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Light Rail Transit

A STATE OF THE ART REVIEW

EXECUTIVE SUMMARY

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Executive Summary

16. Abstract

Operational experience in cities of Western Europe and North America suggests that light rail is a viable transit alternative for U.S. cities as well. This state-of-the-art review seeks to establish a common level of understanding of light rail transit among planners, community leaders and decision makers. Contemporary planning concepts of light rail are reviewed and a description is provided of guideways, stations, hardware, operations and costs. The report examines the developmental trends of the last two decades which caused the renaissance of light rail in some western countries. The review focuses on the range of transit services offered by light rail, the utilization of a range of right-of-way opportunities along its routes, the lower investments and the potential for staged deployment associated with this mode.

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PREFACE

Traditionally, transit planning and development has concentrated on accommodating travel demands in high volume radial corridors that typically can be found in the older, densely developed metropolitan areas. But such corridors represent a relatively small and shrinking share of the total urban travel market. A growing proportion of metropolitan travel takes place in the low and medium density areas that have sprung up on the fringes of our metropolitan areas and that characterize our newer, automobile-age cities.

In these areas, trip patterns are too diffuse and travel volumes too small to justify high capacity transit systems. The need is for public transportation that can function efficiently and economically in conditions of low and medium trip density and still provide a level of service that will attract people out of their automobiles.

Some communities have tried to meet this challenge by introducing the concept of paratransit--flexibly routed shared-ride transportation services involving the use of small- and intermediate-size highway vehicles, designed to provide efficient and convenient service in areas which cannot justify frequent and regular bus service.

Light rail transit may be the forerunner of a similar trend in the field of fixed guideway transit. Its less obtrusive vehicles and guideways, lacking the potentially dangerous "third rail," enable the LRT to penetrate into city and metropolitan areas with minimum cost--often at grade, and using existing rail tracks. Its ability to operate as single cars or as trains without a corresponding increase in operators enables light rail transit to adjust to fluctuating traffic loads and provide convenient peak as well as off-peak service. Its ability to combine operation at grade, in subways and on elevated guideways endow it with a high degree of flexibility in location, design and implementation. Light rail transit should thus become a particularly strong contender for the attention of medium-size cities that aspire to fixed guideway transit, but cannot justify the high cost, long lead times, and disruption associated with the construction of heavy rail rapid transit.

While the LRT concept has undeniably many virtues, it is not a universal solution. There will still be a need for heavy rail technology to meet transit needs in a few high-volume urban corridors, just as there will always be a place for buses, taxis and automobiles in a total urban transportation system. Thus, light rail transit represents a valuable addition to the existing array of transit options from which cities may select the solution that best fits the local needs and budgets.

It is in this spirit that the Urban Mass Transportation Administration is pleased to issue this comprehensive state-of-the-art report on light rail transit. We hope that the report will help localities assess the potential of this technology, and provide them with the essential information needed to determine the suitability of this concept to meet their special transportation and urban development needs.

Robert E. Patricelli
Administrator
Urban Mass Transportation Administration

FOREWORD

For several decades most American cities have depended almost entirely upon the bus as the principal form of public transportation. In the larger cities where densities and ridership justified a higher level of transit service, rail rapid transit and commuter rail have continued to serve as major modes in important corridors. Following recent examples in San Francisco and Washington, D.C., many additional cities have sought in recent years to develop some form of fixed guideway transit to improve the levels of transit service. Recognizing that they did not always need nor could they always justify rail rapid transit, these cities have sought transit options better suited to their needs.

For transit planners and decision makers the search for the ideal transit option is unceasing. It must not only be economically viable or affordable but should be also adaptable to modern urban forms and trip making habits. Thus far, this ideal system has proved to be elusive. Few, if any, new transit concepts have stood the initial test of application, yet maintaining all attributes of the ideal solution. More and more transit practitioners are beginning to turn to concepts which, while perhaps less than ideal, promise the public improved levels of transit service and offer the decision makers implementable transit investments.

To many transit planners and observers, the light rail transit operations in a few U.S. cities and in a number of West European cities, appear to offer, if not the ideal, at least a viable solution to a sector of modern urban travel needs. In most American cities, however, where the transit frame of reference has been the bus, and in those larger and older cities with rail rapid systems, light rail transit might be perceived as a streetcar operation not in consonance with modern urban development patterns and trip needs.

The West European experience offers evidence of successful adaptation of the light rail to the structure and life style of the modern city. The diminishing differences between the life styles and urban conditions in Western Europe and North America suggest that the light rail experience overseas may be significant to American transit as well. If new light rail systems are to be deployed in the United States, however, detailed planning tools based on considerable operating experience will be required to establish their optimum form for American cities.

To assess the applicability of modern light rail technology in Northern America, a comprehensive data base was needed. As a starting point, the Urban Mass Transportation Administration authorized an objective appraisal of the West European light rail experience and a review of the physical performance and costs of various light rail systems, with emphasis on those characteristics most appropriate to transit planning for American cities. In 1975, UMTA retained the services of De Leuw, Cather & Company to carry out this appraisal and review. To collect and interpret the data presented in this report, contributions were sought from a number of specialists both in America and abroad to achieve a balance of views and to serve as an objective background document for policy decisions.

Our investigation shows substantial evidence that light rail is a viable transit option with a wide range of potential applications in American cities. While light rail may not fulfill all transit needs in any one city, nor be suitable for all cities, it can be a valuable addition to the family of modes capable of offering quality transit service while placing lesser demands on strained financial resources. Of equal significance to contemporary planning is light rail's developmental flexibility and its ability to expand with relative ease to match when and where needed a growing demand for transit.

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A significant contribution to the scope, content and quality of this report has been made by the Transportation Research Board Advisory Committee on Light Rail Transit. All of its members have graciously reviewed earlier drafts of this report and have made numerous constructive suggestions which have been incorporated in this final text. In particular, the authors wish to acknowledge the contributions of Messrs. Ronald DeGraw, Robert J. Landgraf, Martin Lenow, Gerald B. Leonard, Harry L. Parrish, Henry D. Quinby, Stewart F. Taylor, Rush D. Touton, and J. William Vigrass. Mr. William Campbell Graeub was instrumental in initiating and coordinating the committee's review actions.

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EXECUTIVE SUMMARY

This report on the state of the art of light rail transit presents a comprehensive overview of the available information on this mode's operational characteristics, economics and technology. The report has been prepared to provide background material for transit planners, community leaders, decision makers and others interested in gaining a better understanding of light rail transit at a time when growing appreciation of its potential as an urban transit mode is developing on an international scale.

In this country, interest in modern light rail applications dates back to 1972-73 when the Urban Mass Transportation Administration (UMTA) of the U.S. Department of Transportation began to encourage cities to examine light rail transit as a serious alternative to bus and rail rapid transit. Later, specifications for a new light rail vehicle were developed under the sponsorship of the U.S. Department of Transportation, and production of the first modern light rail vehicles was undertaken by the Boeing Vertol Company. Further interest in light rail transit was stimulated by the adoption of alternatives analyses requirements as a condition of federal capital assistance to new rapid transit projects.

In spite of growing interest, planning for light rail has suffered due to misconceptions about its potential transit function and its characteristics. The lack of comprehensive information for the evaluation of its capabilities and the concern about the relevance of data showing this mode's growing acceptance in Europe have impeded, to date, the full and unbiased assessment of its potential transit function for U.S. cities. As a step toward the alleviation of these deficiencies, a study of light rail transit for American cities was begun in 1975 for UMTA. This report is the first document prepared in the course of that study.

A fundamental objective of the report is to establish a common level of understanding of LRT. Contemporary planning concepts of LRT are reviewed, and an outline is provided of the types of guideway hardware and methods of operations of light rail systems. Specifically the report adresses the following issues:

- The developmental trends which caused the virtual disappearance of streetcars in most western countries and then their reappearance, primarily in the countries of Western Europe, in the substantially modified technological form of light rail transit, with the capabilities to provide transit services that match in performance and quality the best of other contemporary transit modes.
- The physical and operational characteristics of light rail which distinguish it from streetcars and other forms of rail rapid transit.
- The inherent capability of light rail to deliver a wide range of urban transit services on a full spectrum of right-of-way opportunities making it a low investment transit candidate with a potential for staged deployment.
- The range of transit applications of LRT that are suitable to meet a variety of urban transport requirements and the relationship with other competitive or complementary transit modes.

- The characteristics of the physical elements of a light rail system: rights-of-way, stations, vehicles, wayside equipment and other system related facilities.
- The capital operating costs of light rail systems.

The definition adopted in this report for light rail transit recognizes that it must include not only a description of the technology employed, but also that it must account for the type of right-of-way utilized and the typical transit service and operating modes provided. The definition is that adopted by the Transportation Research Board Committee on Light Rail Transit in spring of 1976:

> *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.*

INTERNATIONAL TRENDS IN THE EVOLUTION OF LIGHT RAIL TRANSIT

TRANSIT AND AUTOMOBILE-ORIENTED POLICIES

The status of transit in American and Western European cities is largely the result of differing policies with respect to the accommodation of automobiles. While automobile usage in the cities of Europe lagged behind that of American cities for some years, today the differences are not significant. However, the urban transportation policies adopted by Western European countries have been markedly different, and there is ample evidence to conclude that they have not made commitments for the urban accommodation of automobiles comparable to those of the United States.

The policies of Western European countries have not necessarily been pro-transit. France and Great Britain, for instance, made only limited investments in urban transportation in the period 1932 to 1960. By the early 1960s, most of the cities in Great Britain and France, with the exception of their capitals, relied almost exclusively on bus transit and were devoid of any transit on separate rights-of-way.

Considerably different policies toward urban transportation were adopted in several other European countries, notably West Germany, the Netherlands, Belgium, Sweden and Switzerland. While in some of these countries, particularly West Germany, investments in street improvements and construction of new arterials and freeways were substantial, attitudes and policies favoring investments in transit improvement were also significant.

TRANSIT POLICIES AFTER WORLD WAR II

The period of post World War II reconstruction found some of the cities rebuilding in the shape they had before the war. Others, such as Hannover and Rotterdam, rebuilt in modern form. The reconstruction promoted a debate about the different transit modes and about the desirable shape and quality of the urban environment.

In West Germany, the report of the Committee of Experts commissioned by the West German government in 1961 thoroughly studied these issues. It represents a landmark in post-war urban transportation planning. Although it consolidated and reconfirmed the thinking and actions which had already been prevalent, particularly with respect to the significance of physically separated transit on shaping the character of the urban environment, the report was significant, because it also estimated the financial needs required for implementation. It also proposed financing methods and advanced the principle that the solution of urban transportation problems must be considered as a joint obligation of the federal, state and local governments. The effects of the report were far reaching. By the early 1970s, some 15 cities were involved in the construction of regional rail rapid transit and light rail facilities.

COMMITMENTS TO RAIL TRANSIT MODES

The birth of the light rail concept is closely tied to the fundamental planning decisions made in the mid-1950s. The conditions after the war, which required the replacement of even the most basic transport facilities, were also conducive to the replacement of prewar transit modes without substantial change to then existing facilities. While buses were increasingly used in a number of the cities of Western Europe in the 1950s, virtually all cities with populations in excess of 200,000 to 300,000 made the long-term decision to use rail systems as the basic mode for their transit.

This planning required that networks in the inner cities be consolidated; that streetcar lines on many smaller streets be abandoned in favor of buses; that private rights-of-way for rail lines be provided; that alignment standards be improved; and that the technology of vehicles, rails and other equipment be considerably improved.

The commitment to rail modes in such countries as West Germany, the Netherlands, Belgium, Switzerland, and Italy resulted in part from the cities' images of their urban life styles and of the role of their public facilities. The commitment also stemmed from a recognition that the physical separation of automobile and transit is a basic requirement for a healthy multi-modal transportation system, and that rail modes usually have a distinct advantage over non-guided modes. In addition, advantages of light rail were recognized in comparison with buses due to better vehicle performance, quieter pollution-free operation, higher labor productivity and greater attraction of passengers.

The early programs for grade separation of streetcars by placing tracks in tunnels in high density areas were followed in the 1950s by decisions in a few cities to build rapid transit with full replacement of streetcars. These cities included Berlin, Hamburg and Stockholm. But as the 1960s and the early 1970s progressed, changes in thinking and attitudes caused a reassessment of the investment involved in constructing grade separated lines. The *underground streetcar* was eventually replaced by the *light rail (stadtbahn)* concept. Nevertheless, due to strong pressures to transplant the philosophy of "rapid transit" cities, such as Hamburg, to smaller cities and due to easier access to construction funds, some medium sized cities with populations of 300,000 to 700,000 began to plan, in the 1960s and early 1970s, rapid transit systems.

TRENDS TOWARD LIGHT RAIL TRANSIT

The latest significant change in attitudes towards transit modes can be detected since 1973. The recognition of limited financial resources in this era and the ebb of excessive optimism about the speed of construction of rapid transit systems contributed to a dislocation of rail rapid transit plans in various West German cities in favor of light rail.

Similar changes are taking place in other European countries as well. In Holland, decisions have been made to develop light rail transit in a number of cities. In Belgium, no further expansion of the first pre-metro line in Brussels is contemplated. Because LRT causes less environmental impact than bus transit and has less impact on urban design than rail rapid transit, it is regarded by some as supportive of policies that place emphasis on environmental issues and the preservation of the quality of urban life.

Recently, the changes in urban transportation policies of the West European countries have been echoed by the start of construction for new light rail systems at Newcastle, England, and at Edmonton in Canada. Planning for light rail transit is also underway in a number of Canadian, U.S. and European cities.

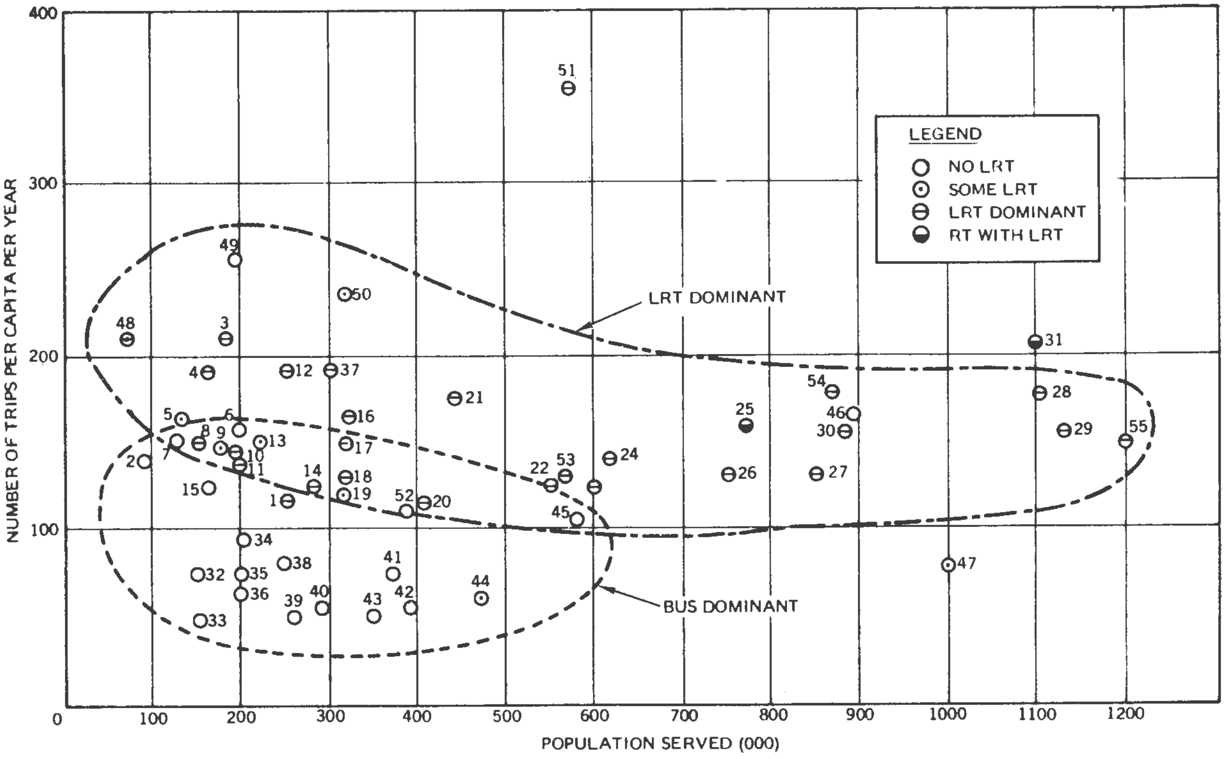
CONCLUSIONS RELEVANT TO FUTURE PLANNING OF LRT

The evolutionary trends of LRT suggest a few conclusions of significance:

- Western European cities which improve transit using separate rights-of-way and rail experience greater transit ridership on a per capita basis than cities which converted to surface buses only. Similar correlations of ridership habit are less distinct for U.S. cities (Figure 1).
- Rational urban transportation policies must encompass different modes of transit, as well as automobile transportation.
- Adopted policies must be consistently pursued for a considerable period of time.
- Substantial investments in transit are necessary to make transit service competitive with auto travel.
- The evolution of light rail transit in the last two decades has produced a highly competitive transit mode, providing passenger comfort, minimal negative effects, and compatibility with both pedestrians and rapid transit operations.
- Light rail installations provide less of a barrier to future expansion options than the more capital intensive rail rapid transit.
- Good solutions to urban transportation problems have been achieved by using several different modes. Light rail is an excellent basic transit carrier in medium to large cities and has potential in special corridor situations.
- Non-capital intensive transit improvements generally encompassed by the term *transportation system management*, need to be undertaken in parallel with developments of fixed guideway transit. They are indispensible for the achievement of high quality transit service.

LRT INSTALLATIONS IN WESTERN EUROPE AND NORTH AMERICA

In 1975, 310 LRT systems with about 50,000 vehicles were in service throughout the world. These systems cover a range from unimproved streetcar operations to high performance networks having characteristics not dissimilar to rail rapid transit. Eighty LRT systems operate in Western Europe and North America. In the U.S.S.R., over 100 LRT systems are in operation including several new ones. Almost all LRT systems in Western Europe and North America are now planning or engaged in improvement programs. Work has begun on several systems as shown in Table 1.



SOURCES: *Statistiche Ubersichten 1974* (Cologne, West Germany: Verband Offentlicher Verkehrsbetriebe), 1975.
M. Bigey, "Le Transport Public, Instrument d'une Politique Urbaine," *Transports Urbains* January-March, 1975, pp. 11-12.

CITY/COUNTRY CLASSIFICATION

WEST GERMANY	1. HEIDELBERG 2. TRIER 3. LUDWIGSHAFEN 4. FREIBURG 5. ULM 6. OFFENBACH 7. PFORZHEIM 8. WURZBURG 9. BREMERHAVEN 10. DARMSTADT 11. MULHEIM	12. KASSEL 13. MAINZ 14. BIELEFELD 15. OSNABRUCK 16. KARLSRUHE 17. AUGSBURG 18. HAGEN 19. KIEL 20. BONN 21. MANNHEIM	22. WUPPERTAL 23. DUISBURG 24. BREMEN 25. NUREMBERG 26. ESSEN 27. HANNOVER 28. DUSSELDORF 29. COLOGNE 30. STUTTGART 31. MUNICH
FRANCE	32. METZ 33. LE MANS 34. TOURS 35. MULHOUSE 36. TOULON 37. SAINT-ETIENNE	38. NANCY 39. LE HAVRE 40. GRENOBLE 41. STRASBURG 42. NANTES	43. ROUEN 44. LILLE 45. BORDEAUX 46. LYON 47. MARSEILLE
SWITZERLAND	48. NEUCHATEL 49. LAUSANNE 50. GENEVA 51. ZURICH		
BELGIUM AND NETHERLANDS	52. UTRECHT 53. THE HAGUE 54. ROTTERDAM 55. BRUSSELS		

Figure 1. Riding Habit as a Function of Urban Area Size and Transit Mode Provided

Table 1. Principal LRT Development Activity in Western Europe and North America (Existing or Planned)

	New Cars	Network Expansion	Light Rail Subway	Self-Service Fares
Austria				
Graz	X	X		X
Innsbruck	X	X		X
Linz	X	X		X
Vienna	X	X	X	X
Belgium				
Antwerp	X	X	X	X
Brussels*	X	X	X	X
Charleroi	Rebuilding System			
Ghent	X		X	X
Ostend	X			X
Canada				
Edmonton*	New System			
Toronto	X	X		No
France				
Lille	X			X
St. Etienne	X	X	X	X
West Germany				
Augsburg	X	X		X
Bielefeld	X	X	X	X
Bochum	X	X		X
Bonn	X	X	X	X
Brunswick	X	X		X
Bremen	X	X		X
Cologne*	X	X	X	X
Darmstadt	X	X		X
Dortmund	X	X	X	X
Dusseldorf	X	X	X	X
Duisburg	X			X
Essen	X		X	X
Frankfurt*	X	X	X	X
Freiburg	X	X		X
Hannover*	X	X	X	X
Karlsruhe*	X	X		X
Kassel	X		X	X
Krefeld	X	X		X
West Germany				
Ludwigshafen	X		X	X
Mainz	X	X		X
Mannheim	X	X	X	X
Munich	X	X		X
Nuremberg	X	X		X
Rhein-Ruhr	New System			
Stuttgart	X	X	X	X
Wurzburg	X	X		X
Italy				
Milan	X	X		X
Rome	X	X		X
Turin	X	X		X
Mexico				
Guadalajara	Trolleybus – Pre-Metro			
Mexico City		X		No
Netherlands				
Amsterdam*	X	X		X
Rotterdam	X	X	X	X
The Hague	X	X		X
Utrecht	New System			
Sweden				
Gothenburg*	X	X		X
Norrkoping		X		X
Switzerland				
Basel	X	X	X	X
Bern	X	X	X	X
Geneva*	X	X		X
Zurich	X	X		X
United Kingdom				
Tyne & Wear*	New System			
United States				
Boston*	X	X	X	No
Cleveland	X	X		No
Philadelphia	X		X	No
Pittsburgh	X			No
San Francisco*	X	X	X	No

*Systems selected for more detailed description.

