerating the car. When these cars were built in the early 1930s, it was not practical to usefully recover the energy wasted in braking. Energy costs were important then, as is indicated by the aerodynamic body shape and the attention given to light weight in the vehicle design. For an interesting history of these cars, one may refer to Chapter 7 of The Red Arrow (1). Some trolley coaches were equipped with special compound field motors that provided limited regenerative braking at higher speeds by means of motor field control (2).

Subsequent developments in motors and motor controls have produced vehicles that have dynamic braking (properly called rheostatic braking) that lessens the duty and wear on the friction brake system. In dynamic or rheostatic braking, the drive motors function as generators during deceleration, but all the resulting electrical braking energy is wasted as heat in the braking resistors. The use of rheostatic braking does not provide any savings in the vehicle's energy consumption.

DEVELOPMENT OF REGENERATIVE BRAKING

Although there is a long history of attempts to develop regenerative braking for start-stop rail transit service, the costs always exceeded the savings. The recent development of solid-state power control systems that use thyristors (silicon-controlled rectifiers) makes it practical to return a portion of the electrical braking energy back to the supply system for use by other vehicles. Several regenerative chopper systems and one inverter system that has alternating-current motors (Figure 1), all of which use thyristors, have been placed in actual transit service. The practicality of using thyristors for power control in conjunction with regenerative braking has been demonstrated in the narrow context of the individual light-rail vehicle (LRV). Not enough attention has been paid to how the regenerated energy flows back through the wayside supply network (the line receptivity) or to the effects of the moving substations that vehicles can become while they are decelerating.

There is an upper limit to the energy that can be recovered by means of regenerative braking that is independent of both line receptivity and the characteristics of the propulsion system. This limit is a consequence of the rolling losses of the vehicle; these are relatively low for rail vehicles, but they are not negligible. The importance of rolling losses can be illustrated by considering the ratio shown below.

maximum vehicle energy recovery factor = (maximum car kinetic energy - braking rolling losses) ÷ (maximum car kinetic energy + acceleration and cruise rolling losses)

In this ratio, the numerator is the net braking energy available for return to the line at the propulsion motor shafts, and the denominator is the gross propulsion energy drawn from the line at the propulsion motor shafts. In other words, the numerator is the maximum possible

Figure 1. Power flow diagram of LRV with inverter.

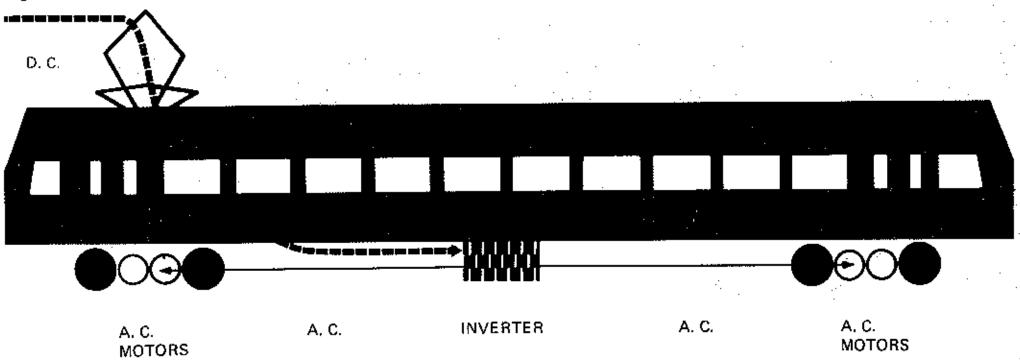
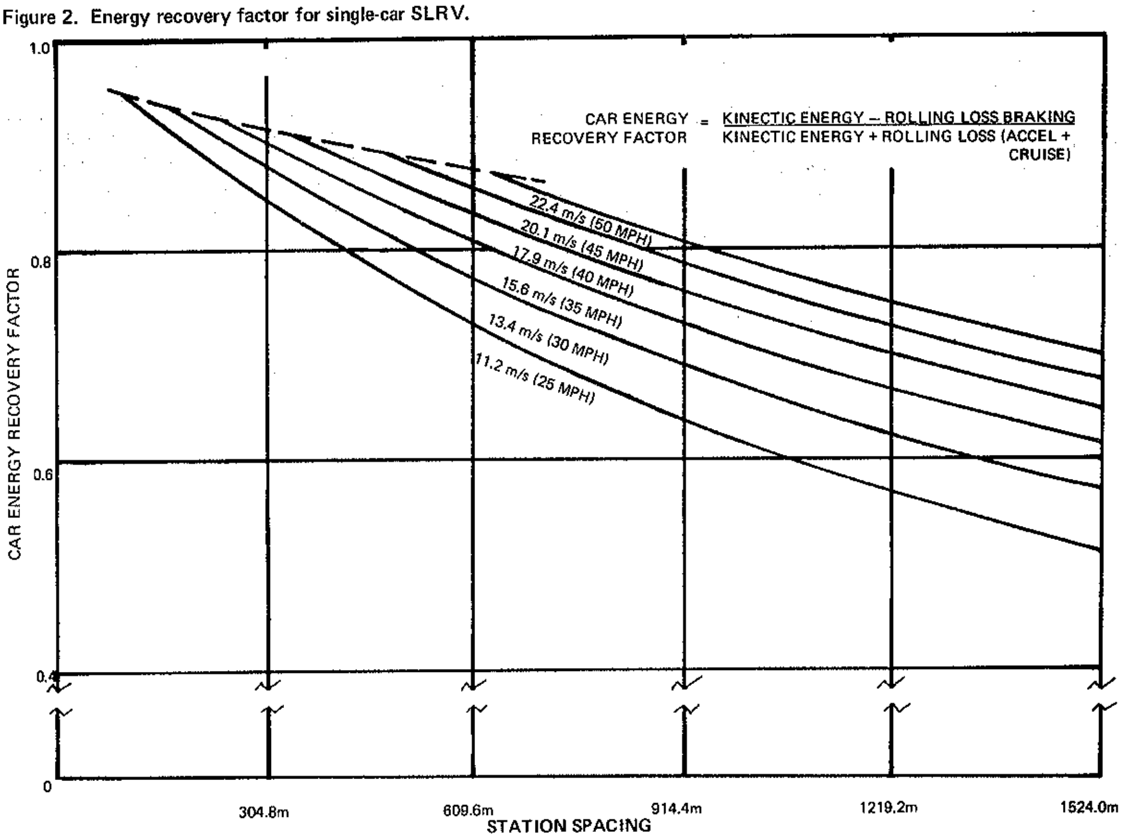


Figure 2. Energy recovery factor for single-car SLRV.



work that can be done on the motors (acting as generators) in decelerating the car, and the denominator is the work done on the car by the motors in accelerating and running the car during a station-to-station run.

Figure 2 shows the ratio calculated for a single fully loaded standard LRV (SLRV) as a function of station spacing. The family of curves shows cruise speeds from 11.2 to 22.4 m/s (25 to 50 mph). The irrecoverable losses that result from running at constant speed between the acceleration interval and the braking inter-

Figure 3. Energy recovery factor for two-car SLRV train.

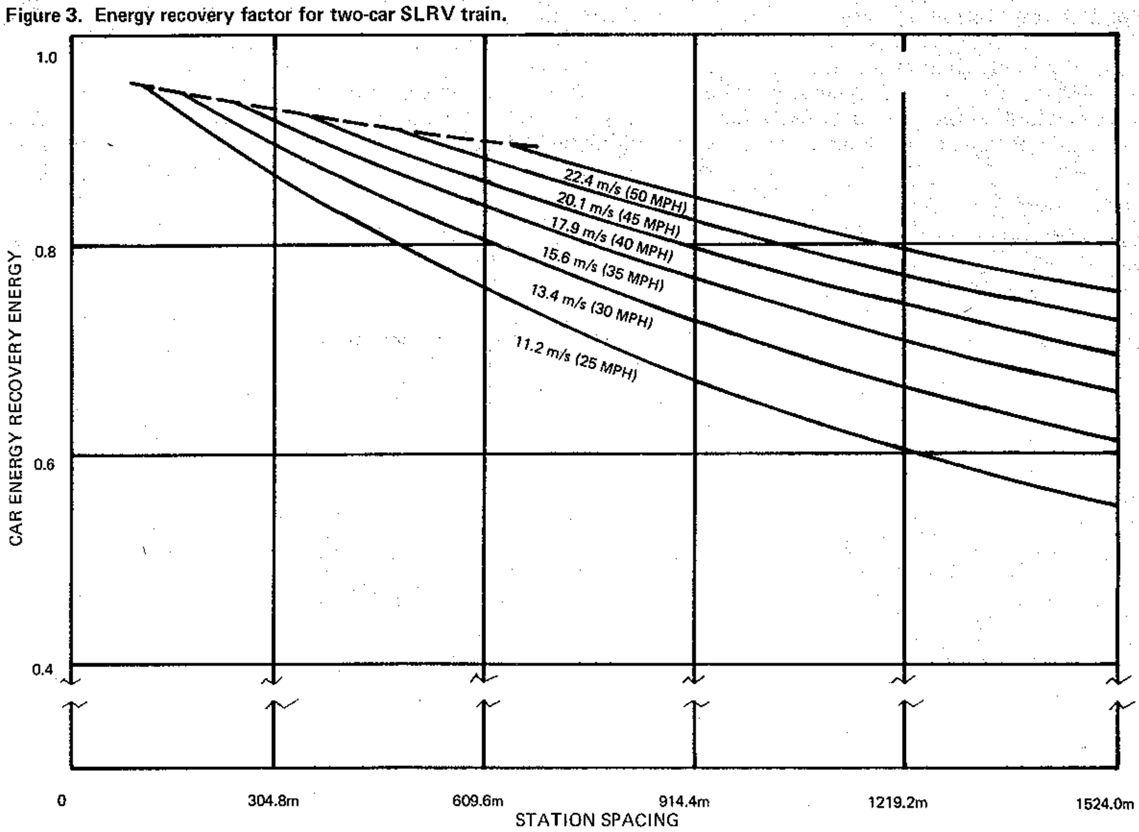
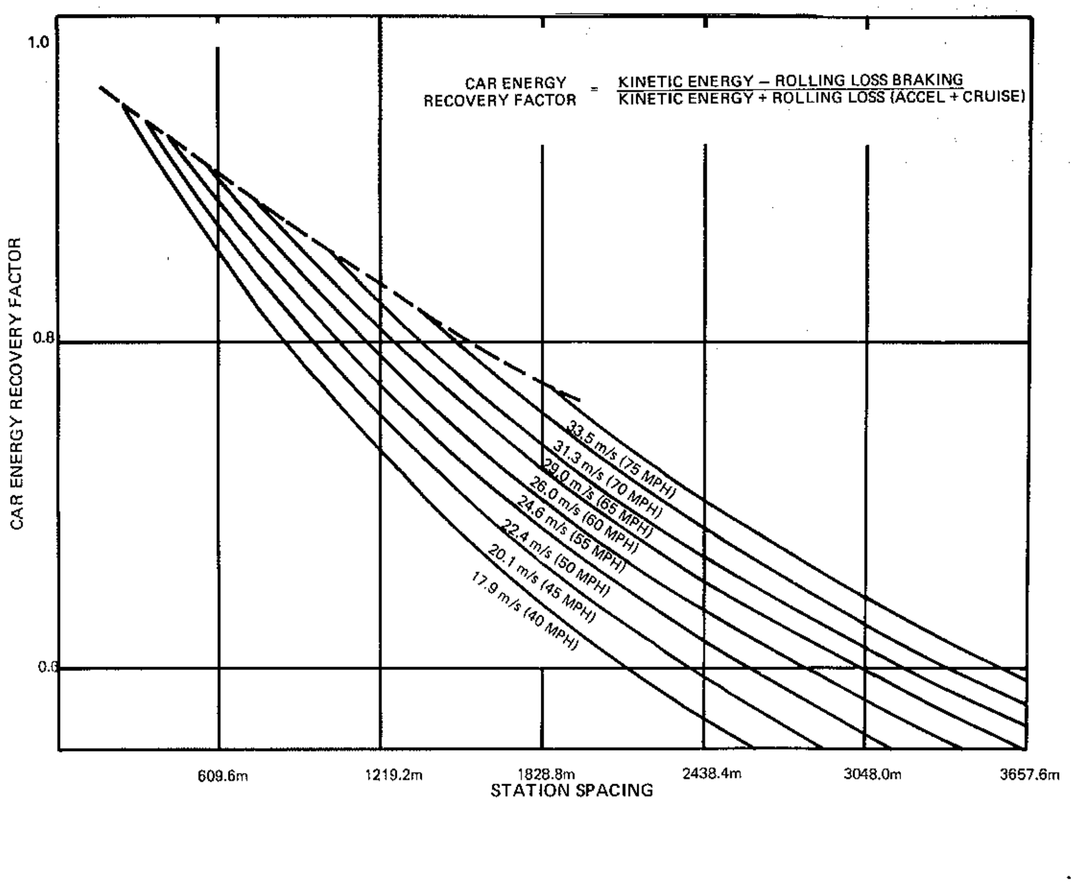


Figure 4. Energy recovery factor for two-car train in Washington, D.C.



val lower the energy recovery factor for longer station spacings.

At higher speeds, the kinetic energy of the vehicle increases more rapidly than its rolling losses. Taken together with the longer acceleration and braking distances, which shorten the steady-speed cruise distance, this causes the ratio to increase as the vehicle cruise speed increases for a given station spacing.

Figure 3 shows the ratio calculated for a fully loaded two-car SLRV train. The only difference between these results and those in Figure 2 is that the frontal area of the vehicle is less important to the rolling losses per car. Similar results are obtained for rapid transit operations; Figure 4 shows the ratio for a two-car train in the Washington, D.C., Metro system.

Regardless of how it is implemented, regenerative braking cannot recover more than the net available braking energy at the propulsion motor shafts. This imposes an upper limit on the regenerative energy savings that depends on the profile of the run. It is apparent that regenerative braking has the best potential in the frequent start-stop operation that is typical of light-rail transit systems.

