LIGHT RAIL TRANSIT

A STATE OF THE ART REVIEW

DOT UT 50009

DEPARTMENT OF TRANSPORTATION
Urban Mass Transportation Administration
Office of Policy and Program Development
Washington DC 20590

SPRING 1976

NOTICE

NOTICE

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price $4.30

Stock No. 050-014-00010-0

Technical Report Documentation Page

1. Report No. DOT UT 50009	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Light Rail Transit: State of the Art Review	5. Report Date Spring 1976
	6. Performing Organization Code
7. Author(s) E.S. Diamant, et al	8. Performing Organization Report No.
9. Performing Organization Name and Address De Leuw, Cather & Company 165 West Wacker Drive Chicago, Illinois 60601	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. DOT UT 50009
12. Sponsoring Agency Name and Address Office of Policy and Program Development Urban Mass Transportation Administration U.S. Department of Transportation Washington, D.C. 20590	13. Type of Report and Period Covered Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

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.

17. Key Words Light rail transit, light rail vehicle, self-service fare collection, mixed traffic operations, semi-metro, pre-metro.	18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, Virginia 22151

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 311	22. Price

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

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

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.

Laurence A. Dondanville
Senior Vice President
De Leuw, Cather and Company

ACKNOWLEDGEMENT

This report has been prepared by De Leuw, Cather & Company for the Office of Policy and Program Development of the Urban Mass Transportation Administration, United States Department of Transportation. The report was prepared by a number of individuals on the staff of De Leuw, Cather & Company with the assistance of international experts in light rail transit. The authors wish to acknowledge the guidance and helpful review extended during the preparation of the report by the staff of the Office of Policy and Program Development and others in UMTA. In particular, the suggestions offered by Messrs. C. Kenneth Orski, Associate Administrator for Policy and Program Development, Jim Yu and Douglas Gerleman are gratefully acknowledged. Messrs. Joseph S. Silien and Jeffrey G. Mora of the Rail Technology Division, UMTA, and Mr. Robert L. Abrams of the Office of Capital Assistance, UMTA, made valuable comments at various stages of the writing of this report. Other UMTA personnel participated in the review of earlier drafts as well.

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.

Other reviewers include Messrs. Robert J. Halperin of Urban Transit Development Corporation, Canada; Doug Kelm, Kenneth P. Fletcher, E. Tennyson and Joseph A. Bosco. Their valuable suggestions are also gratefully acknowledged.

The complete list of contributors to this report is too long for inclusion in this acknowledgement. De Leuw, Cather & Company wishes to extend its appreciation to the following individuals who have helped prepare significant portions of this report: Drs. Vukan R. Vuchic and Brian F. Day of the University of Pennsylvania; Dr. Friedrich R. Lehner of West Germany; Mr. Tom E. Parkinson, Toronto; and Messrs. Thomas J. McGean and Charles P. Elms.

Many individuals on the staff of De Leuw, Cather & Company have contributed material and reviewed significant portions of this report including Dr. Emanuel S. Diamant, Project Manager; Messrs. Laurence A. Dondanville, Hugh T. Boyd, Donald W. Cather and Roy H. Anderson, members of the advisory board and Mr. Gerald D. Fox, Mr. David Morag, Dr. Robert S. Neilsen and Mr. Robert S. Scott, project staff members. Ms. Mary C. Kartman was responsible for editing and for the graphic design of this report. Her contributions are also gratefully acknowledged.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

CHAPTER 1

INTRODUCTION

The past ten years have seen a dramatic reorientation of urban transportation goals. New emphasis has been placed on the need for public transportation and the need to achieve a balance among urban transportation modes. Public policies have been promulgated which resulted in legislative and financial assistance to public transit operating agencies. Due to these developments and other factors, including the economics of operating private automobiles, real and threatened scarcities of natural resources, and environmental concerns, the long decline in transit usage appears to be halted, and modest patronage increases are being recorded.

At the same time, a dramatic expansion of the transit planning horizon has resulted. Transportation planners now recognize the prevalent transit modes of U.S. cities, i.e., bus and rail transit, may not be entirely adequate for the emerging transit needs of U.S. urban areas. Spurred by planning guidelines of the U.S. Department of Transportation, the appropriate roles of the various candidate modes are being evaluated in many metropolitan areas.

Many cities, encouraged by decisions to construct the BART system in San Francisco and the WMATA Metro system in Washington, D.C., and by new transit funding legislation, began planning fixed guideway transit systems. Recognizing that they did not always need nor could they always justify rail rapid transit of this type, some cities looked to fixed guideway transit alternatives of different capabilities and of lower costs which would not require the large capital investments of conventional rail rapid transit. Some interest centered on new transit which ranged from four to six passenger personal rapid transit vehicles to automated intermediate capacity transportation systems moving as many as 30 to 40 seated passengers per vehicle.

Yet as studies progressed in the late 1960s and early 1970s, it became obvious to most metropolitan areas that neither rail rapid transit nor the then available automated guideway transit provided a viable answer to their needs. The developmental experience of the rail rapid transit projects in progress indicated certain adverse environmental effects during and after construction. Rapidly escalating costs were resulting in unprecedented capital investments, often exceeding $40 million per mile. Early automated guideway systems illustrated that environmentally, their structures could deeply affect the community and that the costs of these facilities would be considerably higher than projected initially. Problems associated with technological development, deployment and operational testing added to the basic costs of structures and vehicles indicated that at least initially, costs for intermediate capacity automated guideway systems could run as high as $20 million per route mile. Many cities began to consider busways and all bus systems as alternatives to the high cost fixed guideway facilities. Yet for all bus systems, higher operating costs, downtown distribution problems, and the concern for the availability of fuel created a different set of problems.

At the same time in the early 1960s, several cities in West Germany opted for development of light rail systems rather than rail rapid transit of the type then being constructed in Hamburg, Munich and Berlin. Their experience illustrated that light rail transit offered a potentially attractive concept due to its adaptability to a variety of urban settings, its potentially lower costs, and its capability of staged implementation.

As a result, the potential role of light rail as a viable transit alternative for American cities began to attract the interest of planners. The recent West European experience showed that the few surviving systems in North America did not represent the full potential of the mode. An adequate equipment supplier industry did not exist, and there was little background of professional design experience necessary to conceptualize and implement new LRT systems in the contemporary urban settings of U.S. cities.

Consequently in 1972-73, 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. The first significant UMTA commitment to light rail transit came in 1972 when the U.S. Department of Transportation authorized a grant to develop joint light rail vehicle specifications for use in San Francisco and Boston. These were two of the eight American cities still operating light rail transit facilities. They were in the process of upgrading their systems and were in search of a new vehicle to replace their rapidly deteriorating PCC cars.

Further interest in light rail transit was stimulated by the adoption of alternatives analysis requirements as a condition of federal capital assistance to new rapid transit projects. Light rail became one of the candidate modes to be considered wherever appropriate.

The successful operational experience in Western Europe has been matched internationally by a growing appreciation of light rail as a mature transit mode. A surge of interest in LRT is evident from a number of developments. Recent planning studies have placed emphasis on light rail as a major candidate for urban transit, particularly in the U.S. where UMTA's alternative analysis requirements, as a condition of federal capital assistance, have provided the policy guidelines. Abroad, a number of LRT installations are in various stages of completion. Also, the recent first national conference on LRT, held in Philadelphia in the spring of 1975, attracted a record number of transit planners and operators. And yet, planning for light rail transit has suffered to date due to misconceptions about its potential transit function and its characteristics. The lack of comprehensive information for the evaluation of its capabilities and limitations, as well as the dubiousness often attached to descriptions of the mode's growing acceptance in Europe have impeded, to date, the full and unbiased assessment of LRT as a potential transit form for U.S. cities. As a step towards the elimination of these planning difficulties, a study of light rail transit for American cities was begun in 1975 for UMTA. The first assignment of that study was the preparation of this report containing a comprehensive overview of the available information on the operations, economics and technology of light rail transit.

POLICY STATEMENT ON LIGHT RAIL TRANSIT

To indicate its increasing concern that LRT be given adequate emphasis in the analysis of transit options and adoption of transit programs in various cities, the Urban Mass Transportation Administrator released, in December, 1975, a policy statement regarding federal support for light rail transit. Noting that no new light rail lines had been built in the United States in recent years, the Administrator announced UMTA's intended support of a light rail system deployment as an up-to-date demonstration. The Administrator stressed UMTA's policy not to prescribe light rail for any specific local area and to rely on comprehensive analysis of alternatives for the selection of deployment sites. The UMTA policy statement said in part:

> *During the past year light rail transit has come to be viewed as a serious alternative to buses and rapid transit in meeting the transportation needs of our metropolitan areas. Several cities with*

> *existing light rail systems are taking steps to modernize their vehicle fleets and upgrade service. A number of other cities are contemplating the possibility of introducing light rail to supplement existing bus service. However, no new light rail lines have been built in recent years in this country, with the result that capital and operating data on modern light rail technology is not available.*
>
> *In light of the growing interest in light rail transit and in answer to numerous requests the Urban Mass Transportation Administration is issuing this statement of policy in order to provide the clearest possible expression of its position toward light rail transit.*
>
> *UMTA considers light rail transit as a potentially attractive concept for many urban areas. The features that distinguish it most strongly from conventional rapid transit are the flexibility with which it can be adapted to a variety of urban settings, and its potentially lower cost. In congested downtown areas light rail transit can be operated in underground subways. In lower density areas it can be operated at grade in existing roadway medians, reserved freeway lanes, and in abandoned rail and other exclusive rights-of-way. At heavily traveled intersections and in busy arterials grade separation can be achieved through underpasses or elevated structures. However, with preemptive signals and barriers, surface grade crossings and operation in mixed traffic might be tolerated in some situations. Because much of the track can be built at surface level, the need for costly tunneling and elevated guideways can be minimized and substantial economies in capital expenditure can potentially be achieved.*
>
> *Light rail transit has also other merits. It is a technologically proven concept that requires no costly development program. It can be introduced into a community with a minimum of disruption and can be operated with minimum intrusion in residential areas. It may offer a capability for conversion to higher capacity service, thus allowing a city to match its initial investment to existing and near-term demand and to stage subsequent investment as and when it is required. Because light rail transit holds promise of an economic, versatile and environmentally attractive form of mass transportation, the Urban Mass Transportation Administration believes that it deserves serious consideration by localities bent on improving the quality of their transportation service...*

PURPOSE OF THIS REPORT

A fundamental objective of this report is to establish a common level of understanding of LRT among transit planners, community leaders, and decision-makers at various levels of government. In this report contemporary planning concepts of LRT are reviewed, and an outline is provided of the types of guideway, hardware and methods of operation of light rail systems. Specifically this report should lead to a better appreciation of:

- The developmental trends which caused the ubiquitous streetcars of the 1920s and 1930s to virtually disappear in some western countries, but to reappear in others in substantially modified technological form capable of providing transit services that match in performance the quality the best of other contemporary transit modes.

- The intrinsic physical and operational characteristics of light rail which distinguish it from its more primitive predecessors (streetcars) and the better known 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, which is the root of its potential attraction to American cities as a lower investment transit candidate with a potential for staged deployment.
- The range of transit applications for LRT covering not only a variety of urban transport requirements, but also the relationship between it and 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 and operating costs of light rail systems.

OUTLINE OF THE REPORT

The basic approach of this report is to consolidate the available information on LRT from European and North American experience. Descriptions of a number of relevant systems are presented, and those experiences which may be applicable in the U.S. are identified. Major factors influencing evolution of LRT in Europe and the United States are examined, as is the spectrum of applications open to LRT.

Descriptions and comparisons of LRT vehicles, stations and rights-of-way are presented with emphasis on the advantages and limitations of the various options. A general comparison of LRT operating characteristics is presented, including speed, reliability, capacity, safety, selected environmental impacts, energy consumption, and compatibility with other transit modes. Operating and management techniques used to upgrade LRT and improve efficiency and quality of service are examined.

The costs of implementing LRT systems, both capital and operating, are identified. Particular attention is given to the capital cost consequences of alternative operating and right-of-way strategies, because they greatly affect the total cost per route mile. A comparison of LRT operating characteristics and costs with those of other modes is presented.

DEFINITIONS AND TERMINOLOGY

In recent years, light rail transit has been well publicized and the subject of much discussion in professional circles. Yet concepts and terminology relating to LRT are often imprecise or even incorrectly used. Questions often asked are what is distinctive about LRT compared to other rail transit modes and what is "light" about light rail transit. Definitions in this section are presented to clarify these issues and reduce misunderstandings of what constitutes different transit mode concepts. These definitions also provide a consistent terminology for the topics covered in this report.

DEFINITION OF MODES

Clarification of what constitutes a transit mode is particularly important in addressing light rail transit. A transit mode cannot be defined solely by its vehicle technology. A full definition must include a right-of-way classification, descriptions of the type of service and operation provided, and a statement of the technology employed. For example, the term *bus* does not adequately describe a transit mode. The term *express bus* defines the vehicle and the type of operation. However, the term *express bus on exclusive right-of-way* provides a complete definition of the mode, distinguishing it from surface bus, feeder bus, shuttle bus, and other forms of bus transportation. Similarly *rail transit* is not a sufficient description of all rail modes without further definition of the type of right-of-way.

There is a tendency to equate light rail transit with streetcars, because the two modes use a similar vehicle technology. On the basis of the broader definition of modes, light rail can be shown to be a separate and distinct mode which can function as a streetcar (on surface streets in mixed traffic) when circumstances require it.

RIGHT-OF-WAY CLASSIFICATION

Although a broad range of transit rights-of-way are used by various transit modes, they can be defined in three major categories. Exceptions to these categories may be found. These exceptions, however, should not change the rule.

- Category A – Fully controlled grade separated right-of-way, also referred to as *exclusive, private,* or *separated.* Such rights-of-way are without street running, and do not have at-grade vehicular or pedestrian crossings. Rail rapid transit systems utilize this classification of right-of-way exclusively. Busways are also in this category.
- Category B – Partially controlled right-of-way, also referred to as *semi-exclusive.* This class of right-of-way is partially separated from other traffic, but at some grade crossings and elsewhere, selective sharing of the right-of-way between modes may also exist, e.g., light rail/bus transit lanes or light rail/railroad or rail transit trackage. This category is very broad, encompassing facilities providing operations on street medians, on reserved transit lanes on streets, and on right-of-way with grade crossings. Examples of this category of right-of-way are on the Shaker Heights Line in Cleveland and the Media Line near Philadelphia.
- Category C – Surface streets with mixed traffic, also referred to as *shared.* The vast majority of bus routes in U.S. cities today and older streetcar systems operate on this class of right-of-way. Modes using this right-of-way category are known as surface transit modes.

Contrary to the widespread belief that vehicle technology is the basic feature of a transit mode, it is the right-of-way category which is usually the most important factor in determining transit system performance. There is evidence that the system's ability to attract passengers, its capacity, speed, and level of service are more closely associated with the degree of grade separation and access limitations than with the specific technology used. The different types of right-of-way have varying impacts and require significantly different investments. Systems operating on Category A rights-of-way have the greatest impact on urban form and land use. They also require the highest capital investment.

Buses operating on surface streets, as in Category C, represent the lowest level of operating service. They are not totally competitive with the automobile. Because they must stop to pick up passengers, they operate at slower speeds and attract fewer riders than systems operating on higher right-of-way categories. However, buses require the lowest capital investment, and they have the least impact on urban form and land use.

Transit modes operating on Category B right-of-way afford an opportunity to achieve a compromise between the lower capital cost and the lesser negative urban impact of the lower speed, *shared* right-of-way modes and the advantages of greater travel speed associated with grade separated, limited access modes. Transit operating on semi-exclusive rights-of-way with modern equipment can offer distinctly better performance than streetcars and buses operating on surface streets. Also, some of the higher capital costs and impacts associated with total grade separation can be minimized.

CLASSIFICATION OF RAIL MODES

Rail transit systems are classified primarily by typical right-of-way category and by a group of secondary features (such as power supply method or operating speed) which is influenced by right-of-way category. Table 1, which outlines these characteristics, shows that light rail can operate on all categories of right-of-way, and that LRT can achieve this at the cost of performance degradation which may be acceptable for many urban applications. The effective exploitation of this versatile use of right-of-way is the central issue in the development of light rail systems.

Light rail vehicles span the range between streetcars and rail rapid transit vehicles. In many cities, the same vehicles operate on streetcar as well as on light rail routes. The overlap between streetcars operating under right-of-way Category C and light rail systems operating under right-of-way Category B means that the boundary between the two modes is not sharp. Many streetcar systems are gradually being upgraded to LRT systems. Streetcar systems operating totally at grade in city streets are not LRT systems. However, an LRT system may operate on a streetcar type of right-of-way category in a lower operational mode over a part of its total route length.

Within the same LRT network, different segments may perform different functions, according to demand and the category of right-of-way. Yet the same vehicle can operate within the same system on feeder lines, express lines, and as a downtown distributor in a subway or at street level. On such a system, the quality and scale of the facilities and hence the level of expenditure may be varied according to need, thus avoiding the excess expenditure required for a mode which can only operate on an exclusive right-of-way. Because LRT can use a variety of rights-of-way, it can often penetrate areas where rail rapid transit would be unacceptable or unaffordable, providing a one-seat ride where other modes would require a transfer. A light rail network could therefore be constructed for less initial cost than an equal network requiring a more sophisticated right-of-way, or, for a given level of expenditure, greater network coverage can be obtained.

Some of the principal differences between light rail and rail rapid transit vehicles are features built into the former which make it more compatible with the flexible requirements of LRT operation. These features include high-low platform loading capacities, power through an overhead system combined at times with third rail, ability to operate on tighter radius curves, greater dependence on manual control, ability to stop in shorter distances, and ability to train or operate as single units.

Table 1. Technical and System Characteristics of Urban Rail Modes

	Light Rail Transit	Rail Rapid Transit	Regional Rail Transit
Fixed Facilities			
Right-of-way category	A, B or C	A only	A or B (occasionally)
Control	Visual/signal	Signal	Signal
Fare collection	On board/at station	At station	At station/on board
Power supply	Overhead/third rail	Overhead/third rail	Overhead/third rail or diesel
Stations: Platform height	Low or high level	High level	Low or high level
Access control	May be controlled	Fully controlled	Often controlled
Vehicle/Train Characteristics			
Minimum operational unit	1	1-2	1-2
Typical number of vehicles	2-4	2-10	2-10
Vehicle length (ft/m)	46-108/14-33	49-75/15-23	68-85/20-26
Vehicle capacity (seats/vehicle)	22-93	32-86	80-125
Vehicle capacity (total/vehicle) (for 2.7 ft^2 [0.25 m] per standee)	74-200	100-300	100-290
Operational Characteristics			
Operating speed (mph/kph)	10-30/15-45	15-40/25-60	20-45/30-70
Typical frequency peak hour, (per hour)	Up to 60	Up to 30	Up to 20
Capacity (passengers/hour)	Up to 20,000	Up to 40,000	10,000-40,000
Reliability	Moderate to high	High	High
System Aspects			
Network and area coverage	Good CBD coverage, branching capability	Predominantly radial, some CBD coverage	Radial, limited CBD coverage
Station spacing (ft/m)	800-2500/250-800	1600-6500/500-2000	4000-15,000/1200-4500
Average trip length	Short to long	Medium to long	Long (U.S. average: 22 miles [35 km])
Interface with other modes	Auto, pedestrian and bus feeders; can also feed other transit modes	Auto, pedestrian and bus feeders; can also feed other transit modes	Outlying: auto and bus feeders Center city: auto, pedestrian, bus, light rail and/or rail rapid transit

NOTE: Figures shown are based on existing systems.
The traditional form of streetcar operation is represented by the low end of the light rail transit performance spectrum.

Other differences relate to the right-of-way. Rail rapid transit systems are restricted to Category A right-of-way. But light rail transit may operate in the rapid transit right-of-way category over a part of its total route length. Operationally, the two modes can be fully compatible as at Frankfurt, and on the Cleveland transit system.

While the fully controlled, grade separated right-of-way provides the best environment for any transportation mode, it is costly and disruptive. New transit systems deployed exclusively on Category A right-of-way are, consequently, likely to be limited in extent, requiring substantial secondary feeders. However, where Category A right-of-way is available and does not require the construction of expensive guideway or station facilities, rail rapid transit would be cost competitive with light rail. The selection of the rail rapid mode forecloses the option of future system expansion on Category B or even Category C right-of-way. On the other hand, under favorable physical and economic circumstances, it might be possible to upgrade a system of Category B or C right-of-way to Category A if, for instance, very high capacity or speed became necessary.

Under certain circumstances, light rail can be upgraded incrementally. Consequently, the initial system may be built without excess capacity. Moreover, since the system may be upgraded as a response to bottlenecks, alternative segments may be upgraded or extended if system growth does not follow projections.

An LRT network may also be expanded incrementally, and at a different standard than the original system. Development programs can then be fully responsive to future capacity requirements, funding constraints, or planning goals. By contrast, a rail rapid transit system can be expanded only at the costly high standard of the original network, regardless of demand.

DEFINITION OF LIGHT RAIL TRANSIT

The preceding discussion of mode components and characteristics establishes the framework to define light rail transit. LRT is more than a vehicle technology. It is a mode combining vehicle technology very similar to that of streetcars, but operating primarily on a partially controlled right-of-way.

The distinguishing feature of the light rail concept is its provision to operate safely and effectively through at-grade conflict points. While acceptable standards of safety and effectiveness may vary from application to application, it is this provision which determines if a rail transit system should be classed as light rail. Most of the features commonly identified with light rail are also found on other modes, such as low platforms, short trains or electric operation. The central issues in light rail planning are the implications and opportunities arising from the mode's at-grade capabilities and the technology and right-of-way designs which have evolved to exploit this feature of light rail to the fullest.

A rail transit system which is fully grade separated can at times be described as light rail if its technology and method of operation make it capable of operating at grade. This situation could occur on a new system if the first line of the system was the most heavily patronized, was in the most congested location, or was a line requiring unusually high operating speeds. Such a line might well be constructed partially or completely grade separated. Nevertheless, the mode would be classified as light rail if such a system retained the capability to be extended at grade where appropriate.

Fully automated rail transit systems exclude light rail. Some automation on selected segments of a light rail network, such as in subway, would not necessarily prevent other segments from functioning as light rail, but it is unlikely that automatically operated trains and light rail trains under manual control would operate on the same network.

A simple, clear statement of light rail transit's characteristics is found in the definition adopted in the spring of 1976 by the Transportation Research Board Committee on Light Rail Transit:

> *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.*

RELATED DEFINITIONS

A number of additional terms in limited or common usage in the transit industry are used throughout this report to describe specific operational modes or implementation strategies.