Two principal approaches are used in LRT improvement programs. In one case, high investment improvements with extensive subway and grade separation are being made, mostly at the larger West German and Belgium systems, and in England, Canada, and San Francisco. In the second approach, LRT installations are being upgraded with low cost, low impact improvements primarily using traffic control measures. This is being done at the Dutch, Swedish, and Swiss systems and the smaller LRT systems in West Germany.

Representative light rail systems more fully discussed in the comprehensive report include:

- The LRT system at Amsterdam, which is that city's primary transit mode and is representative of a low cost, low impact and pragmatic transit design concept (Figure 2).
- The LRT system at Geneva (Figure 3) representative of a planning trend in a number of cities where the replacement of worn out streetcar systems with buses and trolleybuses is being deemphasized in favor of upgrading of the existing facilities to LRT service.
- The LRT system (Figure 4) at Gothenburg typical of a low investment approach and a consistent policy of improvement over a period of many years.

Figure 2. LRT Line in Amsterdam with Counter Flow Lane

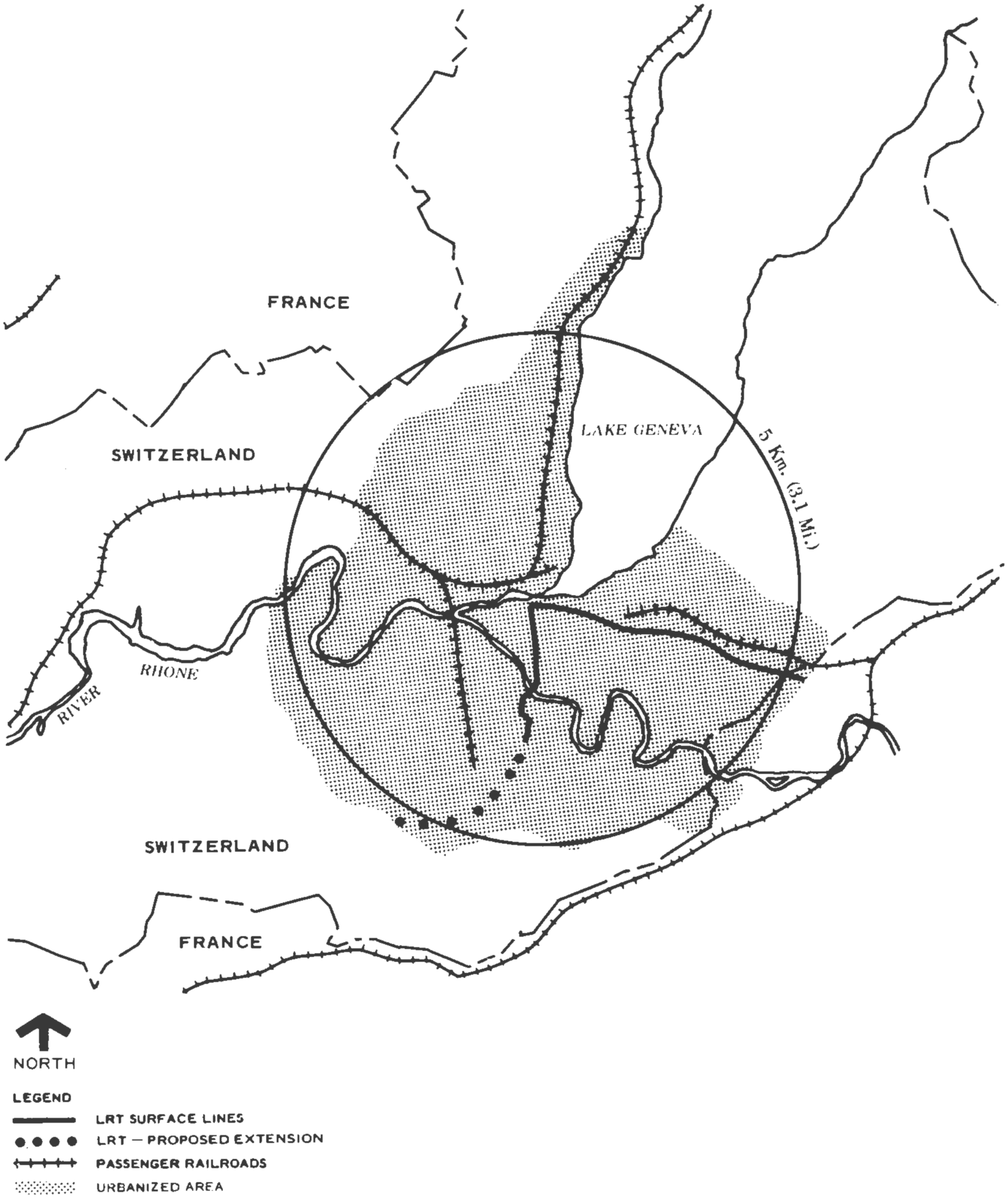


Figure 3. Geneva System

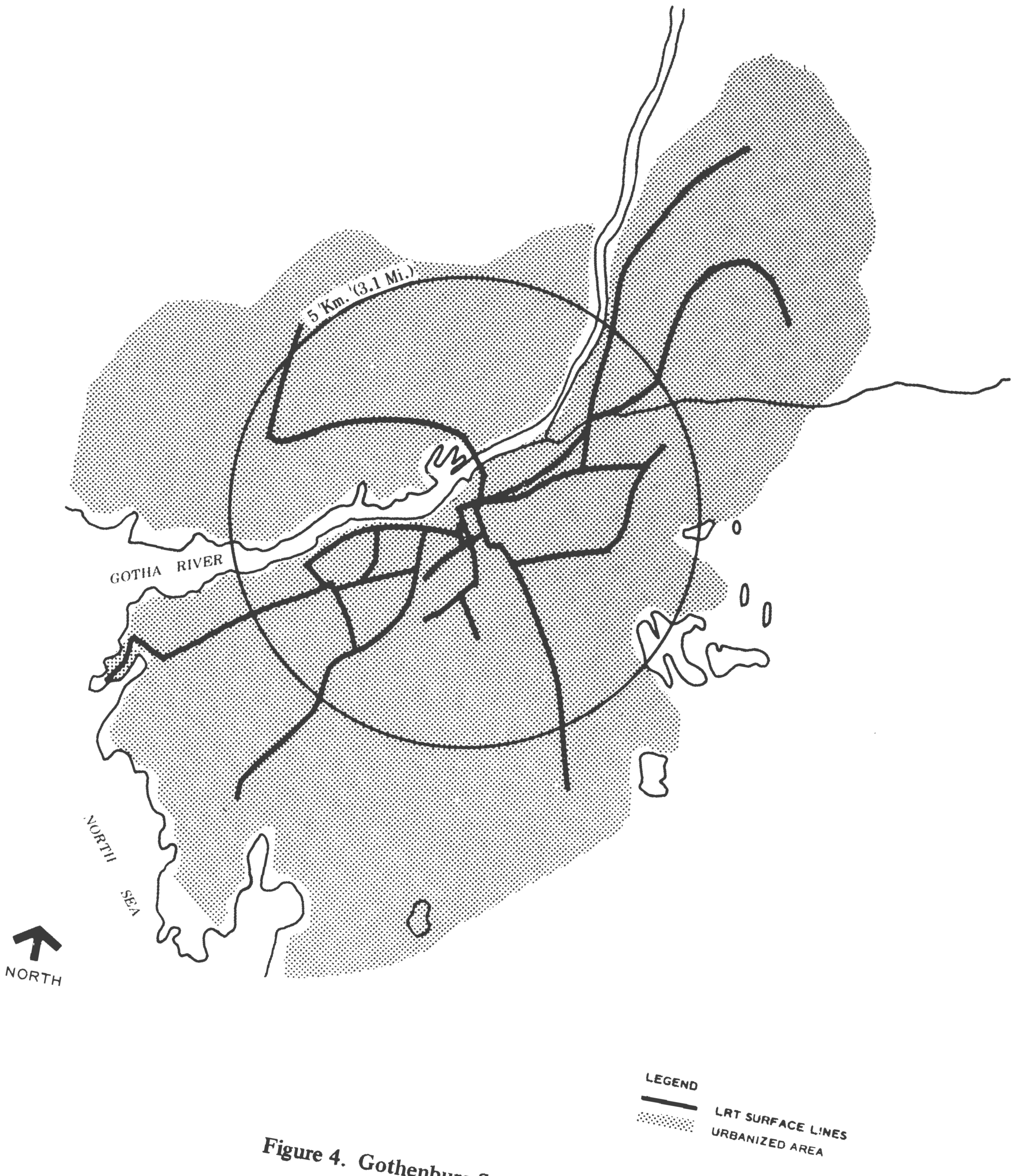


Figure 4. Gothenburg System

- The LRT system at Karlsruhe typical of a policy of retention and modernization of existing LRT installations pursued by small cities (Figure 5).
- The LRT system at Brussels, the prototype of the pre-metro concept, defined as a capital intensive installation designed to permit eventual upgrading to rail rapid transit standards (Figure 6).
- The LRT system at Boston now in the midst of a major renewal program (Figure 7).
- The LRT system at Cologne (Figure 8), one of the major innovative transit systems in Europe encompassing streetcar operations, multi-line subway and planned high speed regional lines.
- The LRT system at Frankfurt where adoption of this mode followed an extensive analysis of alternate modes completed in the 1960s (Figure 9).

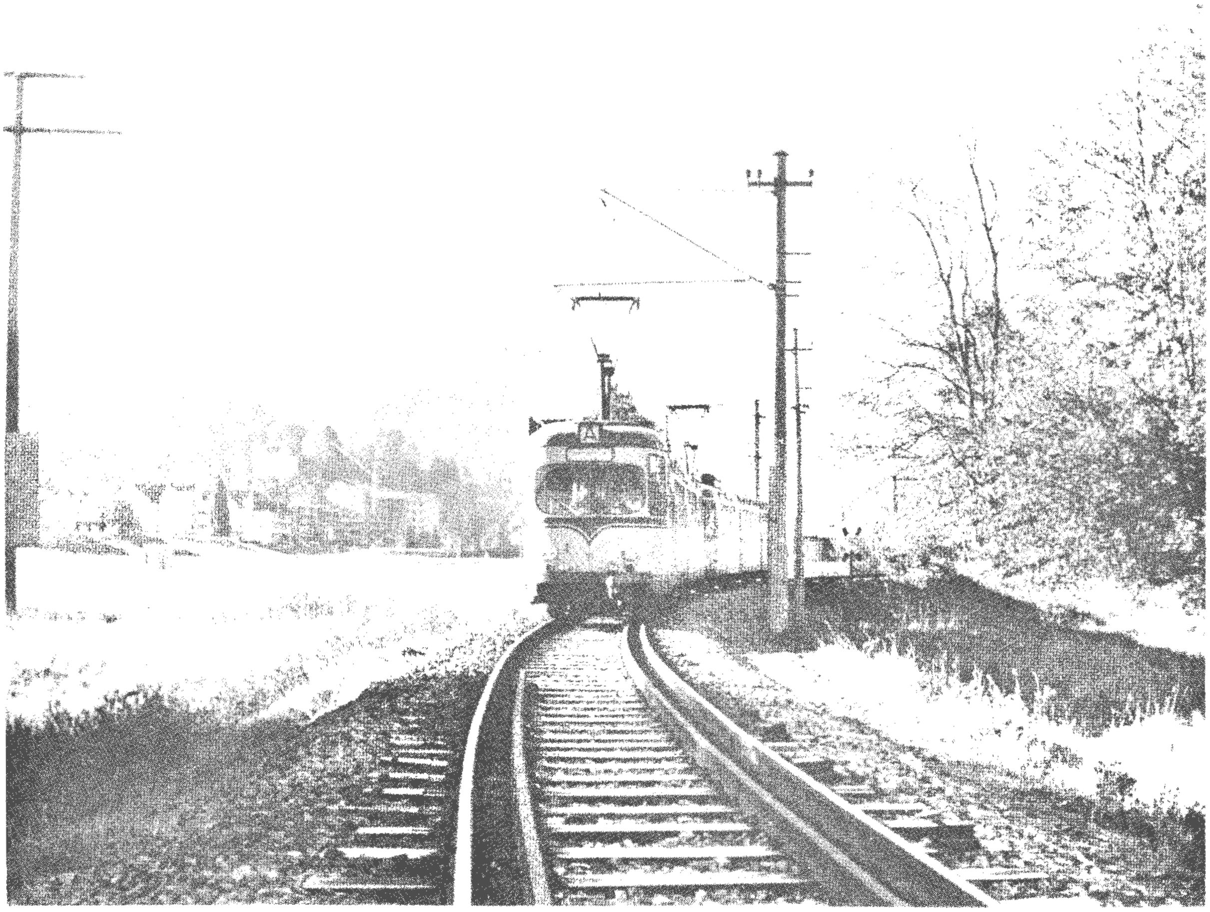


Figure 5. Albtalbahn Interurban Train

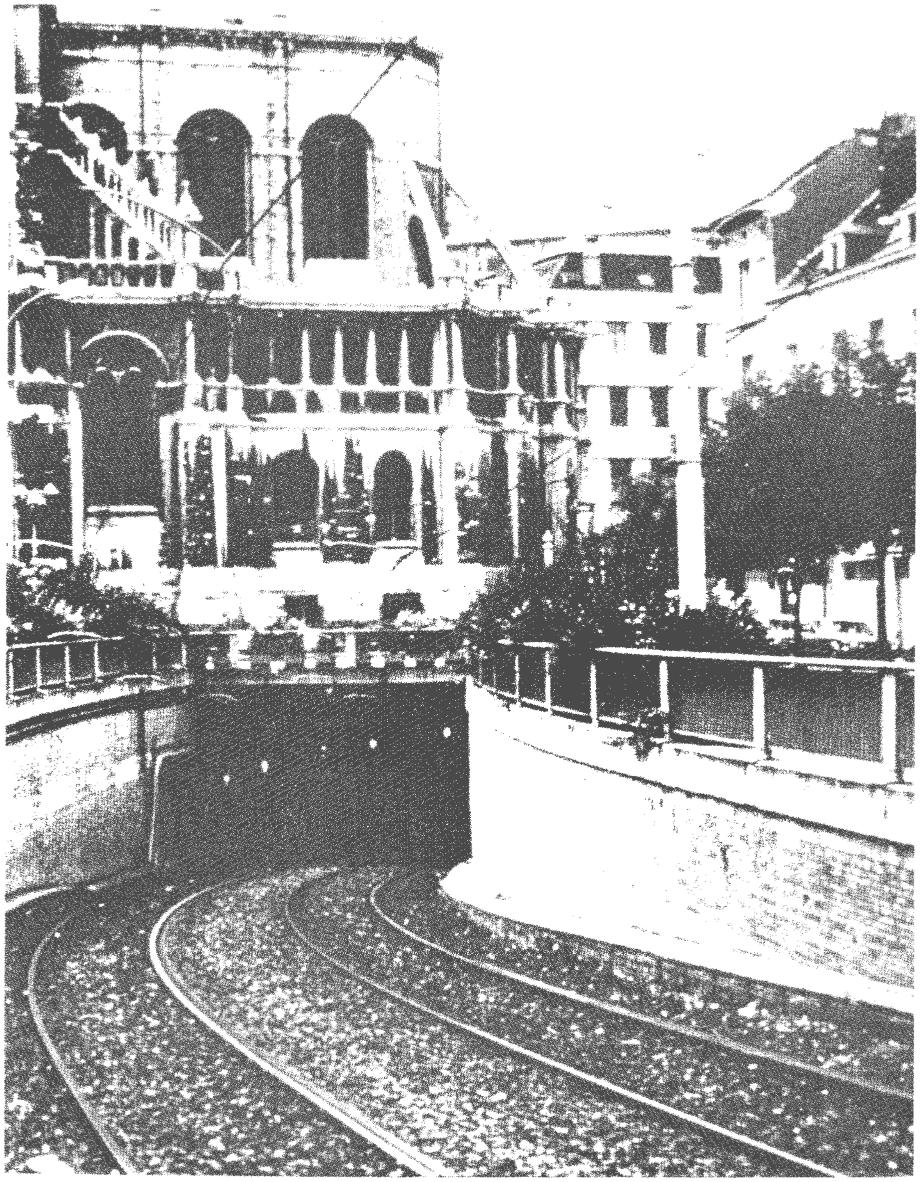


Figure 6. Brussels Pre-metro Subway Portal

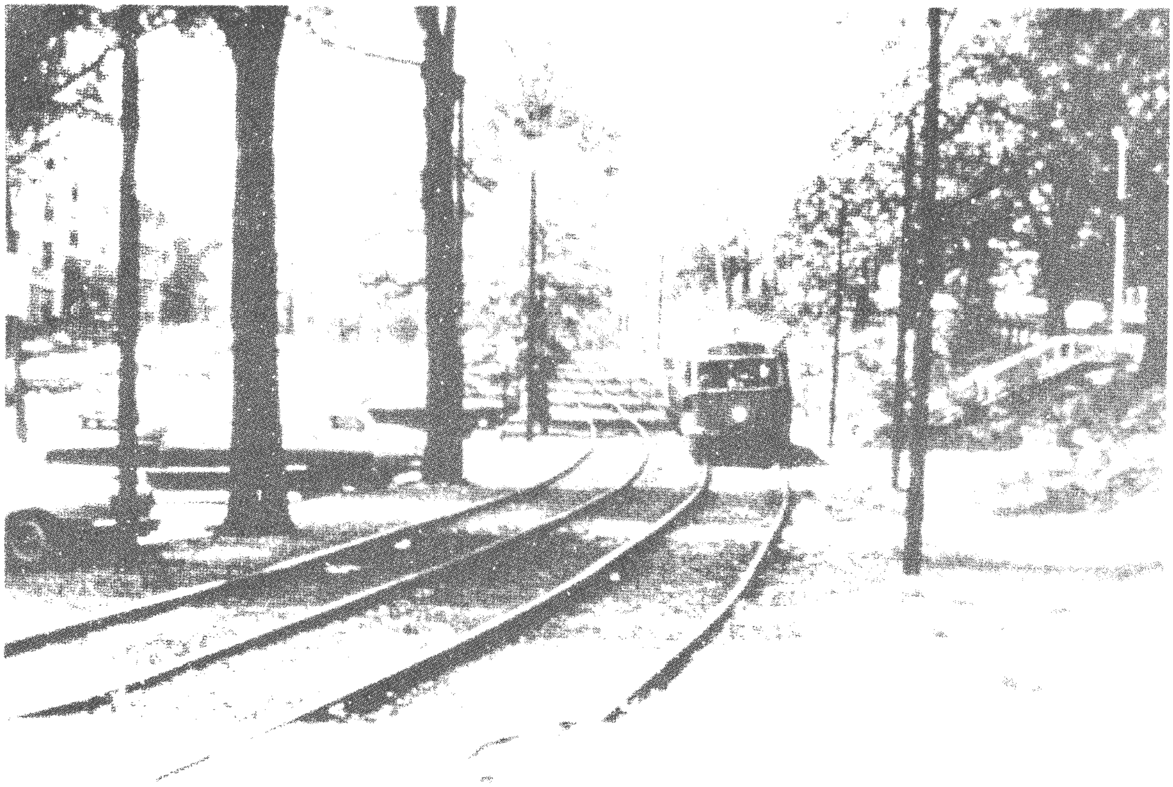


Figure 7. Boston Landscaped Right-of-Way

- The LRT system at Hannover (Figure 10), the most recent installation to open an LRT subway line.
- The LRT system in San Francisco, the leading example of the use of this transit mode in the U.S. (Figure 11).
- The new LRT system (Figure 12) being constructed at Edmonton in Canada.
- The new LRT system being constructed at Newcastle, England (Figure 13).