When an operating property puts a few cars that have regenerative braking into service in a large fleet that does not, it crosses only the first of several hurdles to

Figure 5. Comparison of acceleration at constant rate and constant power.

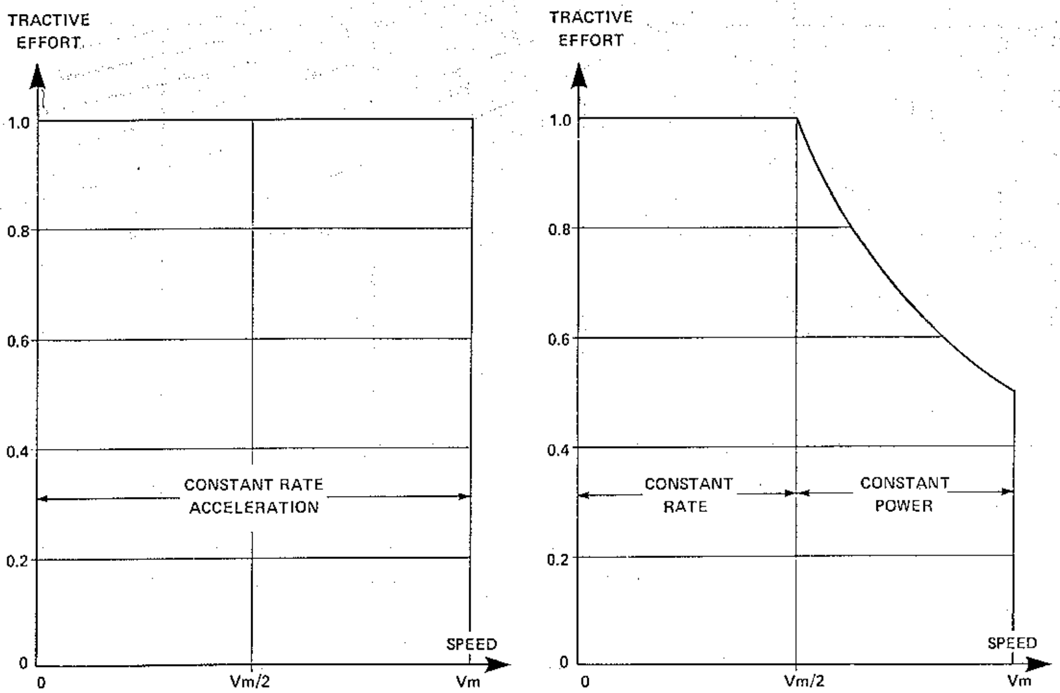


Figure 6. Comparison of acceleration histories at constant rate and at constant power.

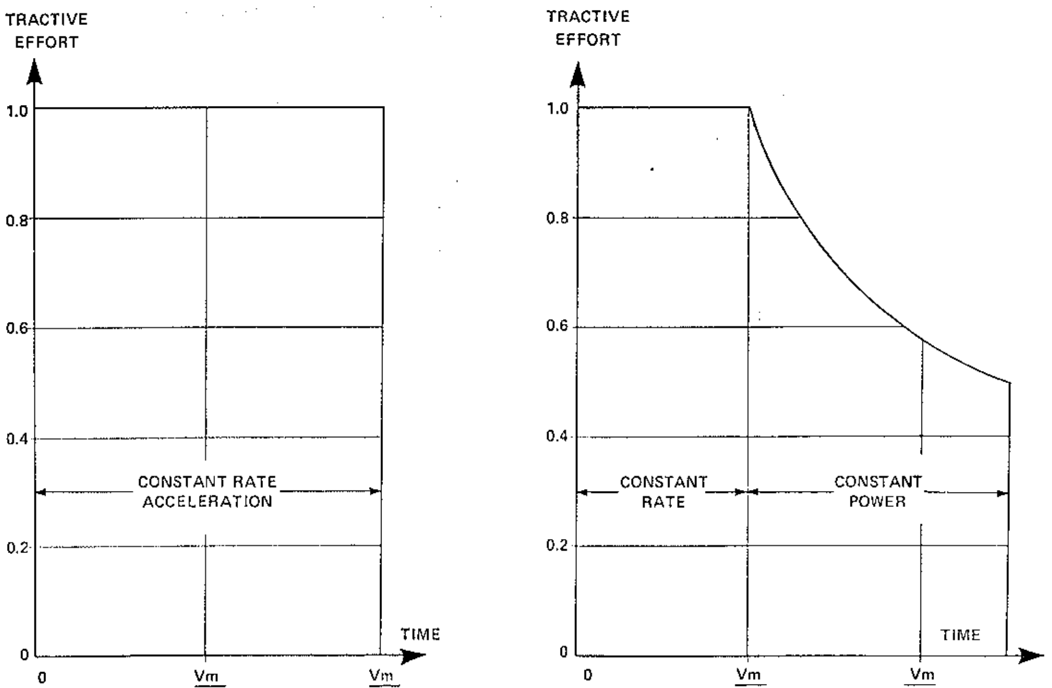


Figure 7. Comparison of power flows for constant rate and constant power.

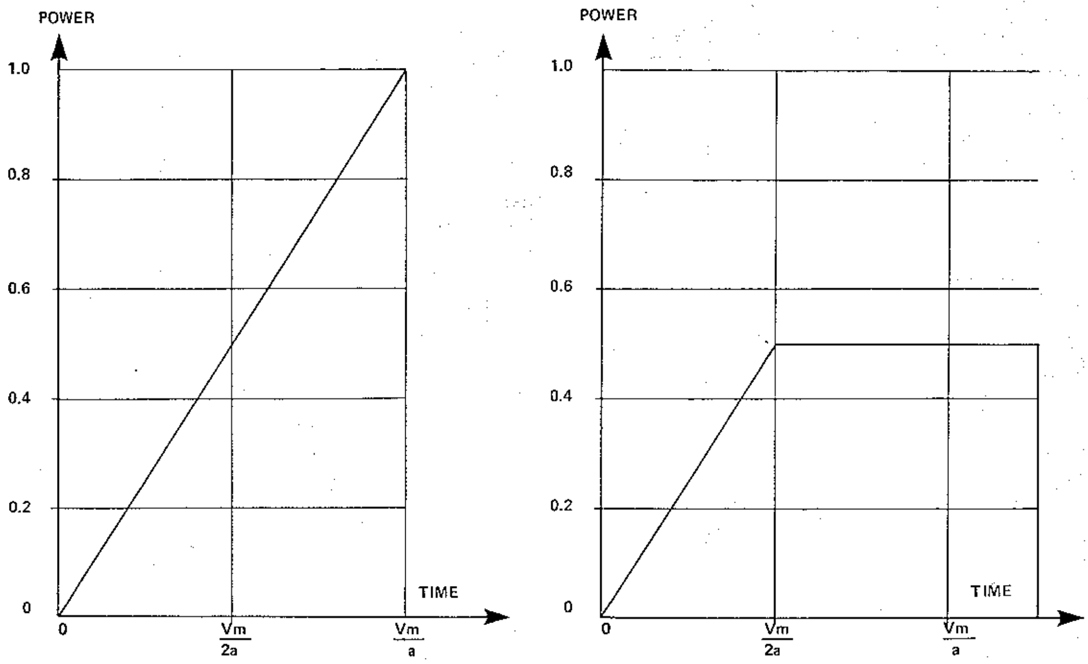
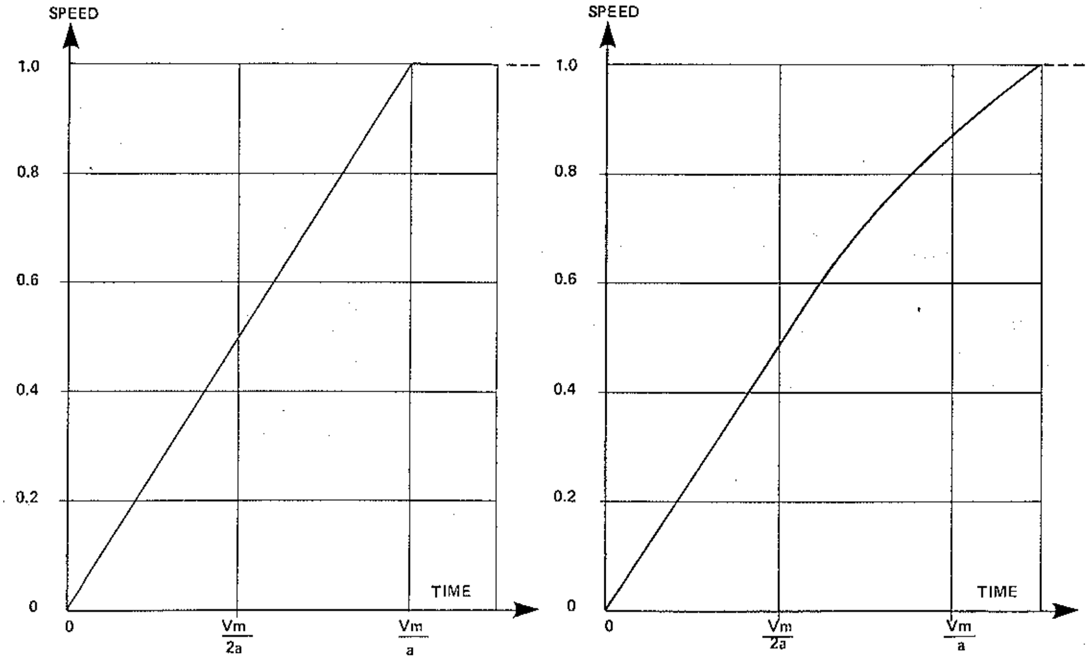


Figure 8. Comparison of speed histories for constant rate and constant power.



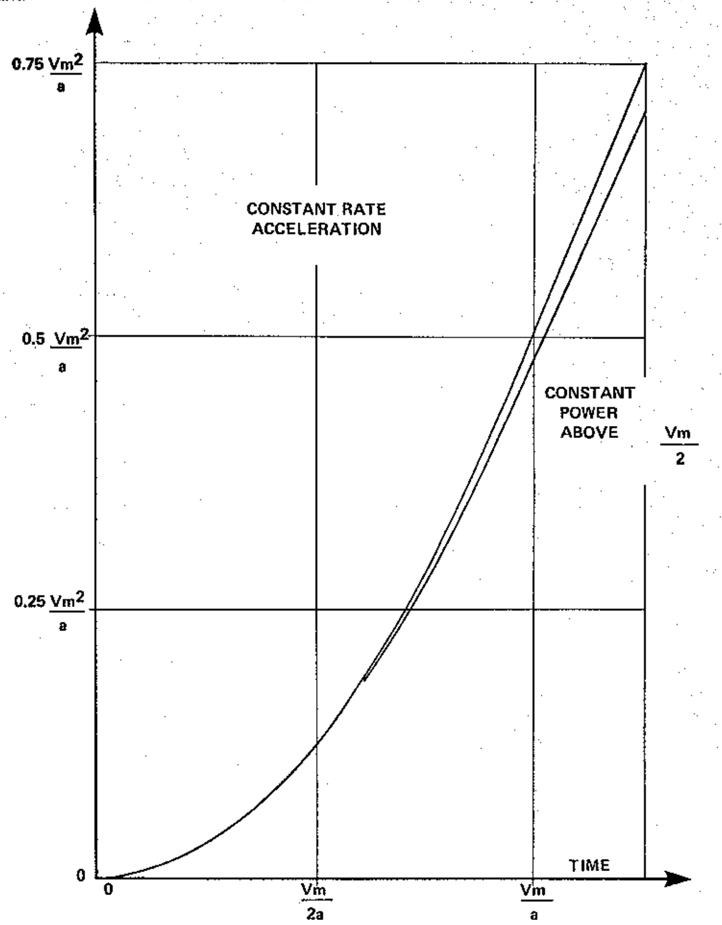
meaningful energy savings. The next hurdle, the handling of the regenerated energy when it returns to the supply, will influence the economic trade-offs entailed in configuring the braking system.

In general, full-rate vehicle deceleration is desired at much higher speeds than those at which full-rate vehicle acceleration is desired. This is a carry-over of placing much more importance on accelerating power than on the dissipation levels of braking power. The mode's requirement for full-rate acceleration only up to a relatively low base speed reflects a proper appreciation of the incremental costs of converting higher levels of propulsion power at substations and of the incremental costs of delivering higher levels of propulsion power to vehicles through third rails or overhead wires.

METHODS OF ACCELERATION

One can compare two possible ways to accelerate a vehicle to a desired speed (Vm), as is shown in Figure 5. The first, a hypothetical way, involves accelerating at a constant rate (a) up to Vm; the second, a practical way, involves accelerating at a constant rate up to half speed (Vm/2) and accelerating at a constant power level from Vm/2 to Vm. The required installed power capability for substations, trolley wire, and the vehicle's

Figure 9. Comparison of distance histories for constant rate and constant power.



propulsion system in the second case is only half that in the first case. There is only a slight reduction in performance. If rolling resistance is ignored, the two cases can be analyzed by closed-form solutions. For typical rail vehicles, the rolling resistance is small in relation to the accelerating tractive effort.

In Figure 5 the curves for the tractive effort versus speed for the two cases are shown. The lower high-speed tractive effort for the constant power (above Vm/2) will cause the car to take longer to reach maximum speed. The curves for the comparative tractive effort, or acceleration versus time, are shown in Figure 6. The time required to attain the desired speed is 25 percent longer for the car going at constant power than for the car going at a constant rate. The curves for the power or energy flow versus time for the two cars are shown in Figure 7. Note that the constant-rate car briefly draws twice the power required by the constant-power car. The area under either curve is the same, which indicates that each car ends up with the same kinetic energy and the same speed, i.e., Vm. The curves for the comparative speed versus time are shown in Figure 8. The longer time required to reach top speed looks important but, from the standpoint of covering actual distance, it is not so important. The curves for the comparative distance versus time are shown in Figure 9. The distance difference looks quite small.