- *Semi-metro* defines operations on rights-of-way that are separated from other traffic over most of the route. Most light rail transit systems fall into this category; the systems at San Francisco, Boston, Hannover, and Frankfurt are examples of semi-metro operation.
- *Pre-metro* defines light rail systems designed to permit eventual upgrading to rapid transit standards without excessive cost or effort. Several systems in Europe are planned as transitional development of an eventual rapid transit system. Certain design features distinguish these systems from semi-metro or conventional light rail transit systems, e.g., greater radii of curvature, lesser grades, provisions for later adjustment of station platform heights to conventional rapid transit levels, and provisions for installation of power distribution and control systems suitable to rail rapid operations. This concept was particularly popular in Europe in the 1960s, before the development of the present generation of light rail vehicles and the current re-evaluation of transit priorities. Many light rail lines, such as Shaker Heights in Cleveland, parts of the Green Line in Boston, and San Francisco's Twin Peaks Tunnel, were originally built to pre-metro standards. Brussels is developing a rail rapid subway system using the pre-metro principle.

TERMINOLOGY USED IN OTHER COUNTRIES

The terms ***streetcar, light rail transit*** and ***rail rapid transit*** are used throughout this report to define alternative rail transit modes. These terms are commonly used in the United States. Terminology which is commonly used in other countries may be used in this report to define specific systems in those countries.

- *Street metro* has been used primarily by British planners to describe a modern streetcar system. This system uses new light rail vehicles, modern crossing protection and traffic signal preemption techniques.
- *Tram* or *tramway* is used in Great Britain, Australia and several other Commonwealth countries to describe conventional streetcar systems. The term is also applied to some systems which operate partially or totally on exclusive rights-of-way and might be defined as light rail systems. *Modern* or *rapid tramway* is used to define systems that have been substantially upgraded and improved since World War II.
- *Underground* and *underground railway* are used to define rail rapid transit systems in Great Britain and several other countries. These systems operate predominantly on exclusive rights-of-way; the terminology is synonymous with rail rapid transit in the United States.
- The terms *semi-metro* and *pre-metro* are used in French speaking countries to denote the same light rail applications as cited before. In France, the term *metro leger* is also used to describe light rail transit.
- *Metro* is synonymous with the term rail rapid transit applied to fully grade separated, limited access transit facilities in the United States. Several transportation agencies in other parts of the world have recently adopted the term *metro* to describe their rapid transit systems.
- *Stadtbahn* is a German word meaning city railway. The term is used to describe a locally owned rail transit system which may be light rail or rail rapid. If the stadtbahn is light rail, high performance is implied. The engineering standards associated with this term vary from city to city. The Rhein Ruhr Stadtbahn was planned to be fully grade separated, while other cities use the term to describe conventional light rail systems.
- *U-Bahn* is applied to all underground rail transit in Germany, whether rapid or light rail. The common belief that this term is synonymous with rail rapid has led to the false classification of some light rail subway operations. Light rail U-Bahn exists in Frankfurt, Cologne, Bonn, Hannover, Stuttgart. In Munich, Berlin, Nuremberg and Hamburg the U-Bahn is rail rapid.
- *S-Bahn* is used to define the regional rail systems operated by the German Federal Railways.

CHAPTER 2

INTERNATIONAL TRENDS IN THE EVOLUTION OF LIGHT RAIL TRANSIT

Most of the recent developments in light rail have taken place outside the United States. The motivations and planning processes which led to adoption of light rail transit in some countries but not in others form the essential background against which policies may be formulated regarding this mode's role in American cities.

Prior international developments span several decades and have taken place mostly in West European countries, but are also found elsewhere. In this chapter, they are not reviewed exhaustively. Rather, emphasis is placed on the attitudes toward light rail and other transit modes; the origins of these attitudes; the actions which followed; and their consequences, particularly the present role played by different combinations of transit modes in various cities.

This review has been confined to countries in Western Europe, the United States and Canada which share broadly similar social, economic and political systems. The time period relevant to the present conditions is mostly since the World War II. Special attention is given to the most recent changes in attitudes toward urban transportation, dating mostly since the early seventies, due to their direct effect on the current role of transit in cities of interest in this study.

IMPACT OF INCREASING AUTO OWNERSHIP ON TRANSIT

No interpretation of U.S. or international transit trends is complete without acknowledging the single most important urban transportation development of this century: the automobile. The widespread introduction of private automobiles created an alternative means of travel superior to transit for many types of trips. Large scale social and physical impacts attributable to this new mode were not felt initially. However, the impact on transit service was, in many cases rapid and severe. It resulted in decreased transit ridership and increased street congestion which paralyzes primarily streetcar operations. Buses also were affected by the impact, but to a lesser extent. Rapid transit running on grade separated rights-of-way felt the financial loss, but was not physically affected by congestion; thus it continued to offer high quality service more competitive to the private automobile.

The design of streets, intersections and the proliferating traffic controls did not provide any special treatment for streetcars. Their operation became both slow and unreliable. The mutual impediments to the movement of both streetcars and automobiles were harmful to both modes. Under these conditions, buses, which were both cheaper and more maneuverable in congested conditions, became the dominant mode. This trend was accelerated by improved bus technology; bus transit became an efficient, modern transit mode.

URBAN TRANSPORTATION POLICIES

In most U.S. cities, and in particular in the newer western and midwestern cities, accommodation of the automobile was a primary planning goal. Streets were widened and new arterials and numerous freeways were built, while large segments of urban land were dedicated to parking. In many U.S. cities, some initial efforts were begun to protect transit from congestion and give it preferential treatment. These policies were short lived. For a time in San Francisco, streetcars on Market Street actuated traffic signals at intersections, but that practice was abandoned. Protection of pedestrians near stops was often inadequate. In terms of consequences to the future of transit, the most serious changes took place where the original streetcar rights-of-way, which separated it from other traffic and were ideal for low investment upgrading of transit, were abandoned and paved over for street widening. Examples of this change can be found in Detroit, Washington, D.C., Philadelphia, Los Angeles and elsewhere.

Maximum accommodation of the rapidly increasing number of automobiles was the underlying planning policy in most U.S. cities, particularly during the 1950s and 1960s. This policy was reflected in the provisions encouraging the construction of urban freeway segments in the 1956 legislation for the Interstate System of Highways. The rethinking of urban transportation policies in the late 1960s and early 1970s came about only when the social, economic and environmental trends resulting from the unimodal orientation of the previous policies began to be questioned by planners and the public alike.

The trends and pressures in urban transportation in European countries were, to some extent, similar to those in the United States, although they took place at a later time period. The rapid increase in the number of automobiles which took place in the U.S. during the 1920s and 1930s, and then continued in the 1950s, could be observed in Europe during the 1950s and 1960s. Today the level of automobile ownership in the cities of several European countries, such as Sweden, West Germany, Great Britain and France, is not much lower than in U.S. cities. However, the urban transportation policies adopted by these countries have been markedly different.

Despite all the reservations that must be applied to making general statements about urban transportation policy, there is ample evidence to conclude that, to date, none of the European countries has made commitments to the accommodation of automobiles in urban areas comparable to that of the United States. The reasons for this difference are numerous, including the generally different character of cities and variations in economic and political forces. A heightened sense of historical value in European cities mitigates against the extensive modification of existing streets and other urban facilities for exclusive automobile use. But in retrospect, the differences are equally explained by the U.S. policies which provided ample financing for highways; stimulated construction of single family houses; and until the mid-1960s, did not significantly assist the maintenance and modernization of urban transit. European countries have developed somewhat different responses to the same pressures and problems. Significantly, the fact that attitudes and policies in European countries have been generally less favorable to the automobile than in the U.S. should not be interpreted to mean that they were all equally pro-transit. In fact, two quite different attitudes can be discerned among the various countries.

EUROPEAN POLICIES OF MINIMUM TRANSIT INVESTMENT

For a considerable number of years (1930-1960), several European countries, including France and Great Britain, made only limited investments in urban transportation. Their efforts to solve the growing problems of congestion and measures to improve mobility consisted mostly of the introduction of regulatory devices (one-way street patterns, traffic signals, protection of pedestrians, etc.) and parking controls. Transit investments were also minimal, often not adequate even to maintain or modernize rolling stock. Transit operators did not have the necessary cooperation and support of city governments and other public authorities to upgrade their major lines. The prevailing policies insisted that transit vehicles should be flexible to "blend" with other traffic and thus achieve the maximum uniformity of traffic flow. The fact that this blending resulted in decreased capacity, speed and reliability of transit was not recognized. In most cases this meant that streetcars, already in poor physical condition, had to be replaced by buses. In some cities, trolleybuses were introduced extensively during the 1930-1950 period, but later even they were replaced by buses. In Great Britain, where cities used trolleybuses at one time, the mode is now extinct. Trolleybuses are still used extensively in some countries, e.g., Spain, Switzerland, and Italy. The few separate rights-of-way for streetcars which had existed were usually absorbed into street widenings, similar to the developments in U.S. cities. Generally, streetcar operation was abandoned before the development of modern light rail.

The result of these changes was that the 1960s found most of the cities in Great Britain and France not only without rail systems, but without *any* transit on separate rights-of-way. While both London and Paris represent very special cases because of their extremely large size and their extensive rapid transit and regional rail networks, transit in other cities was generally unsatisfactory. Unable to compete with the private automobile in service quality, transit retained only captive riders who had no other means of travel, and passengers in cities where parking was limited.

By the 1960s, in the whole of Great Britain outside of London, there were only one subway route, in Glasgow, and commuter rail services in several cities. Apart from a transit oriented streetcar line in Blackpool, buses in mixed traffic provided the only other form of urban transit. Major transit improvement plans were almost nonexistent.

In France at the same time, except for the extensive Paris Metro system and several suburban railroads, single, modernized streetcar routes with some physical separation could be found only in the cities of St. Etienne and Marseille, and an interurban rail line in Lille. Virtually no other transit services could be found on separate rights-of-way; buses and some trolleybuses in mixed traffic became the only modes of urban transit.

In these countries at the time, there was little awareness of the need for measures necessary to upgrade the existing transit, as was clearly illustrated by a significant study of urban transportation undertaken in Great Britain in the post World War II period. In the early 1960s, the British government sponsored a comprehensive study led by Colin Buchanan and widely publicized its report, *Traffic in Towns*.[1] The report, which appeared in 1963, presented a more detailed analysis of urban transportation than any previous similar document in Great Britain. It marked a significant advance in the understanding of the relationship between traffic and cities and the related environmental issues. Buchanan's report took a positive stand with respect to public transport. It pointed out that transit is not only indispensable in cities for a number of categories of travel, but that it is socially and environmentally more advantageous than auto usage. However, the report fell short of suggesting specific measures which would assure transit the role the report recommended it should have. The report paid little attention to modes other than buses, and it failed to emphasize a basic condition for higher transit service quality: separation of transit from other traffic.

This report's lack of emphasis on the measures for the improvement of transit contributed to the lack of transit planning focus in British cities. On one hand, the absence of specific guidelines led to the development of premature plans for "advanced technology" systems, such as the monorail schemes at Leicester.[2] On the other hand, contemporary transportation studies for many urban areas called for drastic reorientation of priorities for public transport in the face of declining ridership. However, effective plans and activities to improve transit services generally failed to materialize.

EUROPEAN POLICIES OF PARALLEL HIGHWAY-TRANSIT IMPROVEMENT

Considerably different policies toward urban transportation were adopted in several other European countries, notably West Germany, the Netherlands, Belgium, Sweden, Switzerland and several others. In some countries, particularly West Germany, substantial investments were made in street improvements and the construction of new arterials and some freeways. However, the most marked differences between urban transportation policies of these countries and those of the United States, Britain and France lie in the attitudes, transit policies, and actual investments made for transit improvements. Developments in these countries, therefore, deserve a careful review.

At the end of World War II, many European cities were in a desperate condition. Destruction had affected not only buildings, but also most utilities as well as transit systems. Many Dutch, Polish and Yugoslav cities had streetcar tracks badly damaged; often only a few vehicles remained in operational condition. However, by far the heaviest destruction took place in German cities: entire sections of Stuttgart, Munich, Hamburg, Hannover, Cologne and many other cities were virtually flattened.

The level of destruction made it possible for the cities to rebuild in a modern form, eliminating old narrow, winding streets which had aggravated traffic congestion and other problems. Some cities preferred to retain their age old character and rebuilt accordingly while others, such as Hannover and Rotterdam, took considerable advantage of the reconstruction opportunity. The new start permitted not only changes in land use and urban form, but also the building of wide, modern streets and arterials. By the early 1950s, the increased number of automobiles was beginning to create a need to accommodate higher traffic volumes.

The auto ownership rate in West European countries lagged behind the U.S. rate by about 25 years. But starting roughly in 1955, concern over the appropriate roles of different modes became an increasingly important issue. As in the United States, an "ultimate" concept of a city fully adjusted to the automobile was discussed. The dominant opinion was then, and still is, that such a city is physically and economically impossible to build, and would be socially and environmentally undesirable. Moreover, it was recognized that high quality public transportation could provide a viable alternative to the automobile. This could be achieved only by physical separation of transit lines from surface traffic. In the late 1950s, well known journals stressed the need for and the importance of grade separation of transit for improved service and increased reliability. That principle was generally adopted in professional circles.

The transportation planning experience of U.S. cities was discussed and carefully analyzed. In 1957, a group of 15 German urban transportation experts visited the United States to observe developments in this area. Their reports, pointing out positive developments but warning against following major trends, such as the neglect of transit, were given full publicity in a special edition of the *Verkehr und Technik* journal.[3]

Although attempts were constantly made to provide separate areas for transit right-of-way, it was clear that the critical segments in the highly congested urban centers could not be grade separated without investments larger than transit agencies and city governments could afford. To thoroughly study these issues and to find the best method for financing urban transportation, the West German government established in 1961 a special 23 member Committee of Experts. It was chartered to study the transportation problems of urban areas and to formulate policies for their improvement. Members of the committee represented experts from professional and academic circles, covering all areas of urban transportation, highway and transit systems, planning and operations.

In its report, the Committee of Experts presented a review and analysis of urban transportation and its interrelationship with other urban functions.[4] Similar to Buchanan's report, the impacts on urban form and environment were pointed out. However, unlike Buchanan, the Committee made specific recommendations for policies and physical design solutions. These suggestions were made possible, in part, by a fairly broad consensus on general policies, and the existence of actual physical plans for improvements in many German cities.

The report of the Committee of Experts represented a landmark of postwar urban transportation in West Germany. Although it basically consolidated and reconfirmed the thinking and actions which had already been prevalent, the report was also noteworthy, because it estimated the financial needs required to implement the measures it suggested. It proposed a financing method 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.

In accepting the report, the West German federal government acknowledged its joint responsibility in solving urban transportation problems. It introduced by legislative act an increase in gasoline tax (initially 0.03 DM/liter or 5% of its price, later increased to 0.06 DM/liter) which provided the financial means for construction of urban transportation facilities. The funds were initially allocated in a ratio of 40:60 between transit facilities and streets/highways. The ratio was later changed to 50:50.

The federal government provided 60 percent of project financing whenever the cities could demonstrate that the remaining matching funds, amounting to 40 percent, were secured. The states accepted their financing share in the amount of 25 to 35 percent of the costs. The remaining 5 to 15 percent of the investment costs would be contributed by local governments. Eligible projects included acquisition of right-of-way, tunnels, viaducts, yards and shops, stations, park-and-ride facilities, etc. Facilities for all modes were included: regional rail operated by the German Federal Railways, rapid transit, light rail and buses. However, financing of vehicles was not covered.

This policy and financing process caused major changes in urban transportation. While the street and highway systems in West German cities appeared to be well designed, regulated and maintained, a program of impressive transit improvements was begun. By the early 1970s, some 15 cities were constructing regional rail, rail rapid transit and light rail facilities. In the Ruhr area, a large regional high-speed rail transit network was started, serving eight cities with populations between 300,000 and 800,000.

ATTITUDES TOWARD MASS TRANSIT MODES

Although the thrust of the funding policies was to hold the balance between public and private transportation, they also had a direct bearing on the selection of transit modes. The evolution of the modern light rail concept can be traced to these decisions.

Although the first transit services to be reestablished after the war were streetcars, the physical facilities, including tracks, vehicles and power supply, were in very poor shape in most of these countries, particularly in West Germany. Following a decade of virtually no investment in transit (1930s), there came the destruction of war. Until the early or mid-1950s, the emphasis in Belgium, the Netherlands, West Germany and East European countries was on the recovery of transit to provide basic services.

The conditions after the war were ripe to effect a change of transit mode without excessive loss of existing facilities. Changing modes would have been an easy option in severely damaged cities such as Rotterdam, Stuttgart, Munich, or some other German cities. Although buses were not produced in great numbers in Germany immediately after the war, a number of factories in Belgium (Miesse), France (Renault, Saviem, Berliet), Italy (FIAT, Alfa Romeo, Ansaldo) and other countries were manufacturing excellent buses and trolleybuses as early as the late 1940s.

The commitments to capital intensive modes were made in most cities during the 1950s, when new equipment for modernization and expansion of transit was ordered in significant amounts. Virtually all cities in West Germany, the Netherlands, Belgium, Sweden, Switzerland and Austria with populations in excess of 200,000 to 300,000 made the long-term decision to use rail systems as their basic transit mode. These cities also introduced bus routes, but primarily to operate on some of the lighter routes, to serve the developing suburbs, to operate as feeders to rail lines and to provide special (e.g., express) services. The heavily traveled lines, the "skeletons" of transit networks, remained the domain of rail modes. This policy was followed in the three largest Dutch cities (Amsterdam, Rotterdam and The Hague), in Belgium (Brussels, Ghent, Antwerp and others), in Italy (Milan, Torino and others), in Austria (Vienna, Graz, Linz, Innsbruck), in Sweden (Stockholm, Gothenburg), in Switzerland (Zurich, Basel, Bern), and in some 40 West German cities. In all of these urban areas, major renovations and modernization of rail systems began during the 1950s and accelerated during the 1960s and 1970s.

Modernization affected equipment and the networks, including the following major changes.

- Networks in inner cities were consolidated to fewer, but higher quality routes. Streetcar lines on many smaller streets were abandoned or replaced with buses; those on major arterials were upgraded to higher standards, mostly through separation from other traffic.
- Private rights-of-way for rail lines were provided wherever possible.
- Alignment standards were improved, station spacing increased, and special signalization introduced, resulting in higher speeds and line capacities.
- In some cities, the heaviest lines were replaced with fully grade separated rail rapid transit (Munich, Milan, Rotterdam, Hamburg).
- The technology of rails, switches and power supply were greatly improved, virtually eliminating vehicle sway, oscillation and noise.
- Large capacity, esthetically pleasing, high speed, quiet vehicles were introduced.
- Fare collection methods were modernized, speeding up the operations and significantly reducing labor requirements and operating costs.

Consequently, while the total length of rail lines and number of vehicles decreased, the available capacity increased due to the higher operating speeds and the larger capacity of the new, often 6- or 8-axle articulated vehicles. Today it is the dominant European practice to use 8-axle light rail vehicles with a capacity of between 200 and 300 persons operated only by the driver. Boarding/alighting is rapid, because self-service fare collection methods permit simultaneous use of all doors. Many smaller cities and towns had no need for transit operations on this scale; their streetcars were replaced by buses. Rural streetcar lines, once common in parts of Europe, were also replaced by bus operations.

THE COMMITMENT TO RAIL MODES

Selection of transit modes is a complex task influenced by many technical, economic, political and even emotional factors. There are many reasons why some countries replaced streetcars with buses while others not only retained, but upgraded and modernized them. Research suggests that the following factors had a major influence on the commitment to rail modes in such countries as West Germany, the Netherlands, Belgium, Switzerland, Italy and others.

- The cities' images of urban life styles and of the role of their public facilities was always very high. Even during the years of rapid increase in automobile ownership and enthusiasm for road construction, professionals and public authorities were pointing out the need for parallel improvements of both private and public transportation. The undesirable consequences of excessive reliance on private automobiles in medium and large cities were emphasized.
- The need for physical separation of transit from other traffic wherever physically and economically feasible was recognized as the basic requirement for competitive transit.
- For operation on separated rights-of-way, rail modes were considered to have a distinct advantage over nonguided modes. They projected a more positive image for passengers, offered greater comfort, faster trips, higher capacity and reliability, etc. Their cost, on the other hand, was thought to be competitive with buses once a separated right-of-way was provided.

Light rail was thought to offer significant advantages over buses in terms of:

- Better vehicle performance due to the characteristics of electric traction.
- Quieter, pollution-free operation;
- Higher labor productivity (two to three times more vehicle capacity-kilometers per driver than buses);
- Greater attraction of passengers, because rail tracks, even in the street without separation from other traffic, but particularly on separate rights-of-way, give a transit system a stronger image than road vehicles which blend with other traffic.

The inability of rail systems to serve extensive networks and low density routes was thought to be a disadvantage that could be overcome by converting certain routes to buses.

The decisions in cities like Paris, Berlin and Hamburg to eliminate streetcars rather than upgrade them to light rail service rested in part on the prior existence of rapid transit networks. The Paris Metro's system characteristics, such as the network density and layout, the station spacings, and the vehicle dynamics, are similar to those of a high quality light rail system placed mostly underground. The system was originally designed to fully replace streetcars, i.e., provide extensive area coverage. In Berlin and Hamburg, rapid transit was initially intended to be a higher type regional system, supported by surface transit. During the 1950s, a change in these systems' design principles was made. It was decided to greatly expand the density of rapid transit networks in each city and to decrease the station spacings. Thus, the systems would provide complete area coverage along the routes and obviate the need for a network of parallel supporting surface transit routes. Buses in these cities serve an extensive network of additional supplementary and feeder routes, but do not directly parallel the rapid transit lines.