Figure 8. Cologne System

Figure 9. Subway Station in Frankfurt

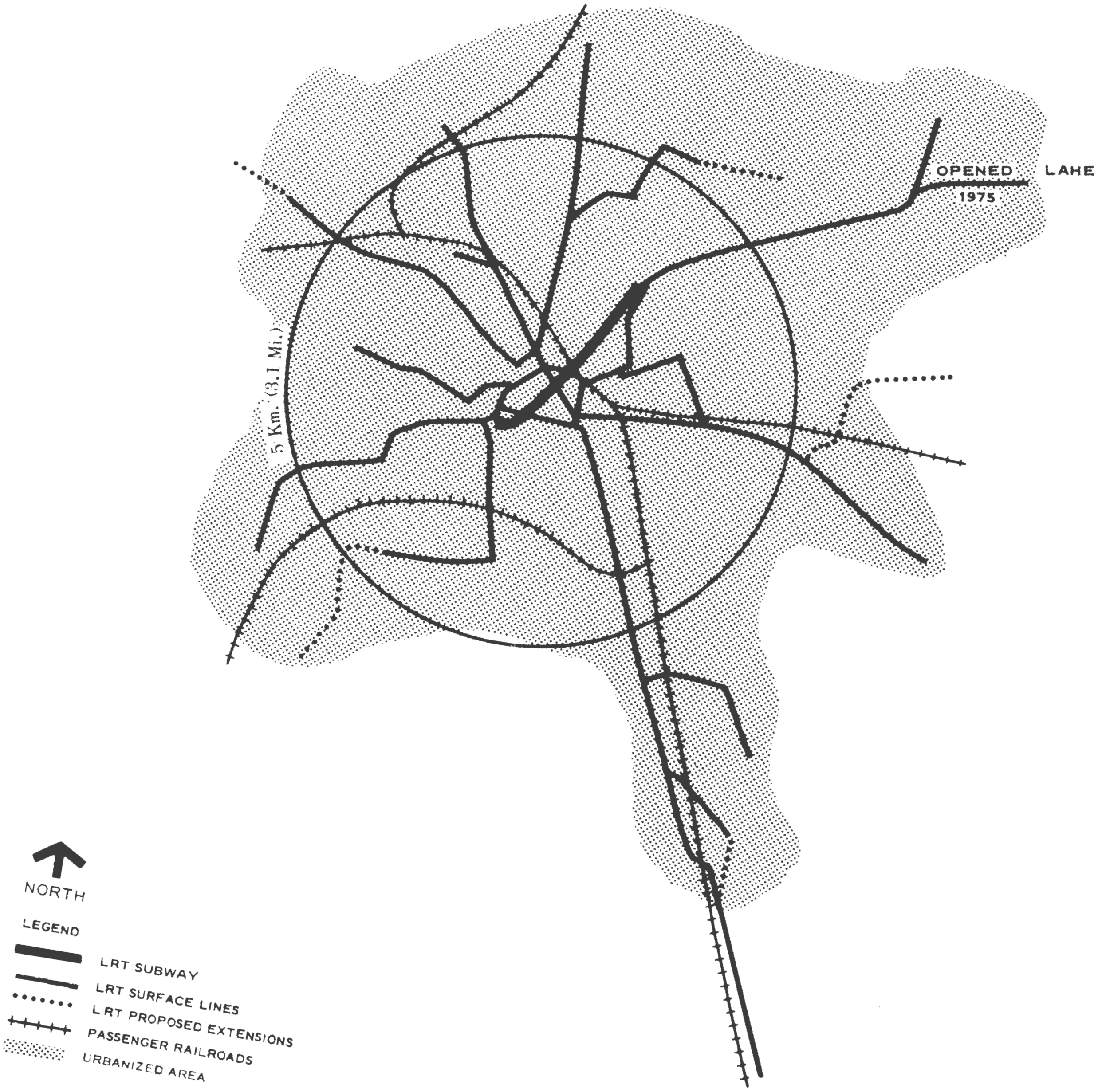


Figure 10. Hannover System

Figure 11. Van Ness Station Under Construction

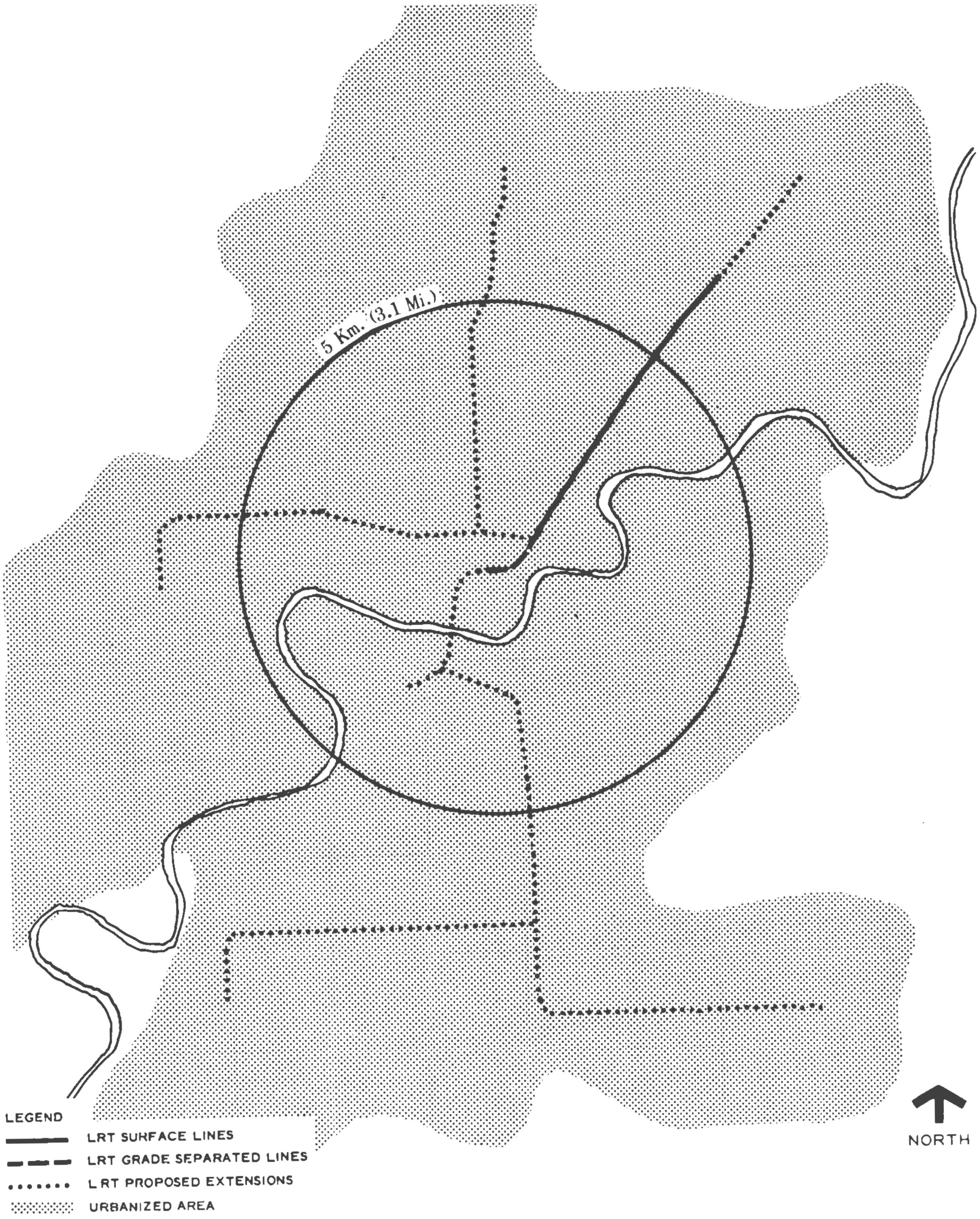


Figure 12. Proposed Edmonton System

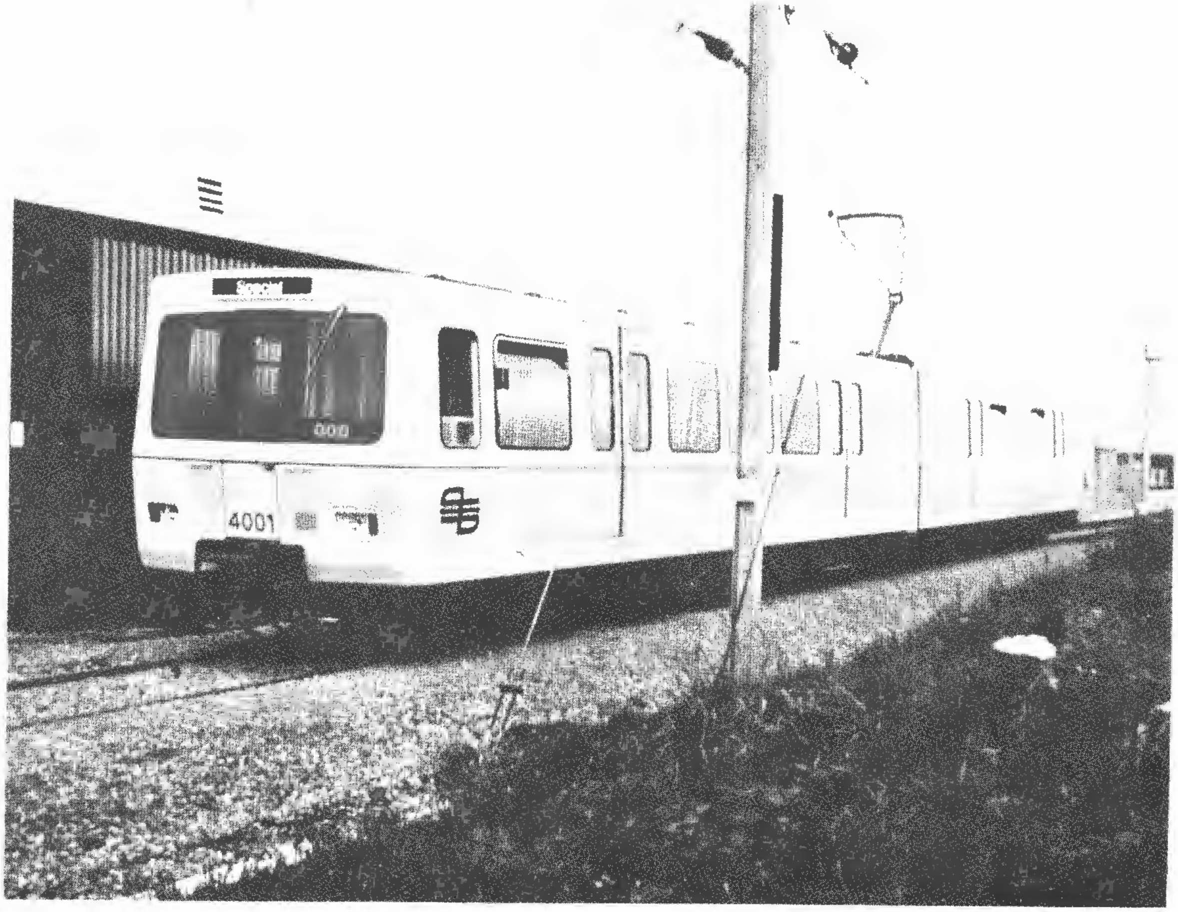


Figure 13. Tyne & Wear Prototype Car

LIGHT RAIL TRANSIT RIGHTS-OF-WAY

A principal distinction of light rail transit is its ability to operate on a variety of rights-of-way and with a range of station configurations. This versatility creates the potential for reduced capital investment, less environmental impact and faster construction than is possible with rail rapid transit. Light rail transit design can be tailored to exploit right-of-way opportunities and to benefit from cost savings which accrue from the selection of appropriate design treatments.

The distinguishing feature of light rail is its capability to use all three of the following basic categories of right-of-way:

- *Exclusive* right-of-way, on which operations are fully controlled and vehicular or pedestrian crossings are prohibited. This type of right-of-way is common to all rail rapid transit systems.
- *Semi-exclusive* or reserved right-of-way, on which operations are separated from other traffic except at grade crossings.
- *Shared* right-of-way, on which LRT operates in mixed traffic with autos, trucks and buses.

In general LRT networks contain segments of right-of-way of each category (Table 2).

Table 2. Right-of-Way Categories for Selected LRT Systems

City	Network Length* (Km)	Right-of-Way Category (%)			Average Speed** (Kph)
		A	B	C	
Boston	41	48	30	22	13 to 35
Brussels	170	6	46	48	17 to 40
Cologne	143	42	35	23	11 to 35
Edmonton (under construction)	7	22	78	–	Estimated 40
Frankfurt	135	←65→		35	20
Gothenburg	84	←84→		16	22
The Hague	84	5	59	36	20.5
Hamburg	53	–	29	71	18
Hannover	88	5	41	54	23
Munich	112	–	68	32	12 to 18
Newark	13	100	–	–	32
Philadelphia (City Transit)	139	2	–	98	16
Philadelphia (Red Arrow)	40	←100→		–	24 to 48
Pittsburgh (existing)	36	←73→		27	18
Pittsburgh (proposed)	36	←92→		8	Estimated 30
San Francisco (before 1978)	30	18	9	73	16
San Francisco (after 1978)	30	36	30	34	Estimated 30
Tyne & Wear (under construction)	55	100	–	–	Estimated 40

*Network length = length of double track.

**Some cities include layover time in their calculations of average speed. These figures should, therefore, be treated with caution. Average speed is also influenced by station spacings, station dwell time, and stops or slowdowns at at-grade intersections. Therefore, the speeds shown represent not only the effect of the various right-of-way categories, but also the effects of other system characteristics as well.

Sources: Dr. Friedrich Lehner; Annual Statistics of the U.I.T.P., International Union of Public Transport, Brussels, Belgium; Direct correspondence with transit operators.

In addition to the most common at-grade installations, the vertical profiles of LRT guideways span a wide spectrum: elevated right-of-way is used for LRT operations on an aerial guideway (viaduct), or on embankments above ground level; depressed right-of-way is used for LRT operations below ground level in open cut; tunnel right-of-way is used for LRT operations which require grade separations in the central business district (CBD) and other major activity centers.

LRT IN SHARED RIGHT-OF-WAY

In most modern LRT systems, some sections of the right-of-way are in mixed street traffic (Figure 14). This operation is typical of streetcars. The level of service is similar to that of buses on streets with the additional disadvantage of lower maneuverability resulting in even greater delays. Few if any new streetcar lines have recently been built in cities that use light rail transit. However, in some cities, such as Gothenburg, Amsterdam, The Hague, Zurich and most West German cities, new traffic management concepts and techniques have been used to improve the performance of streetcars on existing lines and on new extensions.

LRT IN RESERVED STREET LANES

A minimum improvement in the level of service achieved with street operations in mixed traffic is obtainable by locating light rail trackage in reserved transit lanes from which automobile traffic is prohibited. Separation of traffic can be achieved by simple striping on the right-of-way edges (The Hague), diagonal striping across the right-of-way (Hannover and Gothenburg), and mountable concrete or asphalt curbing on the right-of-way edges (Zurich). In some cities, buses may share all or portions of reserved LRT rights-of-way (Figure 15).

LRT IN DEDICATED STREET RIGHT-OF-WAY

Higher levels of service can be achieved in sufficiently wide arterials by full physical protection of LRT tracks on dedicated traffic lanes or on a median. This may be accomplished by the use of curbs and raised medians, by vegetation and by fencing, or by concrete barrier

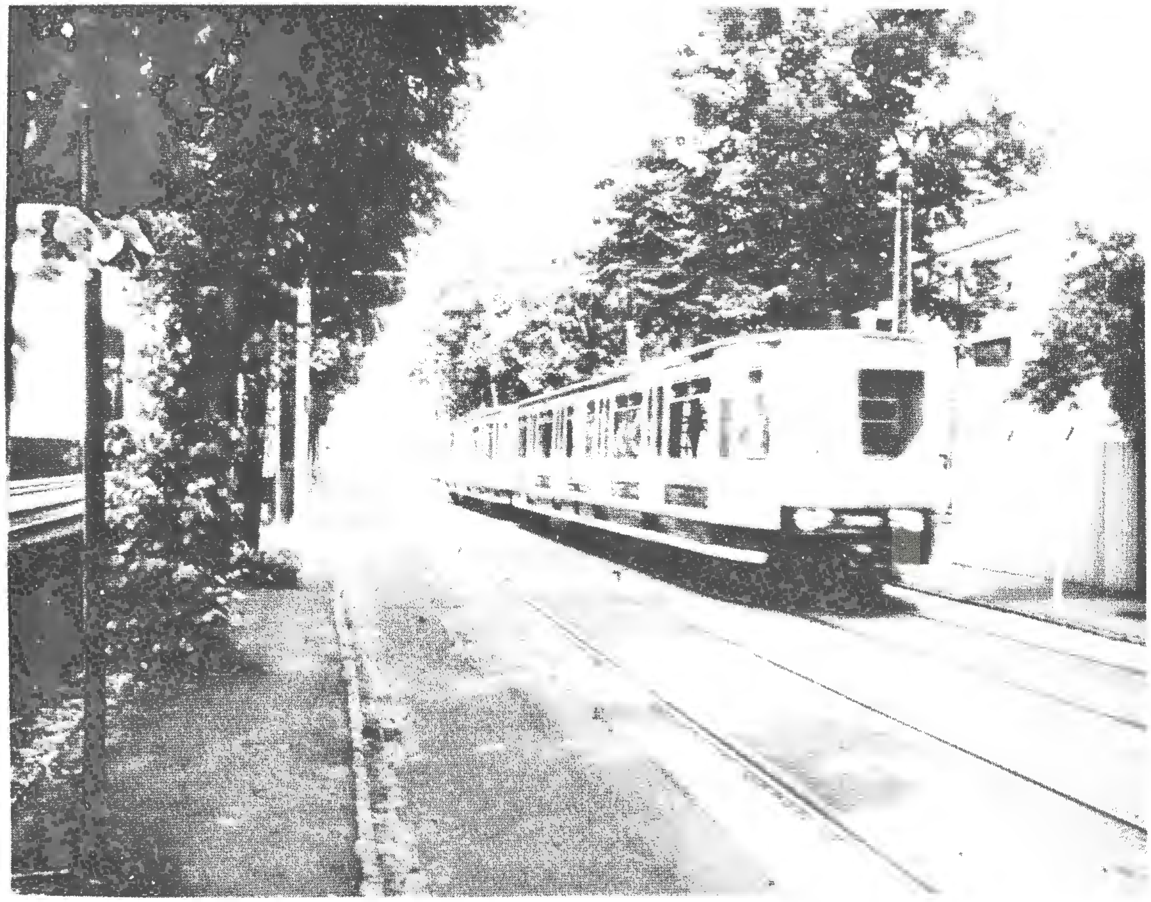


Figure 14. New LRVs Running in the Street in Bonn

Figure 15. Bus and Light Rail Transit Lane in Bonn

walls (Figure 16). Barrier rails and concrete barriers are, however, seldom used along medians on existing systems except in locations where a line passes through an identifiable hazard area, such as the median of a high speed highway. These barriers are rarely aesthetically pleasing, physically subdivide communities, and inconvenience operations and maintenance. Some cities use a low fence or thorny plantings to discourage jay walkers.

Dedicated street rights-of-way allow operating speeds to be increased by as much as 100 percent compared with the operations in mixed traffic or in reserved lanes. Typical speeds range from 11 to 15 mph with 20 mph attained at some sections. In outlying areas, average speeds of 20 to 25 mph may be reached on dedicated rights-of-way with protective grade crossings.

LRT IN MALLS

In some European cities, LRT operates in transit malls in rights-of-way typically delineated by curbs or markings which may be freely crossed by pedestrians. In cities such as Bremen and Mannheim, LRT malls have provided an alternative to subway construction (Figure 17). Speeds in LRT malls are lower than on streets for both safety and environmental reasons.

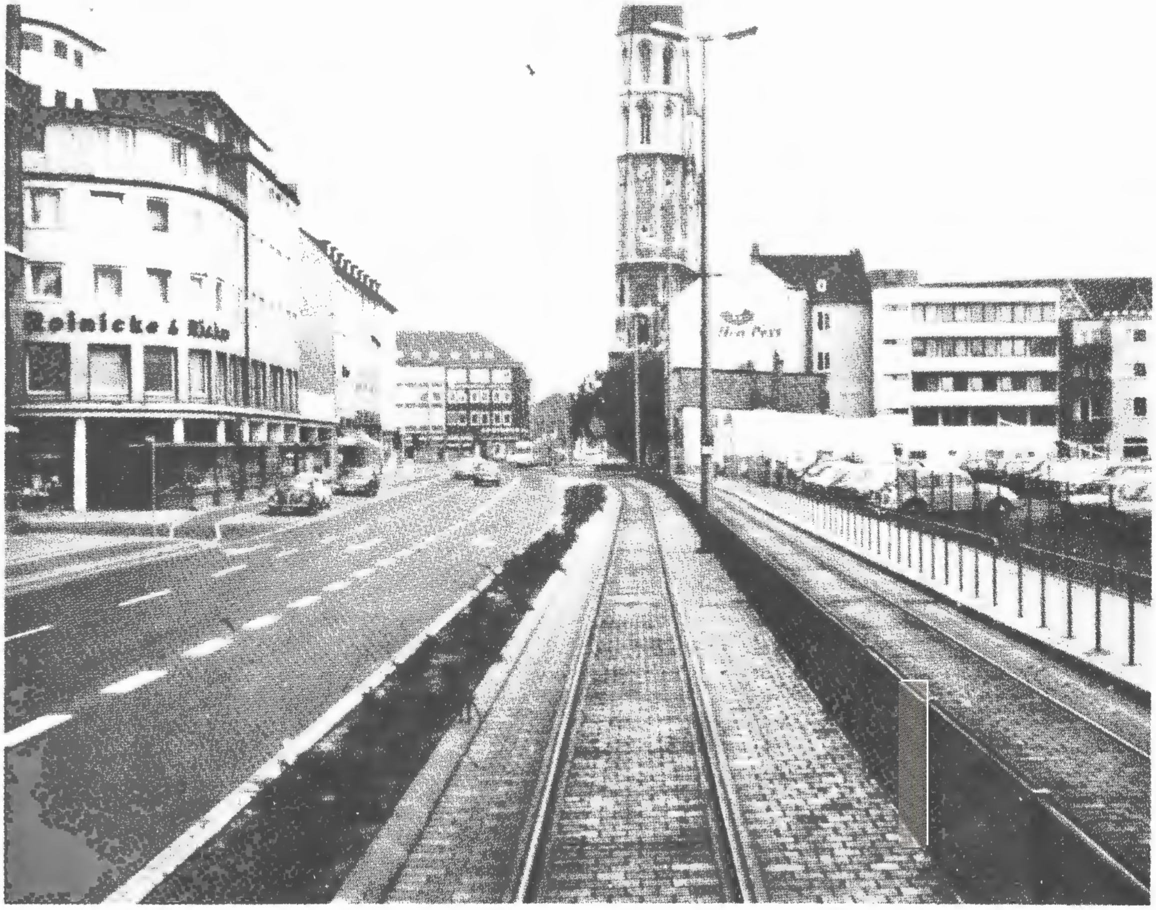


Figure 16. Separation of LRT Tracks and Traffic Lanes by Bushes in Brunswick

LRT IN RAILROAD RIGHT-OF-WAY

Significant locational opportunities for LRT right-of-way exist along railroad rights-of-way. Several forms of light rail installations are possible.