To make this abstract comparison more concrete, consider an SLRV accelerating to 14.3 m/s (32 mph). The design acceleration is 1.25 m/s^2 (2.8 mph/s) up to 7.15 m/s (16 mph). In the constant-power case, this corresponds to a Vm of 14.3 m/s (32 mph) and an a of 1.25 m/s^2 (2.8 mph/s). The normalizing time unit (Vm/a) is 11.43 s. The time at which the lower performance vehicle reaches speed (5/4 × Vm/a) is 14.28 s. After 14.28 s, a lower performance (constant-power) vehicle will be only 6.7 m (22 ft) behind the higher performance (constant-rate) vehicle; both will be moving at 14.3 m/s (32 mph). The lower performance vehicle would pass a given point at most 0.47 s later than the higher performance vehicle. Doubling the installed car, line, and substation power therefore saves less than 0.5 s in reaching a speed of 14.3 m/s (32 mph). This is a small gain in comparison with the cost of doubling the peak power level of the power supply, distribution system, and propulsion system.

Similar considerations would apply in regenerative braking systems, but the braking power would flow from the vehicle's propulsion system back through the distribution system either to a receptive substation or to another vehicle. In nonregenerative braking systems, the hardware design trade-offs involve only vehicle-carried equipment. In the case of dynamic braking, the capability to withstand extra voltage that must be designed into the motors and motor controls to allow for electrical distribution and collection transients can be used to increase the level of the dynamic braking power. Transients on the order of several thousand volts are common on 600-V systems. In dynamic braking, the motors, controls, and braking resistors are not in a circuit with the current collector and therefore need not tolerate supply transients. For any given motor current, the motor speed and motor voltage are proportional to each other. Full-rate dynamic braking is thus available for current series motor and switched-resistor propulsion systems at speeds of two to three times the acceleration base speed for only an increase in the size of the braking resistor.

For a purely regenerative system, the provision of full-rate high-speed braking is not a simple matter. The high levels of braking power must be converted and controlled in the presence of line transients. Theoretically, a mirror image of constant-power operation above some intermediate speed for acceleration should provide a valid model for deceleration. Though the distance penalty would be small for constant-power braking from full speed to half speed and constant-rate braking below half speed, the vehicle operator or train control system would be required to make stopping decisions earlier in time and farther back from the desired stopping point. This is not an attractive prospect in the context of operation in dense traffic. If both full-rate high-speed braking and regeneration are desired, the system designer must be willing to consider:

1. Overdesign of the propulsion system for braking duty,
2. A friction-brake supplement at high speed, or
3. Combined regenerative and dynamic braking.

In the case of the Cleveland Transit System (CTS) Airporters, which have inverters and brushless induction motor drive, early track testing showed that the propulsion system could handle full-rate braking at high speeds. This was a case of overdesign of the propulsion system to accommodate the braking duty. On the new chopper-equipped Montreal Metro cars and the Toronto Transit Commission's H-5 cars, a friction-brake supplement will be used. The Presidents' Conference Committee (PCC) cars in the Hague and Rio de Janiero and the 10 chopper test cars for Chicago provide combined regenerative and dynamic braking by the addition of a modest amount of power circuitry. In the case of the Chicago cars, the power-control chopper automatically wastes, in resistors on board the vehicle, any braking power that cannot be instantly accepted by the supply.

OTHER MEANS OF RECUPERATIVE BRAKING

There are other means of recycling braking energy that are not constrained by power supply and distribution factors. These may be thought of as recuperative braking rather than regenerative braking. The recovered braking energy can be stored during a deceleration for subsequent use by the same vehicle during the next acceleration. The energy can be stored in flywheels (kinetic), in batteries (chemical), or by means of height changes in the route alignment (potential). The dissipation of braking energy can also be used to augment seasonal car heating requirements.

The storage of energy in flywheels has been used on several New York City Transit Authority (NYCTA) test cars. On-board flywheel energy storage requires the use of two propulsion mechanisms—one to drive the vehicle and one to drive the flywheel. On the NYCTA cars, the flywheel storage system added approximately 5158 kg (11 000 lb), 16 percent, to the weight of the empty car. By using direct-current motors with separately controlled field excitation, it is possible to simplify the electric power control apparatus so that no choppers are needed. The interplay of car speed and flywheel speed and separate field control of the two propulsion systems provides the necessary controllability. It is only a coincidence that flywheel energy systems have been developed at the same time as choppers. Flywheel systems could have been developed much earlier. The Advanced Concept Train (ACT-1) cars now under development will use the flywheel storage approach without choppers.

The operational advantages of car-carried flywheel energy storage are that recuperative braking is independent of line conditions and that there is enough stored energy to permit limping into a station if there is a third-rail power outage. The disadvantages are the heavy weight of the propulsion hardware, the hazards of large amounts of mechanically stored energy, the low efficiency of multiple energy conversions, and the steady running energy loss of the flywheel unit.

In order to keep the variations in flywheel speed reasonable, the total stored flywheel energy is currently designed to be twice the vehicle's maximum energy. The kinetic energy of a vehicle at a speed of 22.4 m/s (50 mph) is great—enough to lift the car about 25.6 m (84 ft)—and the flywheels can store twice that amount of energy. A mechanical failure in the shaft, bearings, or gearing may trigger the uncontrolled release of the stored energy.

Energy losses arise in recuperative braking by means of flywheels because the energy must undergo four electromechanical conversions to make a round trip. For a typical single-conversion efficiency rating of 85 percent, the round-trip efficiency would be limited to 52 percent. For an optimistic 90 percent single-conversion efficiency, the round-trip efficiency would be limited to 66 percent.

There is a steady running loss of 22.4 kW (30 hp) for each unit of the ACT-1 storage system. The total stored kinetic energy is 16.3 MJ (12 000 000 ft·lbf), half of which is useful energy for the system. If the flywheel's process of running down is considered as exponential decay, the decay constant is the rate of loss divided by the stored energy or 0.001 375/s. The estimated time for a flywheel unit to coast down to its half-energy state (i.e., that in which it has no useful stored energy) is about 8 min. This is comparable to the terminal layover times allowed for schedule make-up—about 9.7 km (6 miles) of express running at 22.4 m/s (50 mph). Another flywheel loss is that incurred between the time energy is stored during deceleration and the time it is subsequently used during acceleration. Taking 1 min as the combined deceleration, dwell, and acceleration time, the flywheel will lose an estimated 8 percent of its total energy or 16 percent of its useful energy. The 16 percent loss yields 84 percent storage efficiency on top of the estimated 52 percent energy-conversion efficiency previously mentioned, a net of about 44 percent overall propulsion-system efficiency in recuperative braking. The steady constant running loss of the flywheel while the vehicle moves at constant speed will further detract from the overall energy efficiency, even though the flywheel serves no useful storage function during this time.

The disadvantages of weight and safety hazards in vehicle-carried flywheels could be avoided by locating the energy-storage flywheel on the wayside within a properly protected structure at each station. However, if the station spacing is closer than the train spacing, this will result in a greater amount of installed machinery, and each individual machine will be used less frequently and less economically.

Battery-energy storage has not been tried for regenerative braking in transit. The weight, size, and maintenance of large-capacity batteries have been the major problems.

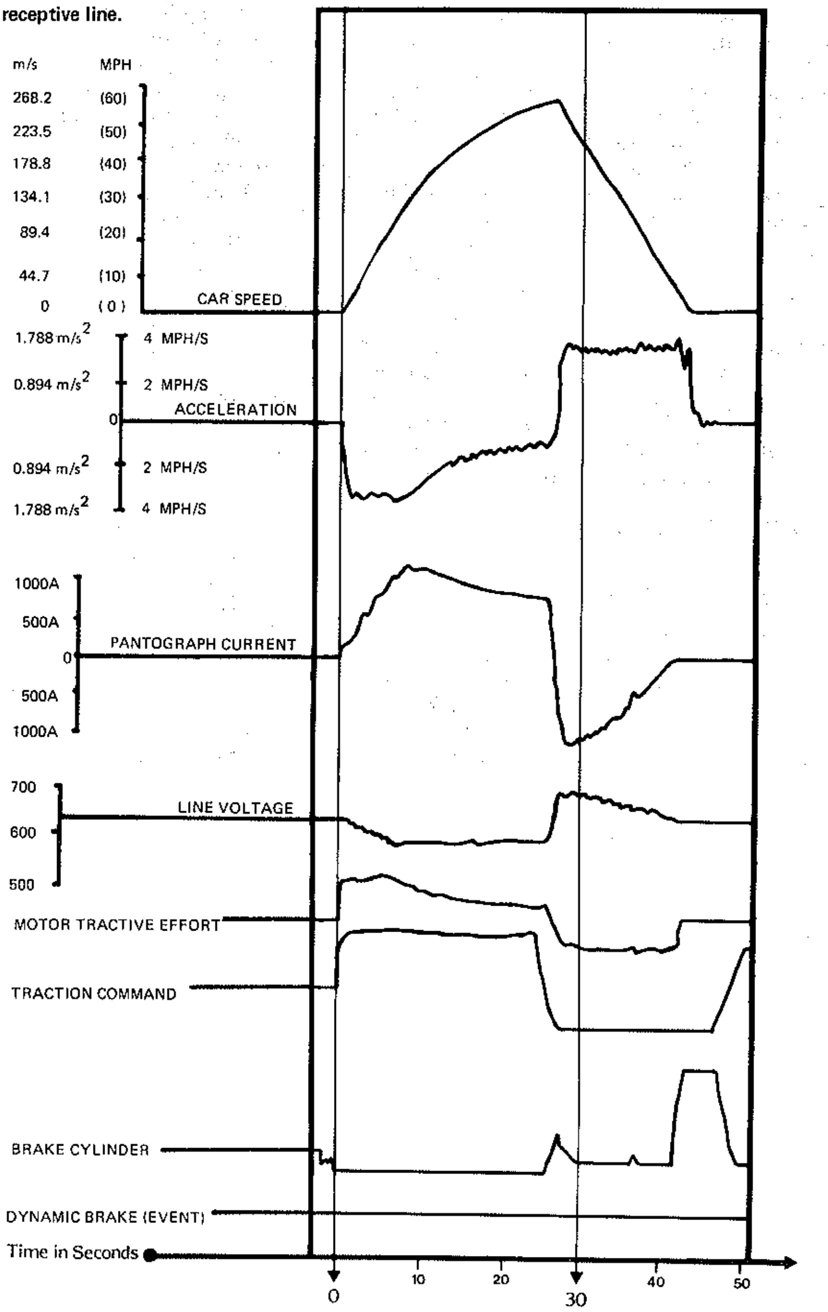
Gravitational storage through height changes is the simplest means to provide recuperative braking at station stops. It imposes constraints on alignment and civil engineering works that are sometimes hard to accommodate. D. T. Catling (3) analyzed the operational aspects of gravity recuperation in a system of hump stations. Practical limitations, such as starting trains with some nonpowered cars on the upgrade approaching a station, limited grade considered to 2 percent. With this modest grade, a drop of 7.62 m (25 ft) resulted in increasing the schedule speed enough to eliminate one train and provide a 14 percent saving in each train's energy consumption for a 32-km (20-mile) 20-station service with a 2-min headway. The concept is attractive for its simplicity, and its implementation need not be systemwide. The trade-off between the value of anticipated energy savings and extra route construction costs can be analyzed only on a site-specific case-by-case basis. The Montreal Metro and some NYCTA lines have hump stations. Occasionally a proposal for a ballistic trajectory transit system reemerges.

REGENERATIVE BRAKING WITH AN INVERTER

Regenerative braking is recuperative braking in which the recycled energy goes back to the supply for use by other vehicles. The inverter-equipped CTS Airporters exhibited the performance shown in Figure 10 on a receptive line. This chart segment shows an acceleration to 22.4 m/s (50 mph) and an immediate deceleration to stop. The inverter drew supply current while accelerating and returned supply current while braking. While it was drawing supply current, the line voltage dropped and, while it was returning supply current, the line voltage increased. Since the response of the friction brake was slightly faster than that of the inverter at the power-to-brake transition, one notes a slight, brief rise in brake cylinder pressure.

The CTS Airporters performed as shown in Figure 11 on a nonreceptive line. These cars carried one-step

Figure 10. Performance of inverter on receptive line.



contractor-controlled resistors that artificially loaded the line to make it receptive. For the case shown, the car was accelerated to 26.8 m/s (60 mph), cruised briefly, and then braked to a stop. The speed and acceleration traces show this. The inverter current trace shows the usual acceleration behavior, which is followed by a short reduced-current cruise interval and finally a swing toward regeneration during deceleration. The line voltage shows some droop during acceleration and a significant rise at the start of braking. This voltage rise triggered the closing of the dynamic brake's resistor contactor, which diverted some of the regenerated current. The friction brake was bleeding off simultaneously; this caused the inverter-regenerated current to increase in order to maintain constant deceleration. Near the end of the stop, the regenerated current was insufficient to offset the dynamic brake's resistor current, and some line power was consumed at the end of the stop. This was a very crude first attempt at addressing the question of receptivity.

A user's view of the CTS inverter and alternating-current motor system was presented by R. T. Bretz in 1973 (4).

REGENERATIVE BRAKING WITH A CHOPPER

The use of choppers and direct-current series motors makes it possible to continuously blend regenerative and dynamic braking so that the line will be fed all available braking current up to its limit of instantaneous receptivity and only surplus braking energy will be wasted in a car-carried dynamic brake resistor. In a system that uses a chopper and direct-current motor propulsion, this can be achieved by adding a thyristor and dynamic brake resistor in the chopper power circuit as shown in Figure 12. The other contactor-staged brake resistor shown at the bottom allows for full-rate braking at high speed. Circuit operation is illustrated in Figures 13 and 14. In Figure 13 the chopper is on, and the loop current is increasing; the motor-generated voltage is imposed across the smoothing inductor and the optional high-

Figure 11. Performance of inverter on nonreceptive line.