POLICY CONSEQUENCES

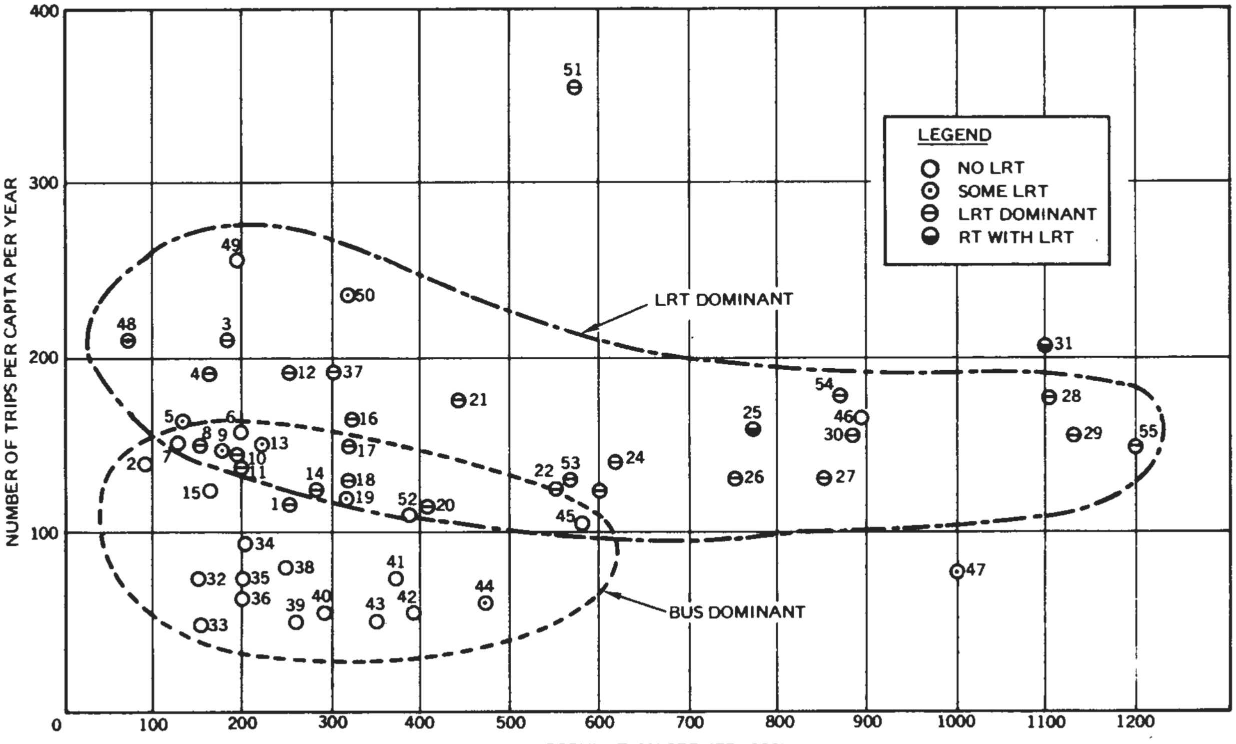
Ignoring for the moment a number of local conditions, such as size and coverage of the transit network, urban form, population density and automobile ownership rate, it can be hypothesized that an important indicator of how well a transit system serves a city is the riding habit (annual transit rides per capita). While the factors omitted must be considered in detailed comparisons of transit usage in different cities, some general observations of this indicator are quite interesting.

To compare the riding habit on different modes, a diagram of rides per capita as a function of city size has been plotted, for a number of West European cities, indicating which modes are major carriers in each city. The digram, shown in Figure 1, using early 1970s statistics, suggests a correlation between transit modes and riding habit. Cities utilizing rail modes (mostly medium size cities with light rail are shown in the diagram) show higher ridership (typically in the range between 120 and 250 rides per capita) than cities served by buses only (mostly between 50 and 150 annual rides per capita).

At first glance, other differences among localities do not appear to influence this correlation significantly. The population density of German cities is, if anything, lower than that of French cities due to post-war reconstruction of many areas. Automobile ownership in the two countries does not differ significantly; during the early 1970s, West Germany had 4.0 persons/car, France 3.6. Differences in topography and other local conditions are not likely to consistently bias the ridership in all cities using one mode in one direction only.

Consequently, it is apparent that Western European cities which improved transit by using separate rights-of-way and rail experienced 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. With few exceptions, American cities that rely on bus transit only show a very low level of ridership compared to that evidenced by European statistics. (In part, U.S. statistics are less precise, because the diffuse character of urban development in America makes it difficult to define the precise boundaries within which transit systems operate, and hence the population served.) The U.S. cities served by rail as well as bus transit show larger ridership statistics, but conclusions similar to those arrived at for European cities are more difficult to draw. At this writing, reliable data is only available for the older and well built up cities where the interplay between transit mode and other characteristics tends to obscure the apparent causal relationships noted in Western Europe.



SOURCES: REFERENCES 5, 6

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

EVOLUTION OF RAIL MODES

The initial proposals for grade separation of streetcars were to build tunnels in high density areas which would follow street alignments. Often this resulted in alignment standards which maintained short radius curves and allowed only small stations. A typical example is the tunnels on the Philadelphia subway/surface system. It is actually an "underground streetcar" system which avoids interference with surface traffic. However, in the tunnels, because of the alignment the speed of the streetcars is nearly as restricted as it is on the surface. The arguments used in debating the merits of this design concept are well-known.[7] Rapid transit offers a much better quality of service, but the investment cost is too high for most medium size cities; only very small rapid transit networks could be afforded. The trade-off is, therefore, between a more extensive network of light rail and the better service quality of rail rapid transit.

During the 1950s, several cities decided to build new rapid transit networks which would fully replace streetcars. These cities (Berlin, Hamburg, Stockholm) already had rather extensive networks of rapid transit and regional rail systems at the time this decision was made. Several other cities decided to build rail rapid transit in some major corridors, and to upgrade the rest of the streetcar network to light rail. Examples are Milan, Munich, Nuremberg and Rotterdam.

The most ambitious rapid transit plan was that adopted for the Ruhr region. The decrease of coal production had serious repercussions on the economy and employment in the region. To bolster the attractiveness of the region as a place to live and to improve mobility of the labor force, a high quality 300 km rapid transit system was planned which would connect the cities of Dusseldorf, Duisburg, Mulheim, Recklinghausen, Gelsenkirchen, Bochum, Essen and Dortmund.

In the 1960s and early 1970s, some changes in thinking and attitudes could be seen in a number of cities. Investment in planning and construction of grade separated lines included the upgrading of alignment, i.e., elimination of small radius curves and low capacity stations which were characteristic of streetcar lines. The concept of the underground streetcar was eventually superseded by the light rail (Stadtbahn) concept. At a somewhat higher investment cost, the light rail concept gained considerably in performance, often approaching rail rapid transit in quality. However, light rail retained a significant cost advantage, because it could operate without full grade separation on sections with little outside interference.

Another change was an extremely strong pressure in some cities to build not light rail, but "pure rapid transit" systems. While total orientation to rapid transit may be appropriate for cities of the size of Hamburg and Berlin, the concept was questionable for cities such as Oslo and Nuremburg with populations in the 400,000 to 500,000 range. Often overlooked was the fact that corridor volumes rather than city size should determine the mode.

The rail rapid orientation developed mainly due to three factors:

- The migration of senior transit officials from rail rapid cities such as Berlin and Hamburg to top positions in other cities helped to transplant the big city, rail rapid philosophy. However, the concept was less practical to smaller cities, because economic and physical conditions were different.

- European cities entered a period of rather easy access to construction funds with often inadequate comparative analysis of light rail and rail rapid transit.
- A strong desire to be "in fashion" was prevalent, causing competition among areas to achieve the status of "rapid transit" cities.

During the 1960s and 1970s, several cities like Dusseldorf, Cologne, Stuttgart and Hannover began to plan rail rapid transit systems, based on the pre-metro approach with light rail as a transitional mode. Even Ludwigshafen (pop. 180,000) and Bielefeld (pop. 170,000) declared that they were planning "pure" rail rapid transit lines.

Attitudes toward transit modes changed significantly since 1973. A certain reduction of many transit plans to a more realistic and economically justifiable scale is now underway in West German cities. This reduction was caused in part by the ebb of excessive optimism about the speed of construction of rapid transit systems, and by the reevaluation of available economic means in times of lowered economic expectations. Uncertainty over future growth projections and the desire to retain planning options underlined the advantages of light rail's versatility. Light rail appears to be dislocating rail rapid transit from the plans of cities like Bielefeld and Hannover. The Rhein-Ruhr system has also been modified. Instead of the initial concept of rapid transit, current plans are for a high quality light rail system coordinated with a regional rail service operated by the German Federal Railways.

Parallel events are occurring in other European countries, particularly in Switzerland, Holland, and Belgium. In Zurich, after two unsuccessful referenda for rail rapid transit, the city is now upgrading the light rail system. In Amsterdam, a rapid transit line is under construction, but no other lines will be built. The light rail system will be further improved and its network expanded. Under a 1975 policy decision by the Dutch Government, other cities such as Rotterdam, The Hague and Utrecht will also develop their light rail systems rather than rail rapid systems. In Brussels, the first pre-metro line will be converted to rail rapid operation in 1976, but further conversions have been postponed indefinitely. New light rail vehicles are being acquired to operate the other pre-metro lines.

The recent emphasis on environmental issues and preservation of the quality of life has had a marked effect on the attitudes toward urban environment and urban transportation. The elements of this philosophy are evident in:

- A strong concern for protection of the urban environment: control of air pollution and noise, improvements in urban form, amenities, historic preservation.
- Increased resistance to unchecked growth and the resulting conversion of medium size cities into super-cities with excessive dehumanizing effects.
- Emphasis on reorienting many CBD streets and areas to auto-free pedestrian malls which can incorporate transit.
- Strengthening of the pro-transit orientation of many local governments and of the population.

In many cases, LRT supports the implementation of this philosophy. It causes lesser environmental impacts than buses: lower noise and no air pollution. LRT can also be built faster, and in some cases, it has less impact on urban design than rail rapid transit. Several light rail lines in pedestrian malls have proved to be very successful (Kassel, Dusseldorf, Bremen, Amsterdam, Frankfurt, Mannheim, Zurich).

Changes in urban transportation policies are also taking place in Canada. Here too, increased emphasis is being placed on light rail. Construction of the new light rail system in Edmonton (originally planned as a rail rapid system); the planning of new routes in Toronto and new systems in Winnipeg, Vancouver and Calgary; and the design of a new light rail vehicle are manifestations of this new trend.

In recent years, interest in light rail has spread to countries which had never extensively used this mode, such as Great Britain, France, the United States, Japan and several third world countries. Numerous new systems are planned and some are under construction. In Britain, a new system is under construction at Newcastle, and others are planned. In France, eight cities are considering plans for light rail. In Japan, some cities may now follow the lead of Hiroshima to retain and upgrade their streetcar systems. Many cities in East Europe are developing sophisticated light rail operations.

CONCLUSIONS RELEVANT TO U.S. CITIES

Between 1900 and 1930, when transit in U.S. cities was using relatively fast, 4-axle streetcars and interurbans operated on some lines with maximum speeds of 60 to 70 mph, most European cities were still served by slower, smaller 2-axle streetcars. Some large, high speed vehicles were produced (e.g., the Italian Breda, Swiss Brown-Boveri, German AEG), but World War II found many German, French and other European cities without these modern vehicles.

The time lag between the increase in auto ownership in the United States and that in Europe and differences in urban conditions and planning practices led to the adoption of urban transportation policies in European countries considerably different from those in the U.S. Two basically different approaches to urban transportation developed in Europe. The consequences of those alternative policies have considerable significance to U.S. transportation planners.

The policies of minimum investment in urban transportation, generally followed in Great Britain and France, resulted in abandonment of rail systems during the post-war period before advances in rail transit technology and operational concepts were widely known. Most British and French cities never had modern rail transit systems. Their transit development since the 1930s followed trends similar to those in U.S. cities. However, a major difference existed in highway commitments. While the U.S. invested heavily in highways (particularly freeways) and parking facilities, the British and French cities made only limited investments. Thus, they suffer today from chronic congestion and inadequate operation of both private and public transportation.

In other West European countries, a policy of parallel improvements of both public and private urban transport was generally pursued; measures were taken to coordinate transportation in a rational manner. The effects of these policies are quite obvious today. Even medium size cities like Gothenburg, Cologne and Frankfurt have high speed, high capacity, light rail systems operating on extensive networks, largely independently from street traffic.

The differences between cities which pursued policies of minimum investment and those which pursued policies of parallel improvements are obvious. As a suggested indicator, riding habit expressed in transit ridership per capita shows that German, Dutch, Swiss and other cities which have been improving transit are considerably ahead of French cities which retained buses only in mixed traffic. The higher quality of transit service utilizing rail modes permitted not only very large cities like Berlin, Paris and London, but also medium cities to maintain *high transit ridership* and a *stable relationship between public and private transportation.*

Statistics from German transit operations indicate that the downward ridership trend was reversed in the early 1970s.[8] Actually most of the medium size cities which have reversed the downward trend of transit passengers are those cities which rely heavily on light rail, e.g., Zurich, Stuttgart, Frankfurt, Cologne, Rotterdam, Gothenburg and others. They have proved that balanced transportation is achievable, and that transit can play a major role in certain categories of travel even in cities with saturation level automobile ownerships. Auto ownership in most of these cities is comparable to that of U.S. cities.[9]

Cities utilizing light rail transit have generally developed a positive attitude to all aspects of transit: the quality of bus service was improved, vehicle comfort was increased, reserved lanes were added, shelters were built, etc. Many of these cities have adopted management procedures to increase the effectiveness of existing transit (system management), upgraded fare collection methods, developed intermodal transit federations and coordinated transit with land use planning.[10]

Certain policies seem to consistently underlie the successful deployment of light rail transit in the cities of Western Europe, which suggests that similar policies may be important to the development of the mode in the United States.

- The establishment of rational urban transportation policies which encompass *different modes of transit and automobile transportation* and relate them to other aspects of urban and land use planning are essential to solve urban transportation problems;

- The adopted *policies must be consistently pursued.* Most of the European cities which have achieved improvements in transportation have been following such policies for some 20 years and have achieved the result much more painlessly than cities which neglected improvements and then attempted to find an immediate solution.

- *Substantial investments in transit are necessary* to make transit service competitive with auto travel.

- *Physical separation of transit rights-of-way from other traffic* is the most important single factor in upgrading transit services.

- *Non-capital-intensive improvements of transit,* generally encompassed by the term, *transportation system management,* have been undertaken in parallel with developments of LRT. They are an indispensable element to achieve high quality transit service. However, these measures alone, without provision of modern transit modes and exclusive rights-of-way, may not be sufficient. Experience outside the U.S. shows that long- and short-term improvements are best applied simultaneously in a coordinated manner.

- The *retention of future options* is a basic feature of light rail which is attaining greater significance in an era of uncertain growth and economic prospects.

- Good solutions of urban transportation problems have been achieved by using several different modes. Light rail is an excellent *basic transit carrier* in medium and large cities, and has potential in special corridor situations.

Although substantially higher capacities are possible with modern LRT equipment, buses (and under certain conditions, trolleybuses) remain a vital supplementary need in such cities. On the other hand, light rail remains inferior and cannot be substituted for rapid transit in heavily traveled corridors in large cities.

CHAPTER 3

REPRESENTATIVE LIGHT RAIL SYSTEMS

In 1975, some 310 LRT systems with about 50,000 vehicles were in service throughout the world. These systems covered a range from unimproved streetcar operations to high performance networks having characteristics not dissimilar from rail rapid transit. In the U.S.S.R., over 100 LRT systems are in operation, including several new ones, generally of modern but conservative design. A further 80 systems operate in Western Europe and North America. The modern light rail concept has evolved in this group as a response to urban transit needs in highly automobile oriented and affluent societies.

DIVERSITY OF LRT SYSTEMS

A number of LRT systems worldwide are planning or are investing in new equipment and network improvements. Others have remained static. Among the latter are the few remaining unimproved streetcar systems (mostly in Eastern Europe or underdeveloped countries), and a few systems scheduled to be replaced by other modes. Almost all LRT systems in Western Europe and North America are now planning or engaged in improvement programs. Work has begun on several new systems, the extent of which is shown in Table 2. Although the systems listed are embarking on long-term improvement programs, they do not exhibit a consistent approach to LRT upgrading. The two principal approaches are adoption of high investment improvements with extensive subway and grade separation plans, and upgrading of LRT with low cost, low impact improvements, primarily by traffic control measures. The former approach is being pursued by most large West German and Belgian systems, new systems in England and Canada, and in San Francisco. The low impact approach is being used by the Dutch, Swedish, and Swiss systems, and smaller systems in West Germany. In the mid-1970s, a trend which became noticeable in Europe toward the development of low impact LRT improvements found its roots in the economic downturn, the renewed environmental concerns, and an increasing funding to facilitate transit operations in cities at the expense of the automobile.

SELECTION OF REPRESENTATIVE SYSTEMS

To demonstrate the variety of LRT developments in recent years and the issues that have influenced system planning, twelve systems have been selected for review. The twelve systems have not been chosen to provide a comprehensive technical compendium, but rather an interpretive description of significant developments in light rail. Sufficient background data is presented to place each system in perspective. An attempt has been made to balance representatives of old systems, evolving systems, and those now under construction by citing examples drawn from both Europe and North America. The wide range of approaches to the development of LRT in different cities and the versatility of the light rail concept are also demonstrated. The twelve systems have been grouped in categories arranged in order of increasing right-of-way quality, starting with systems in operation and ending with new systems currently under construction. The systems were selected for review for the reasons given below.

BASIC LIGHT RAIL SYSTEMS

Amsterdam has the largest Dutch LRT system, the primary transit mode in major Dutch cities. Its recent history, operation and future plans are typical of the pragmatic, low cost, low impact approach to LRT in the Netherlands.

Table 2. 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.

Geneva is representative of a number of cities which were implementing a long term program of replacing their inefficient and worn out streetcar systems with buses and trolleybuses. The development of new LRT technology, its new operating practices and the greater emphasis placed on high quality transit have caused a change of direction of this program towards light rail. The Geneva LRT system is now being upgraded and re-expanded.

Gothenburg was one of the first cities to adopt the low investment approach to LRT, pursuing a consistent policy of improvement for many years. Gothenburg's LRT system represents a level of performance which LRT systems might achieve in the future.

RAIL TRANSIT IN SMALL CITIES

Karlsruhe is a small city which decided to retain and modernize its LRT system some ten years ago, a time when such a policy was contrary to world transit trends. This policy has been well received in the community. A number of other smaller cities have since adopted similar programs.

THE PRE-METRO CONCEPT

Brussels' LRT system is the best developed example of the pre-metro concept, an approach to transit improvement pioneered by that city. The pre-metro program has been under implementation for over ten years. The importance of this concept, and its relevance in the light of more recent LRT development, makes the Brussels' system particularly significant.

SEMI-METROS

Boston was the first city to develop the streetcar subway concept. After years of decline and neglect, this system has now embarked on a major renewal program.

Cologne has one of the major innovative LRT systems in Europe. Its system contains within its network examples of the whole LRT range: sections of streetcar operation, multiline subway and planned high speed regional lines which will provide the fastest transit service in West Germany.

Frankfurt decided to develop its LRT system in the 1960s after an alternatives analysis which compared LRT with other modes. Frankfurt has now developed two LRT subways using two somewhat different variations of LRT technology. One of these has since been adopted for the Edmonton, Canada system.

Hannover is the most recent system to open an LRT subway. Originally planned as a rail rapid line, the Hannover subway is now operated by newly developed light rail vehicles (LRVs).

San Francisco, a leading example of the use of LRT technology in the U.S., is converting its streetcars into a modern system by building a subway downtown and replacing the existing streetcars with new light rail vehicles.

NEW LRT SYSTEMS

LRT is not confined to upgrading existing streetcar systems. In the past two years, work has begun on some entirely new systems. Two of these systems have been selected for review.

Edmonton has pursued a consistent transit development policy for the past decade. As patronage develops on trunk lines, an LRT system is to be constructed to improve service and decrease operating costs. Work began on the first line in 1974, with completion scheduled for 1978. The DuWag U2 car, developed for Frankfurt, is to be used in Edmonton.

Tyne & Wear at Newcastle, England also began construction in 1974 on the 34 mile first stage of a regional LRT network. The Tyne & Wear LRT technology incorporates worldwide developments; adoption of appropriate components was done selectively and was backed by an extensive testing program.

NETWORK COVERAGE

Some cities use LRT as their primary transit mode and operate "full coverage" systems. Others use light rail to meet a smaller portion of their transit needs. Without such distinction, network and operating data comparisons can be misleading. About half of the systems reviewed provide full coverage, while the others range from a single line to partial coverage networks.

AMSTERDAM – A BASIC LIGHT RAIL SYSTEM IN A MAJOR CITY

The development of LRT in the Netherlands has attracted much less attention than the more dramatic progress in West Germany. However, LRT forms the primary transit mode in the three largest Dutch cities, and a new LRT system is now to be built in Utrecht, the fourth largest city of the Netherlands. Government policy backs the development of LRT as the primary urban transit mode. Amsterdam has the largest Dutch LRT system; its development is typical of the pragmatic, low cost, low impact approach to LRT in the Netherlands.

CITY DESCRIPTION

Amsterdam, the largest city and commercial capital of the Netherlands, is a major seaport, connected by canals with the open sea some 20 miles to the west. The population of the Amsterdam region is approximately 1 million, and is relatively stable. The central city is formed around a series of concentric canals with narrow streets on both banks, and is served by only a few radial streets totally insufficient for the city's traffic needs. New highway construction has not been acceptable in this area, though the newer suburbs are served by a more adequate highway network.

TRANSIT IN AMSTERDAM

Transit services in Amsterdam are provided by the city owned Gemeentevervoerbedrijf (GVB) which operates a fleet of light rail vehicles and buses; by the Dutch Railways, which run a number of suburban services; and by several state owned bus companies, which provide regional service beyond the city transit network.

Each mode and system performs a particular role in the overall transit pattern with a minimum of duplication. The railways provide service to the outer suburban communities and to other cities in Holland and beyond. The regional buses provide a denser mesh of service than the railways in the area outside the city, but generally do not compete directly with rail. The LRT system provides service on the more heavily used radial and circumferential routes while city buses provide both feeder service and service on less frequently used lines.

The balance between transit modes in Amsterdam is best shown by their patronage statistics. (See Table 3.)

Table 3. Amsterdam Patronage Statistics

Daily Patronage	Route Number	Mode
50,000-40,000	1 and 3	LRT
30,000-25,000	10 and 13	LRT
25,000-20,000	2, 4, 7, 9 and 24	LRT
	15	Bus
20,000-15,000	16 and 25	LRT
Less than 15,000	17 and all remaining bus routes	LRT

Only one LRT route, No. 17, has less than 15,000 daily passengers. Only one bus route, No. 15, has more than 15,000 daily passengers. The conversion of this bus route to LRT operation is currently under study.

Table 4. Amsterdam Transit Statistics*

	LRT	Bus
Number of vehicles	215 8-axle, double articulation	422
Length of double track (miles/km)	96/155	
Annual passengers (million)	98	54
Annual vehicle – miles/km (million)	5.9/9.5	8.7/14
LRT network coverage – fully developed		
Community transit habit – 152 trips/capita/year		

*The transit statistics presented here are drawn from the data sources referenced, from correspondence with officials, and visits to the systems described. In some instances, it has been necessary to interpret and reconcile conflicting data.[11]

THE LIGHT RAIL SYSTEM

The Amsterdam light rail system shown in Figure 2 in common with most European systems, passed through a period of decline and network reduction during the 1950s. Streetcars were then considered out of date and a nuisance to traffic, and the equipment was old and unreliable. Most of the network cutback occurred on lightly used lines. It was not considered feasible to remove the streetcars in the central area, because the streets do not have sufficient capacity for large volumes of auto and bus traffic.