Exclusive use of railroad trackage is possible where abandoned or relinquished trackage is available. No significant change in land use is involved, and special procedures to maintain railroad operations are not required. Typical installations on existing railroad trackage are found in recent line extensions at Karlsruhe and Gothenburg. In the U.S., the Lindenwold rail rapid transit line and the Boston Riverside LRT line are constructed on abandoned railroad rights-of-way.

Shared operations of railroad and light rail transit on the same trackage is a less desirable alternative due to operational and safety problems arising from conflicting movements. Several examples of this right-of-way utilization can be found in contemporary practice. In Cologne, approximately 5 kilometers of LRT line are operated over a private railroad right-of-way which carries about 20 freight trains daily. The LRT line in Bonn also provides freight service to wayside communities, and parts of the Frankfurt, Karlsruhe and Stuttgart systems share some trackage with freight operations. In each case, trains are operated by the transit company crews.

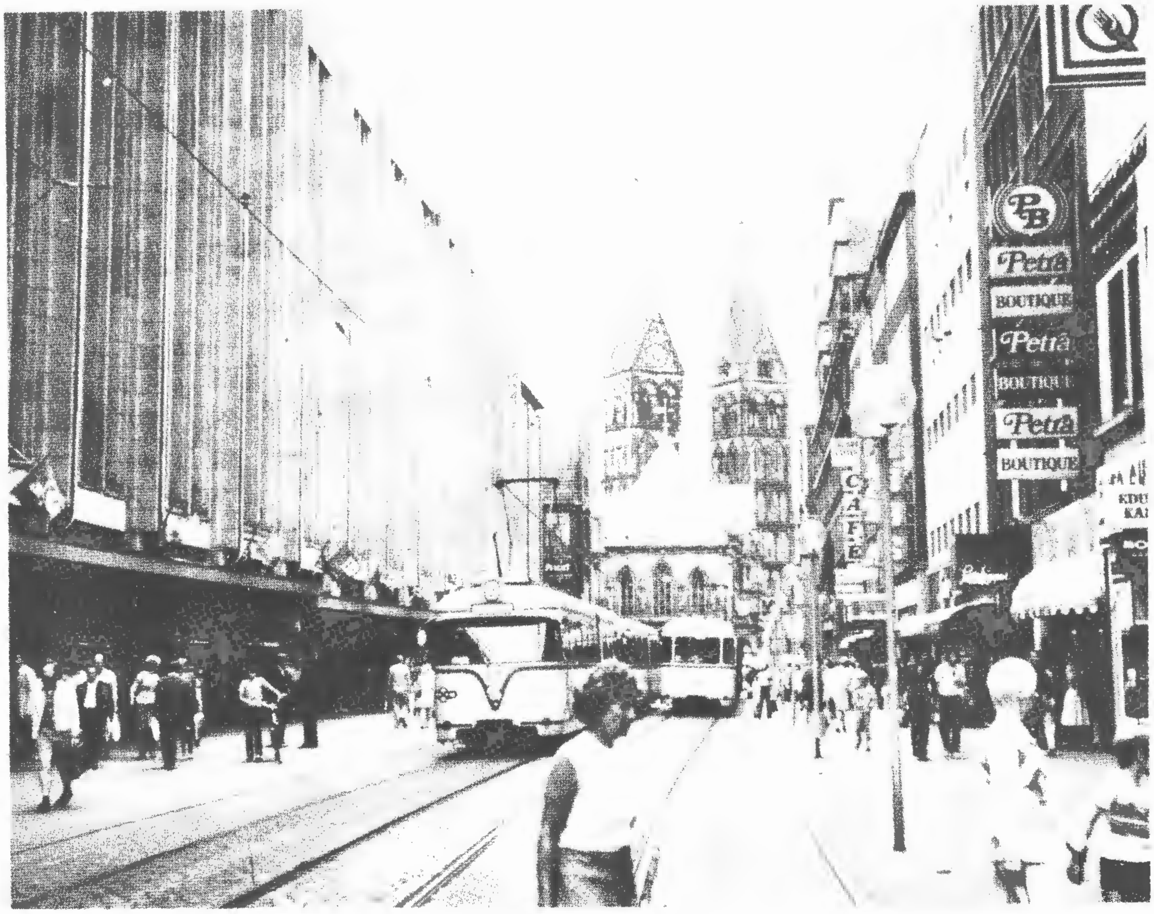


Figure 17. LRT Mall in Bremen

At Stuttgart, the narrower LRT track is co-located with the track of the railroad (Figure 18). In England, one branch of the Tyne & Wear system will be shared with freight operations on joint use tracks. Joint use operation was once common in the U.S., but few surviving examples can be found, for example the South Shore Line in Chicago. Several recent transit studies, including those for Dayton, Rochester, Vancouver and Portland, include a proposal for joint use of LRT and railroad trackage.

If railroad right-of-way can be shared, the use of separate trackage for light rail and for railroad operations avoids institutional, operational and engineering conflicts which would otherwise arise from the joint use of trackage. Multiple use rail corridors of this type are common in Europe and North America.

Joint use railroad right-of-way becomes costly when grade separation is required. This might be necessary where the frequency of railroad operations is high, and significant delays to the transit system are undesirable.

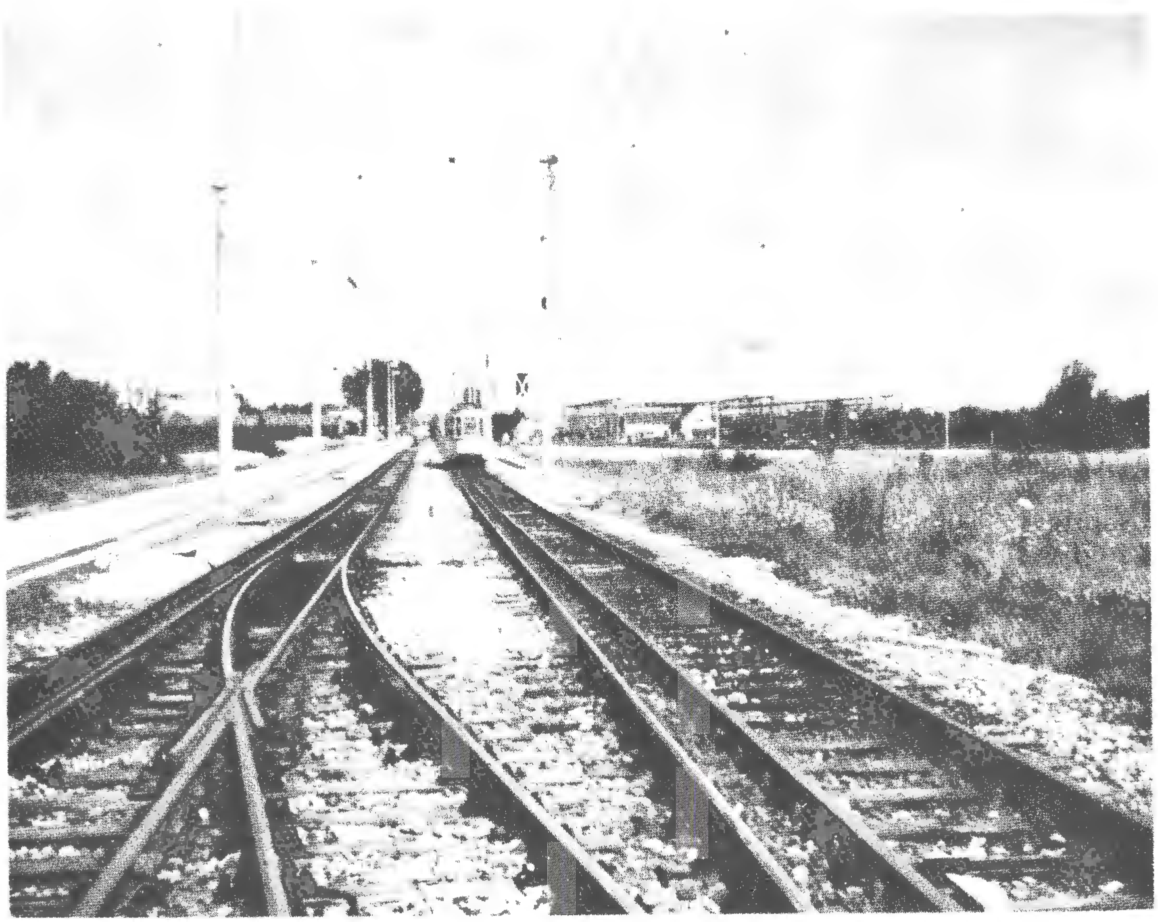


Figure 18. Joint Use Track, Mixed Gauge, in Stuttgart

In any joint use of railroad right-of-way, a number of physical design problems must be addressed. These often include electrification, the installation of power supply wires conforming with railroad clearance requirements (which could result in changes to the pantograph design), design of all structures and grades to meet railroad standards (increasing their size and cost), improvements in the condition of the track to conform to the transit standards, and modifications in wheel design and switches to conform to railroad practice.

LRT IN FREEWAYS

Exclusive operation of light rail transit within freeway right-of-way may be possible on the median or on the spaces on either side of the freeway between the shoulder and the edge of the right-of-way. The median location alternative is particularly viable in new outlying freeways or older freeways with sufficiently wide medians (30 feet or more). Examples of transit operations within freeway medians include double tracked LRT lines on sections of the Ruhr expressway at Essen and a recent LRT extension in Cologne built in the median of a future freeway. When sufficient median width is unavailable, LRT may be accommodated on the shoulder or the edge of the right-of-way. Conflict with on/off ramps and cross streets may have to be resolved by costly design. In addition, LRT lines located in freeway rights-of-way suffer from difficult pedestrian access and poor access from parking and feeder lines.

SPECIAL LRT TREATMENTS

On some LRT systems, aerial or underground sections are used to increase the level of service through high density locations or bottlenecks. The physical requirements of these structures are virtually identical with those of rail rapid transit (Figures 19 and 20). Excessive use of aerial structures or tunnels, however, can eliminate most of the cost advantages of the LRT system. The cut-and-cover method of tunnel construction is most commonly used for LRT, although bored tunnels are sometimes used. LRT tunnels may be narrower than those used for rail rapid transit, but clearance for the overhead wires and the pantograph must be provided.

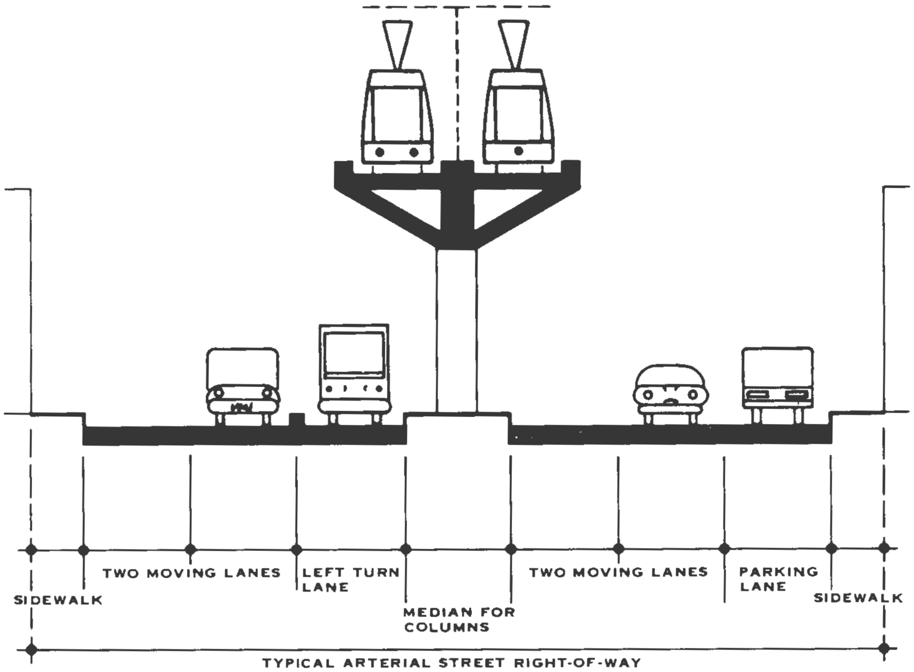
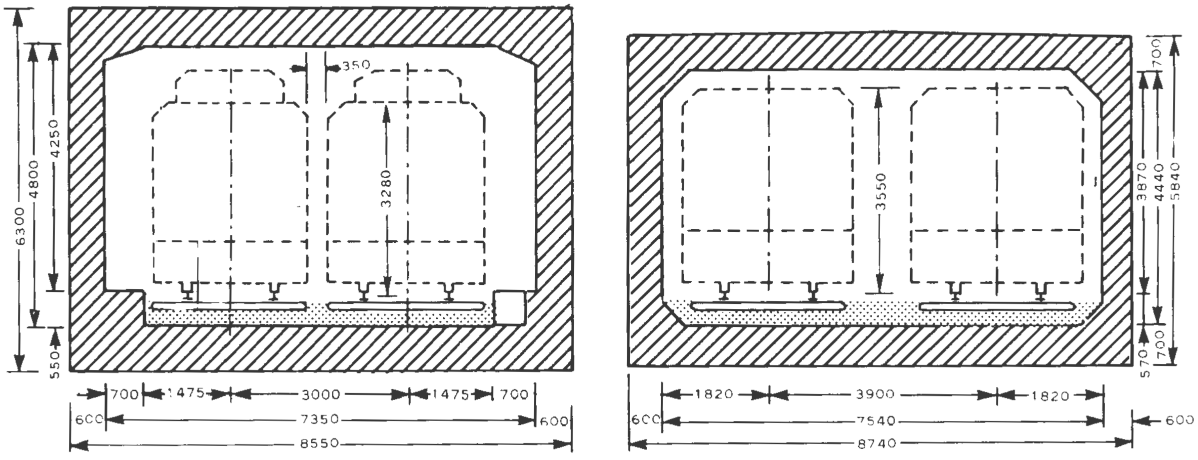


Figure 19. Arterial Street – Section View of Aerial Guideway in Median



FRANKFURT U-BAHN
(Light Rail)

NURNBERG U-BAHN
(Rail Rapid)

NOTE: ALL DIMENSIONS ARE METRIC CUT-AND-COVER TUNNEL

Figure 20. Typical Cut-and-Cover Tunnel Cross Section

LIGHT RAIL TRANSIT STATIONS

As with rights-of-way, a range of potential station configurations may be chosen to conform with the locational opportunities encountered along LRT routes. In general, LRT stations can be subdivided into two basic categories: at-grade and controlled access (usually grade separated).

AT-GRADE STATIONS

At-grade stations are commonly used in at-grade right-of-way sections, both within streets and in separate alignments, such as arterials or railroad rights-of-way. They consist of a paved area often raised somewhat above rail height; a shelter; and minimum amenities, such as information displays, benches, telephones, etc. In recent years, LRT stations at a number of cities have been placed in pedestrian squares and shopping malls. In most cases, crossing of tracks is allowed, since light rail vehicles operate a low speeds in these areas. The safety experience has been good. The track area is sometimes slightly depressed and separated by low curbs to warn pedestrians and facilitate boarding. Major intermodal transfer stations for surface transit are sometimes located on large pedestrian areas separated from automobile traffic. Short walking distances between vehicles of different routes are generally provided (Figure 21). An innovative feature of some light rail stations has been the construction of large mezzanine areas beneath the tracks and street. This promotes traffic-free pedestrian circulation while avoiding the higher cost of placing the entire LRT system underground. Stations of this type exist in numerous cities, such as Brunswick, Krefeld, Karlsruhe and Zurich.

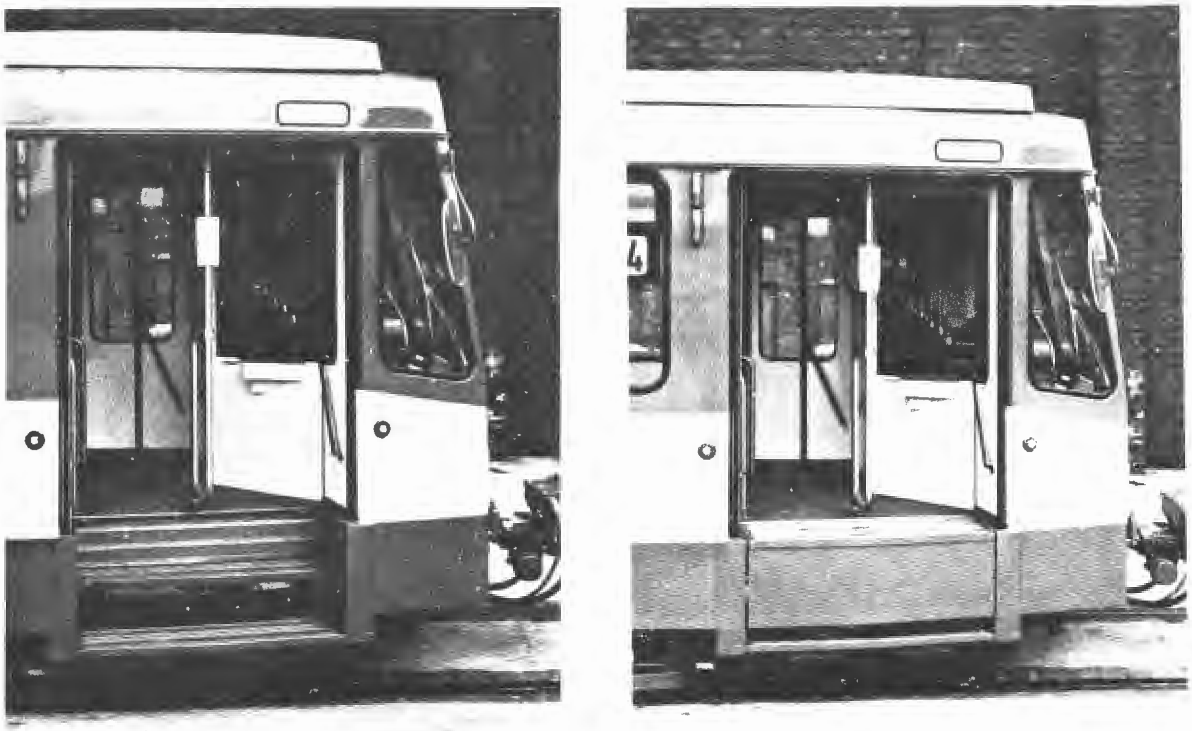
Figure 21. Central Light Rail/Bus Terminal and Transfer Station at Dusseldorf

CONTROLLED ACCESS STATIONS

Controlled access stations handle larger volumes of passengers and are usually grade separated from streets. Since access to this type of station is restricted (unlike most street level platforms which can be approached from several directions), high level platforms can be used, easing and speeding up vehicle loading (Figure 22). On these lines, all vehicles must accommodate high level loading. On some lines, high level loading platforms are using only on certain sections, usually in tunnels, such as in Hannover, or on aerial structures. On these lines, vehicles must be equipped with movable steps (Figure 23) to accommodate loading from both high and low level platforms.

Since light rail lines generally operate with smaller units with greater frequency than rail rapid transit, simultaneous loading of several vehicles is essential for speed of operation at high capacity stations. In most cities where one or more vehicles are permitted to stop at stations, special signals are used to allow the operation of LRVs at very close distances. To avoid confusion for those waiting to board, displays are used on the platform designating the different destinations and stopping positions of the vehicles.

Figure 22. Station With Raised Platform in Bremen



SOURCE: *THIS IS LIGHT RAIL TRANSIT*

Figure 23. Movable Steps for High or Low Level Loading

TECHNOLOGY OF LIGHT RAIL TRANSIT VEHICLES

A wide range of light rail vehicles are planned or in operation around the world. The vehicles vary in size from small two-axle, standard European cars to modern designs over 100 feet in length. Although a degree of standardization has been achieved, almost every major LRT system in Western Europe now operates custom designed vehicles. Table 3 lists the principal light rail vehicle manufacturers. The table also indicates the great variety of light rail vehicles produced in recent years.

DESIGN PRINCIPLES OF LIGHT RAIL VEHICLES

The design of light rail vehicles has evolved from small two-axle and four-axle streetcars to larger and faster cars with single or double articulation. The new light rail vehicles emphasize a faster, quieter and more comfortable ride than that of streetcars. New light rail vehicle designs also stress a trend toward larger vehicles to improve the productivity of operating personnel and thus keep operating costs in check. To achieve a larger vehicle design, manufacturers perfected articulated configurations, which consist of two or more body sections connected by a joint that allows pivotal movement in both the horizontal and vertical planes. This design makes it possible to build longer cars without loss of curve negotiating capabilities. Passengers have free access through the vehicle articulation joint.