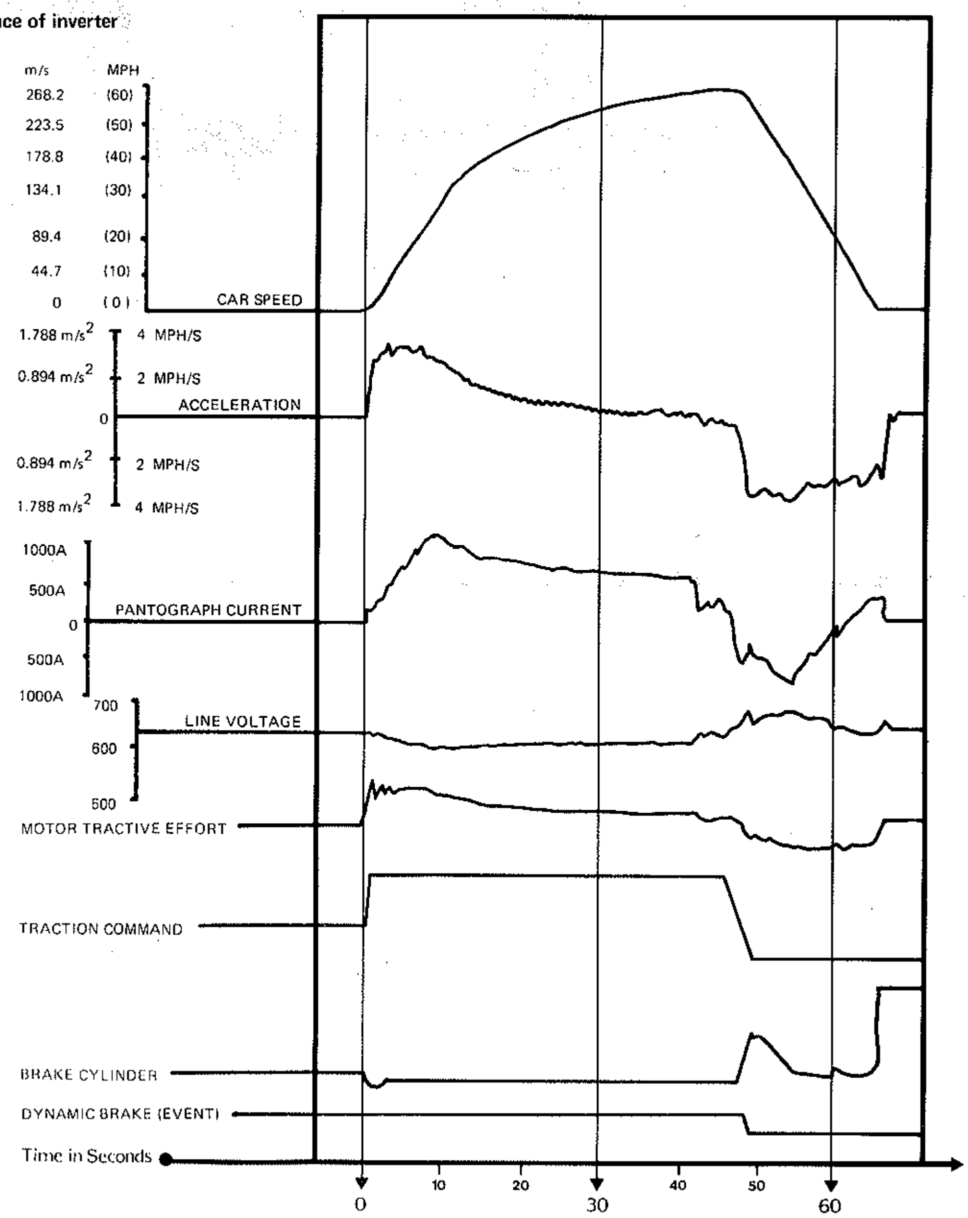


Figure 12. Chopper power circuit for regenerative braking.

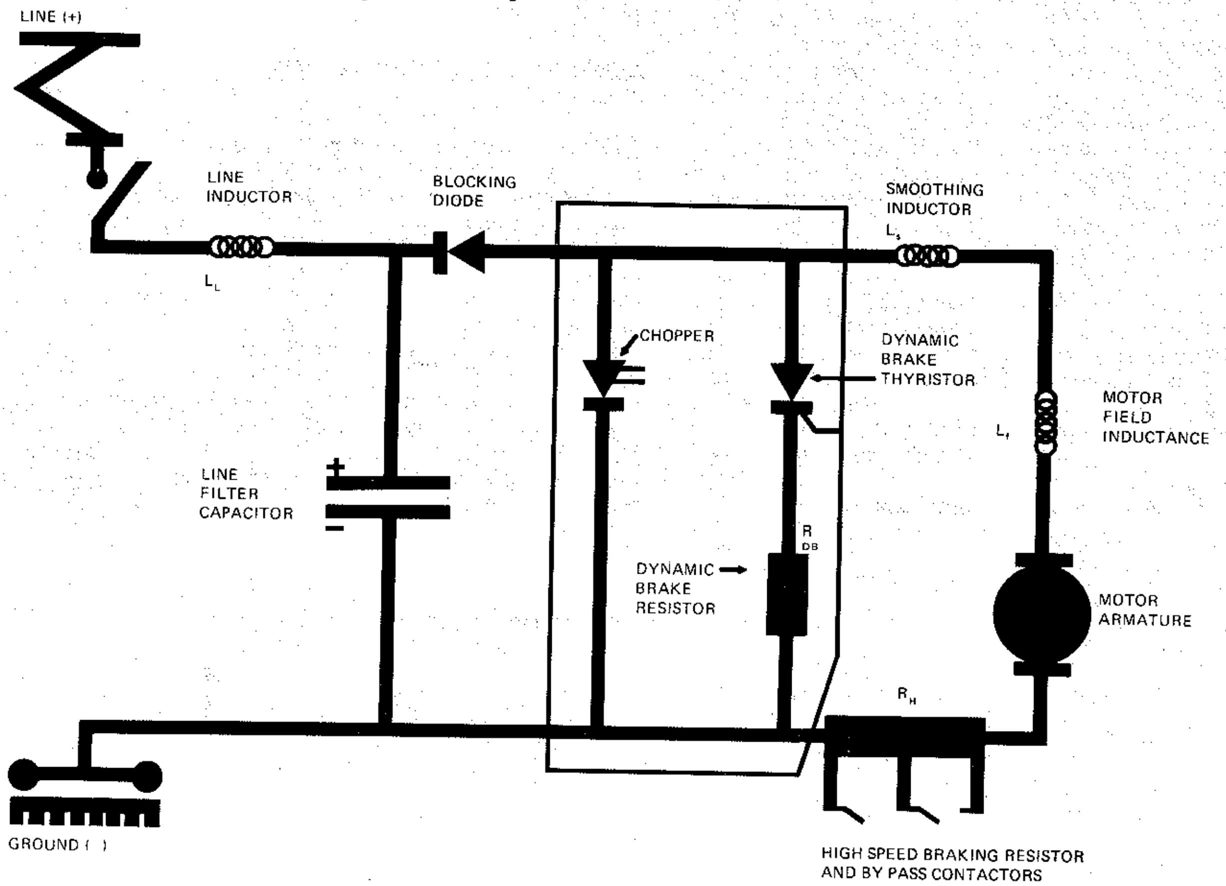


Figure 13. Buildup in the loop current.

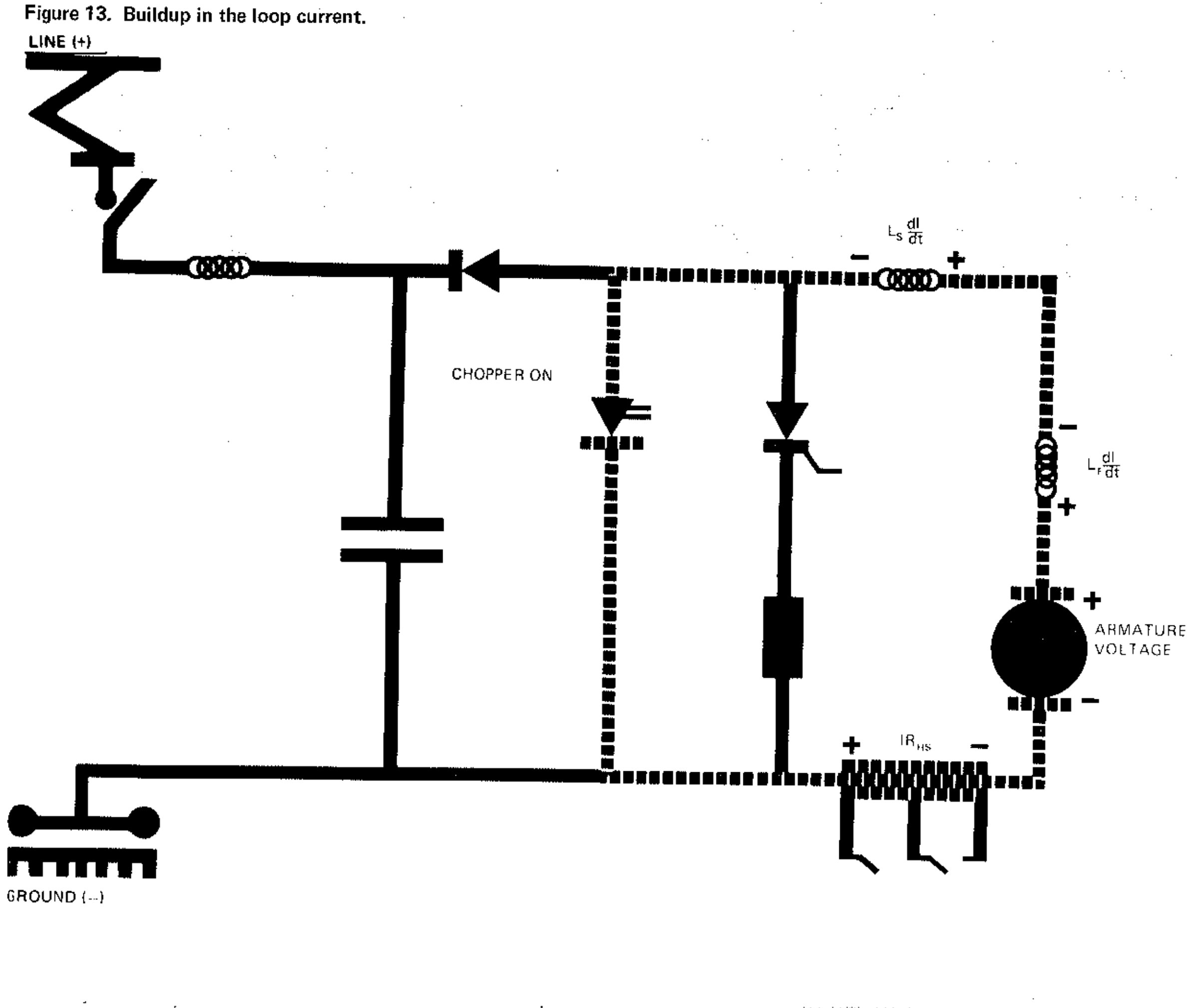
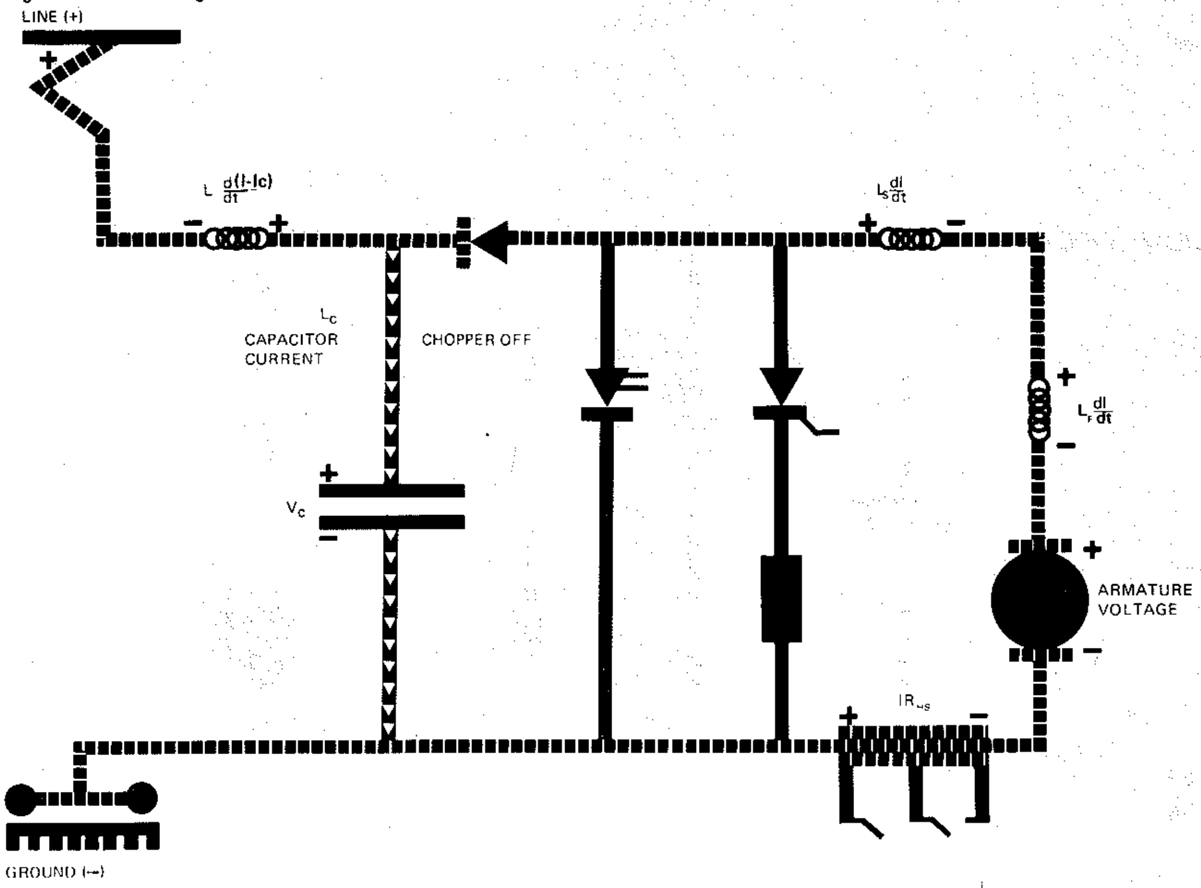


Figure 14. Flow of regenerative current.



speed brake resistor. Electrical energy is being transferred from the motor to storage in the inductor and to optional waste in the high-speed brake resistor. In Figure 14, the chopper has been turned off and the current is spilling over to the line filter via the blocking diode. The combination of motor-generated voltage and smoothing inductor voltage produces a flow of current against the line voltage and the voltage drop in the optional high-speed resistor. The flow of current against the line voltage constitutes useful regeneration. The flow of current against the drop in the optional resistor constitutes energy waste.