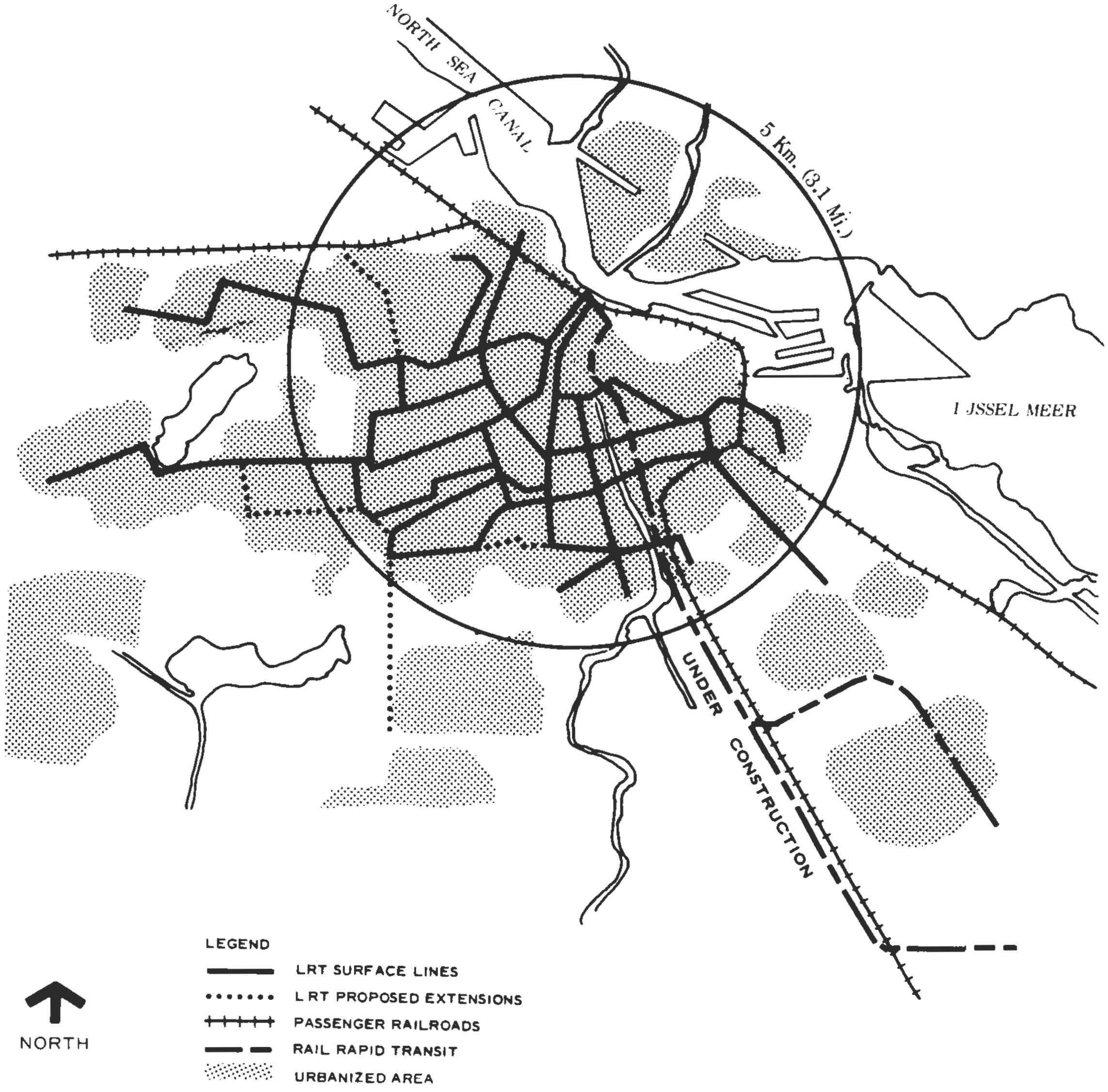


Figure 2. Amsterdam System

Eventually, it became necessary to begin a fleet replacement program. Articulated cars were introduced. Later, the self-service fare system was introduced, dramatically reducing operating cost and improving the quality of service. Public opinion became more favorable to LRT. In 1962, a line extension to the suburb of Osdorp was opened, replacing, in part, a line closed some years earlier. Meanwhile, the original six-axle articulated cars were converted to eight-axle cars, and a new eight-axle car design was ordered. The fleet renewal program still continues, with all except some peak hour trips being made with new 8-axle cars.

Meanwhile, Amsterdam adopted a long-range plan to build a rail rapid system to replace the LRT system. In 1973, construction began on the initial line to serve a corridor not covered by the LRT system. Amsterdam is a low lying city with a high water table and numerous canals; therefore, the construction of the subway portion of this line was both exceedingly costly and disruptive of the historic part of the city. Since 1972, the cost of the first line has doubled, to an estimated 815 million florins ($300 million). These factors led to major protests against the project, with the result that the City Council decided to abandon metro construction after the completion of the line now half built. Current city policy is to maximize the effective use of the LRT system by completing the fleet renewal program, by the selective application of traffic engineering techniques, and by implementing a program of line extensions and conversion of major bus routes.

The latest 8-axle cars, with 64 seats and a crush capacity of 213 persons, are manufactured by Linke-Hoffman-Busch in West Germany. The cars do not operate in trains. At first ticket machines were placed on the sidewalks, but had to be moved onto the cars to thwart vandalism. Cancelling machines are placed at all entrance doors on the car. The single ride fare is 35 cents, but a six ride ticket costs only 18 cents per trip. To further discourage cash fares, Amsterdam transit operators issue only round trip tickets at double the single fare.

PLANNING AND POLICY

The 1973-1974 oil embargo was particularly severe in Holland, and for several weeks, private automobiles were banned on Sundays. There were two lessons: electric transit was a valuable asset in an oil-short future; and the existing transit systems, buses and light rail vehicles were much more efficient when there was no other traffic.

The Dutch experience with rail rapid transit development had not been particularly satisfactory. The first line in the country, in Rotterdam, was constructed under the Maas river to replace a major LRT and traffic bottleneck. The original plan called for an LRT tunnel, but the project was expanded into a rail rapid line from the CBD into the southwest part of the city with considerable construction disruption and at major cost. The resulting patronage (around 8000 per hour, peak hour, peak direction) proved to be well within modern LRT capability. The Amsterdam rapid rail network was conceived at a time when the full potential of LRT was still not generally recognized, and was chosen as a project to bolster civic pride. As described earlier, the attitude of Amsterdam to its metro has changed.

Late in 1975, the Dutch Ministry of Transport announced a policy that all future rapid transit projects would be required to use light rail technology. A development of further interest is the implementation, on a nationwide scale, of a unified signal preemption, vehicle location and track switch operating system, known as Vetag, for the use of all light rail vehicles and buses in Holland (see Chapter 7).

The Amsterdam approach to LRT places emphasis on high quality service with a minimum of investment in construction. Thus, operational improvements are secured primarily by traffic engineering measures such as transit lanes (bus and LRT), pedestrian malls, and signal preemption, and the construction of any new lines grade separated from traffic by at least a median. Long-range plans call for little or no change in the system. The full potential of this approach to LRT is still uncertain, since it has little implementation history, and requires the acceptance of some traffic constraints for its optimum development. However, it is an alternative low cost LRT option with potential for wide application. Figures 3 and 4 illustrate two examples of the Amsterdam approach to LRT.

SIMILAR SYSTEMS

The policies and development of the Zurich LRT system are very similar to those of Amsterdam. (However in the Swiss city, a well organized and vocal automobile lobby fights against reserved transit lanes.) The Swiss community also has rejected plans for a rail rapid system, and the city now intends to develop its at-grade LRT system as the primary transit mode. Other similar LRT systems at Gothenburg and Bremen operate primarily at grade with extensive traffic-free network segments.

Figure 3. LRT Line in Amsterdam with Counter Flow Lane

Figure 4. Off Line Bus Stop on Amsterdam Transit Lane

GENEVA – STREETCAR ABANDONMENT REVERSED

The Geneva LRT is representative of a number of systems which were being gradually replaced by bus and trolleybus operations until recent increased emphasis on public transportation and improvements in LRT operations caused a reversal of the trend.

CITY DESCRIPTION

Geneva is one of the principal cities of Switzerland, with a population of almost 300,000. The total population of the surrounding metropolitan area is about 340,000. Geneva has the distinction of being the city with the highest level of car ownership in Europe: 370 autos per 1000 persons.

TRANSIT IN GENEVA

Switzerland is a country of limited natural resources. It does, however, have plentiful hydroelectric power. As a result, the Swiss government encourages the use of electricity for transportation. The Geneva transit system is run by the Compagnie Genevoise de Tramway Electrique (CGTE), which presently operates a mixed system of buses, trolleybuses, and streetcars. The transit network is essentially radial with two major circumferential routes.

Until the 1950s, the CGTE network was primarily a streetcar network, operating 15 routes within the city. In common with many other cities, Geneva embarked upon a streetcar replacement program in the 1950s, substituting buses and trolleybuses. The primary reason for replacing the streetcar network was its unfavorable performance compared with bus or trolleybus alternatives. For example, most of the routes were single track, located within narrow streets, and operated in mixed traffic with old small streetcars. Moreover, streetcar operations were considered interference to automobiles and other traffic. It was, therefore, a fairly typical case of a poorly built and ineffectively operated streetcar network being replaced by a relatively more efficient bus operation. By 1969, only one streetcar line was left in operation.

Fare collection in Geneva is based on the self-service system, with extensive use of sidewalk fare collection and ticket cancelling machines. Tickets may also be purchased at numerous shops in Geneva. The fare schedule is based on three circumferential zones and is fully coordinated between routes and modes. The operating deficit for 1974 was $6.25 million for the whole CGTE system. This deficit is funded by a subsidy from the canton of Geneva.

Table 5. Geneva Transit Statistics

	LRT	Bus
Number of vehicles	5 6-axle articulated 55 small cars	215
Length of double track (miles/km)	5.2/8.3	
Annual passengers (million)	18	56
Annual vehicle miles/km (millions)	1.4/2.2	5.2/8.4
LRT network coverage – 2 radial lines		
LRT right-of-way type – 43% reserved or better and 57% mixed traffic		
Community transit habit – 220 trips/capita/year		

THE LIGHT RAIL SYSTEM

Light rail in Geneva consists of a single line providing service in two radial corridors illustrated in Figure 5. This line, a remnant of the formerly extensive streetcar network, has been retained primarily because it carries almost 24 percent of the total CGTE transit patronage. Although the route is only 8.3 km in length, some 60 vehicles are used: 55 25-year old motor and trailer vehicles and five newer single articulated vehicles recently obtained secondhand. Patronage on the LRT route is steadily increasing, primarily because of its excellent location in relation to major trip generators: the French border crossing at Annemasse; the Geneva CBD, which includes an LRT pedestrian mall; and a major new employment center.

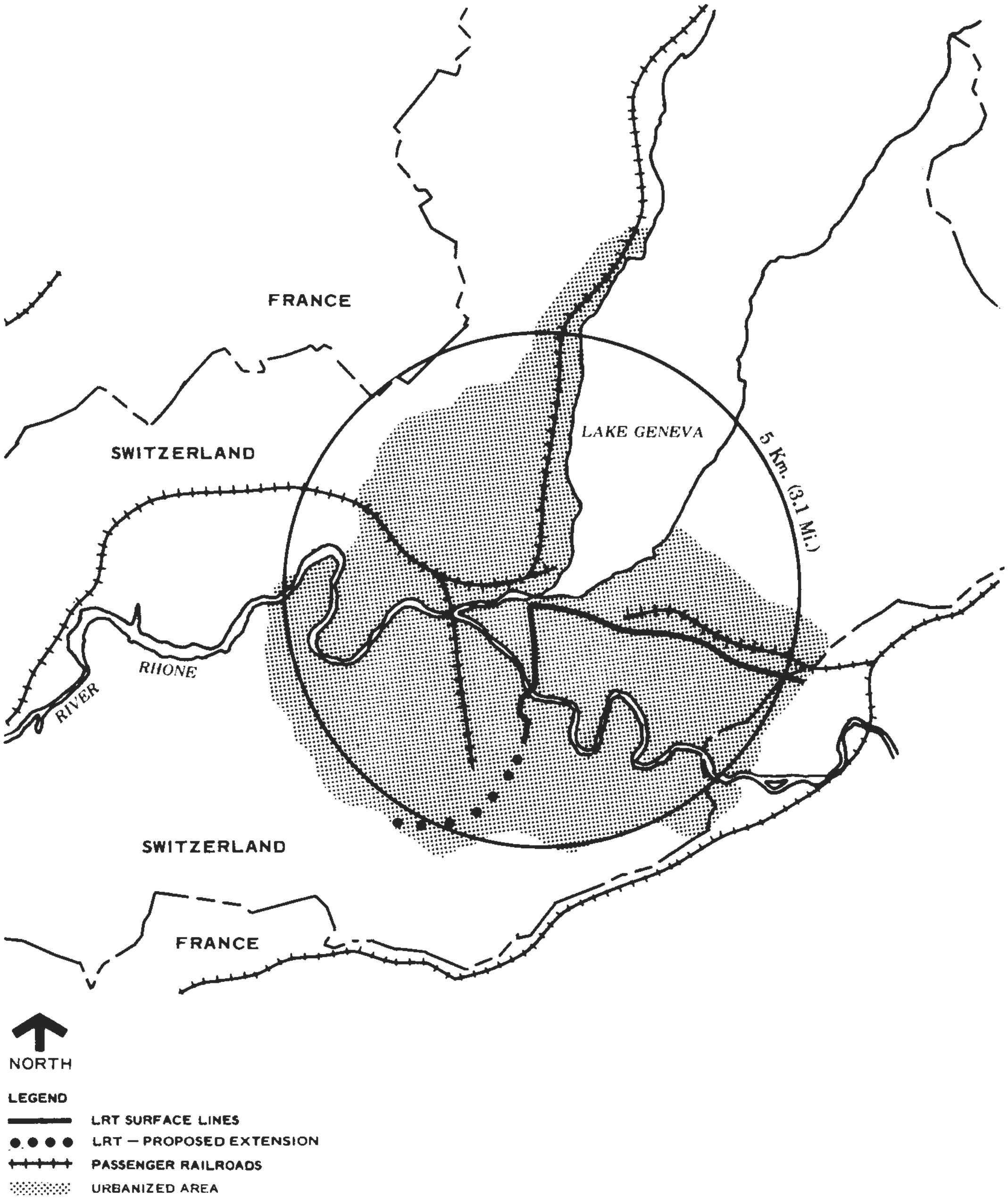


Figure 5. Geneva System

The arrival of the secondhand but modern equipment in 1975 was significant, because it emphasized the decision to re-equip the LRT system and continue its operation, a policy superseding the former trend to replace the streetcars. The primary significance of the Geneva system is not in its technical or operating sophistication, but rather in that it continues to exist at all. Since this line has survived until today's more favorable transit climate, it will now form the focal point of a light rail upgrading program.

PLANNING AND POLICIES

The CGTE has embarked on a long-term plan for the extension and improvement of transit in Geneva. A large part of this program is the purchase of additional buses and trolleybuses, mostly articulated, since buses provide most of the transit service there. New light rail lines, totaling almost ten km, will be constructed to replace bus operation in the most heavily used transit corridors, and the existing line will be upgraded to reserved right-of-way and double track throughout. In addition, a fleet of new vehicles will be acquired, probably of the 8-axle type now standard in Zurich, built by the Swiss manufacturer, SIG.

SIMILAR SYSTEMS

A number of cities which followed a long-term policy of streetcar replacement entered the 1970s with part of their streetcar system still in operation. By that time, the increased priority accorded to transit in most western cities, and the greatly improved light rail technology developed primarily in West Germany, caused a reappraisal of policies with regard to light rail operation. In most cases, this reappraisal led or is leading to new programs emphasizing the future role of light rail. In Europe, these cities include Brunswick, where a formerly extensive system was reduced to two routes some years ago and then expanded again. In 1975, Brunswick opened its fourth route and planned further extensions. In Mainz, two surviving routes are now being extended, and in Bremerhaven, the single surviving route has recently been re-equipped with new light rail vehicles. All three remaining systems in France at Lille, St. Etienne, and Marseilles also belong to this group of LRT. In the U.S., Newark, New Jersey, Shaker Heights/Cleveland, and Pittsburgh are considering the adoption of similar policies.

GOTHENBURG – HIGH PERFORMANCE LRT

The Gothenburg light rail system mixes high performance, exclusive right-of-way operation in suburban areas with operation on city streets in the central part of the city. It is a somewhat unusual system, because it is one of the few modernized light rail operations which still uses non-articulated, 4-axle cars, often in multiple unit operation.

CITY DESCRIPTION

Gothenburg is Sweden's second city and its largest port. It is situated on the west coast of Sweden at the entrance to the Gothenburg-Stockholm canal. The city population is about 450,000, while the total metropolitan region has a population of almost 700,000.

TRANSIT IN GOTHENBURG

Transit in Gothenburg is provided by Goteborgs Sparvagar (GS) which operates a mixed system of bus and light rail transit. The principal routes, and almost all transit in the central part of the city, are operated by light rail vehicles while buses are used both as feeders and on lightly used routes. The configuration of the light rail network is essentially radial, mostly on the south side of the Gota River.

Self-service fare collection was introduced in 1967, with tickets available either from machines or from the driver. Tickets purchased from the driver are more expensive. Fares are based on a simple, two-zone system. The whole light rail network is within the inner zone, except for part of one line. In 1974, the GS system operated at a deficit of $25 million, which was funded largely from the city-owned utility profits. A further subsidy was necessary from the city general fund to cover the deficit.

Table 6. Gothenburg Transit Statistics

	LRT	Bus
Number of vehicles	358 4-axle	283
Length of double track (miles/km)	46/74	
Annual passengers (millions)	60	28
Annual vehicle miles/km (millions)	9.2/14.8	7.8/12.6
LRT network coverage – fully developed		
LRT right-of-way type – 84% reserved 16% mixed traffic		
Community transit habit (city) – 190 trips/capita/year		

THE LIGHT RAIL SYSTEM

The Gothenburg light rail system, illustrated in Figure 6, has been expanded continually and improved throughout its more than 70 years of existence. In recent years, a new high speed line has been opened, which is currently the fastest light rail line in Europe.

The Gothenburg system is one of a decreasing number of light rail systems in Western Europe not using articulated vehicles. To match the operating economies obtainable with large vehicles, the GS system uses multiple unit operations, running two car trains system-wide (Figure 7), and up to four car trains on the new express line. The vehicles are constructed by the Swedish firm of ASEA.

PLANNING AND POLICIES

The Gothenburg system has avoided the construction of CBD subways and other high cost works, but some 85 percent of its lines is on reserved right-of-way. In the central part of the city, the LRT system operates at grade and in many cases forms the boundaries between traffic sectors, which private vehicles may not cross. The traffic sector system divides the central part of the city into five sectors or zones for purposes of automobile access. Drivers cannot cross from one sector to another except by returning to a ring road. In this manner,

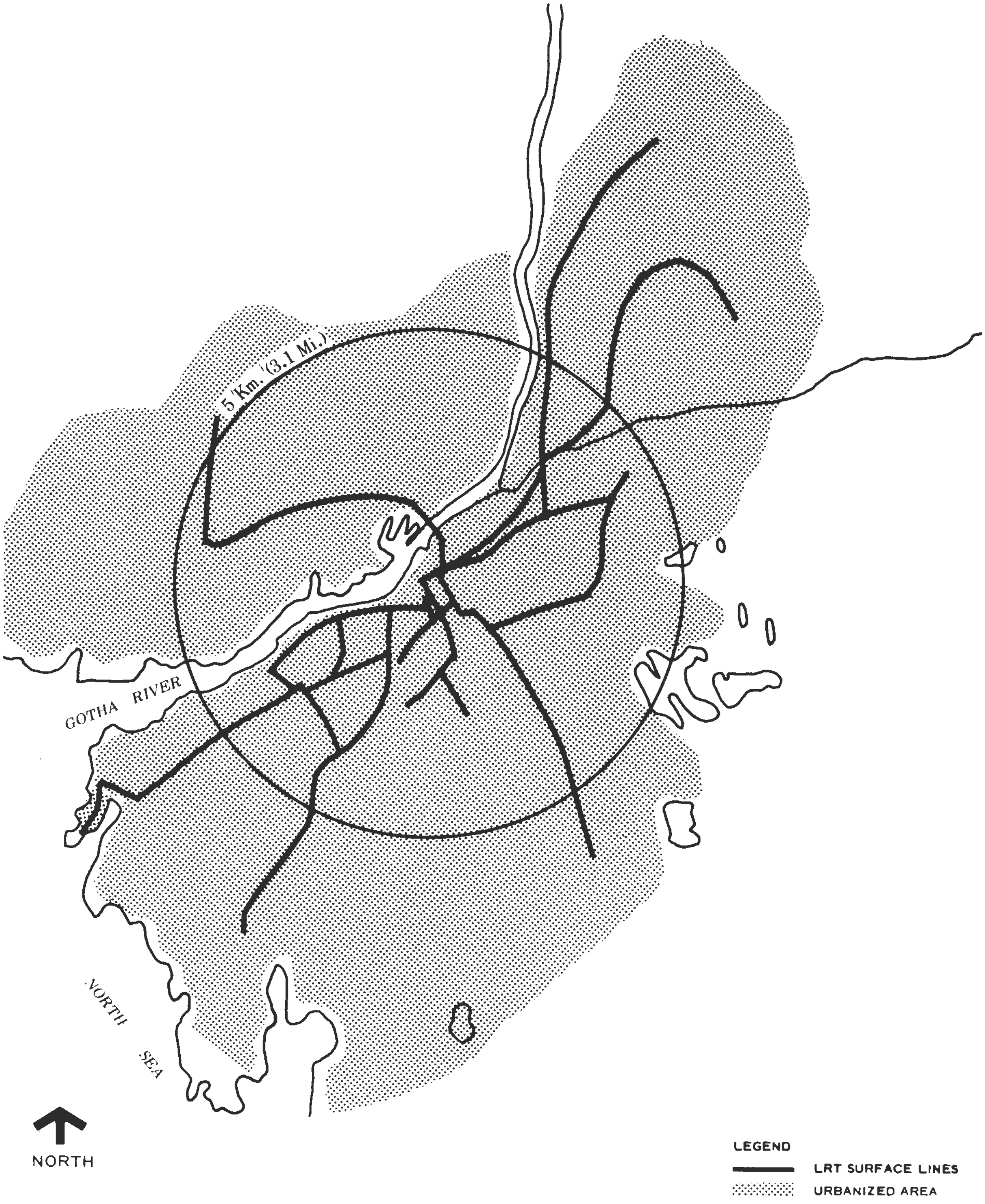


Figure 6. Gothenburg System

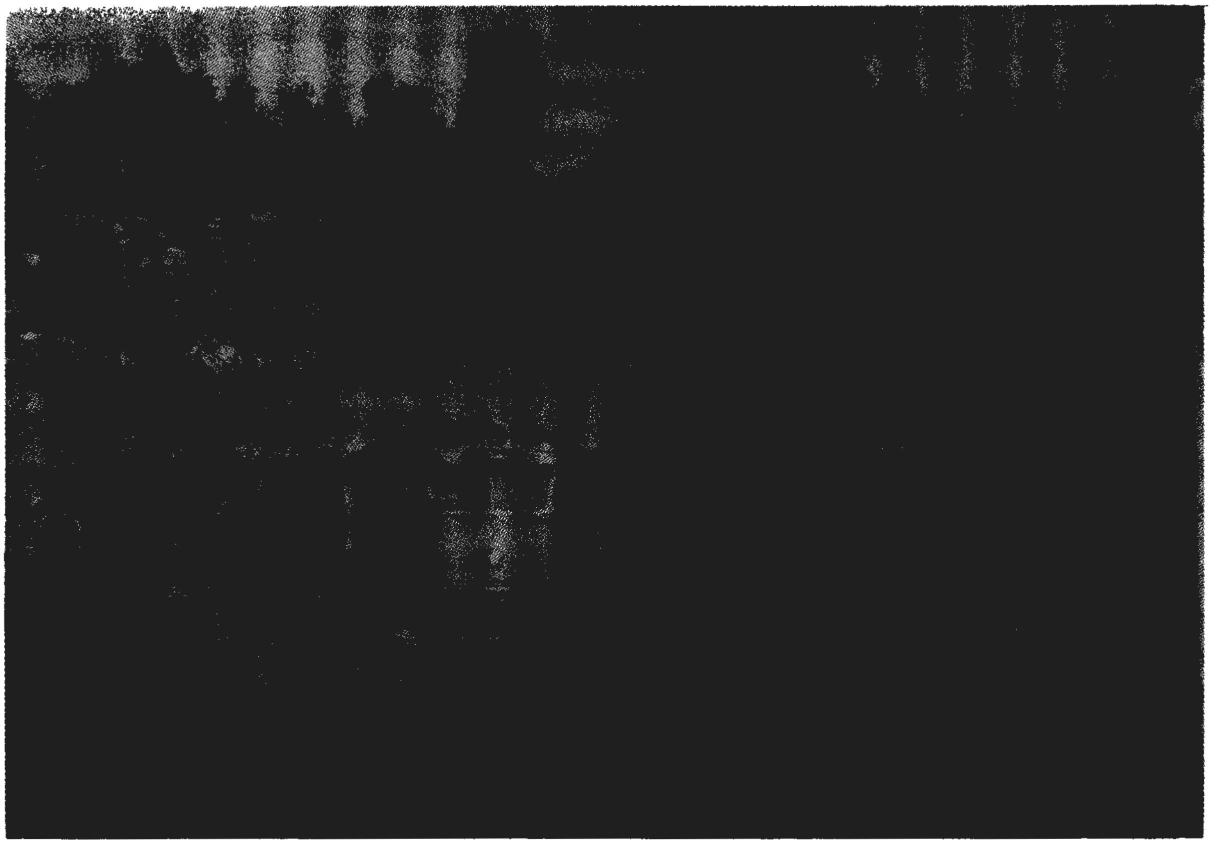


Figure 7. Two Car Train in Gothenburg

auto use in the city is much constrained without denying access to property. In addition, parking price and availability controls are used. To encourage transit use, pedestrian zones and facilities are being developed, and transit service improved.