Table 3. Recent Significant LRV Designs

Configuration	Manufacturer/Type	City/System
4-axle	ASEA (Sweden)	Gothenburg, Melbourne
	Konstal (Poland) PCC	Many East European cities
	La Brugeoise (Belgium) PCC	Antwerp, Brussels, Ghent, The Hague
	Schindler (Switzerland)	Basel
	Tatra (Czechoslovakia) PCC T3-5	Most European cities
	UTDC (Canada) CLRV	Toronto
4-axle articulated	Esslingen (West Germany)	Stuttgart
	Rathgeber (West Germany)	Munich
	Tatra (Czechoslovakia) KT4D	East German cities
	Wegmann (West Germany)	Bremen
5-axle articulated	MAN (West Germany)	Augsburg
6-axle articulated	Boeing (USA) LRV	Boston, San Francisco
	Citadis (France)	Planned
	DuWag (West Germany)	
	B Type	Cologne, Bonn, Rhine-Ruhr
	M-6	Bochum, Gelsenkirchen
	Miscellaneous	Most systems in West Germany
	Hannover Prototype	Vancouver
	U2	Edmonton, Frankfurt
	La Brugeoise (Belgium)	Brussels, St. Etienne, Vicinal
	Konstal (Poland)	Several East European cities
	LHB (West Germany)	Brunswick
	MAN (West Germany)	Nuremberg
	Metro Cammell (England)	Tyne & Wear
	Tatra (Czechoslovakia) K2	Several East European cities
	Schindler (Switzerland)	Basel, Zurich
	Valmet OY (Finland)	Helsinki
6-axle, double articulated	SIG (Switzerland)	Zurich
8-axle, double articulated	DWM (West Germany)	Karlsruhe
	DuWag (West Germany)	
	Miscellaneous	Many West German cities
	GT8S	Dusseldorf
	Hannover 6000	Hannover
	M8	Bielefeld, Essen, Mulheim
	P8	Frankfurt
	La Burgeoise (Belgium)	Brussels
	LHB (West Germany)	Amsterdam

Light rail vehicles are normally classified by the number of axles and the number of articulations. Basic body configurations include:

- Non-articulated vehicles generally using four axles arranged in two trucks. The vast majority of vehicles built for the late 1950s, including the U.S. PCC car, were non-articulated.
- Single articulated vehicles using, in most cases, three trucks with six axles, one truck being located under the articulation joint.
- Double articulated vehicles composed of three body elements with a center shorter than the end sections. Most double articulated vehicles have four trucks (8 axles) with two of the trucks centered under the joints.
- Trailers, vehicles without a driving control position, can only be operated coupled with another vehicle.

A great number of variations and configurations has been developed for light rail vehicles. Figure 24 shows the most important configurations used on LRT systems. Designs 2 and 3 are the most significant to LRT in North America.

Almost all modern LRT vehicles are designed for multiple unit operation. This capability permits greater line capacity and raises operator productivity where one man trains are used. However, longer station platforms are required to accommodate the trains.

Most LRT systems in the United States and many in Europe use single direction cars. However, in recent years a trend to bi-directional cars has become evident. These vehicles are preferred for underground operations since they can turn back at a simple crossover track, and may be loaded from either side of the vehicle.

Light rail vehicle designs feature several different passenger loading techniques. Some vehicles are designed with steps for low level loading, and in some cases, a retractable step design is employed to reduce the number of steps inside a vehicle. Other vehicle designs, such as for systems at Edmonton and Tyne & Wear, use only high level loading (more commonly found on rail rapid systems). High level loading is of interest at stations where large volumes of passengers must be handled, such as on modern LRT subways. Most contemporary LRT designs cannot operate on lines equipped with third rail power distribution, because they have low level steps. However, certain designs, such as the DuWag B car with a retractable bottom step, could be used in third rail operation. Finally, several light rail vehicles are designed to provide both high and low level loading.

CURRENT VEHICLE DEVELOPMENTS

The configuration of modern light rail vehicles reflects, in many ways, the design principles first introduced some 40 years ago in the PCC car. Designed in the period from 1929 to 1935, the PCC car was a radical departure from design practice at that time. Its development was motivated by a need for better performance and lower capital and operating costs. A major design goal was the lowering of manufacturing costs by achieving a high degree of component standardization without losing the ability to adapt to the need of various properties. Some 5,000 PCC cars were built in the United States between 1936 to the mid-1950s. Even today, designs based on the United States PCC car are still being built in Europe. Vehicles produced

STANDARD DESIGNS

1

2-AXLE NON-ARTICULATED. BASIC EUROPEAN DESIGN. WIDELY USED UP TO 1950S. NOW BEING PHASED OUT.

2

4-AXLE NON-ARTICULATED. BASIC U.S. DESIGN. ALSO USED IN EUROPE. THE CLRV FOR TORONTO. SOME PCC CARS (THE HAGUE, GHENT). THE ASEA CARS (MELBOURNE, GOTHENBURG) AND SOME TATRA DESIGNS USE THIS CONFIGURATION.

3

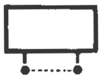
6-AXLE ARTICULATED. THIS IS THE MOST COMMON CONFIGURATION FOR MODERN CARS WHERE WIDTH AND CURVATURE DO NOT IMPOSE SEVERE CONSTRAINTS. FIRST DEVELOPED IN 1890'S FOR CLEVELAND. IS USED FOR BOEING LRV. DUWAG B TYPE AND U2, TYNE & WEAR, AND MANY OTHERS.

4

8-AXLE DOUBLE ARTICULATED. EVOLVED FROM SIX-AXLE DESIGN ABOVE. COMMON IN EUROPE, AND USED ON SEVERAL NEW DESIGNS. MANY SYSTEMS HAVE LENGTHENED CARS OF CONFIGURATION 3 TO THIS TYPE BY ADDING A CENTER SECTION (ROTTERDAM, DUSSELDORF, KARLSRUHE)

IMPORTANT VARIATIONS

5

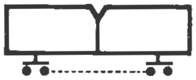


2-AXLE PIVOTAL. PIVOTAL AXLES, WITH A MECHANICAL LINKAGE USED IN BRITAIN AND ELSEWHERE. HAS RESEARCH SIGNIFICANCE.

6

3-AXLE PIVOTAL. COMMON EUROPEAN DESIGN, FEATURING MECHANICALLY LINKED AXLES. NOW LARGELY PHASED OUT IN FAVOR OF BIGGER CARS

7



4-AXLE ARTICULATED. USED IN BREMEN, MUNICH, AND FOR SOME DESIGNS BY TATRA (KT4). PERMIT GREATER LENGTH THAN NON-ARTICULATED, WITHOUT EXTRA TRUCK.

8

4-AXLE ARTICULATED. THE "GT4" ARTICULATED CAR CARRIED ON A RIGID FRAME. THE STUTTGART SYSTEM IS OPERATED BY CARS OF THIS TYPE.

9

6-AXLE DOUBLE ARTICULATED. A DESIGN USED ON SOME SYSTEMS. NOTABLY IN SWITZERLAND-ZURICH, BASEL. CONFIGURATIONS 3 AND 4 ARE MORE COMMON.

10

MARRIED PAIR. COMMON ON RAIL RAPID AND EUROPEAN SUBURBAN TRAINS. MAY BE SIGNIFICANT FOR FUTURE DEVELOPMENT OF LARGE LRVS IN NORTH AMERICA. THE HIGH PERFORMANCE ALTERNATE OF THE CLRV MAY USE THIS CONFIGURATION.

Figure 24. Basic Light Rail Vehicle Configurations

since World War II, principally by Belgian industry, are in use at a number of cities in Western Europe including Antwerp, Brussels, Ghent and The Hague. These new vehicles were modified considerably from the original design, and may incorporate advances, such as electronic equipment and articulated units.

The various light rail vehicle designs produced recently or currently available on the market display wide range of characteristics. While this diversity demonstrates the capability of LRT to operate under a wide range of conditions, it has also led to small purchase orders and relatively high costs as compared with other mass produced vehicular hardware. Table 4 lists some of the most pertinent statistics for a representative cross section of recent vehicular designs available or about to be available in North America and Europe. Several of these vehicle designs are representative of the major contemporary trend in LRT design.

Boeing Light Rail Vehicle

This light rail vehicle is a 6-axle articulated car (Figure 25). The car body is an all welded steel construction. The vehicle was designed to specifications jointly derived by a group of cities in North America under UMTA sponsorship. These LRVs are designed for multiple unit operation on exclusive and semi-exclusive rights-of-way or in mixed traffic. The San Francisco version of the vehicle has movable steps to permit operation at both high and low platform stations.

The Boeing Vertol Company was selected from competitive bidding to produce a joint order of 275 of these vehicles for the San Francisco Municipal Railway (Muni) and the Massachusetts Bay Transportation Authority (MBTA). Test vehicles have been operated at MBTA and at the UMTA Rail Transit Test Track at the U. S. Department of Transportation's Transportation Test Center. The first operational vehicles will be delivered to Boston late in 1976.

The Boeing LRV is designed for 50 mph speed, and features electronic motor controls (thyristor chopper) and anti-slip wheel control, cab signals to be used on lines employing automatic train protection, and automatic couplers designed to absorb energy in minor collisions.

Canadian Light Rail Vehicle

The Canadian light rail vehicle, designed by the Ontario Transportation Development Corporation, is scheduled for production in the late 1970s, when it will become the second LRV to be designed and built in North America. It is a non-articulated, four-axle vehicle designed for single direction operation (Figure 26). An order of 200 vehicles was placed by the Toronto Transit Commission where they will serve initially as a streetcar replacement but higher performance will be achievable later on reserved rights-of-way. The Canadian LRV's performance is similar to that of the earlier PCC car, with a maximum design speed of 50 mph. It uses advanced electronic motor and brake controls and will achieve one of the highest rates of acceleration of all contemporary LRT vehicles.

DuWag Vehicles

DuWag vehicles are used on most of the new West German light rail systems and on a number of systems in other Western European countries as well. Edmonton, Canada, has also

Table 4. Light Rail Vehicles – Significant Recent Designs

Vehicle	Boeing LRV	Tyne & Wear	DuWag B Type	DuWag U2	DuWag P8	DuWag Hannover	U.S. PCC Car	Canadian LRV	Tatra PCC T5	Tatra KT4D
Approximate design year	1973	1973	1971	1965	1970	1972	1933	1975	1972	1971
Systems using (planned for)	(Boston) (San Francisco) (Dayton)	(Tyne & Wear)	Cologne Bonn (Essen) (Dusseldorf)	Frankfurt (Edmonton)	Frankfurt	Hannover	Approximately 5000 built	(Toronto)	Prague – latest PCC design	8 cities in East Germany
Axles/articulation	6/1	6/1	6/1	6/1	8/2	8/2	4/0	4/0	4/0	4/1
Length, feet/meters	71.5/21.8	91.2/27.8	88.2/26.9	75.5/23.0	89.9/27.4	88.5/27.0	43.5 to 50.5/ 13.2 to 15.4	50.67/15.44	49.5/15.1	59.4/18.1
Width, feet/meters	8.85/2.70	8.70/2.65	8.70/2.65	8.70/2.65	7.70/2.35	7.85/2.40	8.33 to 9.0/ 2.54 to 2.74	8.50/2.59	8.53/2.60	7.20/2.20
Floor height, feet/meters	2.82/0.86	3.15/0.96	3.3/1.0	3.18/0.97	3.15/0.96	3.08/0.94	2.75/0.84	3.02/0.92	2.95/0.90	2.95/0.90
Roof height, feet/meters	11.5/3.51	11.3/3.45	11.0/3.37	10.8/3.28	10.7/3.26	10.9/3.31	10.1/3.08	11.0/3.37	10.37/3.16	10.2/3.11
Seats, number/layout	68/2+2	84/2+2	72/2+2	64/2+2	62/2+1	46/2+1	49 to 69/ 2+1 or 2+2	42 or 47 Varies	36/2+1	26/1+1 or 38/2+1
Doors per side										
Number	3 double	4 double	4 double and 2 single	4 double	2 double and 2 single	5 double	2 or 3 double	2 double	3 double	4 double
Type	Plug	Plug	Plug	Folding	Folding	Folding	Folding	Folding	Folding	Folding
Steps	High/Low	High	High/Low	High	High/Low	High/Low	Low	Low	Low	Low
Maximum speed, mph/kph	50/80	50/80	60/100	50/80	45/70	50/80	50/80	50/80	50/80	40/65
Acceleration loaded, feet/second^2	4.1	3.3	3.9	3.3	3.3	3.6	4.6	4.6	4.9	4.3
Deceleration loaded, feet/second^2	5.1	3.3	3.9	3.9	3.9	3.9	4.6	5.1	4.9	4.3
Emergency deceleration loaded, feet/second^2	8.8	10	10	10	10	10	9.5	10	7.5	7.5
Empty weight, 1000 pounds	68	86	86	66	75	85	33 to 42	52	40	44
Maximum design grade (percent)	9.0		6.0	4.4	4.4	5.0	10+	10+	10+	8
Minimum curve radius (feet)	Varies 32 or 42	160	82	82	56	59	Varies	38	66	52

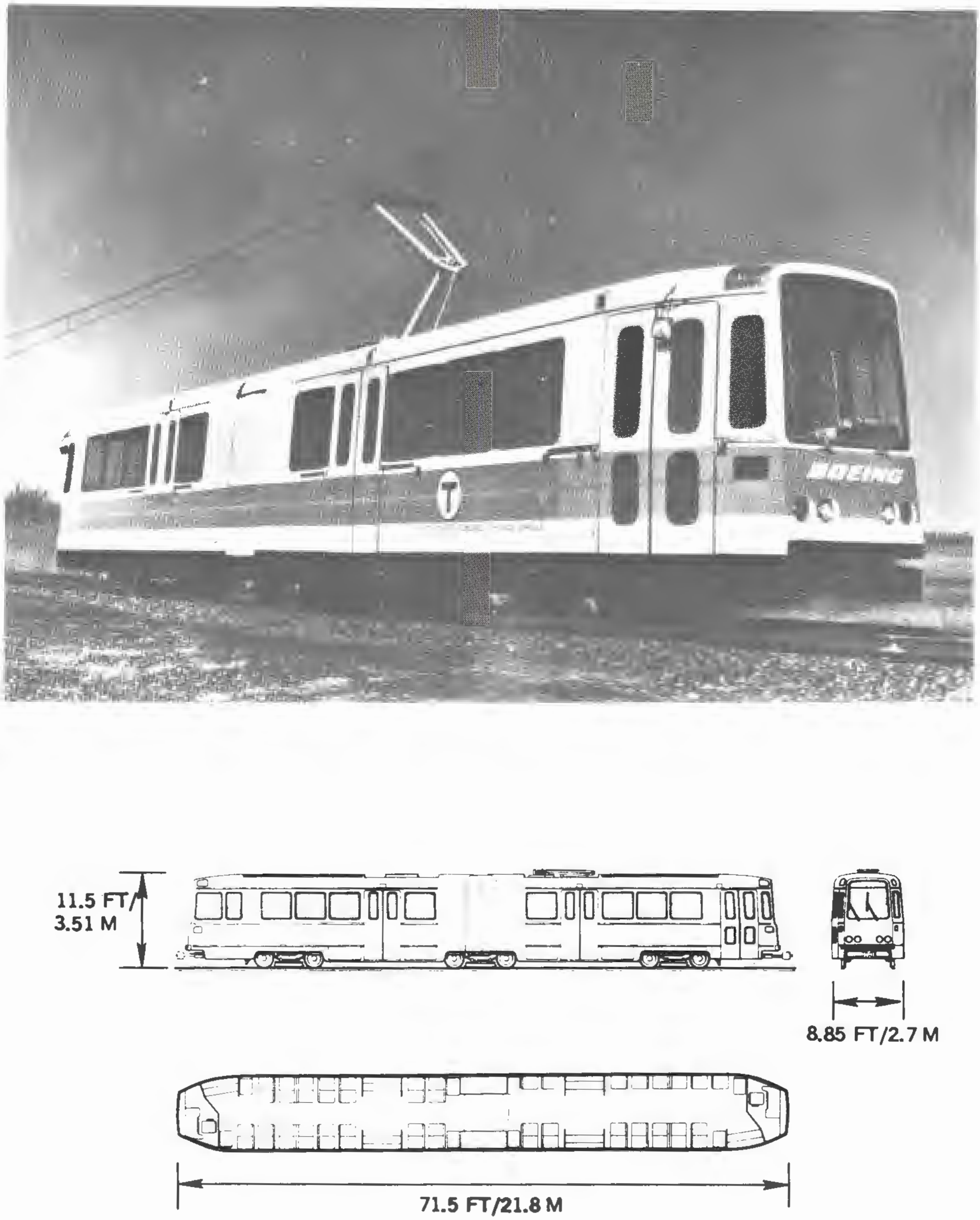


Figure 25. Boeing LRV

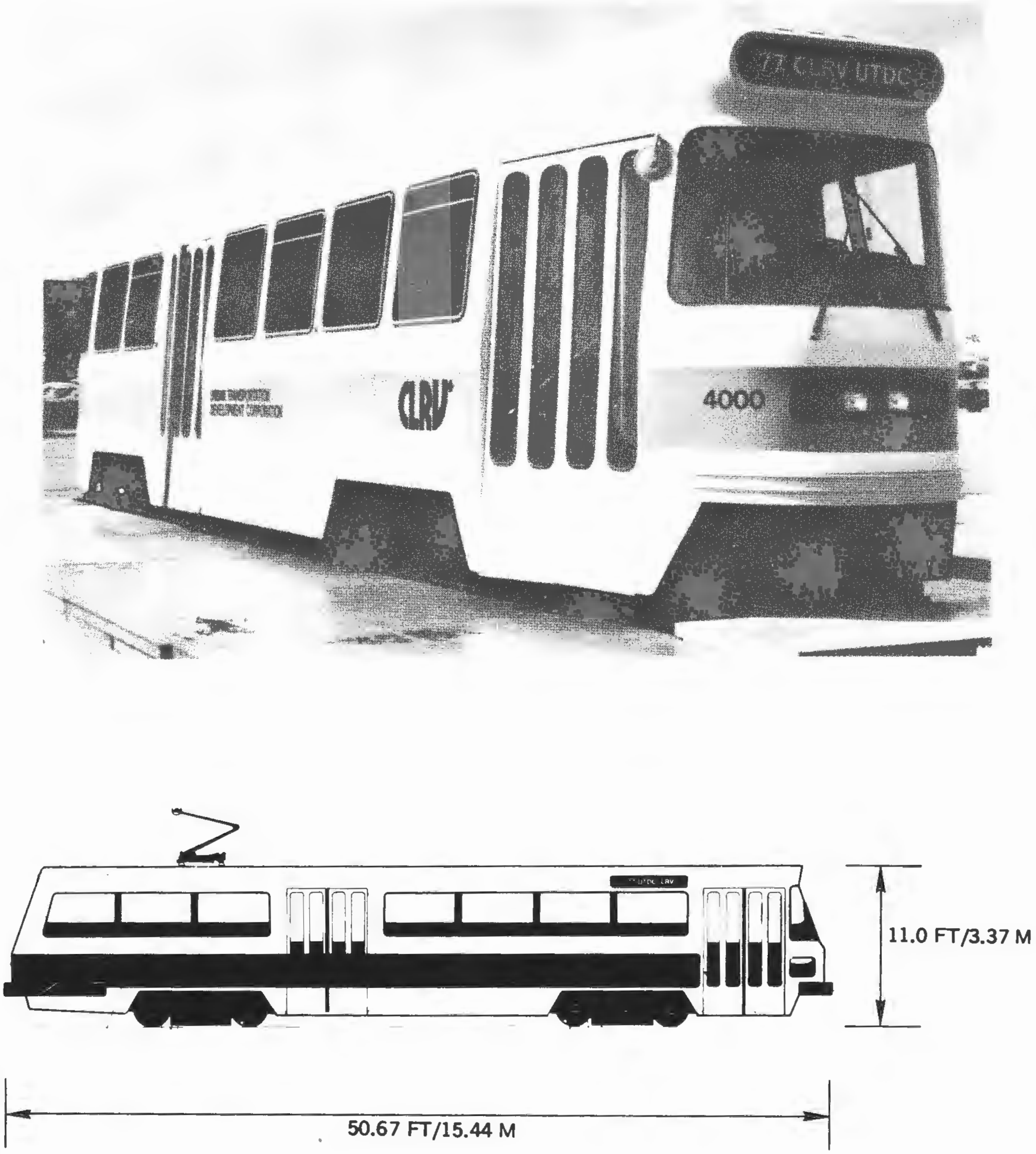


Figure 26. Canadian Light Rail Vehicle

ordered cars from this manufacturer. Significant designs originating from the DuWag production line include the following vehicles.

- The *DuWag Type U2,* designed specifically for Frankfurt, is a single articulated, bi-directional vehicle for use on exclusive semi-exclusive rights-of-way (Figure 27). It has also been used as the model for the LRVs to be installed at Edmonton, Canada. Delivery started in 1968, and 64 vehicles are now in use in Frankfurt. The new LRT system at Edmonton will use 14 vehicles of this type to operate on its first line.

- The *DuWag P8* is a double articulated, bi-directional vehicle designed for multiple unit operation in Frankfurt on lines where track spacing does not provide sufficient width for the U2 cars. From 1972 to 1974, 100 vehicles were purchased and are now in operation. Other design features of the DuWag P8 are movable steps for high or low level passenger loading, coupling compatible with the U2 so they can be operated together in case of emergency, and one of the largest capacities of any current light rail vehicle design.

- The *DuWag Type B* is a single articulated, six-axle vehicle (Figure 28) designed for use at Cologne and at Bonn on surface streets and in tunnels. The first cars were delivered to Cologne in 1973. Since then, deliveries have been made to Bonn, Cologne and the Rhine-Ruhr System. Up to 500 vehicles may eventually be built. With a speed capability of 62 mph, the Type B is the fastest LRT vehicle produced in West Germany. The performance, as measured by its acceleration capability, is among the highest of all articulated LRT vehicles in operation. The Type B vehicle also features movable steps to permit boarding from high and low platforms, automatic couplers, one of the largest passenger capacities of all vehicles currently in operation, and 6 doors per side to permit efficient passenger boarding at stations.

- The *DuWag Hannover 8-axle* is a double articulated, bi-directional vehicle designed for operation in subways and surface rights-of-way with high and low level platforms. One hundred vehicles are being delivered to Hannover for operation in its light rail subway system. It is capable of a maximum speed of 50 mph.