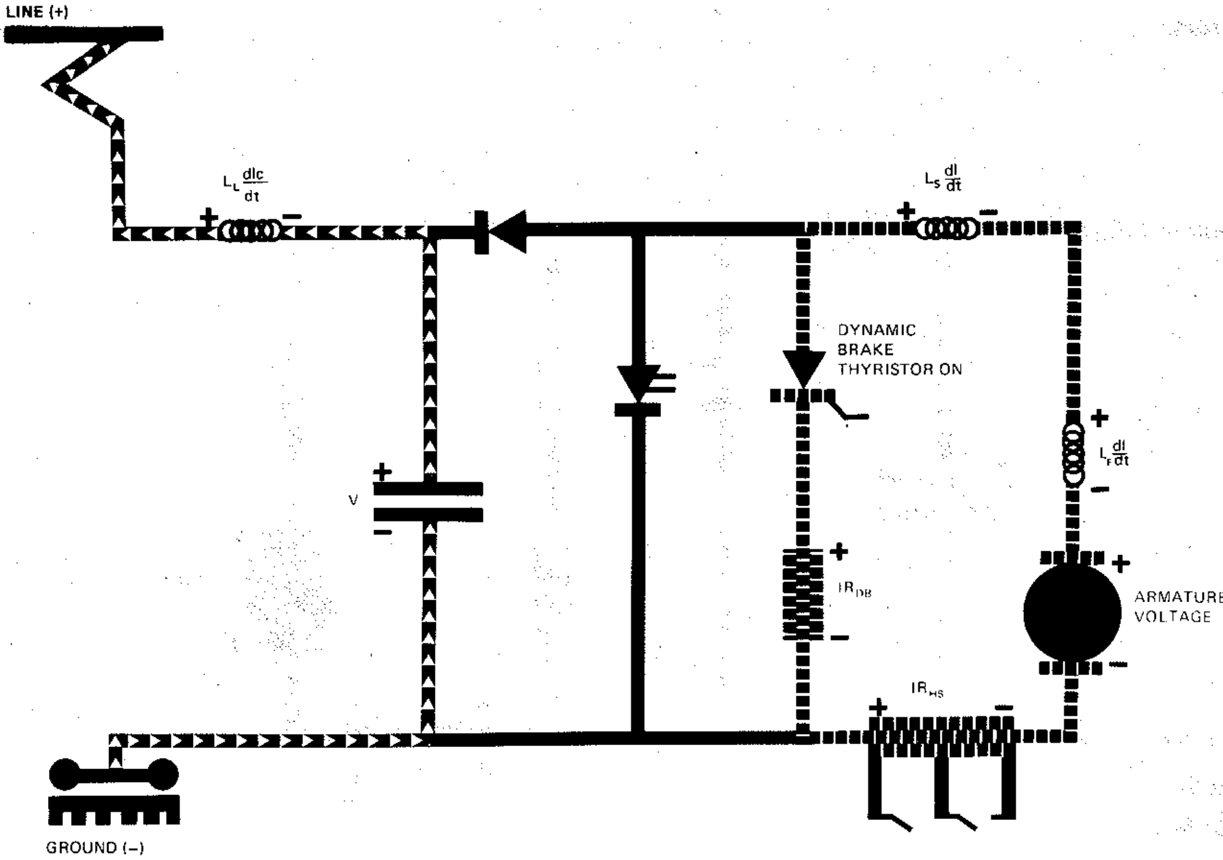
If the line is not receptive, much of the regenerated current will flow into the filter capacitor, which will cause its voltage to rise above a sensing level. When high filter-capacitor voltage is sensed, the dynamic brake thyristor is turned on and the current is diverted to the dynamic brake resistor as shown in Figure 15. A combination of motor-generated voltage and inductor voltage drives the loop current through the dynamic brake resistor and the optional high-speed braking resistor. After the current decays, the chopper is turned on and the whole process is repeated. Thus, once during each chopper cycle (approximately 200 to 400 times/s), the portion of braking energy returned and the portion of braking energy wasted are adjusted so that they do not exceed the maximum allowable line voltage under varying conditions of partial receptivity or nonreceptivity. This type of circuit has been implemented and is used successfully on many chopper-equipped rail cars.

ECONOMICS OF REGENERATION

What are the economics of regeneration? Numerous claims are being made about the amount of energy that can be saved. Most of these claims are for savings in propulsion energy only, and these reductions will not be realized on a properties' electric meters because the car auxiliary and lay-up loads are not reduced by regeneration. Regeneration can help reduce the peak-hour demand and the associated utility demand charge. For a 33.7-Mg (72 000-lb) vehicle traveling at 22.4 m/s (50 mph), each stop involves 16 MJ (12 000 000 ft·lbf) of kinetic energy. At 21.6 cents/MJ (6 cents/kW·h), this is about 27 cents worth of electricity. Since only about half the energy can be recovered, the value to an operating property would be on the order of 15 cents/vehicle stop.

Another way to look at regenerative braking is to consider the trade-off between the daily power required by an electronic cooling blower for a solid-state system and the number of stops per day needed to recover a compensating amount of energy. A 7.46-kW (10-hp) blower running 24 h/d will consume 644 MJ (475 000 000 ft·lbf) of energy. At the rate of 8.1 MJ (6 000 000 ft·lbf) of recoverable energy per stop, a vehicle with regenerative braking would have to make 79 stops at 22.4 m/s (50 mph) just to offset its blower consumption. At an average speed of 8.94 m/s (20 mph) and 1 stop/mile, it would require 4 h of car operation to reach the point at which the savings in regenerated energy offsets the added blower consumption. The fact that several properties that are exposed to severe winters (e.g., Cleveland and Boston) do not believe that the recovery of dynamic brake heat in season is worth the maintenance expense of a ventilating air-flow deflector indicates that traction energy costs are less important than maintenance costs. Regeneration may be a fad that will be of

Figure 15. Flow of dynamic brake current.



little importance to present-day transit operations if it adds to maintenance costs.

It is obvious that there are problems in vehicle energy economics at present. The fact that the ACT-1 development program is proceeding with a propulsion system that suffers a steady 22.4-kW (30-hp) flywheel running loss and with an air comfort system that requires a steady 59.7-kW (80-hp) shaft power input indicates that total vehicle energy is not all that important. If there is a constant 82.1-kW (110-hp) parasitic load on each vehicle, regenerative power savings look very small.

In summary, serious efforts to reduce transit energy consumption should take into account the simple expedients of seasonal recovery of dynamic braking heat, skip-stop and request-stop operation, local and express scheduling, and reductions in car lay-up time with auxiliaries running. These measures can provide immediate savings without recourse to complex propulsion technology and exposure to its attendant risks and expenses.

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Investigating the Potential for Street Operation of Light-Rail Transit

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This paper examines the potential for light-rail transit (LRT) operations in the street with mixed traffic. It is hypothesized that street operation of LRT is possible, and in some areas desirable, for both cost reduction and service improvement. It is believed that the potential cost savings in construction should lead planners to consider using LRT in streets. However, little work has been done in analyzing the problems associated with street operation. This paper attempts to establish a systematic framework for investigating the potential for a shared street environment and to stimulate a discussion among LRT planners about the role of street operations in proposed systems. The methodology used in this study has two phases: the identification and investigation of the associated problems and the analysis of various design elements and strategies. Several possibilities for street operation are discussed and the generic problems of street running and traffic conflicts are analyzed. The approach is based on existing data from Toronto.

Many current light-rail transit (LRT) planning studies for North American cities have emphasized the use of private right-of-way. However, an important advantage of LRT is its ability to serve downtown areas by running through city streets where exclusive right-of-way, usually a subway, is prohibitively expensive. Little current research has been devoted to analyzing the potentials and problems associated with a shared street environment.

In general, planners have considered using street right-of-way for LRT operation only where a center median strip is available to separate LRT operations from automobile and pedestrian traffic. Although private right-of-way will undoubtedly be necessary to achieve high running speed, the degrees of reservation that are possible range from an exclusive median for LRT (full reservation) to fully integrated street running in vehicular traffic. Some of the alternatives are listed below.

1. Suburban collectors—In some medium-density suburban areas, street running with stops at corners may provide residential access times superior to those found in conventional line-haul, pedestrian- and automobile-feeder transit systems.
2. Downtown distributor—In central business districts (CBDs) LRT street operation may be a feasible way to provide distribution service in conjunction with high-speed routes running on segregated rights-of-way between the suburban areas and the urban core. Adequate levels of service can thus be provided while the high costs of CBD subway construction are avoided.
3. Limited-traffic streets—Certain streets can be used by LRT at speeds that compare favorably with separated running if measures are taken to reduce competing vehicular traffic. These measures may include contraflow lanes, in which LRT vehicles operate in a direction opposite to that of automobile traffic; traffic restraints; transit priority signals; and diversion of traffic to adjacent streets.
4. Automobile-free zones—Pedestrian malls and transitways in downtown areas can be used for LRT without compromising transit service and can enhance these areas.

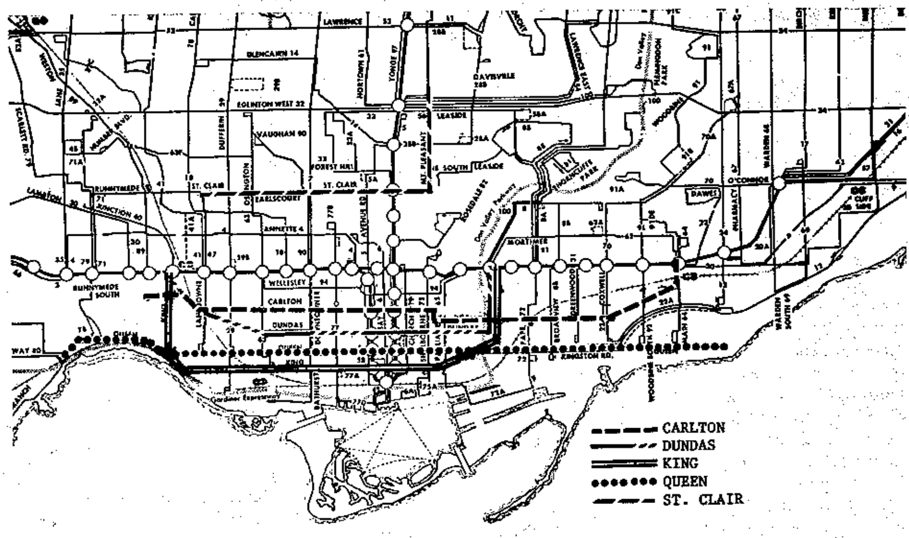
Historically, rail transit was placed in the centers of streets. Gradually, as the availability and popularity of the automobile grew, motor vehicle traffic began to interfere with streetcar operation. This produced an increase in the streetcar's travel time and made the service less attractive. In the period following World War II, streetcars in the United States were regarded as inhibitors in the urban streets. The removal of streetcars followed two basic trends. In most cases, tracks were removed and service discontinued. Where the streetcar lines were retained, every effort was made to separate them from automobile traffic. Some larger cities turned to heavy-rail transit or elevated systems or (as in Philadelphia and Boston) placed the most congested portions of the existing streetcar operation underground. San Francisco is now preparing to run its Market Street Streetcars in a subway one level above the Bay Area Rapid Transit line.

Today, in the face of escalating costs for rail rapid transit, North America is experiencing a resurgence of interest in LRT. Concurrently, federal transportation policy has placed emphasis on transportation system management to improve the efficiency of all modes and increase the effective capacity of streets to move people as well as automobiles. In this context, reinstitution of LRT street operation can be feasible if new strategies are developed to create a suitable shared street environment. The increased emphasis on planning for pedestrian malls and large-scale automobile-restricted zones can give LRT street operation a major role in providing distribution and collector service throughout these areas. The ability to operate at grade with closely spaced stops and to conveniently serve shopping areas is a highly desirable characteristic for LRT operations in pedestrian zones. The problems of conducting street operations in heavy automobile and truck traffic may be insurmountable, but LRT operation may be possible in less dense traffic or in conjunction with more advanced traffic control and signal strategies.

Modern LRT street operations exist throughout Europe; several cities (Amsterdam, the Hague, and Zurich) have added new street trackage. Many European cities have instituted transit priority schemes, generally in the form of reserved transit lanes. Other priority techniques found throughout Europe include the exemption of transit vehicles from barred turns, signal priority, and various regulations that give transit vehicles the right-of-way over other vehicles. While many successful European mixed-traffic techniques may be adopted in North America, one must be careful in comparing European street systems and those in North American cities because of the differing social and driving characteristics. A survey of European transit systems by R. Bennett and C. Elmberg (1) showed that observance of transit priorities by the motoring public depended on the type of priority. Observance of physical or operational priorities was generally satisfactory there, but North American drivers are less likely to abide by such regulations. Both Toronto and Philadelphia have experienced major problems because motor vehicles have used reserved streetcar lanes.

Although several North American cities, including Boston, New Orleans, Philadelphia, Pittsburgh, San Francisco, and Toronto, currently operate on-street

Figure 1. Routes of five streetcar lines in Toronto.