Originally developed in Bremen, the use of traffic sectors has been adopted by a number of European cities as a traffic constraint measure. The use of the LRT routes in the central part of the city as sector boundaries virtually eliminates cross traffic, so that normal incentives for the construction of central area subways are much diminished. There is currently no plan for subways in the central part of Gothenburg.

Sweden has recently adopted a planning policy designed to de-emphasize growth in the major urban areas of the country including Gothenburg. As a result, by the year 2000, the population is not expected to greatly exceed the present level. Such a policy obviously has an important impact on transportation services, since it changes the emphasis from new works and expansion to improvement of the existing system. Future plans will, therefore, concentrate on service improvements such as reliability, reduction of operating costs, and further minimization of outside interference with light rail operations. Some limited network additions may also be anticipated, primarily through the conversion of major feeder bus routes to light rail operation.

SIMILAR SYSTEMS

Gothenburg may be considered as a highly developed, small city light rail system. Other cities pursuing policies of light rail improvement without subways or extensive grade separation, such as Bremen and Zurich, may ultimately reach Gothenburg's level of development.

KARLSRUHE – A SMALL CITY LRT SYSTEM

The Karlsruhe LRT system may be considered representative of a well developed, small city light rail system.

CITY DESCRIPTION

The city of Karlsruhe lies between the River Rhine and the Black Forest, near the French border. The city population is approximately 270,000 but a total of almost 360,000 live within the transit service area. Formerly the capital of one of the small German principalities, Karlsruhe has an unusual street layout in the form of a fan radiating from the central palace. Founded in 1715, Karlsruhe is relatively young and therefore does not have the congested medieval city core typically found in many other European cities. Today, Karlsruhe is a busy industrial center, an important railroad junction and river port.

TRANSIT IN KARLSRUHE

The city-owned utility, Stadtwerke Karlsruhe, is responsible for the provision of electricity, central heating, gas, water, and transit, as well as operating the river port. The transit system consists of a 40 km urban LRT network, a 40 km interurban LRT extension, and a bus network. The modal roles in the city are strongly defined, with all heavily used lines and all lines in the central part of the city operated by light rail vehicles. Feeder services and lightly used circumferential services are provided by buses. The pattern of urban development in Karlsruhe did not follow the formal fan pattern laid out by the original city planners, but developed heavily along one major axis, Kaiser Strasse. The transit system is consequently concentrated along this axis.

By the early 1960s, the LRT system at Karlsruhe had become very rundown, and needed extensive renewal of rolling stock and repairs to its physical plant. At that time, after a debate on the future of the LRT system, the City Council decided to retain and modernize the operation. As a result of improvements carried out since then, the Karlsruhe light rail system is now a model of efficient and up-to-date operation. The combined system employs approximately 1000 people, operates 125 light rail vehicles and 90 buses. The interurban section of the system is built to railroad standards, and also provides railroad freight service. Almost all of the LRVs on the system are 8-axle, double articulated cars; older 6-axle cars are in the process of being converted to 8-axles through the addition of a center section.

Self-service fare collection is used throughout the system, with extensive use of ticket machines. Fares may also be paid to the driver at a premium rate. In 1974, the operating deficit was approximately $7.5 million, five million of which was covered by a cross transfer of profit from the other city utilities, while the remainder was financed by a direct grant from the city.

Table 7. Karlsruhe Transit Statistics
(City System Only)

	LRT	Bus
Number of vehicles	66 8-axle double articulated	85
	24 6-axle single articulated being converted to 8-axle	5 articulated
	10 trailers	
Length of double track (miles/km)	25/40	
Annual passengers (millions)	43	12
Annual vehicle miles/km (millions)	3.4/5.5	2.1/3.4
LRT network coverage – fully developed		
LRT right-of-way type – 70% reserved 30% mixed traffic		
Community transit habit (city) – 203 trips/capita/year		

THE LIGHT RAIL SYSTEM

The urban and interurban portions of the light rail system operate as two distinct divisions sharing common trackage in the central part of the city, as illustrated in Figure 8. The interurban line, known as the Albtalbahn, was constructed in 1958 to replace a former narrow gauge line. It is operated by 8-axle light rail vehicles, running in single or multiple unit trains of up to three cars. Figure 9 shows a typical Albtalbahn train on exclusive right-of-way.

Operation of the city network is characterized by the heavy flow of traffic to the main street of the city, which in turn requires the routing of most of the light rail vehicles on this street. Figure 10 shows how the average daily patronage on different links of the system is matched by the number of LRT routes providing service to that link. The double track line on Kaiser Strasse is currently handling approximately 50 trains per hour in the peak, close to its estimated capacity. Fifty-three percent of all trips on the system start or end from one of three central stops on this street. Part of the street is presently being converted into a pedestrian mall, with vehicular traffic restricted to light rail vehicles.

System patronage has been stable for a number of years, but since 1970 when the LRT improvement began to take effect, patronage has increased consistently at the rate of about 5 percent per year. To increase capacity to match this rising patronage, 24 of the 6-axle, single articulated cars are being converted to 8-axle cars by the addition of new central sections. To keep pace with the maintenance needs of the expanding transit system with its increasingly sophisticated equipment, a new central workshop is now under construction on the west side of the city to handle all bus and light rail vehicle maintenance.

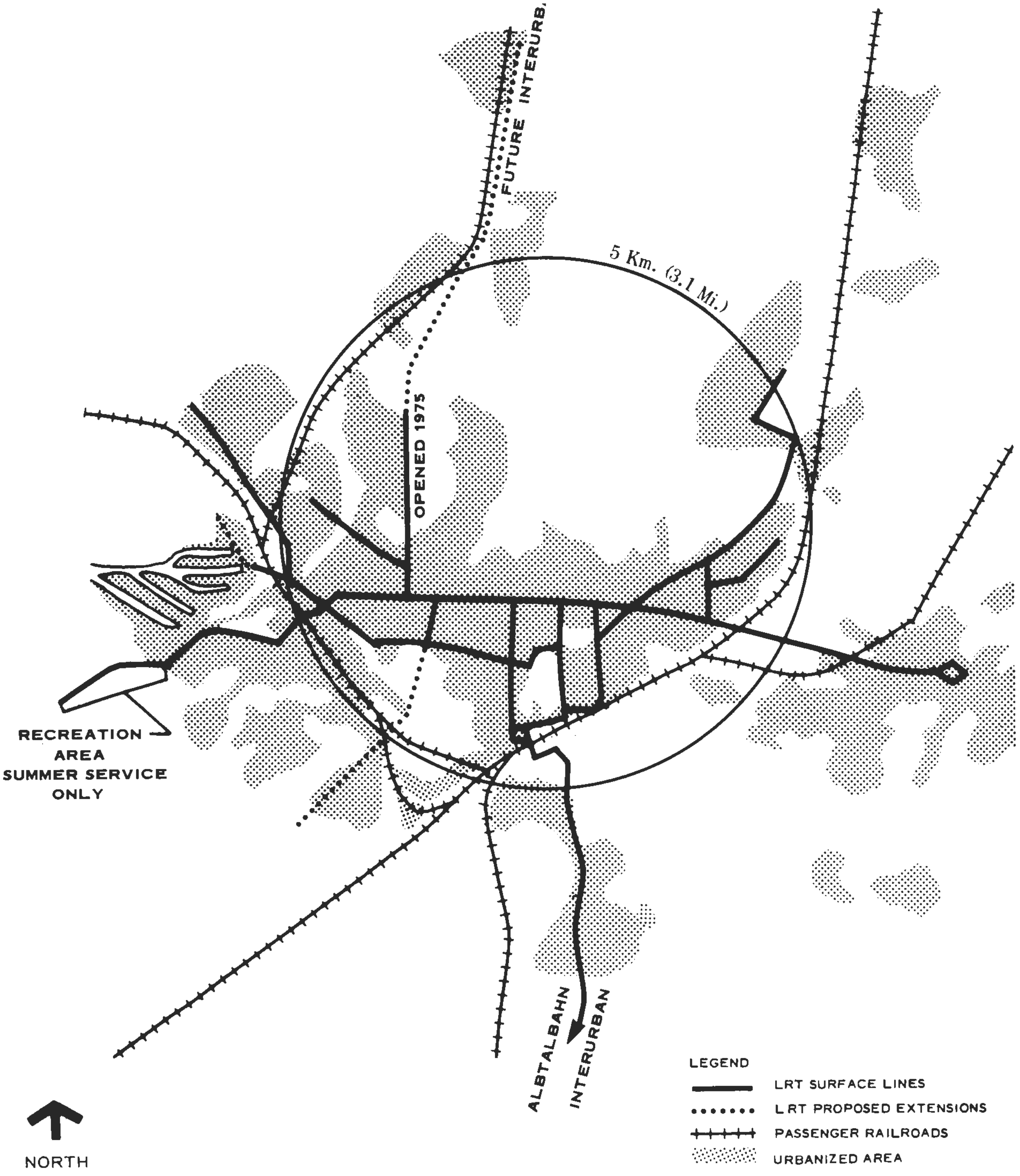


Figure 8. Karlsruhe System

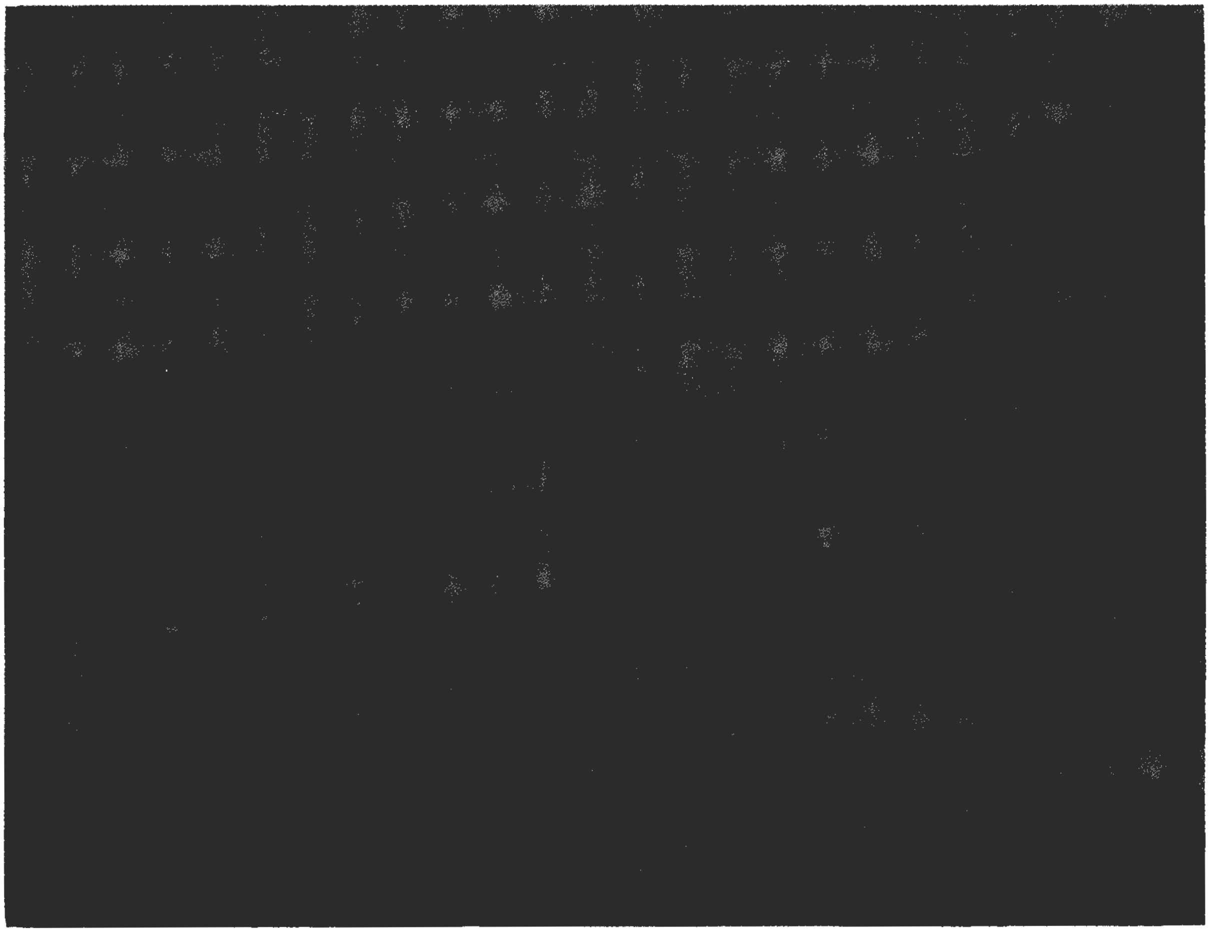
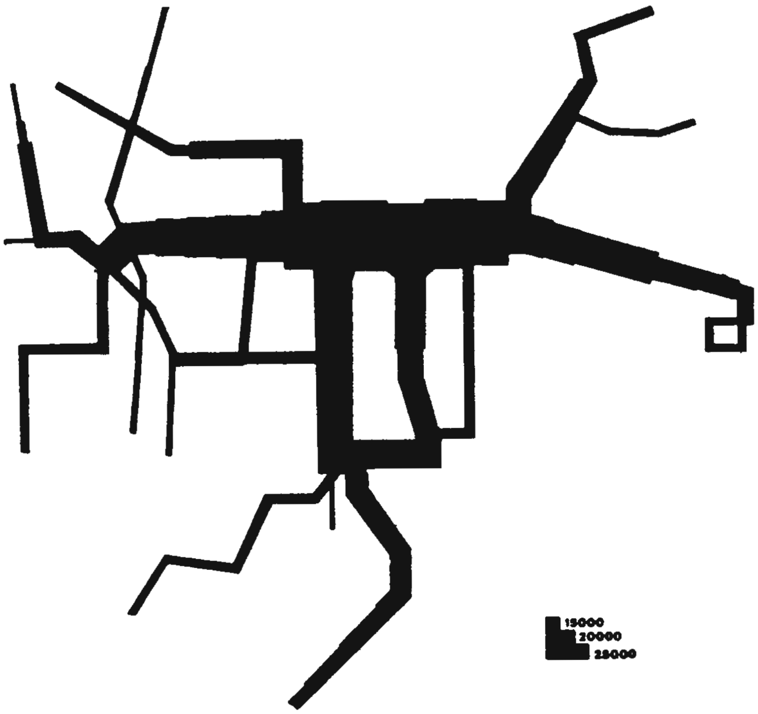


Figure 9. Albtalbahn Interurban Train

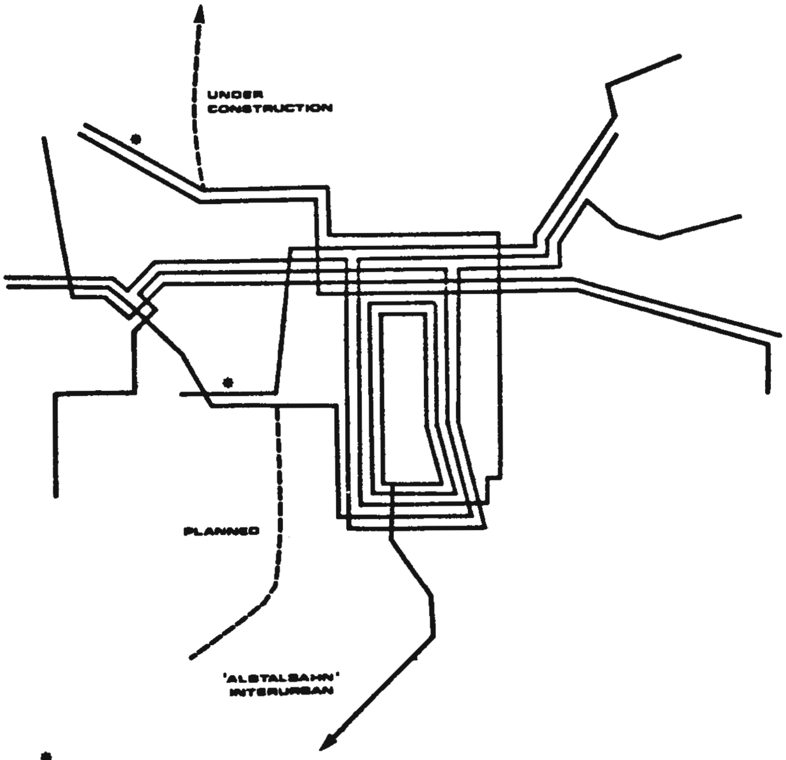
The Stadtwerke Karlsruhe pursues a policy of good neighborliness toward the community, with regard to its design and maintenance standards. Design efforts have been made to achieve the minimum obtrusiveness of tracks and overhead. The reduced visual impact is achieved largely through landscaping and through coordinated design with street lighting and other overhead utilities. Track grinding is performed two or three times a year over the whole system, according to need. A program to convert all track switches from the old trolley wire actuated type to a new automatic type actuated by vehicle route code has just been completed. The old system suffered from lack of reliability, and operated at low speeds for safety reasons. The new system permits higher speeds, incorporates an automatic safety interlock, and has a history of high reliability.

PLANNING AND POLICIES

The city transit system's policy is to provide rail service for major demand corridors and to use the bus system as a feeder and in lightly patronized corridors. LRT is the only transit mode in the central part of the city. The system planning staff continuously reviews travel demand and patronage as a guide to long-range planning and possible network adjustments. The general criterion for possible extensions of the light rail network is line patronage between ten and twelve thousand passengers per day, or a feeder bus headway of less than five minutes in the peak hour.



KARLSRUHE
DAILY PATRONAGE DIAGRAM FOR MAIN TRANSIT LINES



KARLSRUHE
LIGHT RAIL ROUTE DIAGRAM

Figure 10. Balancing Service and Patronage – Karlsruhe Transit System

The first part of a major new line extension in the northwest part of the city was opened in November, 1975. It is anticipated that further extensions to this line will be made as funding permits. Because equipment will be diverted from another line which is presently served by two routes, the operation of the new line will neither require additional light rail vehicles nor will it add to the yearly vehicle miles of operation. However, it will enable the transit authority to replace six buses which are presently providing feeder service in this corridor. In the southwest part of the city, another LRT extension is planned to replace the only other feeder bus line which meets the patronage criterion for conversion to light rail.

In the longer term, if the system patronage continues to increase, the central segment will become overloaded. A number of alternatives are being considered to resolve this situation. One is to construct a two-level system with a continued street surface operation for short routes while the interurban and longer LRT routes would be connected to a short length of subway, in semi-metro fashion. This alternative would provide a bypass of the congested segment of the system. Since the two routes would not be on precisely the same alignment, this plan would also increase the system coverage in the central part of the city. As a general policy, all new construction is built without grade crossing if possible. However, there is no program for the construction of grade separations on the existing system, nor is it considered realistic to plan for total grade separation, even in the long run.

SIMILAR SYSTEMS

Karlsruhe is typical of a few small size cities which have decided to retain and modernize their LRT systems. Such cities are examples of small scale, multi-modal transit planning. Generally, similar systems can be found in West Germany at Bielefeld, Krefeld, Augsburg and Wurzburg; in Switzerland at Bern; and in Austria at Graz and Linz.

BRUSSELS – A PRE-METRO SYSTEM

At about the time Frankfurt and Cologne were beginning to build their light rail subways, Brussels too began subway construction. However, the Brussels concept was to develop subways for initial use by streetcars, and then, when enough of the system was completed, to change to rail rapid operation. This approach is known as the pre-metro concept.

CITY DESCRIPTION

The city of Brussels is the largest city and the capital of Belgium. With a population of 1.2 million, it is a major center of light industry and the European Economic Community's administrative center.

TRANSIT IN BRUSSELS

Some 70 percent of all transit services in Brussels is provided by the Societé des Transports Intercommunaux de Bruxelles (STIB). The SNCV, a nationwide transit operator, also provides light rail and bus service in the Brussels region, mostly on rural and suburban services. Other transit services are provided by the Belgian State Railways and local bus operators. Brussels has one of the densest LRT networks of any city, supported by a bus network giving comprehensive coverage throughout the city. There is less coordination of transit in Brussels than in many Dutch and West German cities, due in part to the division of operations among several companies. Compared to the West German or Dutch systems, use of light rail is somewhat ineffective, requiring duplicate bus operation on some lines to provide sufficient peak hour capacity.