- The *Tyne & Wear* vehicle is a 6-axle, single articulated, bi-directional vehicle (Figure 29) derived from the DuWag Type B car and built specifically for the LRT system at Newcastle, England. The vehicle is assembled from components supplied by a number of manufacturers. So far, only two prototype test cars have been constructed. They are now undergoing trials prior to placing orders for the rest of the fleet. It is estimated that 90 cars will be required by 1980. The vehicle allows passenger boarding from high level platforms only, is powered by 1500 volts (a unique feature in LRV design), and is capable of higher performance than the conventional British rail commuter rolling stock.

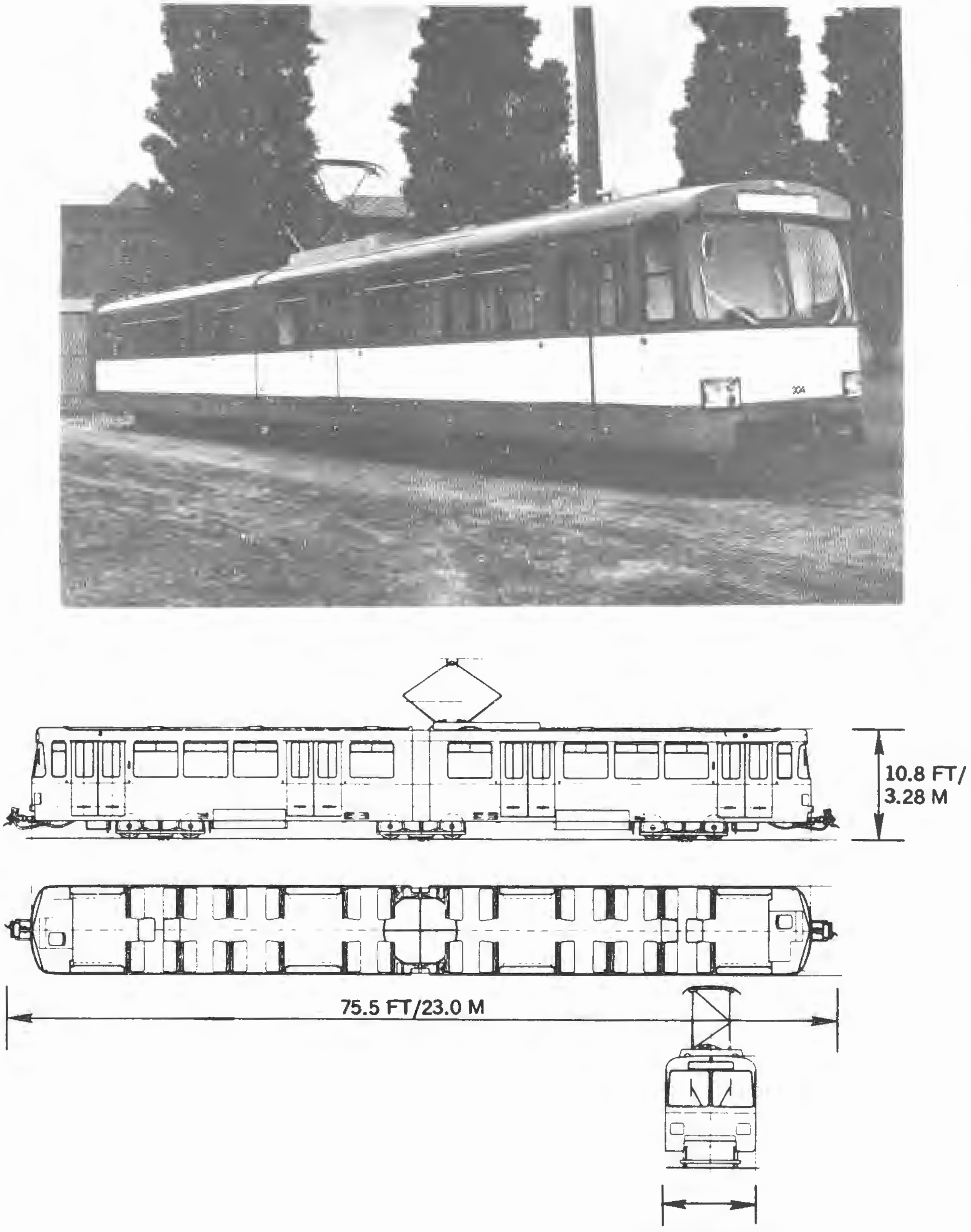


Figure 27. DuWag U2

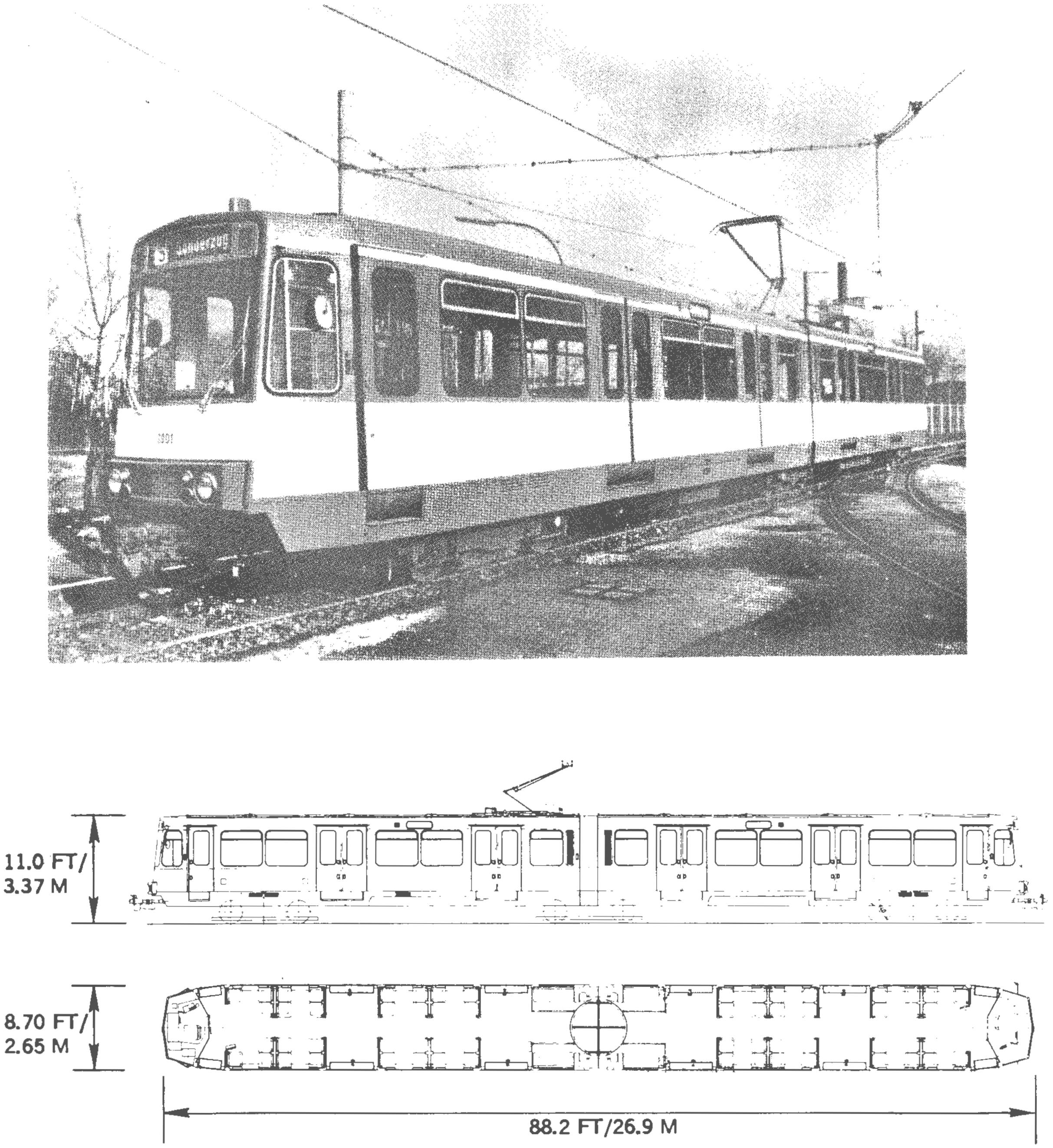


Figure 28. DuWag Type B

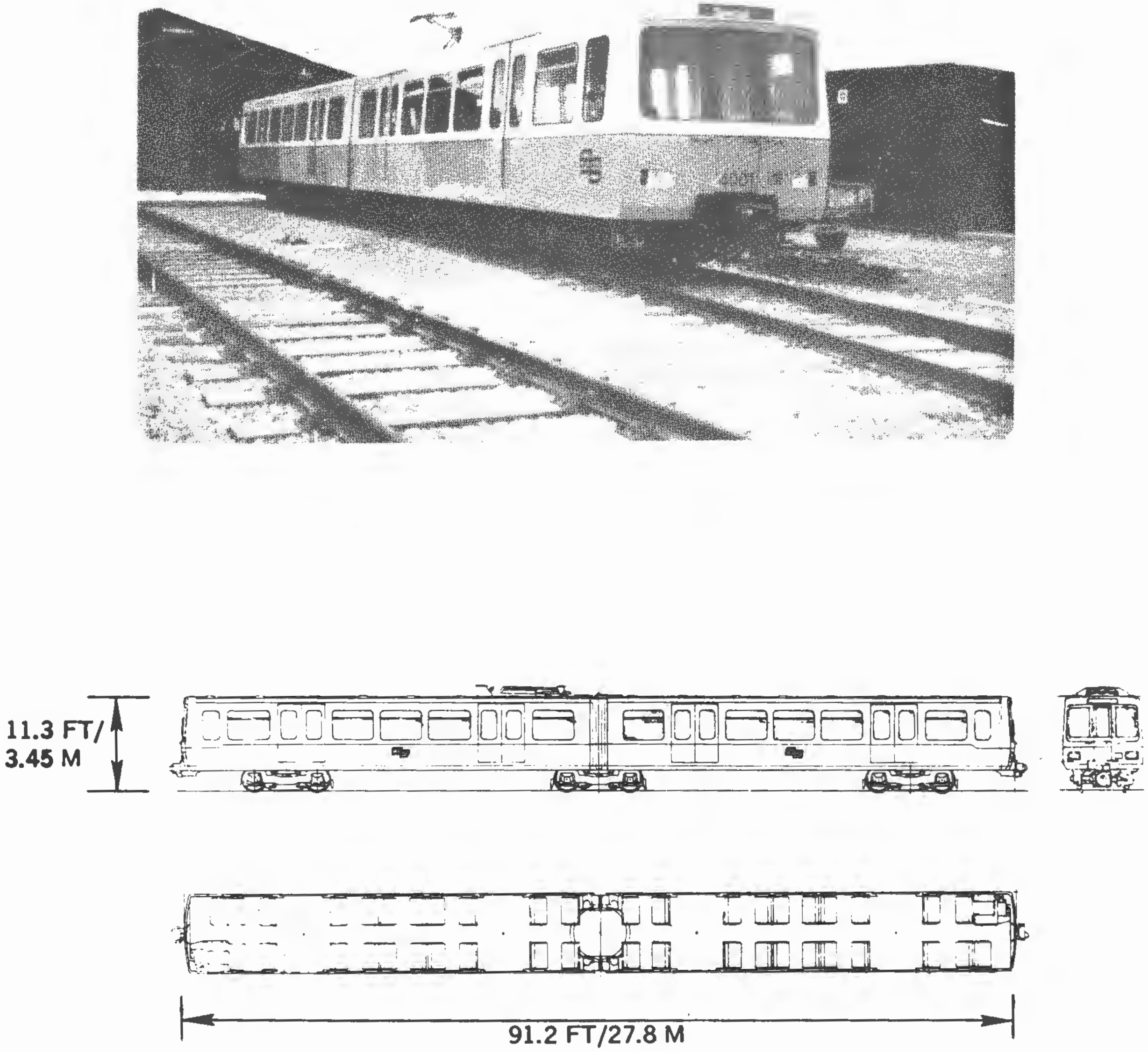


Figure 29. Tyne & Wear Car

Tatra Vehicles

Tatra vehicles, produced in Czechoslovakia, are derived from the earlier PCC designs. These vehicles are noteworthy in that they represent a relatively small, low cost and are considerably more austere than is common practice in the West European LRT industry. To date, no Tatra vehicles have been sold on the western market.

PERFORMANCE OF LRV

The performance of transit vehicles is generally described by their capacity, turn radii, grade climbing capabilities, speed, acceleration and braking.

Capacity

The seating capacity range of modern LRVs is as high as 72 seats in the DuWag B Type car. Total capacity, including standees (allowing of 2.7 feet^2 per standee), ranges up to 180 for the same car. Maximum capacity based on this standard for the Boeing LRV is 152 and for the DuWag B Type, 180 passengers.

Speed Acceleration and Deceleration

Maximum and average acceleration for the representative vehicle speeds are shown in Table 4.

Grade Climbing

Light rail vehicles are capable of climbing steeper grades than those normally encountered in rail rapid transit operations. Non-articulated units have the capability of climbing up to 12 percent grades, while the articulated vehicles can negotiate grades as steep as 9 percent.

Braking

Braking rates of light rail vehicles under normal conditions are generally comparable to the performance of other rail transit vehicles. However, emergency braking rates are considerably higher due to the use of supplementary magnetic track brakes not commonly found in rail rapid transit. Tests have shown that the emergency stopping distance of light rail vehicles is comparable to that of rubber tired vehicles. This capability is a major factor in permitting light rail to operate on street rights-of-way and through at-grade intersections.

LIGHT RAIL VEHICLE SUBSYSTEMS

While most of the equipment carried on light rail vehicles is similar to that found on other rail transit cars, several of the components are noteworthy.

Wheels

All new LRT vehicle designs utilize resilient wheels which greatly reduce squealing on short radius curves.

Braking

The braking system used on light rail vehicles distinguishes them from other rail transit cars, since it makes possible the operation of LRT in the proximity of street traffic. Three different and independent braking subsystems are used on light rail cars. The first two, dynamic brakes and friction brakes, are common to the standard technology of rail transit vehicles. The third, the electromagnetic track brake, is effective primarily as an emergency stopping device. When actuated, this brake grips the track, producing a powerful retardation which is largely independent of the vehicle load or wet or icy conditions.

Motor Controls

The motors of LRT vehicles are controlled by regulating the motor current and voltage. Two techniques are used: the traditional rheostatic approach and, in new designs, electronic solid state methods (chopper). With the newer techniques, smoother control and energy savings are achievable. Regenerative as well as dynamic braking can be achieved. Theoretical energy savings for vehicles so equipped may range as high as 20 to 30 percent when regenerative braking is included. Chopper motor controls add approximately 6 percent to vehicle costs and require sophisticated electronic maintenance.

VEHICLE STANDARDIZATION

Standardization of vehicle design is a major issue confronting the light rail vehicle supplier industry. The variety of vehicular designs and operations in Western Europe and North America illustrates the lack of equipment standardization. The resulting high costs of light rail vehicles have been responsible, in part, for the limited proliferation of this mode. Standardization of design can be instrumental in reducing the dimensional variability of available vehicle designs. It could reduce costs of acquisition to agencies purchasing only a few cars as part of network expansion or in the implementation of a first network segment. Standardization can also reduce the impact of variable design features, such as floor height and vehicle width, on the configuration of stations and LRT subways.

TRACK, POWER AND VEHICLE CONTROL SYSTEMS

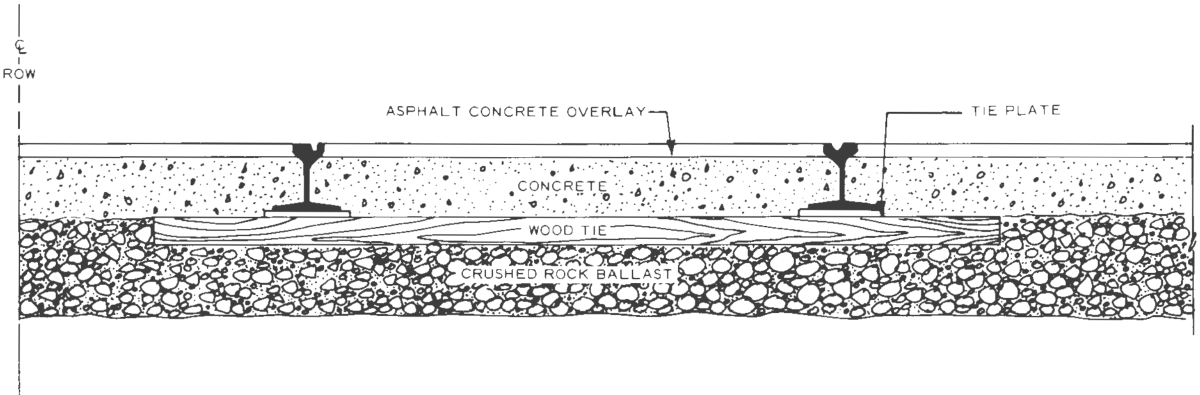
TRACK

There are three basic different track configurations used in light rail systems. *Open track,* similar to the track used on railroads, is the most common form of construction on modern LRT systems. *Fixed track,* used extensively on rail rapid transit systems, is normally used on certain LRT guideway structures or in LRT tunnels. The rail is attached directly to the structure but elastomeric pads are used to reduce vibrations. *Paved track* is used whenever LRT shares its right-of-way with rubber tired vehicles, such as at grade crossings or in transitways shared with buses.

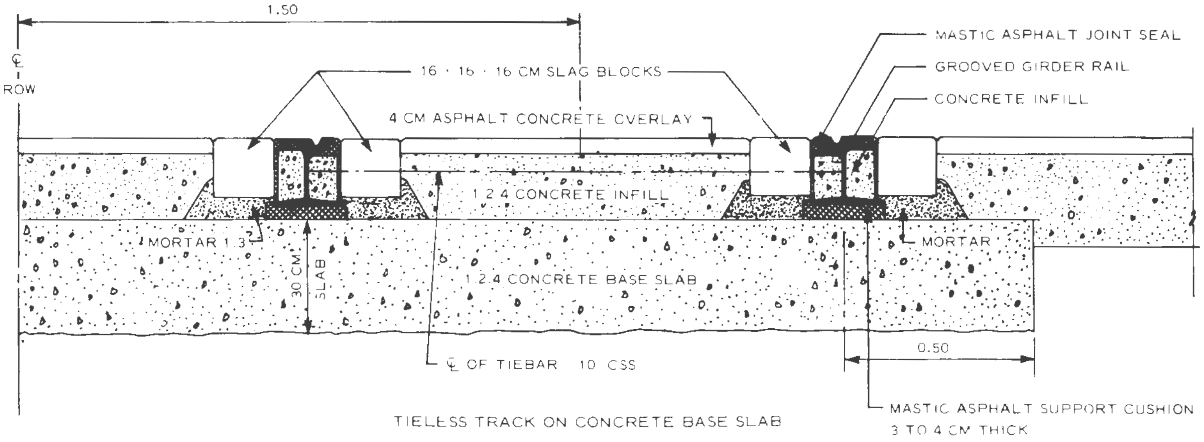
In North America, paved track (Figure 30) is constructed basically in the same manner as open track, using ties and ballast covered in some form of pavement placed over the ties up to the rail head. An entirely different form of paved track construction has evolved in Europe, commonly referred to as tieless track. Since it is constructed with the rails not rigidly attached to the adjoining pavement, noise and vibrations are reduced and pavement life is increased.

RAIL

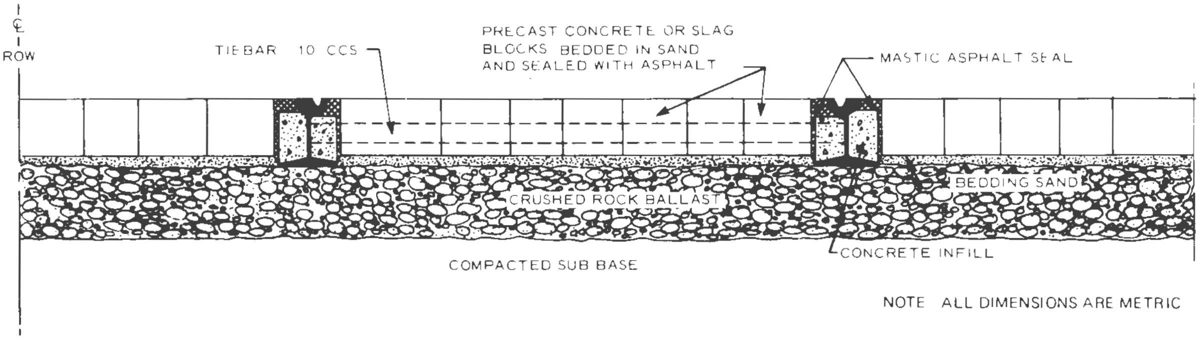
Modern LRT, rail transit and railroad systems almost invariably use welded rails in track construction. Welded rail provides a quieter and smoother ride, requires less maintenance, and



NORTH AMERICAN PAVED TRACK



TIELESS TRACK ON CONCRETE BASE SLAB



TIELESS TRACK ON BALLAST BASE

Figure 30. Paved Track Sections

eliminates the need for electrical rail bonding at joints. Two types of rail are used on LRT systems: T-rail, which is typical of that used on conventional railroads; and girder rail, which is used in pavement. The groove of the girder rail produces a permanent flange for the wheel, and its greater depth provides the stiffness necessary to preserve the pavement.

GAUGE

The standard gauge in LRT systems, as in railroad practice, is the 4.708 foot (1.436 meter) gauge. It is common in Europe and North America, although examples of nonstandard gauge are found in many cities.