LRT lines, there is little information transmitted to the planning community on the degree of operating success of these streetcar systems or on the potential for improving their performance. Most often, one hears only criticism, which is probably justified, of mixed-street operations because of their slow running times and undependable service as a result of interference from congested vehicular traffic.

We believe, however, that the potential cost savings in construction should lead to consideration of using LRT in streets. Exclusive transit lanes should be preferred, but these are not always possible. This leads to the alternative of mixed-traffic street operation.

As the first step in this study, we defined and identified the major causes of street operating delay. In searching for current streetcar information, we found that a great deal of data had been accumulated on several LRT routes in Toronto (2). Toronto is a growing North American city that has a strong streetcar orientation in its public transit system. We feel that problems of LRT operation in Toronto are similar to those that would occur in any new or existing mixed-traffic LRT system in the United States or Canada. Five LRT routes in Toronto have therefore been examined closely in regard to the problems and potential that must be determined before new LRT systems in a shared street environment are recommended or implemented.

BACKGROUND

Metropolitan Toronto encompasses an area of 624 km^2 (240 $miles^2$) and a population of 2 300 000; it is the fifteenth largest city in North America. Toronto is a city oriented toward public transportation; some 70 percent of peak-hour travelers use mass transit (3). All LRT operations are under the jurisdiction of the Toronto Transit Commission (TTC), a fully integrated public transit agency.

The streetcar system currently has a total of 11 routes covering 74 km (46 miles) and has 338 light-rail vehicles (LRVs). Virtually all routes use mixed-traffic street operations. Basically, the streetcar routes run in an east-west direction; most routes converge in the major downtown sector. The streetcar lines constitute the major mode of surface transit serving the central city. They carry 4000 to 9000 passengers/h/direction in the rush hour.

Due to the city's development pattern, the streetcar routes pass through areas of each of the basic land uses: residential, light commercial, heavy commercial, and industrial (3).

ROUTE DESCRIPTION

This analysis examines the five routes—Carlton, Dundas, King, Queen, and St. Clair—shown in Figure 1. The first four are primarily downtown routes although they extend into dense residential areas. The Carlton route runs past the University of Toronto and the Ontario Parliament buildings. The King, Queen, and Dundas routes traverse the major office district of the city; the King route extends through the major manufacturing sector. The St. Clair route runs through a major shopping district surrounded by residential streets whose population ranges from middle to upper middle class. All five routes run east-west, have double tracks, and run in the center of their respective streets. A short stretch of the Queen route, located on the outskirts of the city, runs in a segregated median strip along a major artery. The St. Clair line had diagonal striping across the pavement to separate automobile and transit traffic. However, objections to the striping were made by motormen, who complained of headaches. The striping is now being allowed to fade.

DATA COLLECTION

During 1973, TCC accumulated data on various delays encountered by streetcars. Little more was done with this study because of budget constraints, although left turns were eliminated at several intersections. Observations were collected by a full-time traffic checker.

Data were collected for delays in eastbound and westbound directions for four different time periods in the morning peak, midday off-peak hours, afternoon peak, and evening. Routes were divided into 12 to 16 segments on the basis of important intersections and stops. Each delay was assigned to one of 12 categories:

1. Passenger service time,
2. Other delays due to TTC operations,
3. Traffic signal,
4. Left or right turn,
5. Accident,
6. Traffic congestion,
7. Yield and merge,
8. Pedestrian crosswalk,
9. Parked automobiles,

Figure 2. Total operating delays.

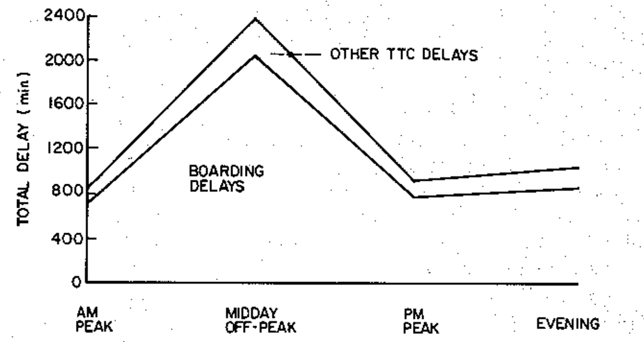
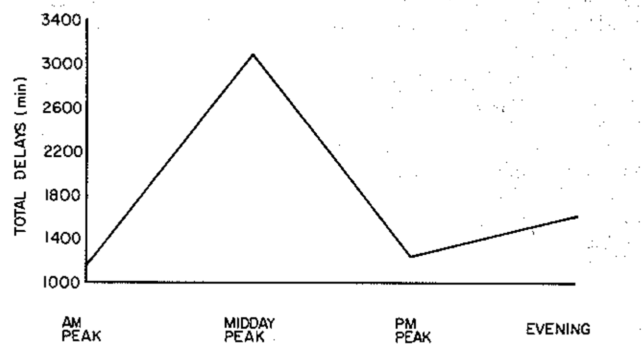


Figure 3. Street delays for all routes.



10. Traffic officer,
11. Construction, or
12. Miscellaneous delays.

Guidelines were established for what constituted a delay, and all delays were recorded in minutes. We conducted a preliminary investigation of the data; our findings are given below.

OPERATING DELAYS

Operating delays were those attributed to passenger service time (boarding delays) and those caused by TTC operations (i.e., operator lag or other transit vehicles ahead). All other delays were considered street delay. For all routes, operating delays accounted for about 40 to 45 percent of the total delay, as shown below (1 km = 0.6 mile).

Route	Round-Trip Distance (km)	Operating Delay (%)	Street Delay (%)
Carlton	29.8	41.7	58.3
Dundas	21.1	41.4	58.6
King	25.6	41.6	58.4
Queen	33.6	41.6	58.4
St. Clair	19.4	46.9	53.1

Operating delays, adjusted for the length of route, were greatest for the Dundas and St. Clair lines. However, the St. Clair line experienced large delays at the transfer station with the Yonge Street subway, since streetcars must await connections with the subway. For all routes, delays caused by TTC operations remained approximately 10 to 15 percent of the total operating delays (0 to 10 percent of the total delay incurred).

On most routes, boarding is done in the center of the street with no special passenger provisions. Along St. Clair Street, there are boarding platforms that offer the passenger refuge from the surrounding street traffic. At the time the data were collected, Toronto had a conventional fare system, and the operators made change. The TTC has since switched to exact-fare collection, which has probably resulted in a reduction of boarding delays.

The data indicated that all routes except St. Clair had boarding delays ranging from 85 to 90 percent of the total operating delays (35 to 40 percent of total delay incurred). Boarding delays along the St. Clair line made up a much lower percentage of the total operating delay and averaged only 27 percent of the total delay incurred; this indicates that protected passenger platforms may reduce scheduled running times by 10 percent. Further analysis showed that boarding delays were greatest for midday off-peak hours and approximately equal for other hours of the day (Figure 2). This may be because passengers who use the transit system during off-peak hours tend to be senior citizens or shoppers with packages, both of whom can be expected to board more slowly.

STREET DELAY

The most obvious effects of LRT operation in a shared street environment were found in the street delay categories: traffic signals, left or right turns by motor vehicles, accidents, traffic congestion, locations where traffic must yield and merge, pedestrian crosswalks, parked automobiles, traffic officers, construction, and other miscellaneous traffic delays. Throughout the Toronto system, street delays accounted for 55 to 60 percent of all delays incurred. They were found to be highest during the midday off-peak period (Figure 3). This may be because traffic lights are more effectively synchronized during the peak periods to ease the traffic flow along arterial roads. The LRVs are thus able to take advantage of the extended green cycle.

The length of street delays varied among routes and among segments of each route. Several variables were analyzed to account for the significant range in delay. The variables were land use, volume of motor vehicle traffic, roadway width, and number of intersections.

Land use was divided into four types: residential, light commercial, heavy commercial or office district, and industrial. Correlation between these categories and street delay proved to be virtually nonexistent. Minutes of delay ranged from 11.0 for light commercial to 15.23 for residential. However, it must be noted that, since all streetcar lines in Toronto serve the nucleus of the city, the densities for each type of land use do not vary significantly in the area studied.

Traffic volume, roadway width, number of intersections, and traffic volume per roadway width were all tested for correlation with total street delay time. In each case, the correlation proved to be not significant. Among the variables examined, the number of intersections had the largest effect on street delay.

The overwhelming cause of street delay was traffic signals, which accounted for 86.9 percent of all street delays and remained approximately constant across all routes and times of day. The second largest cause of delay was traffic congestion, which made up 5.7 percent of street delay. All other causes of street delay were relatively insignificant.

An understanding of street delay can be gained from the route-delay profiles of the Toronto streetcar lines (Figures 4 to 8). Several patterns of delay can be distinguished. The Dundas line exhibited major traffic congestion along the Jarvis-Parliament segment, where there is a circular bend in the road. The King route had significant delays on the segment where the line turns from King Street onto Broadview Avenue.

IMPLICATIONS

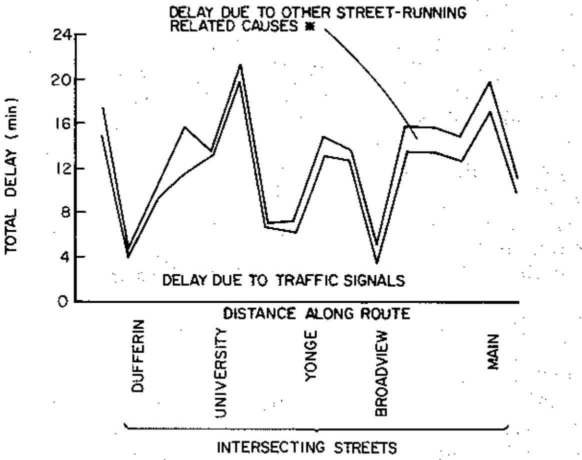
The analysis of the Toronto streetcar delay data reveals that delays caused by boarding passengers and by traffic signals together account for 90 percent of all delays incurred—boarding delays make up 40 percent of the total and traffic signals the remaining 50 percent. Efforts to reduce streetcar delay should therefore be directed to improving these two major elements.

Boarding delays could be reduced by providing platforms (preferably high-level platforms) that offer the passenger a refuge in the street center. The installation of low-level platforms along the St. Clair route has substantially reduced boarding delays and has not created any major traffic problems. Contrary to the fears of many planners, pedestrian access to the street-island platforms has not produced any significant problems.

Installation of traffic signal preemption capability for LRT street operation can drastically reduce delays. In the case of Toronto, it appears that total delays could be reduced 50 percent if LRVs were given 100 percent priority. An example of the large time savings possible is shown for the Carlton route in Figure 9 and for all routes in the table below (1 km = 0.6 mile).

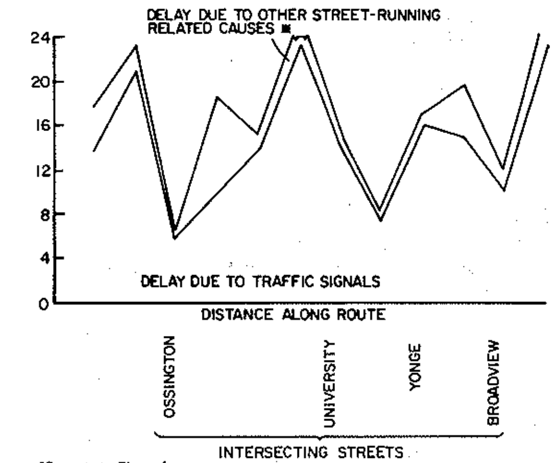
	Average Speed (km/h)	
Route	Existing	With Preemption
Carlton	16.5	22.7
Dundas	14.9	22.2
King	16.8	22.7
Queen	18.1	21.3
St. Clair	15.2	22.4

Figure 4. Route-delay profile for Carlton line.



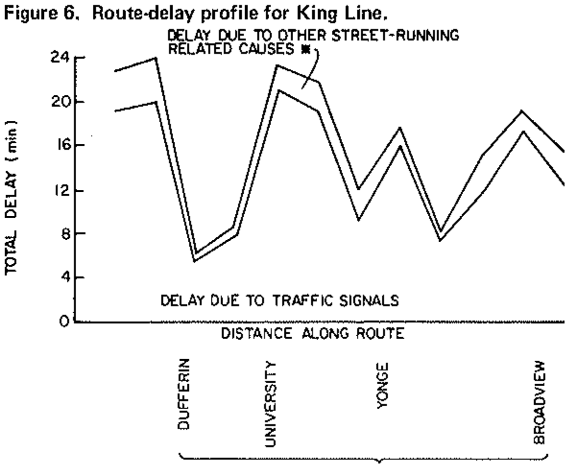
*Left or right turns by motor vehicles, accidents, traffic congestion, yield and merge, pedestrian crosswalks, parked automobiles, traffic officers, construction, and miscellaneous delays.

Figure 5. Route-delay profile for Dundas line.



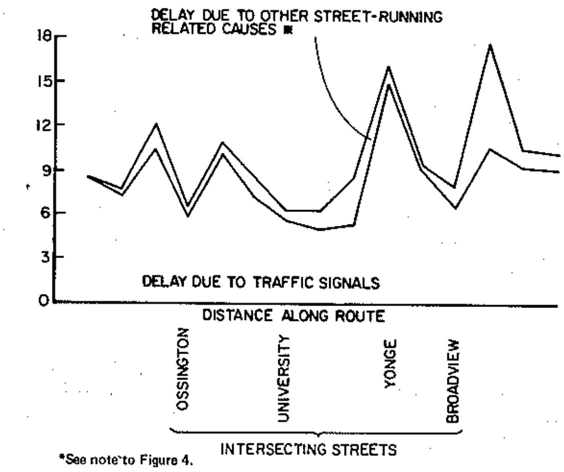
*See note to Figure 4.

Figure 6. Route-delay profile for King Line.