Fare collection is self-service, although a few conductors are still used on the older streetcars. In 1972, passenger revenue met about 45 percent of the system operating cost of $68 million. The balance is provided from a federal operating subsidy.

Table 8. Brussels Transit Statistics (STIB System)

	LRT	Bus
Number of Vehicles	45 rail rapid (being delivered) 110 8-axle double articulated (on order) 129 6-axle 420 smaller cars, mostly PCCS	541
Length of double track (miles/km)	106/170	
Annual passengers (millions)	127	48
Annual vehicle miles/km (millions)	14/23	9.3/15
LRT network coverage – fully developed		
LRT right-of-way – 6% subway, 46% reserved 48% mixed traffic		
Community transit habit – 185 trips/capita/year (STIB and SNCV Systems)		

THE LIGHT RAIL SYSTEM

Two LRT systems are operated in Brussels. The STIB system is a standard gauge operation with 23 lines carrying over half of all transit trips in the city. By contrast, the SNCV system is primarily a suburban operation, carrying less than five percent of all transit trips on its narrow gauge LRT operation. It does not play a significant role in LRT development in Brussels. The Brussels LRT network is illustrated in Figure 11.

The 170 km STIB system is primarily a radial network, with two circumferential lines. Most of the existing vehicle fleet is based on the PCC design, manufactured by the Belgian firm of La Brugeoise. Brussels streetcars use both pantograph and trolley pole pickup, some cars being equipped for both. A characteristic of the STIB LRT system is its use of relatively small cars, usually as single units, a practice considered inefficient by other European operators. The recent order of 110 new 8-axle cars suggests that Brussels too plans to move towards more productive operation. Other features of the Brussels system include the extensive use of traffic signal preemption and the establishment of park-and-ride facilities. However, the feature that dominates transit planning in Brussels is the pre-metro project: since

Figure 11. Brussels System

1965, Brussels has been constructing a network of subways, intended to form a full scale rapid transit system, but to be operated initially with streetcars.

PLANNING AND POLICIES

Patronage on the Brussels system began a steady decline in the late 1950s due to auto competition, congestion, and a shorter work week. To improve operation in the increasingly congested city, construction of a subway system was begun on an incremental basis, diverting streetcars into the subway by means of temporary ramps as each segment was completed. The plans call for replacement of these streetcars with conventional rail rapid trains as viable lengths of subway are finished. Buses and light rail vehicles will provide feeder service. This step-by-step planning approach to building rail rapid transit is known as pre-metro, implying the intention to ultimately construct a fully grade separated route to be used by rail rapid transit or *metro* trains.

In 1969, the first pre-metro section was opened, reducing travel time and increasing daily ridership by 40 percent on the five LRT lines running into the pre-metro subway. During peak hour, patronage increased by 90 percent. A year later, a second pre-metro line was opened on a different route, also carrying five LRT lines. More recently, a 2.2 km tunnel was opened under a congested zone on one of the ring routes. Figure 12 shows one of the pre-metro portals.

To permit Brussels streetcars, which can load only from street level, to use the high platform pre-metro stations, 30 meters of the 95 meter long station platform are constructed at a lower level. (An alternative technique, used where there is adequate clearance overhead, is to raise the track in the station on extra ballast to achieve low level loading. The Boston Green Line and the Dusseldorf LRT system use this technique.)

It is anticipated that in 1976 the first pre-metro line will be sufficiently developed to permit the introduction of rail rapid transit trains in place of light rail vehicles. When the conversion of the first pre-metro line to rail rapid transit takes place, the five LRT lines which presently feed into the tunnel will be cut back to the point where they intercept the new line, and will continue to function as feeders. In the future, passengers on those lines that operate in the subway will be required to transfer. The greater speed of the new rail rapid transit train will compensate in part for the transfer delay.

The adoption of the pre-metro concept in Brussels in 1965 was a major advance in LRT planning. However, having created a superior LRT operating environment, Brussels failed to exploit it, and continued to operate single cars at low speeds with inadequate capacity through the subway. The recent introduction of larger 6- and 8-axle cars indicates that the planners are aware of this neglected potential. It appears that the commitment to full rail rapid transit which made sense in 1965, prevented Brussels from exploiting subsequent LRT developments which may be making the pre-metro concept redundant. The latest indications are that Brussels does not plan to continue with the metro conversions after completion of the first line conversion in 1976, at least in the foreseeable future.

SIMILAR SYSTEMS

The city of Stuttgart operates a well developed pre-metro using meter gauge tracks. Conversion to rail rapid transit will require a gauge change, but that is still some years in the future. The extension of the pre-metro subways will require that some LRT lines which now use the subway be converted to feeder bus, because there is no provision for access from branch feeder lines in the next subway extension. This seems to be a disadvantage to current users of the LRT feeder lines. Stuttgart is currently making a reappraisal of its original plan, and may change to a permanent semi-metro LRT.

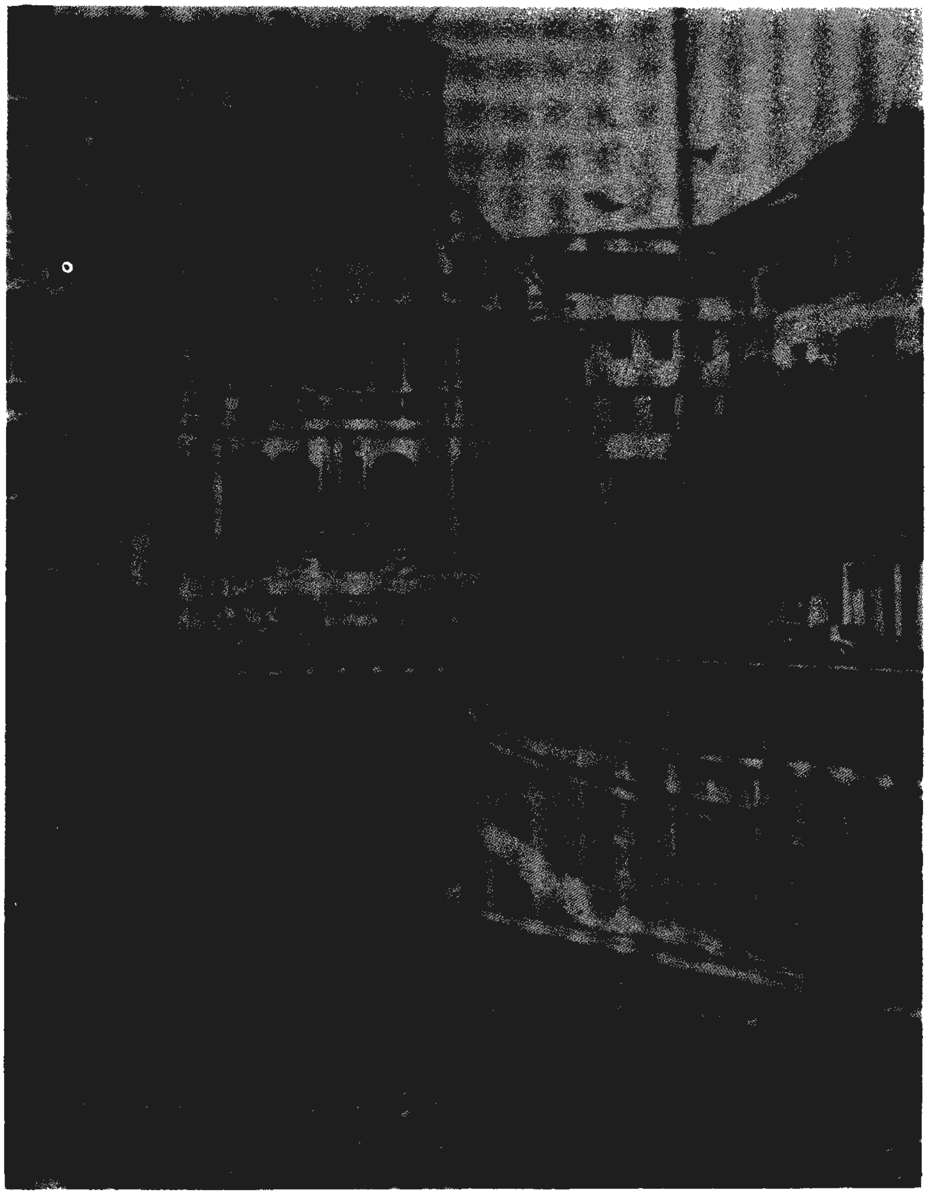


Figure 12. Brussels Pre-metro Subway Portal

BOSTON – THE FIRST SEMI-METRO

In 1897, Boston opened the world's first streetcar subway, thereby anticipating the contemporary developments in light rail transit by some 70 years. This pioneer light rail subway is still in operation, and is now midway through a major refurbishment and renovation program.

CITY DESCRIPTION

The city of Boston, with a population of 614,000, is the core city to the eighth largest metropolitan area in the United States. It is a port city, state capital, and an important cultural, commercial and insurance center. An unusual feature of Boston is that it lies on a peninsula in Massachusetts Bay, with the CBD placed on the east side of the city. This unusual layout and the numerous narrow streets in the old part of the city have served as strong incentives to develop and maintain a healthy public transportation system.

TRANSIT IN BOSTON

Boston was one of the first cities in North America to develop a public transportation system, presently operated by the Massachusetts Bay Transportation Authority (MBTA), a regional public agency. The MBTA operates a coordinated network of three rail rapid lines, a light rail system, an extensive network of bus routes and one of the five remaining trolleybus systems in the United States. In addition, several rail commuter lines are operated, and some 20 private bus operations are active in the region, mostly in the suburban areas.

The four urban rail systems in Boston are known as the Red, Orange, Blue, and Green Lines. The Red Line is a conventional rail rapid transit line, and has recently been extended and reequipped with new rolling stock. Further extensions to this line are planned. There is also a minor LRT operation known as the Mattapan Line, consisting of a short feeder line operated as part of the Red Line. The Orange Line operates conventional rail rapid transit and formerly included an extensive elevated section. In 1975, part of the elevated line was closed and replaced by a subway. At that time, a further line extension was opened. The Blue Line began operation as a streetcar tunnel beneath the Charles River, and was converted to a high platform rail rapid transit operation in 1924. An unusual feature of this line is that it uses third rail power pickup in the central part of the city, but switches to catenary pickup on part of the suburban sections of the route. The Green Line consists of a light rail subway through the Boston CBD, branching into four surface lines. It is operated by a fleet of nearly 300 PCC cars which can operate in trains of up to three vehicles. The entire system uses low level platform loading. The Green Line is also the most heavily travelled of Boston's four subway lines.

In addition to the services it operates itself, the MBTA also coordinates private bus and commuter rail operations. The bus system operates in part as a feeder to the various rail systems. It provides service on lightly used routes and line haul service in corridors where rail service is not available.

A combination of coin-operated turnstiles in the subways, fare box collection on vehicles, and prepaid passes are used for fare collection. A three zone system and different fares for different modes tend to make Boston's fare structure more complex than in other U.S. cities. In 1973, the MBTA operating deficit of about $104 million was financed by local taxes, and by a grant from the Commonwealth of Massachusetts.

Table 9. Boston Transit Statistics

	LRT	Bus
Number of vehicles	296 PCC	1,264
Length of double track (miles/km)	24/38	
Annual passengers (millions)	172	
Annual vehicle miles/km (millions)	5.4/8.7	40/65
LRT network coverage – sector of city		
LRT right-of-way type – 15% subway or elevated, 33% other grade separated, 30% reserved 22% mixed traffic		
Community transit habit – 65 trips/capita/year		

THE LIGHT RAIL SYSTEM

The Boston LRT system, shown in Figure 13, consists basically of the remains of the Boston streetcar system, formerly one of the largest in the world. In 1956, the Riverside section of the Green Line was opened as a high speed LRT operation along an abandoned railroad right-of-way. This 12 mile extension allowed streetcars to operate farther from the city center than would be feasible using the slower, on-street routes of the other branches of the Green Line. The subway section of the Green Line currently carries some 11,000 passengers in the peak hour, peak direction. At this level, the PCC cars are operating at crush loads despite the use of three car trains. Despite a renovation program aimed at improving the conditions of the cars and stations, reliability of the 30 year old equipment is causing increasing problems. In many instances, replacement parts must be fabricated by the MBTA or obtained from out-of-service vehicles. Figure 14 shows a Boston PCC car operating on a well landscaped section of the system.

PLANNING AND POLICIES

The MBTA has embarked upon a major transit development program designed to improve conditions and increase patronage. A significant part of this effort is directed toward improving the LRT lines. The program includes the purchase of 175 new articulated Boeing LRVs, replacement of much of the track with new welded rail, refurbishment and reconstruction of the power pickup system, improvements to the stations and control system, a new maintenance facility, and renovation of an existing maintenance facility. Major efforts will also be directed toward improving system safety and security and transit marketing.

Two network extensions are planned. One will extend the line from its present northern terminus for a distance of just over one mile. The other extension consists of the re-opening of the line to Watertown, which was converted to bus operation in 1969. This line was retained intact pending a reappraisal of MBTA policies with regard to light rail operation and the acquisition of new equipment.

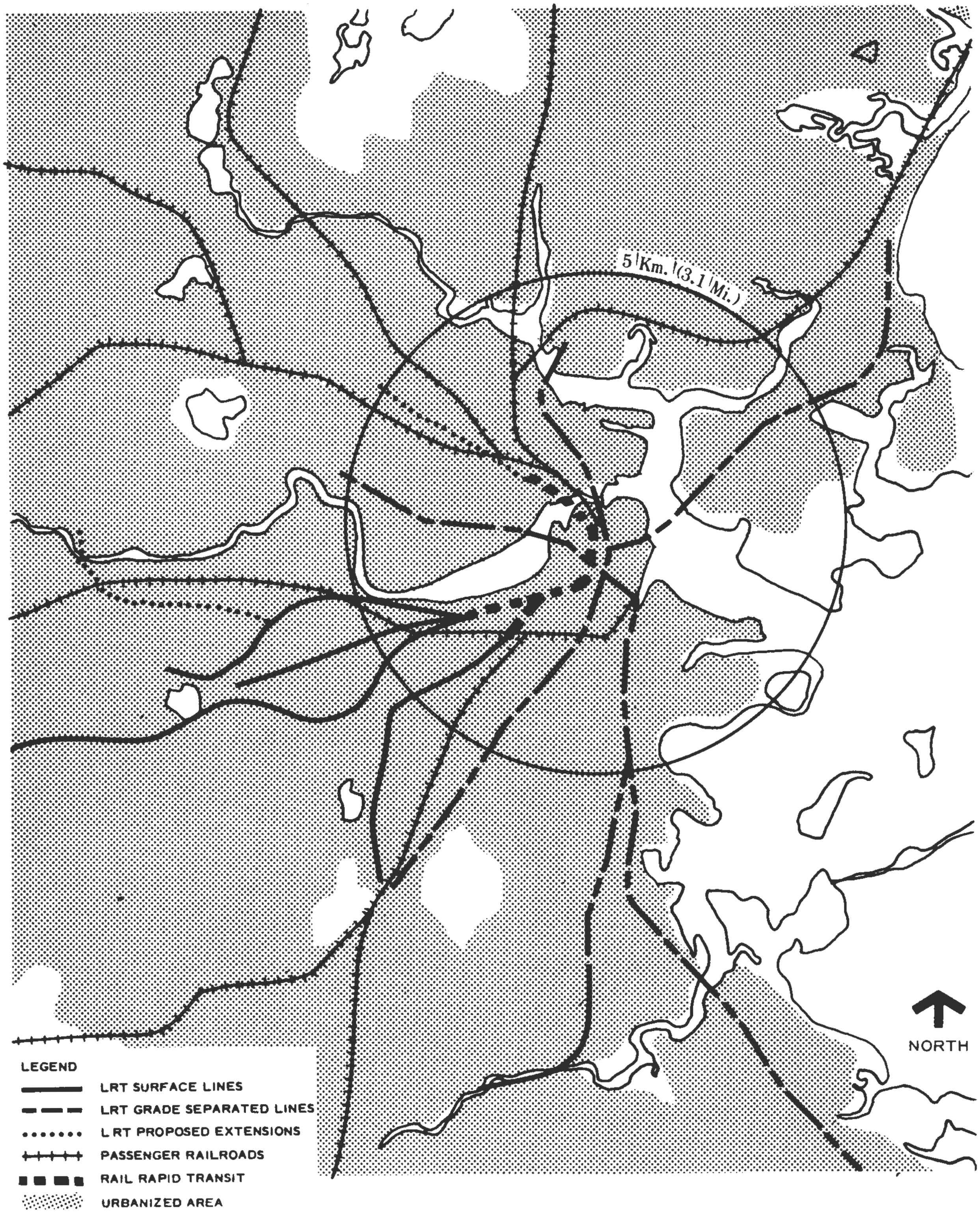


Figure 13. Boston System

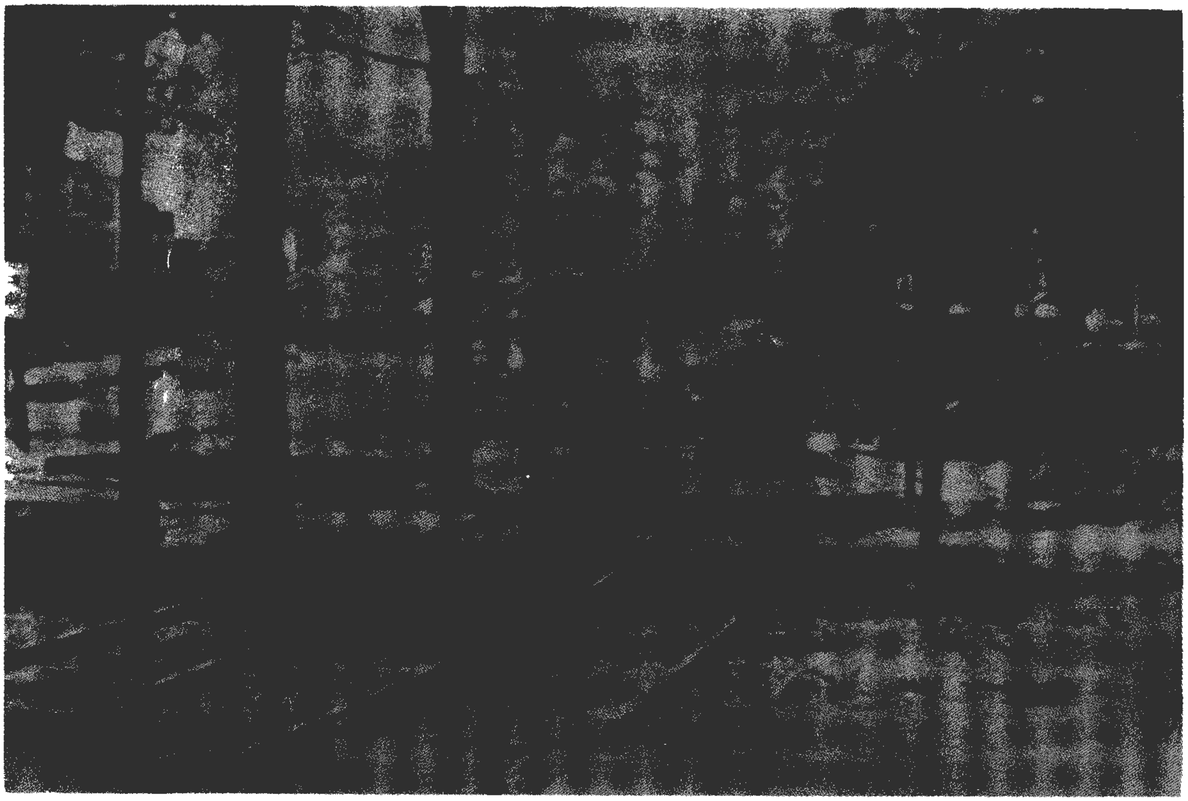


Figure 14. Boston Landscaped Right-of-Way

SIMILAR SYSTEMS

Although Boston's semi-metro service is broadly similar to other operations of this kind, no other system can point to such a long record of continuous operation. A number of similar operations in North America, including Rochester, New York; Providence, Rhode Island; and Cleveland, Ohio; were abandoned with the cessation of streetcar service in these cities.

COLOGNE – A REGIONAL LRT SYSTEM

The Cologne LRT system demonstrates the diversity possible within a light rail system. It is representative of a high performance LRT system incorporating segments which require high speed operation. Cologne and the neighboring city of Bonn are developing a regional LRT network incorporating two conventional light rail systems, centering on the cities' subways and surrounding surface LRT networks.

CITY DESCRIPTION

The ancient city of Cologne lies astride the Rhine River in northwest Germany. With a population of some 840,000, Cologne is an important administrative, commercial and industrial center and the core city for a metropolitan region of 1,270,000 people. Extensively rebuilt after World War II, an important feature of Cologne planning has remained its policy of constraint on automobile traffic. A major tool of this policy is the limitation of parking spaces. Approximately 70,000 spaces are provided to meet a potential demand in the central city for approximately 140,000 spaces. This policy has had a major impact on highway construction and has provided the impetus for better public transportation.

TRANSIT IN COLOGNE

Transit service in the Cologne area is provided by the Kolner Verkehrs-Betriebe (KVB) which operates the urban bus and LRT network, and by the federal railways which operate an extensive local passenger service to the suburbs, the S-Bahn. The light rail system is the principal public transit mode, one of the best examples of a fully developed light rail network. The KVB bus system functions primarily as a feeder to the light rail network, and also provides service on a number of lightly traveled and circumferential routes. There are no bus routes operating through the central part of the city.

The Cologne system uses the conventional self-service fare collection system. Tickets are available from machines and from the vehicle operators. In subway sections of the route where the stations are equipped with ticket offices, the driver does not sell tickets. Transfers are allowed among all transit lines up to one hour from the initial ticket validation. The fare collection system is enforced by a team of KVB inspectors who typically will saturate one line and cite all fare evaders. KVB fares are set by the City Council as a matter of city policy. The KVB is part of a city-owned utility company which also operates the gas, electricity, and water systems. A major part of the system operating deficit ($40 million in 1974) is funded by the transfer of profits from utilities. The balance of the operating deficit is received directly from city funds.

Table 10. Cologne Transit Statistics

	LRT	Bus
Number of vehicles	230 8-axle 11 6-axle 82 4-axle	264 20 split level
Length of double track (miles/km)	89/143	
Annual passengers (millions)	104	48.1
Vehicle miles/km (millions)	10.1/16.6	10.8/17.3
LRT network coverage – fully developed		
LRT right-of-way type – 42% grade separated, 35% reserved 23% mixed traffic		
Community transit habit (city) – 200 trips/capita/year		

THE LIGHT RAIL SYSTEM

The existing Cologne light rail system (Figure 15) is operated primarily with a fleet of untrained uniform 8-axle cars. These 99 foot long cars are among the largest vehicles used on any light rail system. During the peak hours, this fleet is augmented by a number of smaller 4-axle cars which are operated in two-car trains.