POWER SUPPLY SYSTEMS

Distribution

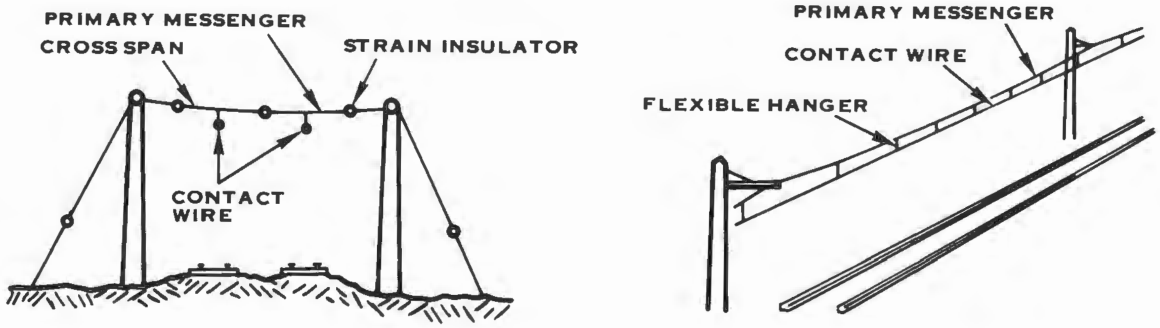
Direct current (DC) is the prevailing method for the electrification of light rail transit systems. Common voltage for operation of LRVs is 600 volts. However, the new Tyne & Wear system has a significant distinction; it is designed for 1500 volts DC. The higher voltage will reduce electrical component sizes, and will increase operating efficiency and substation spacing.

Power Collection

Most light rail vehicles collect power from the overhead contact wire by means of a pantograph or a trolley pole. Modern light rail vehicles almost exclusively use the pantograph. This collector is suitable for operation with a single contact wire or with a multi-wire, cantenary system (Figure 31). Both single contact wire and catenary systems may be supported on poles placed centrally between the tracks or outside the tracks. In certain installations, the supports for the wires may be anchored to buildings and other utility poles.

The visual aspects of the overhead power supply are sometimes targets of criticism. New developments in electrical conductors and insulators combined with a heightened understanding of the principles of visual design make possible the configuration of the power supply system that could be more acceptable to the community (Figure 32). This requires that all nonessential circuitry be placed in underground conduits, that plantings and structures be used to disrupt the wire silhouette, and that multiple use be found for the support poles combining certain utilities with the power distribution system. Existing structures should be used, where possible, to support the wires, rather than poles, and cantilevered support arms of tapered tube design should be used.

Because of their at-grade operations, few LRT systems have third rail power supply. Under special circumstances there are advantages to equipping LRT systems for pantograph *and* third rail. Benefits include lower height requirements for tunnel sections, easier conversion to rail rapid transit, and more efficient operation in both heavily and lightly traveled lines.



SIMPLE CROSS SPAN-SIMPLE CONTACT WIRE

SIMPLE CATENARY SUSPENSION

Figure 31. Simple Contact Wire and Catenary Systems

Figure 32. Overhead System at Brunswick

SIGNALS AND TRAIN CONTROLS

Most LRT systems are operated by manual control. Some newer installations are equipped with Automatic Train Protection, which provides the operator with direct indication of the condition of the track ahead. Automatic Train Operation, such as is used on rail rapid transit systems, is not practical for LRT systems, because it requires complete grade separation. Fully automated unmanned operations are not used for the same reason. The type of automation suitable for LRT and the technological and economic circumstances which would promote its application to rapid transit are still uncertain at this writing.

OPERATIONS OF LIGHT RAIL TRANSIT SYSTEMS

LEVEL OF SERVICE

The level of service in light rail operations, as described by its achievable speeds, headways and line capacities, is a key attribute essential to the determination of this mode's potential role in urban transit.

Operating Speeds

For systems designed to operate essentially with fairly close station spacings, as in most transit installations, the achievable levels of acceleration and deceleration are as important to determining the average operating speeds as the cruise speed capabilities of the vehicles.

The performance of LRT systems, as measured by the achievable service acceleration and braking rates, is relatively high. Acceleration rates range from 2.5 to 6 feet/second^2 with an average of about 3.5 feet/second^2. LRT vehicles are capable of braking rates which are much higher than those of railroads. Service deceleration rates of 5 feet/second^2 and emergency deceleration rates of 6 to 8 feet/second^2 are achievable. This superior braking capability makes it possible for LRT to operate in mixed traffic where automobile deceleration is typically about 8 feet/second^2.

As a rule most European systems restrict LRT speeds to automobile limits except for operations of fully protected right-of-way. Table 5 shows typical speed constraints for some European light rail systems.

Schedule speeds, as measured on operating LRT systems, vary widely. By improvements in design and operation, schedule speeds for a number of European LRT systems have increased from approximately 8 mph in 1963 to the 10 to 14 mph range in 1974. At Cologne, measured scheduled speeds range from 10 to 13 mph in street traffic, 15 to 20 mph for median strip operation, and up to 25 mph on right-of-way without crossings.

Line Capacities

LRT systems using automatic block signalling systems are normally operated at headways ranging from 90 to 120 seconds. Shorter headways of 30 to 60 seconds are possible under manual control at lower speeds.

As with all other fixed guideway transit, the carrying capacity of LRT depends on headway, vehicle size and train length. Significant new parameters in estimating light rail transit capacities are the design and policy considerations which reflect the specific local constraints of at-grade operations in usable right-of-way. Normal street traffic operations at crossings and economical station platform lengths limit the maximum train size to three to four cars.

Table 5. Typical Speed Restrictions for LRT

The Hague:	Same as autos in mixed traffic – 31 mph (50 kph) On private right-of-way – 43 mph (70 kph)
Cologne:	Legal limit for auto traffic – 31 and 43 mph (50 and 70 kph) LRV operator may proceed at his own discretion
Zurich:	Speed limit for all vehicles is 37 mph (60 kph)
Karlsruhe:	Civil speed in urban areas – 12 mph (20 kph) On street medians – 37 mph (60 kph)
Frankfurt:	Operating speed on A lines – 43 mph (70 kph) Elsewhere at 31-37 mph (50-60 kph), slowing down for crossings where stations are also located
Mannheim:	Maximum speed of light rail vehicles on pedestrian mall – 16 mph (25 kph)
Dusseldorf:	Operating speed on private right-of-way – 31 mph (50 kph) Governed by same laws for autos on streets
Bremen:	Maximum speed of 37 mph (60 kph)

Theoretical LRT capacities have been projected for three unit Boeing vehicle trains operating at 120 second headways on mainly reserved rights-of-way. Somewhat more than 6,000 seated and 19,000 total passengers could be carried per hour in this modal operation. At the lower headways possible when vehicles are operated under manual control, the carrying capacity of single Boeing vehicle units has been projected at 4,000 passengers per hour seated and 13,000 passengers per hour including standees.

Table 6 gives maximum line section capacities for selected light rail systems in Europe. While many existing LRT lines operate with peak hour volumes as low as 2,000 passengers, new lines projected to operate at such low volumes cannot be easily justified. In most cases, LRT is designed for peak hour volumes of 4,000 to 14,000 persons.

Pedestrian Movements

Preservation of the freedom of pedestrian movements along its route is a major concern in planning LRT. At vehicular grade crossings, pedestrian crossings are easily implemented. Pedestrian crossing configurations, such as the *zee* design used in Europe, are available to facilitate movement across LRT tracks.

Operations in Mixed Traffic

This type of at-grade operation of LRT systems introduces a number of operational ramifications, including procedures for handling the interface with vehicular traffic and pedestrians at intersections along the route.

Table 6. Line Capacity for Selected Light Rail Systems

City	Private* Right-of-Way (Percentage)	Maximum Frequency (Vehicles per Hour)	Maximum Achieved Capacity (Passengers per Hour)
Brussels	N/A	51-72	9,600**
Cologne	77	56-62	13,600
Dusseldorf	36	92	14,000
Frankfurt	65	23	8,200
			11,000***
Stuttgart	58	40	12,000
Hannover	46	80	18,000
Gothenburg	84	88	7,200
			12,000****
Bielefeld	48	24	4,300
Basel	N/A	60	14,500

*Right-of-way categories A and B
**With equipment presently on order
***Rate for 15 to 30 minute interval
****Rail rapid line with modified LRT vehicles

Source: V. Vuchic, "Light Rail Transit Systems, A Definition and Evaluation," 1972 PB-213447 with updated percentages from Dr. Friedrich Lehner.

Conflicts with vehicular and pedestrian traffic must be resolved at all at-grade intersections, including grade crossings in existing railroad rights-of-way and street and highway crossings for LRT lines located in the median strip of an arterial. A range of operational strategies is available to control the LRT crossings and maintain safety, as well as transit and vehicular capacities, through the intersections. These strategies range from standard signals which do not give LRT priority at crossings to signals whose phasing is actuated by the approach of a light rail vehicle, to signal control which will allow light rail vehicle override (preemption). The more sophisticated signalling techniques decrease the potential LRT delays and help, therefore, improve performance on the at-grade portion of the route. For higher LRT crossing speeds, gates in combination with flashing lights may be required for safety reasons.

The preemption of cross traffic by modifying the timing of the signals to give crossing priority to the LRT is a technique used to increase this mode's operation speeds. A number of manual and electromechanical techniques are used to achieve preemption. Intersection signals can be activated by automatic track circuits or through signals obtained via the pantograph from the overhead wire. Automated preemption systems are also available. Vetag, a system used in Holland, detects, identifies and positively locates selected vehicles in the stream of road traffic. It is adaptable to automation of LRT signalling. The preemption of traffic signals as a means to upgrade LRT performance is being used increasingly in Europe. Examples are the LRT systems at Basel, Switzerland and at Nuremberg, West Germany.

Other techniques used at intersections to maintain LRT higher speeds range from the elimination of left turns for automobiles to the prohibition of cross traffic, and eventually to the grade separation of the transit right-of-way. In European cities, such as Rotterdam, Dusseldorf and Hannover, signal preemption, elimination of turns, and prohibition of cross traffic are used singly or in combination where grade separation is not provided.

Operations of LRT through intersections may limit parallel and cross street traffic capacity. If the arrival of LRT vehicles could be fully coordinated with the traffic signals at the intersection, it would be possible to avoid delays in cross traffic or reductions in cross street traffic capacity. In real installations, however, some LRT vehicles could arrive at the intersections when the cross traffic has a green light. If provisions are made to preempt cross traffic, the green time available to it would be decreased. An advanced form of traffic control which coordinates the timing of cross traffic signals with the speed of approaching light rail vehicles to help synchronize train arrivals with green cycles would be an effective means to improve the operations of both LRT and vehicular traffic.

While movable barriers provide greater intersection safety, they also reduce significantly the traffic volume to the crossing because of the delays associated with raising and lowering the barrier. The diversity of traffic conditions in street geometrics is so great that generalizations regarding the best means for managing transit and vehicular movements through intersections are not practical. Appropriate strategy must be fitted to each specific instance to account for all of the affected operational, economic and environmental factors.

The interface of LRT with vehicular traffic and pedestrians at crossings requires that operational measures designed to enhance safety be given a high priority in planning of at-grade LRT routes. While operational safety practices and the safety statistics are known, for slow speed streetcar type operations in mixed traffic, data to help describe the safety of higher performance operations typical of LRT service are scarce and, where available, not fully applicable to traffic conditions in this country. Until a detailed and interpretative analysis of European safety records is made, it appears prudent to state the crossing safety goals for LRT in largely qualitative terms. For social, political and economic reasons, the accident rate should be maintained at levels considerably below those experienced by both the existing domestic LRT operations and at railroad crossings. These goals could be approached by a number of strategies, including:

- Complete grade separation for LRT crossings of heavily traveled highways, perhaps for those carrying more than 5,000 automobiles per lane per day.
- When feasible, restriction or elimination of automobile left turn movements.
- LRT speed reductions through intersections to a rate close to that prevailing on the adjacent surface streets.
- Installation of occupancy detectors to insure positive slowdown and stop commands to light rail vehicles when the intersection is occupied.
- Installation of positive crossing control devices, such as gates, to restrict access of other vehicles and pedestrians to the intersection shortly before and during the passage of the LRV.

GENERAL OPERATIONS

Fare Collection

Self-service fare collection is generally described as a significant operational attribute of light rail systems. Self-service fare collection is characterized by the absence of gates for control of passenger entry or exit. It does not require the vehicle operator to monitor fare collection onboard. Different procedures are used to implement this fare concept. Monthly passes, ticket vending machines located on streets and discounts for prepaid tickets, are provided. Enforcement of the fare payment is provided by roving inspectors who make periodic checks. The success of light rail operations in Europe is attributed by some authorities to the adoption by most cities of this form of fare collection. Major reasons cited to support the adoption of this concept include financial savings, reduction in staff work load, and relief from shortages of staff. Increases in schedule speed because of shorter station dwell times have also been cited. According to a 1973 survey, 45 percent of the transit agencies surveyed in Europe were using self-service fare collection, and 75 percent expected to use it in the future. There is no evidence that any city, having adopted this system, abandonded it at a later date.

Provisions for the Handicapped

Provisions to facilitate the access of handicapped on and off transit vehicles are required by current U.S. transit policy. Conventional designs of light rail vehicles operating in at-grade rights-of-way with low level station platforms hinder the movement of handicapped onto and off the higher level of the vehicle floor. Raising the station platform level to match that of the vehicle floor or dropping the level of the vehicle floor to match that of the street station platform are the two design solutions proposed to solve this difficulty. The Boeing LRV incorporates an adjustable height loading platform which can be used for this purpose. The French Citadis LRV design features an overall lower floor level which could also facilitate access of handicapped.

Vandalism and Passenger Security

Vandalism and passenger security are problems on European transit, as they are on American systems. On LRT, the problem can be mitigated by the use of larger capacity articulated vehicles in lieu of unattended trailer cars. However, on unattended street level platform stations, particularly in areas with a substantial crime rate, vandalism and passenger security would be problems comparable to that experienced on other transit operations.

Maintenance

Light rail operations do not require significantly unusual or different maintenance practices. Modern LRT vehicles rely heavily on complex electronic and electrical equipment. The maintenance of these components is not different from that required by other modern rail transit vehicles. Maintenance of the overhead power distribution is, however, a unique requirement for LRT systems.

Energy

Energy consumption for typical LRVs has been estimated and corroborated with operating experience. Consumption is in the range of 10 kwh per vehicle mile for operations at typical speeds and number of stations per mile. Higher values have been noted on LRVs operating on segments with significant grades or with more stations per mile. Estimates of energy consumption, as well as measurements on operational vehicles, indicate that the new LRVs utilize up to twice as much energy as the smaller, lighter PCC cars of the earlier streetcar system. This matter is explained by the greater weight and increased performance of the newer vehicles.

Compared with rail rapid transit, LRT consumes more energy in mixed traffic due to more frequent stops. With priority signalling and private rights-of-way, LRV energy consumption per vehicle mile could improve, particularly for vehicles equipped with chopper motor controls and with regenerative braking.

SELECTED ENVIRONMENTAL IMPACTS

Noise

Noise levels are comparable with buses and rail rapid transit. Significant noise abatement can be achieved with proper vehicle design and track maintenance. A major LRT noise source is wheel squeal which can be controlled using resilient wheels and other special means. In particular, the use of lubricants on specific segments of the track have shown that squeal can be reduced substantially.

Air Pollution

As for the other electrically powered transit systems, the contribution for LRT to air pollution is restricted to the emissions at the power generating plant. No significant additional adverse effects are noted.

CAPITAL AND OPERATING COSTS OF LIGHT RAIL TRANSIT

Projections of capital costs, based on construction cost information available in the U.S., are generally sufficient for preliminary planning of LRT. While adequate data are readily available and applicable for preliminary estimates, it is not advisable to draw conclusions about the capital and operating costs of specific transit systems. Varying site and facility conditions, labor agreements, the regional structure and other factors can have an impact upon system cost. Consequently, there is no alternative to basing definitive cost estimates on sound preliminary engineering, including specific assessments of rights-of-way and the system's projected operating characteristics. Unit prices and average cost estimates must, therefore, be used with discretion.

Operating and maintenance (O&M) cost data drawn from the recent experience of European and American LRT systems are in reasonably good agreement. Since in most instances the accounting procedures of transit operating agencies do not separate records for the various levels of their light rail operations, it is difficult to segregate the factors which significantly influence the costs. Consequently, the O&M costs incurred by existing properties in the operation of LRT must be used with caution when projecting the costs of new installations.

Vehicle Costs

A range of cost data is available for the light rail vehicles currently being produced in Europe and North America, but it is subject to uncertainties of inflation and cost increments caused by varying degrees of sophistication of vehicles' subsystems. Vehicle costs have been escalating at a far greater rate than most other capital cost items over the past few years. On an average, rail car costs in the United States have increased approximately 27 percent in the past 15 years on a basis of cost per pound and 65 percent on the basis of cost per square foot. (Cost per square foot of usable floor area or per pound of vehicle weight are useful measures for comparative evaluation of costs for transit vehicles.) The greater increase as stated in cost per unit of usable floor area results, in part, from the operators' specifications for higher performance of the new vehicles and the resulting increase in technological sophistication of their components.

Some current vehicle costs (and estimates) include the following:

- *Boeing* LRVs currently being prepared for delivery to Boston have a contract price of approximately $330,000 per unit. The costs of the vehicles produced for San Francisco, without air conditioning and with a different seating configuration, are approximately $300,000. Based upon this figure, the San Francisco vehicles cost $4.50 per pound of vehicle weight or $500 per square foot. Future procurements for Boeing vehicles are likely to bear a significantly higher price tag due to inflationary pressures and an overall reassessment of production costs.

- *The Canadian* non-articulated LRT vehicle, to be produced for the Toronto Transit Commission, has a price tag of approximately $363,000 per unit in 1975 dollars. On an area basis, the Canadian LRV costs approximately $880 per square foot. It is expected that future orders will cost more, probably as much as $490,000 per unit for vehicles delivered in 1979.

- *European* cars of comparable complexity to the American products sell for similar amounts. For instance, the new DuWag 8-axle cars being assembled for Bielefeld cost approximately $426,000 per unit. This translates into approximately $5.70 per pound or $620 per square foot. The DuWag U2 cars ordered for Edmonton, Canada, are priced at $540,000 escalated to 1977 costs.

  Cheaper vehicles of smaller size and of considerably more austere design are reported to be provided by Tatra, but as yet no vehicles of this type operate in Western Europe. Vehicles produced in Western Europe based on the old PCC design have been sold in recent years at lower prices. However, they are also smaller vehicles and of more austere design.

FACILITY UNIT CAPITAL COSTS

Comparative analysis of cost projections for facilities (1974-1975 data) drawn from several sources suggests some degree of consistency among various estimates. Some of the variations in the costs cited below can be attributed to different design assumptions. For instance, since the cost of electrification depends primarily on the number and length of trains operating within a given section, it is heavily influenced by the assumed demand level. Widely spaced single unit LRVs will cost out low, while for multiple unit operation at close headways, the high figures will be more representative.

The variability of structural costs (stations and guideways) should be viewed in light of the great variations which are possible in site conditions and other local features.

The overall correlation among available data sources lends credence to the use of these data for the preliminary estimates. However, it must again be cautioned that use of such data for planning and alternatives analyses is no substitute for actual field investigations and engineering analyses which must be carried out to provide the more accurate and narrower ranges of unit costs for site-specific situations.

Guideways

Estimates for aerial guideways range from roughly $3 million to $17 million per mile. For at-grade locations, estimates range from $340,000 to $1 million per mile. Where occasional grade separations are necessary, the latter values escalate from $1 million to $5 million per mile. For subway installations, costs range from a low of $18 million to a high of $34 million per mile. (Substantial deviations can be expected when favorable geological conditions are found along the route or when unusual construction difficulties are encountered.)

Trackwork

Estimates range from $540,000 to $1 million per mile.

Stations

Estimates range from $20,000 for a low level platform design to $12 million for an underground station. Costs of $1.3 million to $4.5 million are being cited for aerial stations.

Power Supply

Estimates range from $500,000 to $1.8 million per mile depending on the type of installation being used.

Controls

Cost estimates range from $190,000 to $2.65 million per mile, reflecting different degrees of sophistication of the technology utilized. For grade crossings, costs for controls have been estimated from $25,000 to $200,000 per intersection.

SYSTEM CAPITAL COSTS

Projections of systemwide costs show considerable variations. Basic design aspects of an LRT network may cause costs to differ widely, from as high as those of an equivalent rail rapid system to mere fractions of it. For instance, for a *predominantly grade separated* design with sophisticated train control and grade separated station facilities, little difference will be found between the cost of LRT and the cost of rail rapid transit. For systems which are entirely underground, the projected facility cost for both LRT and rail rapid transit ranges from somewhat less than $40 million per mile to more than $70 million per mile. With only partial underground right-of-way but still maintaining complete grade separation, the projections for both systems drop to a range from somewhat less than $20 million per mile to roughly $30 million per mile. For a more austere design with alignments on street medians, at-grade crossings, manual operation, few sophisticated train safety controls and simple passenger loading platforms, LRT can show a considerable competitive edge. LRT costs will average somewhere between $15 million and $30 million per mile for systems with *some* at-grade facilities. By exploiting the ability of LRT to operate totally at grade along streets or on existing railroad rights-of-way, facility costs as low as $3 million to $10 million per route mile are achievable.

OPERATING AND MAINTENANCE COSTS

The available statistics of O&M costs for European and American installations correlate fairly well. For the West European and U.S. properties surveyed, costs ranged from slightly under $1 per vehicle mile to slightly under $2.50 per vehicle mile in the period 1973/1974 (Figure 33).

Variations occur between U.S. and European costs of energy reflecting the higher cost of fuel in Western Europe. Operator wages in 1974 were fairly uniform in West Germany but were significantly lower than U.S. wage rates.