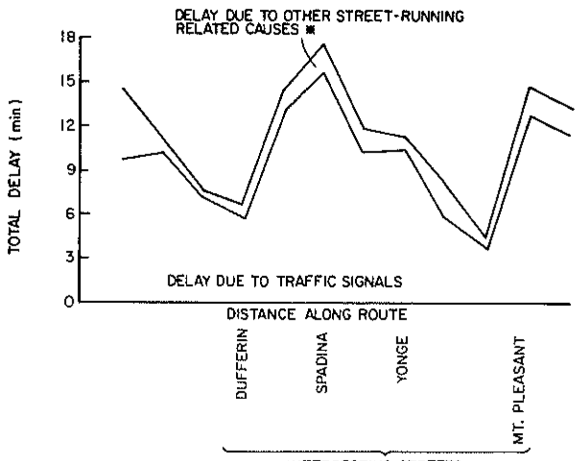
*See note to Figure 4.

Figure 7. Route-delay profile for Queen line.



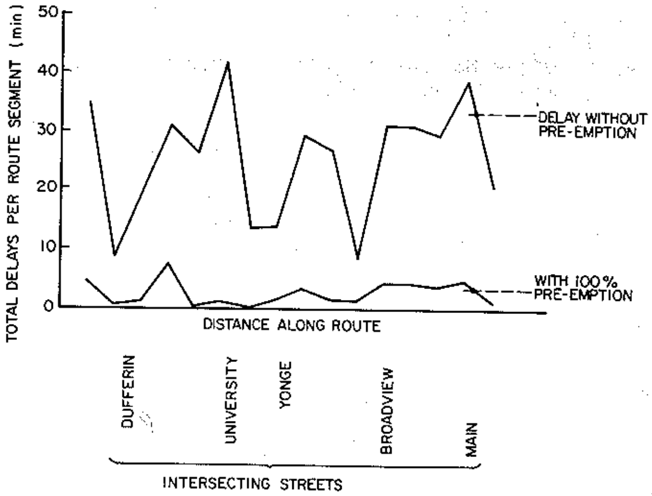
*See note to Figure 4.

Figure 8. Route-delay profile for St. Clair line.



*See note to Figure 4.

Figure 9. Effect of signal preemption on street delays along Carlton line.



The Dundas route would benefit the most; its average speeds could increase from 14.9 to 22.2 km/h (9.3 to 13.9 mph), a 50 percent improvement in average speed (4). The routes' average speed would rise from 16 to 22.4 km/h (10 to 14 mph), a 40 percent increase.

Surprisingly, streetcar delay due to traffic congestion was extremely low; it accounted for only 3.3 percent of the total delay. This finding seems to refute some of the criticisms leveled against street running of transit vehicles, i.e., that conflict between transit and motor vehicles is the major cause of delay. Of course, it must be noted that schedule speeds are based on the average speed that can be attained in mixed traffic.

Although improvements may be instituted to reduce the delays in the other categories mentioned, the data from Toronto's operations indicate that these variables are relatively unimportant in regard to transit travel time. In fact, the eight other categories of street delay account for a mere 4.2 percent of all delays incurred as is shown below.

Type of Street Delay	Percentage of Total Delay	Type of Street Delay	Percentage of Total Delay
Traffic signals	49.97	Pedestrian crosswalk	0.67
Left or right turns	0.98	Parked automobiles	0.10
Accidents	0.32	Traffic officer	0.12
Traffic congestion	3.30	Construction	0.76
Yield and merge	0.84	Miscellaneous	0.43

Thus far, Toronto has instituted several measures, such as banning left turns by motor vehicles, to alleviate delay at specific intersections. The TTC is currently exploring the use of signal preemption.

CONCLUSIONS

As the experience of the TTC has shown, LRT operation in streets can provide a workable solution for some urban transport problems. The advantages of street operation are greatly reduced capital costs in construction, faster construction time, and less environmental disturbance. Since urban real estate costs are climbing, LRT street operation is a relatively low-cost solution to providing a widespread, line-haul transit system capable of transporting large volumes of passengers. The subway-surface LRT lines in West Philadelphia and San Francisco are also excellent examples of the street operation of widespread collectors for LRT systems.

These exceptions notwithstanding, street operations have been deemed largely impractical for LRT systems in North America. However, there are many dimensions to the problem, and trade-offs are possible. While the past 50 years has seen a diminishing of streetcar priority in street traffic, there is no reason that priorities cannot be changed in the interest of moving people, rather than motor vehicles, more efficiently.

The data from Toronto indicate that improvements in two areas, boarding and signal preemption, can significantly reduce running times. Boarding delays can be lessened by the installation of platforms, as was shown by the St. Clair route. Island platforms have been used successfully, both in Toronto and in Philadelphia. The plans for a new LRT line in Calgary include high-level island platforms that are accessible from the street and from overhead walkways.

The other area in which significant gains in transit speed can be made is in traffic signal preemption. The technology of traffic signal control systems is becoming less and less expensive as sophisticated low-cost microprocessors are becoming more readily available. Several cities in Europe have installed modified forms of signal preemption. The LRT systems in Berne and Glasgow use traffic signal synchronization that is based on transit speeds rather than motor vehicle speeds. Berne has included a provision for longer green cycles for LRVs that is actuated by overhead contacts. The city of Melbourne has also instituted a signal priority system that can be actuated by overhead wire contacts, loop detectors, or push buttons on the transit vehicle. The institution of such transit priority measures in Europe and Melbourne has resulted in patronage gains.

However, systemwide signal preemption is still relatively untried in the United States. Many opportunities for the implementation of such control systems exist throughout the United States. Recent decisions to rehabilitate LRT lines with street trackage (as in Pittsburgh) may provide an ideal opportunity to test the effectiveness of transit priority measures.

It appears that signal preemption strategies, if they are successfully implemented, can produce significant increases in running speed—almost enough to make street running comparable to running in private right-of-way in which the stops are closely spaced. Moderate traffic density and traffic signal controls may make street operation an optimal strategy for LRT systems.

Various other traffic control measures can be promoted, such as legally restricting parking at transit stops. However, as the Toronto data show, these measures will have little effect on reducing the overall delay. In addition, observance of this type of regulation in Europe has been poor (1).

The results from Toronto indicate a strong potential for street operation of LRT. Significant reductions in delay time can be achieved by means of improvements that will yield benefits in the form of improved service levels and better utilization of the two most costly transit resources: labor and car fleet.

ACKNOWLEDGMENTS

Assistance in compiling the data for this paper was obtained from two primary sources, the Toronto Transit Commission and the Department of Roads and Traffic of Metropolitan Toronto. We are especially indebted to D. C. Phillips of the TTC and M. Stanojevic of the Department of Roads and Traffic. In addition, we would like to thank George R. Beetle and John W. Schumann for their helpful comments.

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Part 5

Workshop Reports

Institutional Barriers to Implementing Light-Rail Transit

Jeffrey G. Mora, Urban Mass Transportation Administration, U.S. Department of Transportation, workshop moderator
Glen D. Bottoms, U.S. Department of the Treasury, recorder

The workshop session began with a brief description by the workshop moderator of the different types of institutional barriers that might confront localities seeking to implement light-rail transit (LRT). These include the blurred definition of LRT, especially its streetcar image, the problems of selling the concept, and perceptions of LRT as being second best; the issue of who makes the decision about LRT in view of the roles of the Urban Mass Transportation Administration (UMTA), the Environmental Protection Agency (EPA), the U.S. Department of Housing and Urban Development, local public agencies, and consultants; and the complexities of the governmental process (pressure groups, citizen influence, scarce resources, and the conflict between environmental disruption and public works projects).

LRT has suffered from the lack of a clear perception of the concept. For many, the term brings visions of noisy, cumbersome, antiquated vehicles rambling conspicuously through crowded city streets. To others, LRT represents a second-best or lesser alternative that is forced on local areas by an economizing administration. In a period when central cities are chronically short of cash and plagued by a shrinking tax base, these cities will seek to maximize federal funding possibilities. Conventional rapid transit projects fulfill this goal.

Institutional barriers at the federal level are perceived at the local level to be of a bureaucratic nature; highly specialized, regularized, and technical requirements give rise to much of the criticism. Another sticking point is the overlap between programs of different agencies. For example, EPA's Transportation Control Plan requires localities to formulate a package of often stringent measures to achieve improved air quality, but this package can contain elements that run counter to reducing air pollution over the long term and hinder the planning for long-term metropolitan transportation goals.

One of the questions raised at the workshop was how an urban area goes about achieving a consensus to ensure the implementation of capital improvements on a systemwide basis without a public referendum. One proposed solution described how Toronto conceived, planned, and built a subway in the late 1940s. A small staff within the existing transit agency (the Toronto Transportation Commission) initiated the idea, undertook to sell the idea to key decision makers and the public, and eventually financed the endeavor without federal or provincial funds or participation. It was pointed out that such an approach is no longer possible in today's environment.

One participant voiced an opinion that state departments of transportation have continued the preoccupation with highways that characterized their predecessor organizations and have failed to give support to nonhighway projects. One locality, having secured the necessary local approvals, could not elicit a matching commitment from the state department of transportation for a major transit (nonhighway) project. Rather than finding the department of transportation receptive, they found themselves in an adversary relationship. While it was pointed out that localities can appeal directly to the state legislature for relief in such cases, it would seem more logical to make major efforts to reorient the state department of transportation to a multimodal approach. Another participant pointed to the imbalance transit projects face because of state funding requirements. The local level frequently gets no encouragement from the state-level agency for transit-oriented improvements. On the contrary, the state departments of transportation (for the most part originally highway departments) are adept and well schooled in securing funding from both the Federal Highway Administration and the state legislatures and can promise localities firm funding for local highway improvements. Furthermore, highway projects do not have to undergo the alternatives analysis or public referenda for federal funding that are now required for major transit investments. Given the choice of assured funding for the highway improvement or an uncertain future for possible transit funding, localities frequently take the obvious course. Who is to play the advocacy role for transit at this critical level?

Many participants indicated that the metropolitan planning process, supposedly structured to encourage multimodal transportation planning (and subject to various federal regulations to validate the process), can be subverted by state agencies and federal funding inequities.

Many participants articulated a deep sense of frustration over the emerging framework at the federal level for the examination and evaluation of proposed mass transportation facilities. One view held that it was unfair to promulgate an alternatives analysis requirement without also requiring a similar exercise for proposed highway projects. This comment underlined the dichotomy within the U.S. Department of Transportation for administering mass transit and highway programs (two separate agencies) with different viewpoints, rules, requirements, and funding arrangements.

Another view that emerged is that the problem with UMTA is only a reflection of the problems that can be encountered in the political process. A general attitudinal change must come to the congressional leadership and to the public. The recent failure of Congress to approve a gasoline tax boost and the reluctance of cities and states to make hard choices with regard to the automobile indicate that the national mood has not significantly changed.

A spokesman from private industry voiced a deep disappointment with UMTA's lack of action in approving LRT systems. Unfortunately, private industry assumed that a policy statement issued by UMTA on LRT in 1975 would result in emphasis on LRT by the agency. Local areas must develop specific proposals and survive a series of critical analyses before funds can be committed to the desired alternative. Of the LRT project applications received by UMTA from 1975 to 1977, only one survived the examination process, and there is some question whether it could accurately be called LRT.

A congressional aide gave an overview of congressional intent with regard to the urban mass transportation program, pointing out that the UMTA program is one of the last big discretionary grant programs in the federal government. He noted that there are some members of Congress who advocate vesting in Congress the authority to approve or disapprove project proposals on a case-by-case basis (as is now done with U.S. Army Corps of Engineers projects).

Another participant thought that the relative weakness of the transit industry itself was a formidable barrier. The organizations that should be initiating new proposals and policy initiatives are primarily occupied with operating what they have. In this same vein, it was felt that the industry trade association, the American Public Transit Association (APTA), has proved to be a weak advocate for transit in general and for fixed-guideway solutions in particular. Since the membership of APTA consists primarily of bus operators, the organization reflects an emphasis on the bus mode.

The workshop closed with a short summary highlighting the following points: the definition of LRT is blurred; there are different planning criteria, funding ratios (federal-local), and approval processes for highway and transit projects; state departments of transportation have a lack of commitment to nonhighway projects; and the problems do not originate only at the federal level. Barriers to implementation of both LRT and mass transit projects in general are found in abundance at all governmental levels.

Motor Vehicle and Pedestrian Interface With Light-Rail Transit

Henry D. Quinby, Consultant, San Francisco, workshop moderator
Lee H. Rogers, Institute of Public Administration, Washington, D.C., workshop recorder

The main issue dealt with in this session was the problem of finding the space within which to develop a surface-level light-rail transit (LRT) system. It is necessary to find sufficient, well-located space in the major corridors of a city if the challenge of providing optimal development of LRT is to be met. In the discussions of this subject, it was indicated that several American cities have primary and secondary arterial routes that no longer have as much through traffic as they used to, largely because of the expanded urban freeway system. These arterials seem likely candidates for future deployment of LRT systems.

It was asked how LRT lines could be placed into arterial or other roads of limited width. Discussion related to the use of medians in highways not built to interstate standards and to the development of side-of-road operation with and without vehicle accident barriers. The use of coupled one-way streets and curb lanes was also discussed as a way to improve the capacity of urban transport while minimizing the impact on private vehicles and the owners of abutting property. Restricting the use of narrow downtown streets to pedestrians and LRT operation was reviewed.

Every urban community must deal with the need for greater capacity in handling passengers and goods in the face of the negative aspects of increasing the width of existing surface transport networks. LRT can provide a low-cost solution to this problem, since it does not require a heavy investment in aerial structure or underground facilities. The use of existing or abandoned railroad rights-of-way and other corridors should be looked at judiciously and not perceived simply as an expedient.

LRT also provides the best potential for obtaining surface-level linear parks; it was felt that the concept of linear parks, as applied in San Francisco and various European operations, should be reviewed. There is a great need to introduce planners, architects, and community leaders to methods of developing linear parks.