Figure 15. Cologne System

One unusual feature of the Cologne system is the operation of one of the western suburban lines along a privately owned freight railroad. It operates under the protection of conventional railroad signaling. All switches on the joint trackage are equipped with movable frogs. Approximately 20 freight trains use this section daily, but since the light rail headways on this line are seldom less than 20 minutes, there are no serious operational conflicts.

Operation on the central subway sections of the Cologne LRT system is controlled from a computerized central control which also features a train display board. The central control operates by visual block signals which are also equipped with automatic train trips. Track junctions in the subway are not grade separated. This allowed substantial cost savings at the expense of capacity and operating constraints. At the present time, the busiest part of the subway carries 47 trains per peak hour, which is close to the line capacity. The introduction of the B Type cars will substantially increase line capacity, because their capability to run in train, due to their greater length, will permit the operation of fewer trains per hour.

THE COLOGNE-BONN REGIONAL LRT SYSTEM

An important facet of the Cologne transit improvement program is the conversion of the two regional lines which run to Bonn, 23 miles to the south, to light rail operation and then integration with the rest of the light rail networks. The combined system will have sections of trackage in mixed traffic, high speed regional lines, and subway. When completed, it will provide direct service from central city to central city without a change of mode.

The two existing electric railways between Cologne and Bonn are currently operated by a separate company whose lines end at terminals in each city. The upgrading plan includes reconstruction of these lines as light rail routes, and the integration of their operation into light rail networks at each end. Since they also carry railroad freight traffic, one element of their upgrading is the conversion of all switches to movable frog operation suitable for small flanged light rail equipment. Integrated operation is scheduled to start in 1978.

The DuWag B Type car was introduced in 1973 to operate on this system. This 6-axle articulated car, presently the fastest rail transit vehicle in West Germany, will eventually supersede the existing fleet. B Type cars are now in use on the Bonn LRT system; some initial cars are being delivered to Cologne. The B Type car is equipped for both high level and low level platform loading through the use of movable steps.

PLANNING AND POLICIES

In the late 1950s, a transportation study was made in Cologne to determine the future of the streetcar system, then much in need of renovation. As a result, it was decided to embark on a long-range improvement plan with the eventual goal of total grade separation. It was to be achieved by the staged construction of an extensive network of subways in the central part of the city and the gradual upgrading of other lines as the opportunity arose. Unlike the pre-metro approach, there was to be no transition point to conventional rail rapid transit.

The first segment of the subway was opened in 1968. Since that time, six additional grade separated extensions have been opened. The subways are constructed with low level platforms, and the whole system is operated with the existing LRVs. As a result of incremental LRT improvements, there is now an unusually high level of accessibility to the central city from the suburbs. Any one of several downtown subway stations can be reached from any one of about ten radial lines. By contrast, a conventional rail rapid system, which typically has fewer branches, would require a more extensive feeder and distribution system and more transfers.

The long-range plan is for the Cologne system to become as independent as possible of outside interference from traffic and other conflicts. The conversion of on-street trackage to median trackage and construction of grade separations is being continued wherever appropriate. The impact of this program is shown by the change in right-of-way type. In 1960, approximately 56 percent of the network was on some kind of reserved right-of-way; by 1974, this had reached 72 percent. There is no final target date for the completion of this program, because by consistently improving the worst locations, the achievement of 100 percent grade separation has less and less importance.

Apart from the extensive central subway network, a new circumferential line was opened in 1974, constructed largely on aerial structures. Much of this line is designed to run in the median of an expressway which is yet to be completed, shown in Figure 16.

In the absence of other standards, the Berlin subway cross section was adopted for the initial tunnels in Cologne in the early 1960s, imposing a constraint on vehicle size. In particular, vehicle width is restricted to 2.65 meters (8 feet 8 inches) which many operators consider less than optimum. Nevertheless, this width has become the standard for new LRT in Germany. The existing electric rail cars now in use between Cologne and Bonn cannot use the subway because of tight clearances. Trains from this interurban line will not be able to enter the Cologne subway until they consist of the new B Type cars, which will be delivered in 1978.

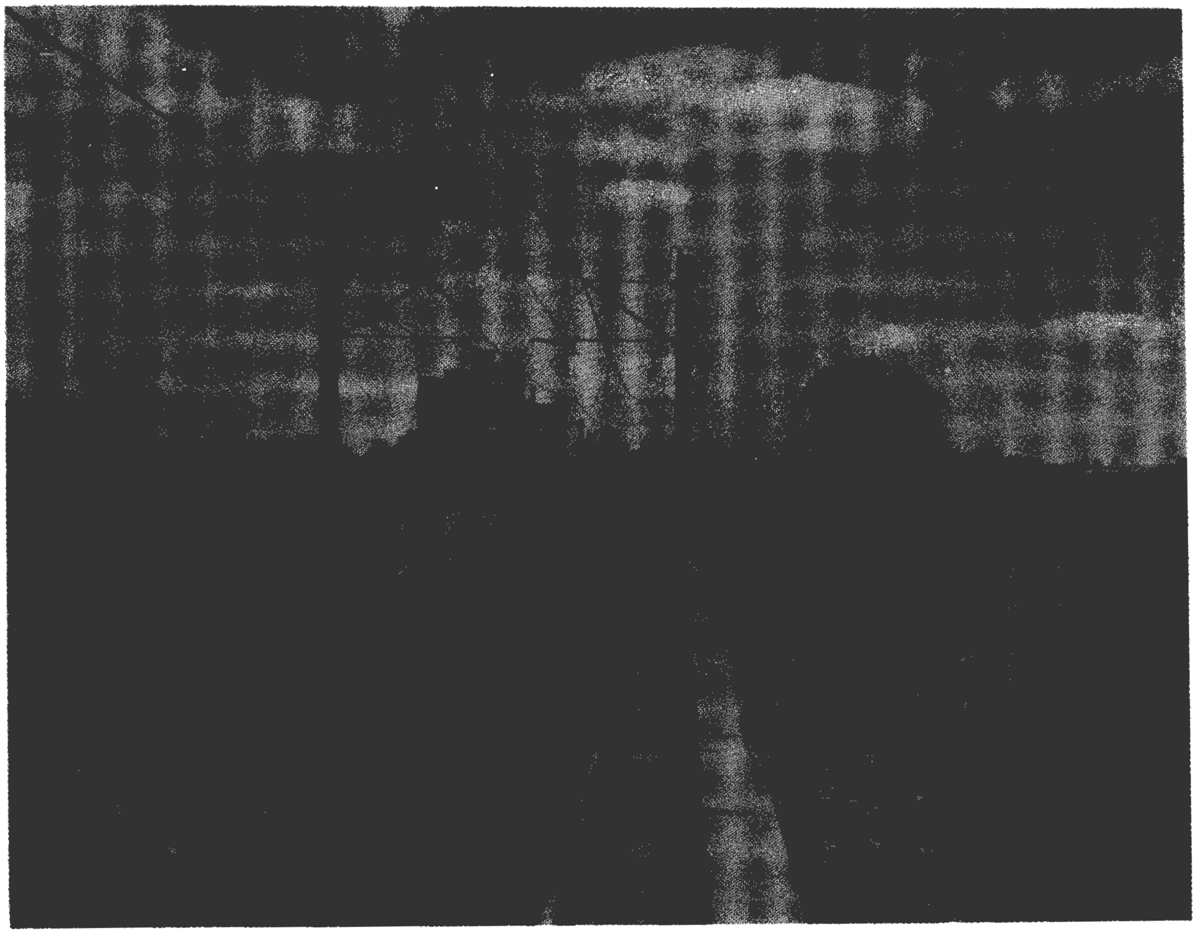


Figure 16. New LRT Line in Future Expressway Median

SIMILAR SYSTEMS

There are no systems currently in operation which exhibit all the features of the Cologne system. A number of systems incorporate urban and regional light rail operation, including those in Karlsruhe, Bern, Mannheim and Dusseldorf. The new Rhein-Ruhr system now under construction is currently undergoing a reevaluation of its rail mode, and will probably change from rail rapid to a light rail system of the Cologne type. This system has already selected the B Type car for its initial operations.

FRANKFURT – ONE OF THE FIRST EUROPEAN LRT SYSTEMS

The Frankfurt light rail system is one of the major light rail systems in Europe. Frankfurt performed an alternatives analysis in the early 1960s and elected to develop its light rail system at a time when most cities were considering rail rapid transit. It now operates two separate and distinct, highly developed light rail systems. One of these has been selected as the prototype for the new LRT now under construction in Edmonton, Canada.

CITY DESCRIPTION

The city of Frankfurt, with a population of almost 700,000 is the core city of a major metropolitan area with a total population, including several satellite cities, of 1.8 million. Situated near the center of West Germany, Frankfurt is the principal commercial center in the country and an important meeting point of West Germany's freeway and railroad systems. A city of diverse industries and commercial enterprises, it is also the site of West Germany's principal international airport and of a major river port.

Frankfurt is the center of one of the most highly developed highway networks in Europe. Numerous freeways connect the satellite communities and suburbs, providing service close to the central part of the city. Not surprisingly, Frankfurt also has one of the higher levels of auto ownership, 296 per 1000 population. Unlike most European cities, Frankfurt's suburbs extend for many miles, contributing to the problems of transit and traffic circulation.

TRANSIT IN FRANKFURT

Frankfurt is served by a well organized transit system consisting of an extensive network of suburban passenger railways operated by the federal railroads, and an extensive network of bus and light rail operations administered by the regional transit federation (FVV). The FVV is both the local transit operator and the regional transit coordinating agency. Transit by all modes within the FVV jurisdiction is fully integrated; passengers may transfer from mode to mode without payment of separate fares.

The suburban railway operation (S-Bahn) consists of fifteen basically radial routes, including a recent bypass line built to serve the international airport. The light rail network is also radial, and buses supplement the rail systems in corridors not otherwise served. Buses also provide feeder service and service in low patronage corridors, particularly in the outer suburbs. There is no through bus service in the central part of the city.

The extensive suburban railway system is currently handicapped by its failure to penetrate the center of the city. It is now constructing the first stage of a major new crosstown line in subway connecting the east and west portions of the network. The first stage of this railway will be completed in 1978.

Self-service fare collection is used throughout the system, primarily with sidewalk ticket vending machines. Cash fares may also be paid to the driver, but the rate for on-board payment is high to encourage prepayment or the purchase of a pass. Tickets are normally valid for a set time period for a particular direction of travel. The passenger may transfer between modes or between lines in any combination during this period, so long as he does not reverse his direction of travel. Revenues from the railways and transit systems within the FVV zone are pooled and then divided according to an agreed formula between the federal railway and the FVV. Since the operating revenues are not adequate to cover expenses, additional funds are provided from the profits of the city owned utility systems.

Table 11. Frankfurt Transit

	LRT	**Bus**
Number of vehicles	138 8-axle 92 6-axle, including U2 cars 230 others, trailers, small cars, etc. used in peak hour	172 conventional 45 articulated 19 double deck
Length of double track (miles/km)	84/135	
Annual passengers (millions)	151.2	29.7
Vehicle miles/km (millions)	14/23	7.5/12
LRT network coverage – fully developed		
LRT right-of-way type – 65% grade separated or reserved		
Community transit habit (regional) – 100 trips/capita/ year (on FVV system only)		

THE LIGHT RAIL SYSTEM

The Frankfurt light rail system (Figure 17) is comprised of three distinct groups of lines: the A Lines, the B Lines, and surface streetcar lines. The A Lines are a group of four lines operating radially from the CBD through a common subway, leading to surface trackage which then branches to four separate destinations. The A Lines use intermediate level loading platforms except for the outer ends of two branches, which still use low level loading. Cars on these lines have movable steps. The trunk segment of the A Line was constructed in the early 1960s.

The DuWag U2 car was developed to operate the A Lines. It is a 6-axle, articulated vehicle, equipped for intermediate level platform loading only. Because part of the system is not equipped with such platforms, a number of old streetcars were fitted with retractable

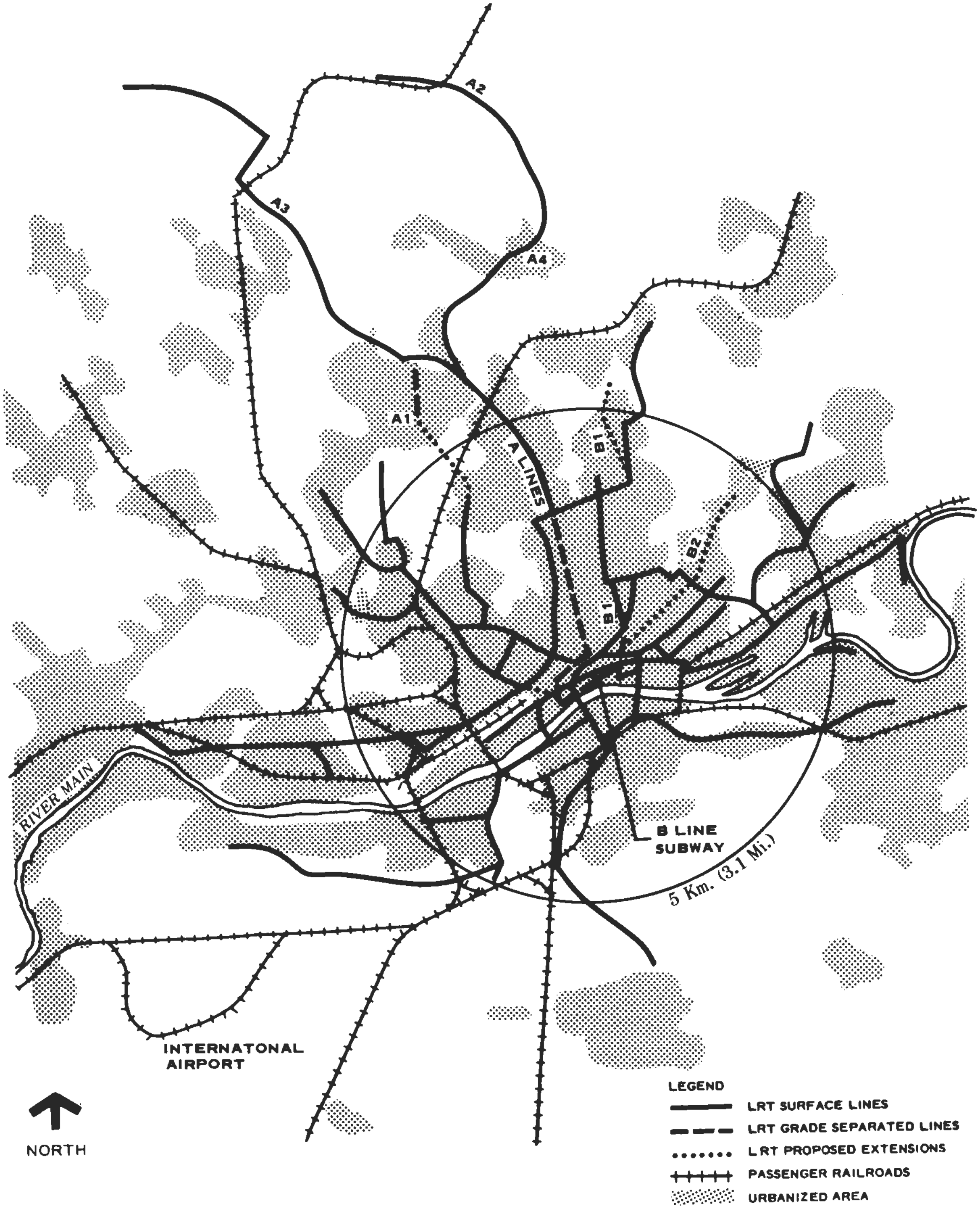


Figure 17. Frankfurt System

steps for intermediate and low level loading. These vehicles are now used on both the subway and surface portions of this route.

The A Lines, called *U-Bahn* in Frankfurt, are frequently confused with a rail rapid transit system. The U2 vehicles look more like rail rapid transit cars than traditional tapered LRVs. However, since much of the route is at grade with frequent grade crossings, and power is supplied from an overhead catenary, the system can be readily identified as light rail. Figure 18 shows a subway station the A Line. Note the compact contact wire support system.

The portion of the A Line operating on the surface through the inner suburbs runs in the median of a narrow four lane arterial street. This line is of particular interest to planners, because the use of this somewhat narrow and densely built-up street as both a traffic arterial and as a major light rail route has attracted some adverse criticism from the community. The main complaint is that there is too much transportation activity on the street. Due to heavy street traffic, the stations which have high level platforms require extensive barriers and splashboards on the backs of the platforms to protect waiting passengers (Figure 19). Moreover, because this is a major light rail line, crossings and conflict points have been minimized. As a result, access across the tracks, particularly for pedestrians is severely impeded.

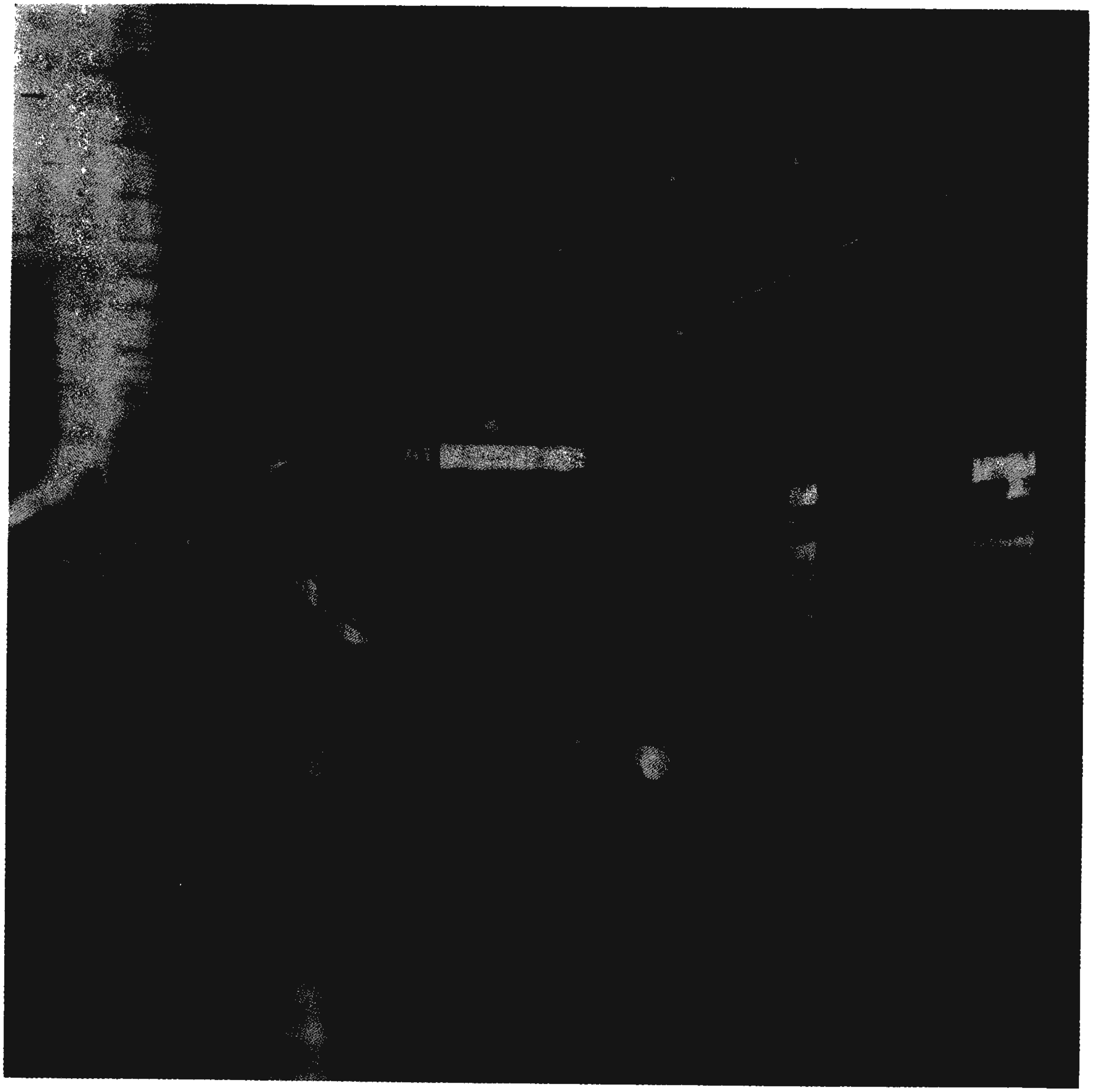


Figure 18. Subway Station in Frankfurt

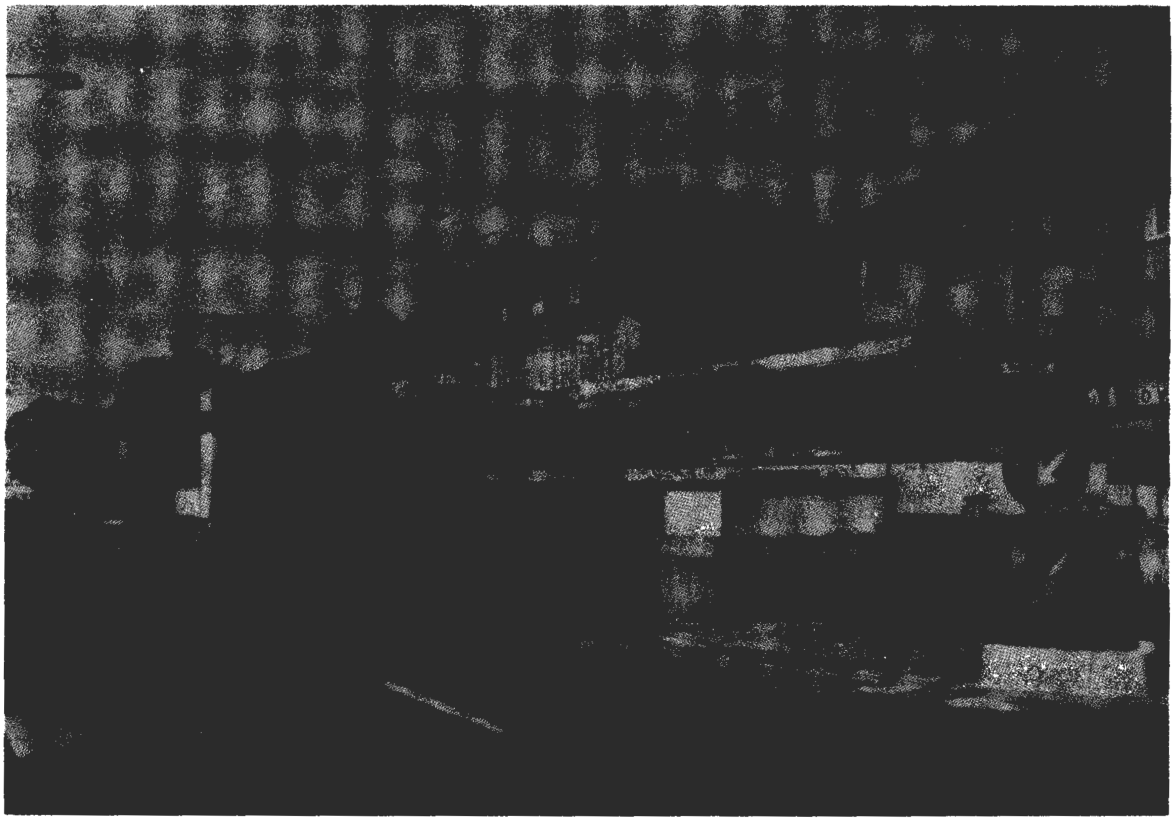


Figure 19. Surface Station on Frankfurt 'A' Lines

A lesson from the Frankfurt experience is that if LRT is located in the middle of a traffic arterial on a narrow street in a residential area, adverse impacts cannot be avoided. Where automobile traffic diversion is not possible and the route is required as a transit artery, then consideration must be given to the construction of fully grade separated trackage as was done on the CBD portion of the A Lines.