Most of the available operating and maintenance cost data are derived from systems that operate on an average speed of less than 12 mph and an average vehicle usage of less than 50,000 miles per vehicle per year. High performance light rail systems should be capable, on the average, of schedule speeds greater than 15 mph resulting in higher annual vehicle usage and lower average operating cost per vehicle. Sensitivity calculations show that increasing the schedule speed from 10 to 15 mph results in an average increase in vehicle utilization from 40,000 to 56,000 vehicle miles per year. It is estimated that the higher speed could result in a decrease in operating costs of approximately 15 percent.

GENERAL PLANNING CONSIDERATIONS FOR APPLICATIONS OF LIGHT RAIL TRANSIT

Light rail transit is a broadly defined generic transit mode. Because of historical trends in transit and the wide range of LRT applications, services and operations, planners in this country have not readily perceived this mode's role in modern transit. Both planners and non-professionals are usually challenged when dealing with LRT as one of several candidate transit modes. As a step towards generalization and increasing the utility of the information available from European and North American installations of light rail, certain planning considerations can be stated.

ELEMENTS OF LIGHT RAIL TRANSIT PLANNING

Conventional transportation planning has always stressed travel time as the principal parameter for projecting the demand for transit. To obtain favorable transit travel times, systems featuring high speeds and stations located close to employment centers and easily accessible from residential areas have been proposed. Rail rapid transit lines were often the principal recommendation of the transportation planning studies carried out in the last 15 to 20 years. But often some transit corridors were identified in these studies and described as suitable for an "intermediate" mode with the attributes of rail rapid transit but with lower

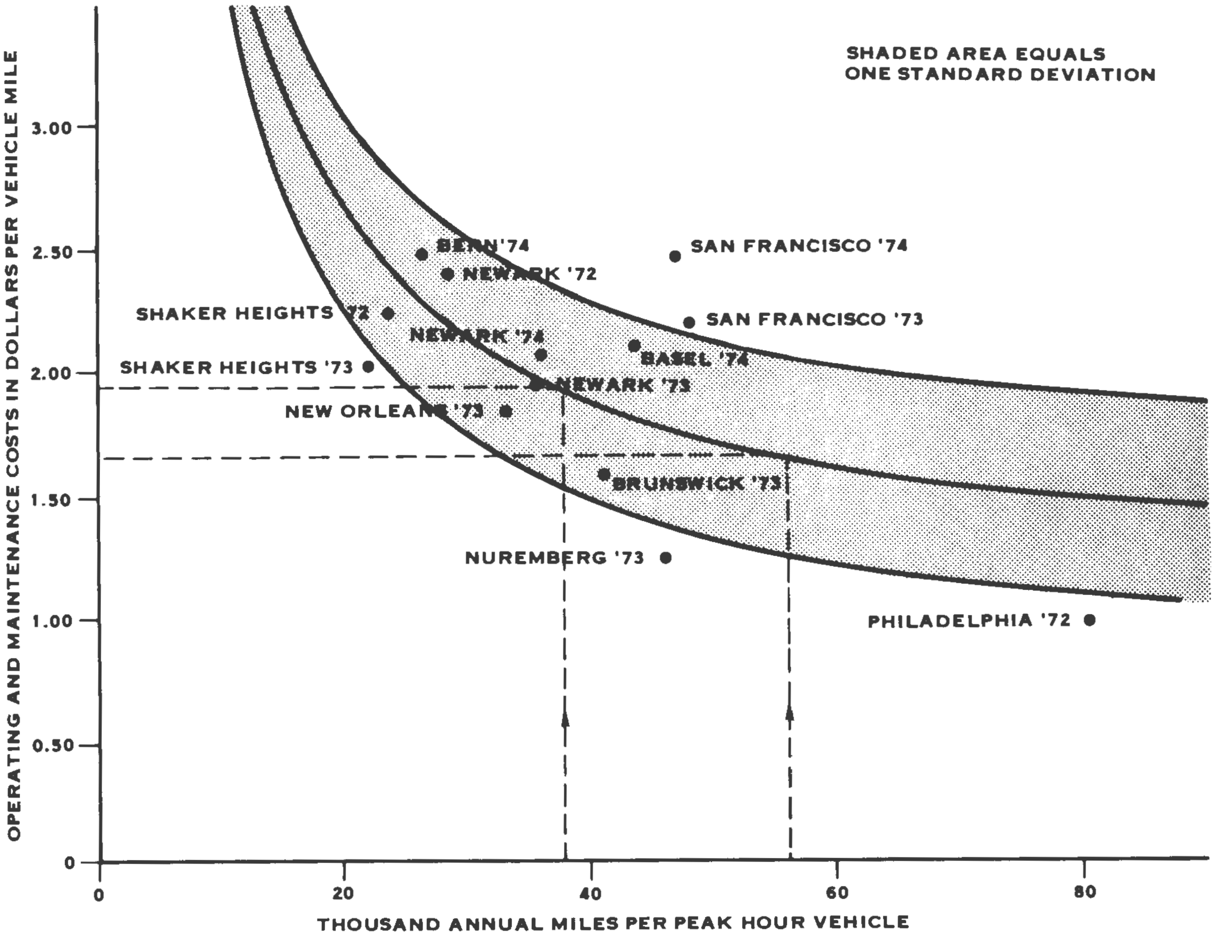


Figure 33. Relationship Between Vehicle Usage and Operating and Maintenance Costs*

*ALL COSTS ARE ADJUSTED TO 1974 DOLLARS.

capacity and with lower cost. As demonstrated in a number of cities in Western Europe during the last decade, LRT installations using fairly conventional technology embodied the characteristics of this so-called intermediate mode.

The advent of simplified transportation planning procedures in recent years has deemphasized the need to precisely define the alignments of fixed guideway transit alternatives. As a result, the simplified procedures have focused attention on issues of urban structure, land use planning, environmental and social impacts, financing and cost.

While total transit travel time remained an important factor in determining patronage, the effect of reductions in travel time through high operating speeds became better understood. It became clear that for low to moderate passenger volumes, the major capital investments normally required by fully grade separated rail rapid transit would be difficult to justify. This finding is significant with respect to potential LRT applications, and suggests that for systems designed to handle low to moderate passenger volumes, simple facilities and at-grade alignments are preferable. It also became apparent that significant advantages could accrue to transit investment if capital costs could be tailored to patronage estimates, and the system could be incrementally upgraded and extended as patronage increased in future years. These are requirements that closely match the attributes claimed for light rail transit.

While the basic attributes of light rail transit appear to fit the operating and investment requirements for a number of urban areas, prudent planning cannot assume that the implementation of LRT routes or networks will be a panacea for all transit problems. LRT is but one member of a family of transit modes that collectively forms an alternative to the automobile as other transit systems do. LRT has the capability to handle rush hour trips to the central business district (CBD) when the road system is saturated and difficult to expand. In addition, LRT operations can provide transit service for a multiplicity of other destinations and at times outside the peak periods. Also, adoption of LRT will usually require that other steps be taken to adjust and render compatible with the transit mode the operation of automotive and existing surface street transit.

NETWORK DESIGN CONSIDERATIONS

Recent work on the consumer response to transit characteristics suggests that an important variable influencing ridership is the availability of a multiplicity of convenient destinations, in addition to the central business district, which reflects the dispersion of trips in typical North American cities. To best serve the central business district, transit systems have often been designed in the shape of a number of unrelated radial routes, each oriented to a single corridor and focusing on the CBD. In the larger North American cities, good connectivity was the aim of bus operations on a grid system of routes. Often the grid system established clearly defined transit corridors on which implementation of LRT may be considered. However, the structure of the existing grid lines is less suitable to LRT applications as the distance from the BD increases.

One answer to improving area wide mobility while still serving the dominant CBD demand lies in combining elements of radial and grid systems into a "cobweb" with a limited number of nodes at which several of the routes come together. When the arrival of the various transit modes is coordinated at these nodes, transfer times can be minimized and these locations may become the centers of activities supported by the movement of transit riders. Such transit planning concepts are significant for LRT installations where the network may be conceptualized as an array of local or feeder routes complementing an array of line-haul routes interconnected at focal points and at the CBD. The modal point concept, also known as the "timed transfer focal point", has been used in several cities in Europe, such as Cologne and Munich, and in Canada at Edmonton, Victoria, Vancouver, Peterborough.

LRT APPLICATIONS

Light rail transit can and does fulfill many facets of transit operations. LRT installations may constitute the basic transit mode in cities. They may provide line-haul routes to and through the CBD or cross town. They may serve activity centers or provide circulation in the CBD, or they may be used for special applications. The starting point for the planner interested in the potential applications of LRT is to identify potential passenger volumes that can be combined with existing right-of-way opportunities in network configurations and offer an improvement over existing transit at an acceptable or affordable cost.

LRT as the Basic Mode (Medium and Some Large Cities)

The most common application of LRT is as the basic transit carrier in medium sized cities such as The Hague, Zurich, Cologne, Rotterdam, and Gothenburg. While the physical dimensions and population density of these cities are not very much different from those of older U.S. cities of similar size, there are considerable differences in their urban characteristics and those of younger U.S. cities, such as those in the southwestern part of the country. Generally, the requirements for transit in medium sized cities which made LRT a viable transit mode are improved speed, reliability of service, seating and riding comfort and greater line capacity than could be provided by ordinary bus service. In the medium sized cities, most typical LRT networks consist of diametrical routes, often with two or more branches in the outlying areas.

In some larger cities, such as Boston, Cleveland, San Francisco, Philadelphia, Rotterdam, Oslo, Prague, Budapest, Milan and Toronto, light rail and rail rapid transit operate in a complementary manner. LRT is used as a main carrier in corridors not served by rail rapid transit, as a high performance feeder to rail rapid lines, or as a surface carrier on more lightly traveled routes.

Light Rail Transit in Medium and Small Cities

In low density, medium sized and small cities, LRT is used in certain corridors more heavily traveled than those served by a complementary bus operations. Examples of this type of application are found at Geneva and Bern in Switzerland, Bielefeld in West Germany and Linz in Austria. In the U.S., the recently proposed LRT lines at Dayton and Rochester are also examples of this type of installation.

Light Rail Transit as a CBD Access Mode

LRT operating on radial or diametrical routes which terminate or go through the city center provide a connection between outlying areas and the CBD. Diametrical lines can usually provide better distribution in the CBD than can the radial lines and avoid the problem of stub and terminal operation in high density centers. Examples of radial alignments are the five LRT routes in San Francisco, the Shaker Heights Line, the Pittsburgh system and the subway/surface lines in Philadelphia. Diametrical lines include the north-south streetcar lines in Philadelphia, the east-west routes in Toronto, and a great majority of LRT routes in West European cities such as at Rotterdam, Dusseldorf, and Stuttgart.

LRT is a CBD circulation mode. LRT can be operated on CBD surface streets with mixed traffic, but the service is unsatisfactory in many ways. Most cities which use LRT in this manner are making efforts to upgrade operations. Two major procedures used for upgrading transit service are preferential treatment and grade separation. Preferential treatment on surface streets follows the approaches discussed elsewhere in this review.

Grade separation by placing the LRT in tunnel is found in a number of cities, such as Boston, San Francisco, Hannover, Stuttgart and Cologne. Elevated alignments will rarely be acceptable because of environmental concerns. Grade separation requires a substantial investment, causes major economic and traffic disruptions during construction, and makes the transit stations somewhat less accessible than they would be if located on surface streets. However, grade separation secures higher speeds and thus improves the performance of the whole network. Conflicts between automotive and pedestrian traffic are permanently eliminated. Finally, the further upgrading of LRT to rapid transit is made possible (pre-metro), particularly if that is planned from the beginning (e.g., Brussels).

LRT as a Feeder

Feeder services are a vital part of the LRT system. Where suitable low cost alignments are available, LRT can branch and provide its own collection/distribution service, as is done on Boston's Green Line network. In most cases, however, other modes provide feeder services to the LRT lines involving, of course, transfers. Other examples of LRT provide feeder service to rail rapid transit and regional rail as is done in Philadelphia, Rotterdam and Toronto, among others. LRT installations designed to provide feeder service of this kind require the existence of reasonably heavily traveled access corridors to the stations to be served, the availability of reserved rights-of-way, and an economic justification predicated on the higher speed and higher quality service offered by LRT in a minimum route length necessary to make the operation economically viable. Appropriate conditions of this kind exist in many American cities.

LRT as a Special Application

LRT can be used to provide collector/distributor services to major transit lines, parking lots, airports and other activity centers. Also, installations to provide tourist services and operations at pedestrian malls have been designed for LRT use. While some of these concepts may have potential use in U.S. cities, they are less significant for contemporary planning in the application of this mode to solve major urban transit problems.

COMPARISON OF LIGHT RAIL TRANSIT WITH OTHER MODES

Certain fundamental considerations dictate the scope and direction of analyses devoted to the comparative evaluation of transit modes. Among these are the physical characteristics of the area, the transportation infrastructure, the status of the existing transit services, and the nature of the demand to be served by the combined new and old transit systems. The systematic evaluation of transit alternatives has been identified by UMTA as one of the procedures that will guide future Federal decisions in determining an area's eligibility for Federal assistance for major fixed guideway investments.

COMPARISON OF PROPOSED LRT SYSTEMS

LRT installations have been proposed and evaluated recently at a number of metropolitan areas in the United States. The general system characteristics of the proposed LRT systems, such as length of route, number of stations and their spacing, service requirements and other operational factors vary greatly as shown in Table 7 for five evaluations recently completed. The service characteristics of the proposed systems also vary substantially as shown in Table 8. These tabulations show that the proposed systems are considerably different in many important characteristics, ranging from total line-haul route mileage to the proportion of guideway proposed on aerial structure or tunnel (at Buffalo an extensive tunnel structure is proposed) to projected daily passenger volumes. Significant differences in capital cost are also evident. On a per mile basis, costs range from $1.56 million at Dayton, which makes extensive use of at-grade operations on existing rail rights-of-way, to $32.6 million at Buffalo.

COMPARISON WITH OTHER MODES

Comparisons of some generalized modal characteristics can be made between LRT systems and other transit modes, but the comparative evaluation is more straightforward when the analysis can be restricted for a specific corridor. The recently completed evaluation of

Table 7. Comparison of System Characteristics of Light Rail System Alternatives Evaluated for U.S. Cities

	Pittsburgh Pennsylvania	Dayton Ohio	Denver Colorado	Buffalo New York	Los Angeles California
Total line-haul route miles	22.4	12.2	79.1	10.7	41
• Aerial (miles)	1.2	–	25.5	2.0	2.5
• At-grade; exclusive (miles)	16.2	11.3	50.7	1.2	26.5
• At-grade; on-street (miles)	3.5	0.9	–	–	–
• Tunnel (miles)	1.5	–	2.9	7.5	12.0
Number of stations	58	15	65	18	40
Average station spacing (miles)	0.4	0.8	1.2	0.6	1.0
Number of line-haul vehicles	167	48	230	92	225

Table 8. Comparison of Service Characteristics of Light Rail System Alternatives Evaluated for U.S. Cities

	Pittsburgh	Dayton	Denver	Buffalo	Los Angeles
Total line-haul route miles	22.4	12.2	79.1	10.7	41.0
Minimum headway in minutes	1	7	1	2	2
Daily line-haul trips in thousands	73.9	N/A	209.2	131.0	235
Daily line-haul trips per route mile	3300	N/A	2600	12,200	5,700
Daily line-haul vehicle mile in thousands	14.8	8.1	53.6	13.1	62.0
Daily line-haul vehicle miles per route mile	660	664	677	1224	1512
Average line-haul operating speeds in mph	16-22	N/A	21-35	26.5	31-39
Daily average passengers per vehicle mile	5.0	N/A	3.9	10.0	3.8

transit alternatives in the South Hills Corridor at Pittsburgh* provides data for four alternative transit modes in a fairly narrow corridor. Since routing, operational differences and the population served varied little between alternatives, the comparative evaluation of these four alternatives is significant, because the often confusing effects of site or routing specificity, usually associated with transit alternatives data, are neutralized. Specific and generalized comparative conclusions are, therefore, of some value to LRT evaluations at other sites as well.

For the specific conditions of the Pittsburgh study which evaluated LRT along with rail rapid transit, a bus option operating partially on exclusive guideway, and a rubber tired automated guideway transit (AGT) option with feeder services provided to all modes by conventional buses, the following comparative conclusions could be drawn.

Capital Costs

The bus alternative had the lowest cost due in large part to the partial at-grade operation of this system. Capital costs of the LRT are somewhat higher, but still are low in relation to the cost of rail rapid transit and AGT. Again, this is primarily the result of the extent of operations at-grade.

Operating and Maintenance Costs

While differences exist among modes for most O&M cost elements, the varying requirements of feeder service for each of the altneratives largely cancel the differences in average system costs as stated on a per vehicle mile basis. The differences that can be projected among the O&M costs for each of the four modes are small enough and of little consequence in determining their economic ranking modes.

Line-Haul Capacity

Capacity on the line-haul portion of route is determined by the combined influences of vehicle size, headways and train lengths. Using a liberal allowance of square footage per passenger to estimate the capacity of each vehicle, and headways considered to be within the state of the art of the guideway technologies, a wide range of capacities ranging from 8,000 to 40,000 passengers per hour can be estimated for the four modes. LRT projected capacities, assuming a maximum train consist of three cars and operation at 90 second headways, is estimated at 14,000 passengers per hour. This figure compares with 10,400 passengers projected for an express bus system using articulated vehicles operating at 30 second headways.

Average Scheduled Speeds

Light rail speeds vary from 16 to 22 miles per hour, while existing rail rapid transit systems operate at speeds in the range of 18 to 28 mph. Depending on the number of stops made, express buses operate in the range of 6 to 22 mph.

System Attraction

Relative productivity measures, such as annual riders per route mile or per vehicle mile, can be used to describe a system's attraction. The number of passengers per route mile is a surrogate for network coverage; in certain cases, higher numbers indicated coarser networks.

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*_Comparative Analysis Study of Alternative Transit Systems: South Hills Corridor_ (Chicago: De Leuw, Cather and Company), prepared for the Port Authority of Allegheny County, Pennsylvania, March, 1976.

The number of passengers per vehicle mile is an indicator of the relative productivity of the system. Statistics from a number of European cities for light rail, bus and rail rapid transit for European and U.S. cities indicate that the productivity of LRT compares favorably with that of the other modes.

Travel Time and Accessibility

Of the four modes evaluated, AGT and rail rapid transit provide the fastest travel time on the fixed guideway portion, but longer trips on the feeder system and the greatest number of intermodal transfers are required. For LRT, the travel times on the guideway are longer but fewer, shorter feeder trips are required. A higher percentage of riders walk to stations. The travel times are longest for the bus system, but this mode requires the least number of intermodal transfers.

Passenger Comfort and Convenience

Because of the ratio of seats to available floorspace for standees, the ratio of seated to standing passengers is highest in a bus even when fully loaded; however, of all modes, buses are least convenient to board. For LRT, the ratio of seated to standing passengers is somewhat lower. Rail rapid transit and *some* AGT vehicles have provisions for accommodating the lowest percentages of passengers in seats (i.e., provide the lowest ratio of seats to floorspace and can, therefore accommodate large numbers of passengers during peak hours); these modes also have the highest levels of convenience in boarding.

Transfers

Bus transit generally requires the lowest percentage of transfers, with LRT next in ascending order and AGT and rail rapid transit at the high end of the scale.

Service to Transit Dependents and Handicapped

The ability of a system to serve transit dependent groups can be described in terms of the walk-in coverage, ease of boarding the vehicle and provision for passenger accommodations in station design. In terms of walk-in coverage, buses provide the highest level of service to transit dependents because of their direct penetration into neighborhoods. LRT is somewhat inferior in that respect. Rail rapid transit provides the lowest level of direct access due to limitations in corridor coverage and greater distances between stations. From the standpoint of vehicle boarding ease, AGT and rail rapid transit provide the highest level of service, because handicapped can board directly from station platforms. LRT and bus alternatives are somewhat inferior in this respect, requiring special boarding facilities at an additional cost per vehicle. From the standpoint of station convenience, the AGT and rail rapid alternatives, requiring fully grade separated stations which have elevators and escalators, rank high in their ability to handle handicapped passengers conveniently. The LRT and bus alternatives, however, with their station platforms at street level, are more exposed to climatic variations and less convenient for aged and infirm persons.

Passenger Security

Rail rapid transit provides the best in-station security in an overall sense, because fewer stations are involved, and on new systems, security measures can be easily implemented. LRT and bus transit offer the best onboard security where operating policy and vehicle characteristics require that operators be present at all times.

Passenger Safety

AGT and rail rapid transit, because of their exclusive guideways, are safe systems. LRT's at-grade operations increase the risk of vehicle-to-vehicle and vehicle-fixed object collisions, but the effects may be mitigated by the lower speeds of this mode. From the point of view of *risk exposure,* which needs to be considered in vehicle-to-vehicle and vehicle-to-fixed object collisions, LRT vehicles would involve, on the average, fewer passengers than on a rail rapid train but probably more than on AGT or in bus transit. Therefore, the probability of injury or fatality may not be significantly different on LRT than on other guideway modes.

Potential for System Expansion

Bus transit provides the greatest potential for expansion of service within its service area. LRT has the greatest expansion potential beyond its immediate service area, while automated guideway and rail rapid transit systems would be the most difficult to expand because of lesser right-of-way opportunities and restrictions of at-grade operations.

Schedule Reliability

As a measure of a transit system's reliability, schedule reliability (i.e., the percentage of passengers completing trips on schedule) suggests that, at the current state of the art of the technology of LRT, rail rapid and bus transit, all modes are equally reliable.

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