The merits of substituting grass or other materials for the usual ballast-and-gravel or dirt-track foundation was discussed. Outside of mixed-traffic locations in public streets, it was felt that asphalt and concrete should be limited in their use because of their rather dull and uninteresting appearance. Some types of gravel-and-brickwork and grass rights-of-way were described that strike a balance between track-structure service life and perceived aesthetic impacts. New Orleans was cited as an excellent example of heavy landscaping of median LRT lines; there are shrubs, trees, flower beds, and visually attractive landscapes that blend the uses and the activities of the transport corridor. Such measures reduce the visual and automobile pollutants within the areas traversed.

There is some difficulty in placing LRT operation in existing streets, particularly in cities that no longer have street railway operations or laws that effectively promote LRT. In some cases, public service commissions have set unrealistically low operating standards because of their inexperience in regulating this mode. The use of mixed-traffic lanes was considered acceptable in outlying areas where congestion infrequently occurred. Within the central city area, preferential treatment through traffic signals or actual physical barriers was desired to maintain reliability and productivity for LRT operations. Speed limits for other powered vehicles were considered to be applicable to LRT vehicles within the street as long as the velocity was not more than 70 km/h (40 mph).

The participants agreed that standards for grade separation of LRT at principal perpendicular avenues and arterials should be developed. If LRT systems operate at headways of up to 6 min, there seemed to be little difficulty in maintaining surface-level crossing of principal arterials. In the case of interstate highways or expressways, more expensive solutions would be required. LRT has the ability to use variable speeds or to dampen its performance when required to do so by other considerations, although the latter should be extremely limited since greater reliability is considered a specific asset of this technology. However, in mall operation, for example, LRT should not be operated at speeds higher than 24 km/h (15 mph); there are various methods to enforce such speed limitations. In mixed traffic, some physical barriers are required when there is a high incidence of property damage due to conflicts at intersections or junction points.

The criteria for spacing the actual crossing of LRT lines by both pedestrians and motor vehicles were reviewed. Pedestrians can be handled in a variety of low-cost and effective ways. European experience indicates few safety problems with pedestrians in any state of physical or mental alertness. With respect to motor vehicles, the spacing of crossings depends on local circumstances. The volume of average daily traffic and peak-hour traffic on both highways and the LRT line would have to be considered to competently determine the spacing necessary. Objections to numerous street closings should be met by pointing out that this measure limits or restricts the movement of through traffic in the inner portions of neighborhoods. Although it does restrict some local trip operations, its value to the community lies in the channeling of through traffic to the major corridors that are provided. Regulations designed for the control and operation of LRT in a variety of urban settings must be developed. Although California's Public Utilities Commission is currently drafting such regulations, these should probably not be the basis for national standards.

The community and the traffic engineering profession have in LRT a mode that has a very limited impact on the urban fabric and street network. LRT systems can preempt traffic flows in a manner that does not create sizable congestion problems. The use of European tramway and light-rail standards can permit major savings in capital and operating costs. Dusseldorf, Cologne, and some of the Rhine-Ruhr cities were cited as examples of cities where such standards can be observed.

Strategies for protecting level crossings were reviewed. The participants concluded that the maximum design standard for grade-crossing protection should be class 1 railroad gate procedures. Both the regulatory authorities and the operators and union personnel may seek stricter protection of grade crossings, but this is mainly because they are unfamiliar with methods of deploying modern LRT operations.

Cities that initiate totally new LRT operations should undertake major driver-education measures on how to make left turns in the face of LRT operations. It may be politically and socially possible in some communities to restrict left-turn operation at low-volume intersections. Where major left-turn movements will be generated, proper traffic engineering criteria should be used to minimize potential conflicts. In effect, a dual method of traffic signaling for through traffic and light-rail vehicles should be made. Left turns should not be made from locations on the track structure; special lanes to the right of the track should be provided if sufficient widths are available.

Within the corridors served by LRT, special evaluations should be made for feeder bus services to terminal stations and intermediate stops. In the alternatives analysis evaluation, planning should determine what percentage of the corridor residents or potential transit users would be directly served by the LRT line and what percentage by a feeder bus operation. In many European cities, more than 70 percent of the central city population resides within 400 m (1300 ft) of arterial public transport services. In cities like Hannover, Cologne, Dusseldorf, and Essen, such a percentage more frequently resides within the influence area of LRT lines. Bus and LRT transfer areas need careful planning and continual evaluation of the needs of all types of passengers. Direct cross boarding between bus and LRT could be provided and, depending on climatic conditions, covering or heating should be maintained.

In light of the difficulties that Santa Clara County, California, has had in proposing rail alignments for LRT operations, it was concluded that more information should be gathered on the institutional and regulatory aspects of joint LRT-railway operation along common rights-of-way and on common trackage. Although former street railways had dual operation and interurban routes frequently had freight-train and light passenger-car operation, current vestiges of such systems do not have these dual purposes today. Examples in Germany, Belgium, and California indicate that such sharing of trackage becomes legally much more difficult than has been appreciated. Handling of accidents and aspects of liability and maintenance should be further documented to aid the advancement of LRT technology.

Finally, the requirements for handling elderly and handicapped patrons with LRT systems was reviewed. The most significant problem identified was passenger loading on street levels with and without high platforms. Although the Boeing Vertol light-rail car has a proposed wheelchair lift, it was indicated that such a lift was not able to relate adequately to normal, narrow pedestrian and passenger platforms unless the width is doubled.

A pervasive theme throughout the workshop dealt with the trade-offs between reduced physical, design, and cost alternatives, including more at-grade (or surface) operation, some mixed-traffic operation, and selective single tracking, on the one hand, and on the other hand, reduced LRT performance characteristics and operating economy and increased interference, conflicts, accidents, and so on.

Intermodal Integration

Brian E. Sullivan, British Columbia Ministry of Municipal Affairs and Housing, workshop moderator
Christopher Lovelock, Harvard School of Business, workshop recorder

Intermodal integration is successful in situations in which there is ease of transfer, compatibility in scheduling, and carefully designed and located facilities. A fare structure that supports transfer is equally critical. Intermodal integration is especially important to light-rail transit (LRT) because LRT will never be the sole transportation mode in an area; it must be one part of a family of modes that serves an urban area.

It was observed that there is no simple solution to the problem of modal transfer. The facility design, for example, depends on whether the transfer point serves a distribution or collection function. The size of the passenger volume involved is equally important.

Two schools of thought were identified in regard to the layout and functions of transit systems in metropolitan areas. One holds that there is only need for services that run point to point (a radial system) without transfers. The other holds that, in a comprehensive service (a grid system) for a metropolitan area, there are too many trips that have too little volume to permit all-day point-to-point service and that, therefore, some transferring is essential. Further discussion of this issue centered on two points. First, in the United States a transfer has a negative consumer connotation because in recent years the use of transfers has not been well executed; there are a few cities in Canada in which they have been handled well. Second, pricing is very important in making transfers acceptable. In addition to financial disincentives, it was also felt that inclement weather and the fear of crime deterred the use of transfers.

The idea of time as a factor in choosing whether or not to take advantage of a transfer was also discussed. This is important in facility design in terms of providing a dispersal function for two modes that have different headway characteristics; i.e., if one mode is delayed, the transfer is missed, and the transfer ride is lost. The particular circumstances in local situations should be the factor that dictates the facility requirements. How quickly people can be moved from one mode to another may determine the success of the design. If a large volume of people must be moved through a transfer point, grade separation may become a major means of making transfers workable and attractive to riders. However, in other settings it may not be needed at all. It depends entirely on the make-up and match of the headways involved. Reliability is seen as critical.

It was observed that in Europe one mode is selected to serve one particular travel desire and other modes are coordinated with it. In the United States, United Kingdom, and Canada, bus and rail usually compete, but this depends on local circumstances. One participant stated that in Boston, for example, the commuter bus competes with the commuter rail because of their bases in historic services. Before the Massachusetts Bay Transportation Authority (MBTA) owned both, they competed; now that MBTA owns both, they still compete. In Cleveland, before the rapid transit system was established, the buses operated several express services directly into the central business district (CBD). Now that the buses turn back at the rapid transit stations, many patrons were lost and have still to be regained. In the case of Toronto, there were never large express surface services into the CBD. Participants stated that many communities are beginning to realize the utility of having two services.

It was felt that damaging competition was the result of organizational in-fighting and that the United States has not been very sophisticated in terms of finding ways of constructing incentives within the marketplace for coordination and cooperation between competing operators. The growth of federal programs that subsidize operations should permit the development of ideas that support cooperation. Furthermore, there has been a tendency in the last 10 years to believe the solution to this problem lies in the acquisition of the competing operators and their consolidation into a larger and larger operation under public ownership. It was felt that this creates larger and more difficult management problems. It is more difficult to promote coordination in operations that cover a large area with thousands of buses but have a very narrow range of management control. More attention should be given to finding ways of creating incentives for the operators and looking for new markets.

Sophistication and Complexity Versus Economy: The Problem of Gold-Plating

Tom E. Parkinson, Transit Services Division, British Columbia Ministry of Municipal Affairs and Housing, workshop moderator

All aspects of overdesign were considered in this workshop session. Overdesign is not necessarily bad if it attempts to increase reliability, extend component life, or reduce maintenance; it can also improve public acceptability, reduce energy consumption, and lower noise levels. The problem is to distinguish between good design that advances the state of the art in a cost-effective way and unnecessary overdesign.

In view of the limited experience with new light-rail transit (LRT) systems in North America, how can one define overdesign? It was proposed that the experience in heavy-rail transit over the last 15 years could in part be extrapolated to LRT. Furthermore, overdesign is often introduced early in the planning stages when system designs for civil engineering, railroad or rapid transit power supply, signaling, and fare collection are being selected; e.g., LRT in Buffalo was burdened with inefficient fare collection, and subway standards were applied to signaling and power supplies on Toronto's Scarborough line. It was stated in rebuttal that the Urban Mass Transportation Administration (UMTA) applied sufficient monitoring and safeguards to avoid blatant modal bias in alternatives analysis. In Toronto, the extra costs of applying subway standards are only a small proportion of the estimated total cost and represent the engineer's desire to be conservative and to ensure that the system can be built within estimates. The objection was raised that others, seeing the high quotes for Toronto's signaling and power supply systems, would be suspicious of the lower estimates in their own studies, despite the fact that actual costs in Edmonton, for example, are less than half Toronto's for power supply and one-third for a functionally similar signaling system. The discussion ended with statements of the need for planners, engineers, and economists to work together more closely in the design stages of an LRT system.

A vigorous discussion that centered on signaling referred to Burgin's paper in this Report recommending against any move away from relay logic. A supplier stated that proven, cost-effective solid-state signaling components are available and should be used. Several participants contradicted this; they noted that what a supplier regards as proven and cost-effective on the test bench often turns out to be a technical and economic disaster in the extremely adverse environment of urban rail transit. This led to comments on the unfortunate process in a small industry whereby much of the learning curve for innovations takes place in revenue service, where problems directly affect the quality and reliability of daily service. Despite the best intentions and the availability of such testing facilities as those at Pueblo, constraints of time and money dictate a situation in which components can often never by truly tested except in the rigors of daily revenue service. The need for any signaling at all was addressed by comments that Chicago had a better safety record when the rapid transit system was mainly under visual control than it does now with a full signal and communication system. The moderator pointed out that this was not a fair comparison since it is no longer possible in the 1970s to select, train, supervise, and discipline operators in the way that was possible in previous generations.

The signaling discussion ended with the suggestion that we will soon be able to compare actual systems. Next year Edmonton opens its LRT line with a low-cost relay logic system that uses European rather than Association of American Railroads (AAR) standard components and signal-light aspects, while the San Francisco Municipal Railway (Muni) will start operating a cab-signal system that will have hybrid components (i.e., some solid-state devices). In the near future, the approved and funded Calgary LRT proposes to build some sections of line that have no signaling at all, while Toronto's funded Scarborough LRT line proposes to use AAR subway signaling standards.

The discussion on gold-plating began with its definition as spending more than is needed to do the job and went on to explore UMTA's, consultants', and operators' attitudes toward gold-plating. UMTA was defended as rightly wanting to advance the state of the art, but workshop participants felt that UMTA also had a desire for high technology for its own sake. Some regarded consultants as having a vested interest in increasing the civil engineering costs, since their fees may be set on a percentage basis; others defended consultants since they often only follow their clients' wishes. Operators may have no financial investment in a system that has 20 percent local and 80 percent federal funding. The decision makers within the operator's management may not consult with those who would operate and maintain the over-designed system. However, UMTA was regarded as having effective control over most such abuses. It is understandable that the consultant and his client have preference for the easiest rather than the cheapest solution to certain design questions. For example, it is easier to build a grade separation than to negotiate with traffic engineers and public utility commissions for a controlled grade crossing at which LRT is not impeded by severe speed restrictions or the fear of having even the smallest negative impact on automobile flow.

Overdesign was discussed with respect to portions of Muni, the Washington Metro, and Los Angeles' perennial proposals for rapid transit in which only the best would do. Comments were made that a city would hardly accept LRT with grade crossings if it thought there was a chance of getting a fully grade-separated rapid transit system.

Chopper control was discussed at length. In summary, it was felt that UMTA had mandated chopper controls in the standard light-rail vehicle but that claims for energy and maintenance savings with choppers had been overstated. It was agreed that well-maintained resistive controls are as smooth as chopper control except on trolley coaches and that starting-power losses were lower than expected; in many cases, this loss can be used to heat the car interior during the colder months. The more skeptical, conservative European approach was discussed and several participants speculated that in the next decade alternating-current motors with suitable power conversion would supersede both resistive and chopper control.

A discussion on the merits of power collection by means of pantographs or trolley poles failed to reach any conclusion. Each has several advantages and disadvantages, and the workshop was split into two camps.

In summary, it was apparent that the participants were aware of many mistakes during the past decade in LRT and rapid transit planning and design that can be attributed to gold-plating. They were uncertain who was in charge to ensure that the lesson had been learned and that the mistakes would not be repeated. The concept of LRT as an application of proven technology does not mean that advances are not desirable. The problem was in determining in the long run which advances are necessary or desirable and are cost-effective.