The second group of LRT in Frankfurt comprises the B Lines. The first of these opened in 1974. They are of conventional semi-metro design, operating on existing surface tracks through the streets and in the central part of the city in subway. Unlike the A Lines which began operation over largely new trackage, the B Lines operate on existing trackage on city streets. Consequently, a new car was developed to operate within the narrow vehicle envelope permitted by the close spacing of the tracks. An 8-axle double articulated car was designed by the DuWag Company with adjustable steps for loading either from subway platforms or from the street. This vehicle has now been put in service both on the B Lines and a number of all-surface city routes.

The third group in Frankfurt is the surface streetcar lines, which still comprise the major part of the Frankfurt network. The operation of streetcar lines in the severely congested central part of the city provides continued impetus for the construction of further subway routes. During 1975, to lessen the impact of traffic on streetcar operation, two major sections of street in the CBD were closed to all traffic except streetcars, creating extensive pedestrian malls. Figure 20 shows a three car train of old streetcars operating on surface tracks in Frankfurt. Such a train requires a crew of four, and is now operated only in peak hours.

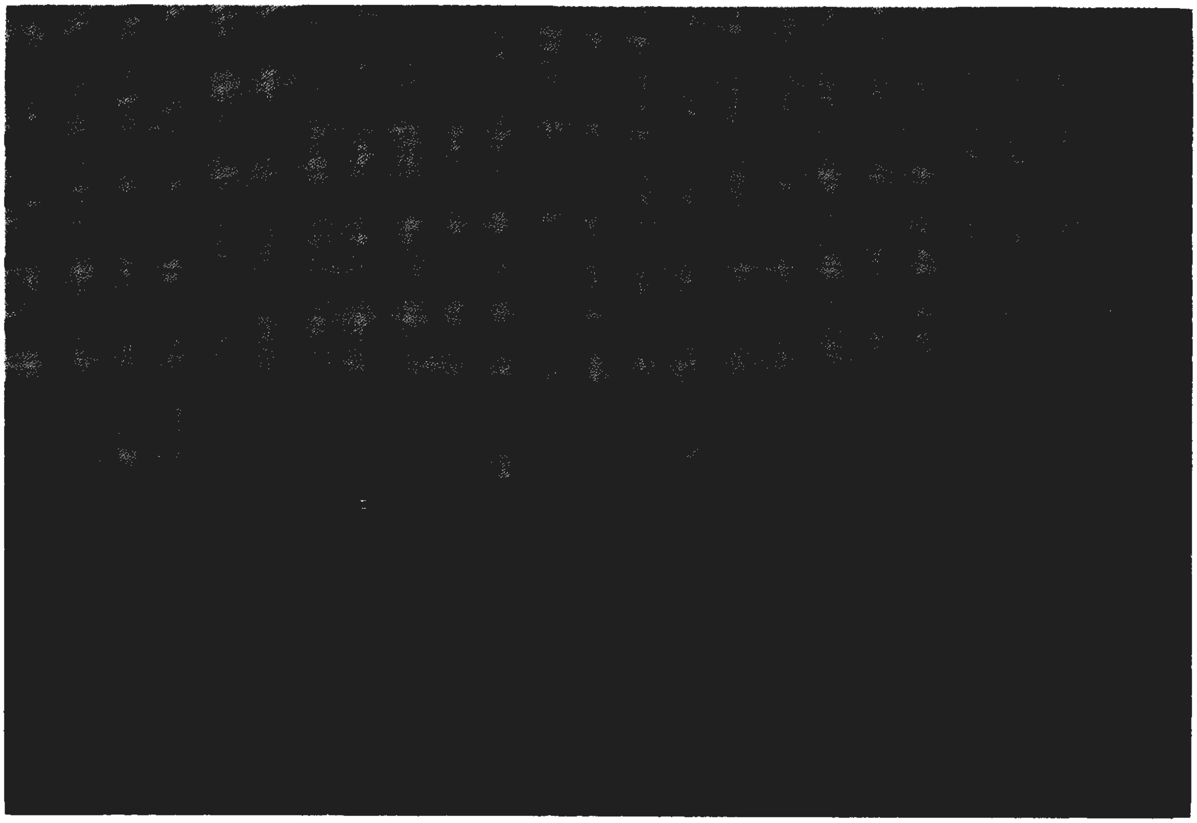


Figure 20. Train of Old, Small Streetcars in Frankfurt

An unusual feature of the Frankfurt LRT system is that there are no pedestrian barriers between the tracks in stations. Accidents involving pedestrians are the second most common safety hazard on the Frankfurt LRT system. "Vehicles intruding onto trackway" cause most of the accidents.

SIMILAR SYSTEMS

Although no other system offers the diversity in light rail operation of the Frankfurt system, examples of the individual types of operation used in Frankfurt exist in most cities having LRT systems.

HANNOVER – RETREAT FROM THE METRO CONCEPT

Hannover is representative of a group of cities which had planned at one time to construct rail rapid transit systems, either directly or via the pre-metro approach. High capital costs of rail rapid transit and the improved performance of modern light rail equipment have caused a revision of these plans.

CITY DESCRIPTION

The Hannover metropolitan area comprises a major industrial and commercial center with a population of some 1.1 million people. Approximately 600,000 people live in the city of Hannover itself. Although heavily damaged during the war, Hannover has now been completely reconstructed, much of it in the old style. Significant features of the city are the numerous large parks and the extensive pedestrian malls in the central part of the old town.

TRANSIT IN HANNOVER

Transit services in the Hannover metropolitan area consist of a single coordinated system controlled by Grossraum-Verkehr Hannover. This agency was established in 1970 to replace a number of public and private transit companies then operating in the Hannover region. It is charged with the administration of the unified fare system, and the coordination of planning and transit operation. It also has local taxing powers.

The principal regional transit operator is USTRA, which is responsible for the operation of LRT and bus services within the central part of the metropolitan area. USTRA operates a well developed LRT system with an extensive supporting bus service. The LRT system consists of some nine major radial routes, with various branches, supported by an extensive feeder bus network. In addition, some buses operate through the central area and on several circumferential routes. At one time, an extensive rail freight service operated on the LRT network serving as a collection and distribution system for the federal railways. This service was abandoned in 1953 and replaced by truck distribution routes.

The self-service fare collection system is used in Hannover, with heavy emphasis on prepaid tickets. Approximately 30 percent of transit riders use passes, 60 percent use multiride tickets, and only about 10 percent pay the cash fare. Approximately 2 percent of all riders are checked by inspectors; the fare evasion rate is estimated to be less than 2 percent. In 1974, the transit operating deficit was almost $20 million per year, about half of it attributable to central city operation. This deficit is partially funded by revenues from the profitable gas and electric utilities. The rest of the deficit is financed directly from public funds. The city contributes 66 percent, and the rest is provided by the surrounding metropolitan areas.

Table 12. Hannover Transit Statistics

	LRT	Bus
Number of vehicles	100 8-axle being delivered 22 6-axle 283 small cars and trailers	200 conventional 70 articulated
Length of double track (miles/km)	55/88	
Annual passengers (millions)	86.5	27.8
Annual vehicle miles/km (millions)	12/19	7.2/11.6
LRT network coverage – fully developed		
LRT right-of-way type – 5% subway, 41% reserved and 54% mixed traffic		
Community transit habit – 121 trips/capita/year		

EVOLUTION OF LRT IN HANNOVER

Apart from the closure of some lightly used streetcar lines in the central city and of several of the interurban routes, the Hannover LRT network (Figure 21) has remained essentially unchanged for many years. In 1964, a long-range transportation plan was developed to build a pre-metro light rail system consisting of five lines running in tunnel through the center of the city. No timetable was established for conversion to rail rapid transit. In the meantime, lack of capital and the stablization of the Hannover growth rate led to a reexamination of the plan. This reappraisal resulted in the decision to proceed with the light rail tunnels, but to postpone the rail rapid conversion indefinitely.

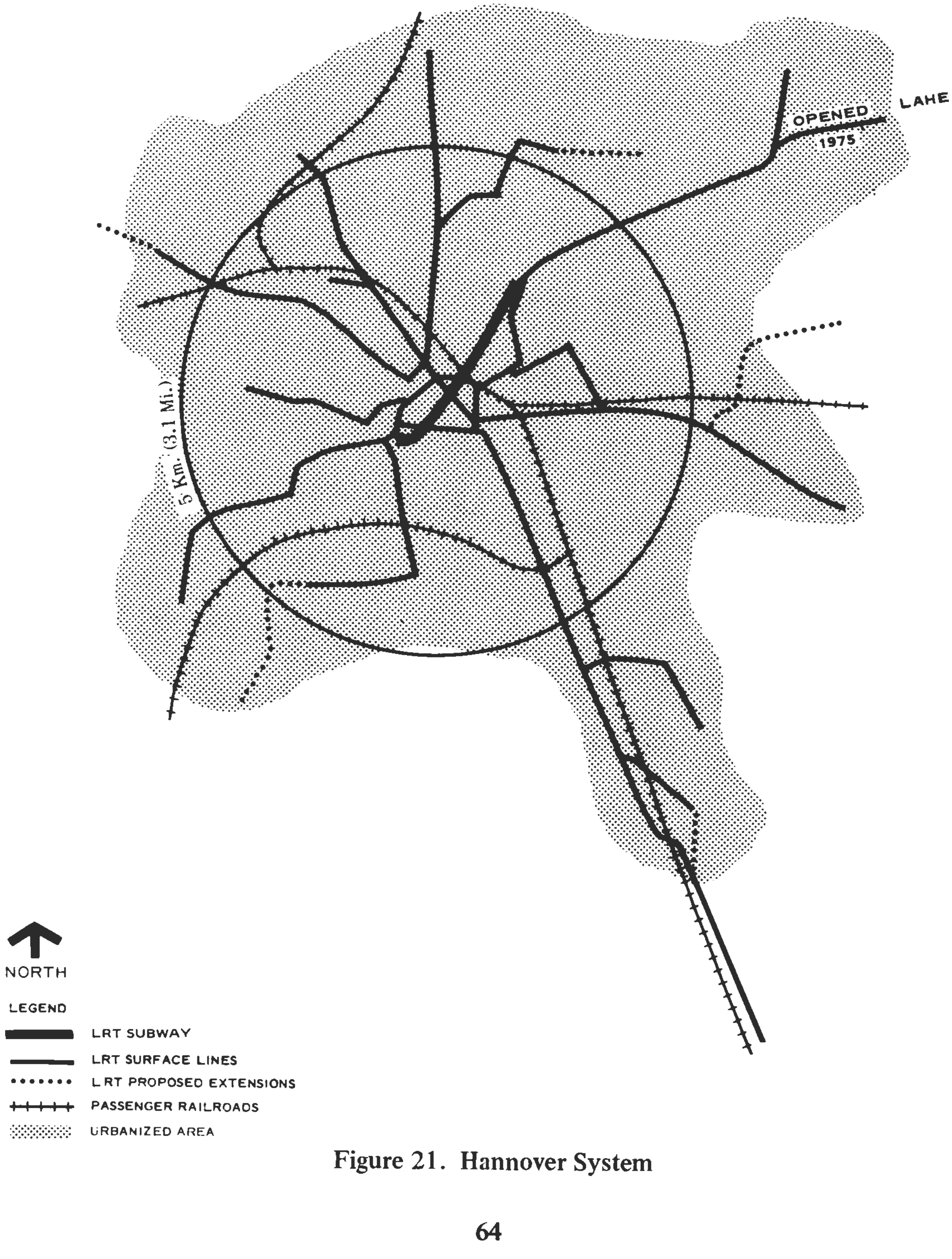


Figure 21. Hannover System

A prototype car was developed by DuWag to operate on the new system. After an extensive testing program, an 8-axle double articulated car equipped with retractable steps and capable of operating in trains of up to three cars was selected. Owing to the close track spacing on much of the existing system, this car is only 2.4 meters (7 feet 9-1/2 inches) wide (instead of the preferred German standard width of 2.65 meters or 8 feet 8 inches). Three-across seating is therefore necessary, reducing the potential seating capacity on the system. The provision of 5 double doors on each side of these cars further reduces the space available for seating. The new cars are almost 90 feet long, but have only 46 seats.

Hannover's reduced growth rate and the less favorable financial climate make it probable that the system will remain a semi-metro operation. This is best evidenced by the construction of the latest extensions, particularly that to Lahe, as conventional, at-grade median lines with signalized intersections and at-grade stops. The initial section of subway began operations in late 1975, followed shortly by the opening of the Lahe extension. Meanwhile, construction is continuing on subways to serve other LRT routes in the central part of the city.

As part of the new commitment to permanent semi-metro operation, USTRA is co-sponsoring a project funded by the federal government to develop a computerized control system. The objective of this system is to improve schedule adherence by minimizing the impact of disturbances on the surface parts of the network on flow through the subway system. This control system will involve equipment on each car to relay to the central control the car location. The central control computer compares the actual with the scheduled location of the car, and then instructs the driver to speed up or slow down accordingly. The control system also permits the preemption of traffic signals. The city traffic department does not generally permit preemption of traffic signals, but will accede to occasional preemption if it is restricted only to late running vehicles (about one car every ten minutes). The computer data system will also permit continued monitoring of system performance, and will facilitate maintenance of positive service connections at transfer points. This control system will be completed by the end of 1976. If it can make a major contribution to improving the reliability of semi-metro LRT operation, it will remove one of the principal arguments for converting to rail rapid transit.

THE LIGHT RAIL SYSTEM

The Hannover light rail system uses a well developed network serving all areas of the city. A number of minor line extensions and branches are planned to extend it to areas of sufficient patronage potential. The vehicle fleet is a mixture of old two- and four-axle and larger single and double articulated cars. The small, old cars run in trains of two vehicles during peak hours, and require crews of two men. The newest vehicles are the 8-axle, double articulated cars constructed for operation through the subway. One hundred of these vehicles are on order. They may be operated as single units or in trains of up to three cars controlled by a single operator. These cars are equipped with thyristor (chopper) controls, which is regarded as an experimental system on West German light rail vehicles. Since the West German government will fund only one demonstration of a new device at a time, this installation is serving as a prototype for the whole German LRT industry.

Major parts of the LRT upgrading consists of constructing LRT medians to replace mixed traffic operation (Figure 22) and the introduction of LRT/pedestrian malls.

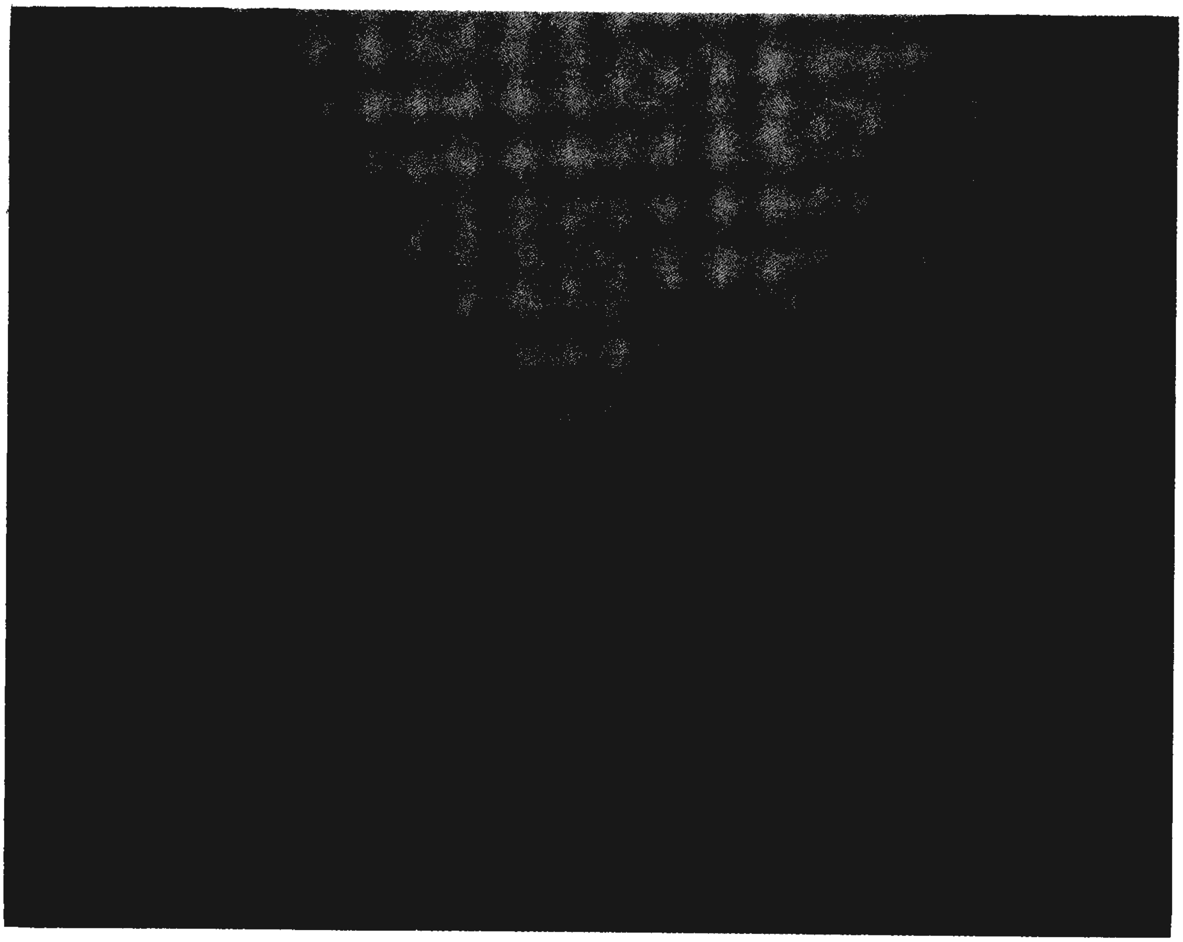


Figure 22. Hannover LRT Paved Median (Tieless Track)

LRT is operated on public streets under the conventional traffic laws. However, when the vehicles operate on private trackage or in the subway, the operation is governed by the company rulebook. Particular attention is paid to track maintenance. The Hannover track grinding car operates over the entire system once a week, travelling at scheduled speed, to prevent any buildup of rail corrugations.

Operations in subway are controlled by block signaling. One impact of this has been the longer headways than the minimum possible with street operations. It has led in turn to the need to operate larger cars and trains of cars to maintain the system capacity. For example, LRV headways on street operations can be as short as 40 seconds, while the new signaling system is designed for two minute headways. It is anticipated that this headway can be reduced at a future date.

An interesting feature of the Hannover system is the new terminal station at Lahe, which is laid out to permit direct cross-platform interchange between light rail vehicles and feeder buses in *both* directions using a single platform (Figure 23).

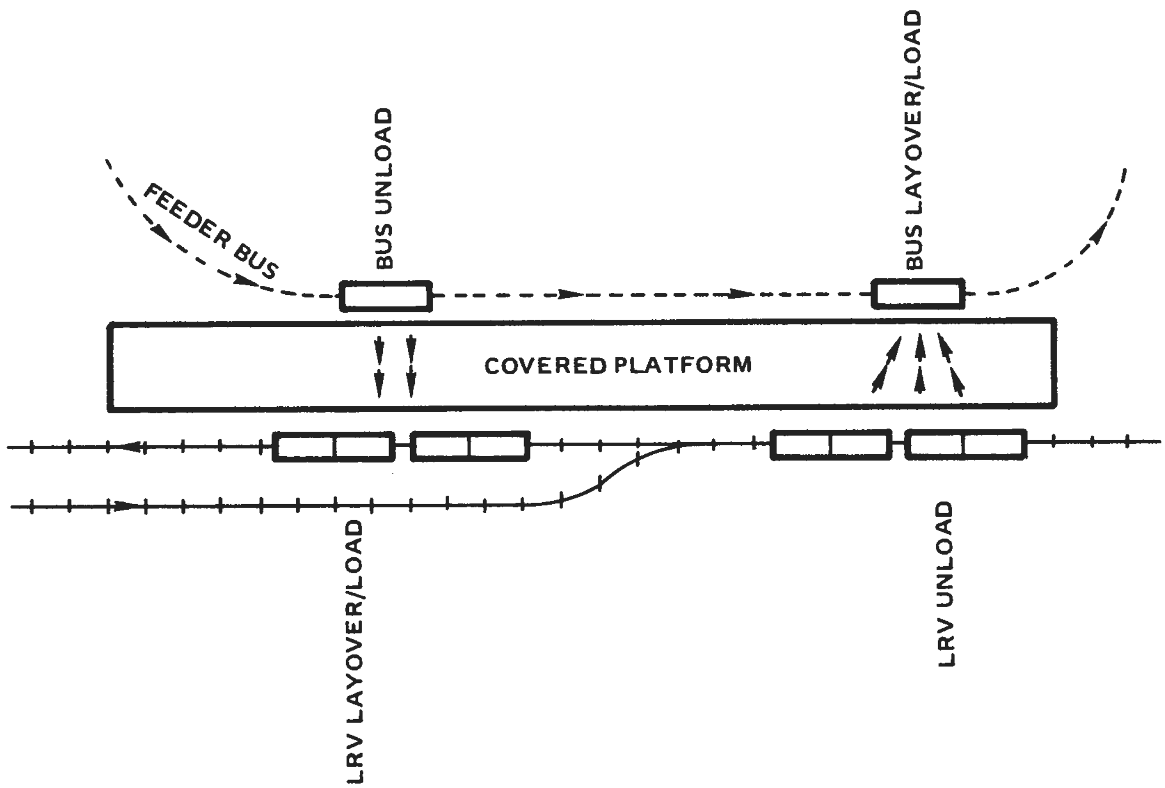


Figure 23. Two-way Cross Platform Transfer at the New Lahe Terminal

SIMILAR SYSTEMS

The technology and operation of the Hannover system is essentially the same as that adopted on a smaller scale in San Francisco. The concept of a high investment semi-metro with extensive subway or elevated sections, which does not plan to proceed ultimately to a fully grade separated system, is new. There are, as yet, not many similar systems. However, the planning philosophy in The Hague, Dusseldorf, and Basel is very similar.

SAN FRANCISCO – MODERN LRT IN THE UNITED STATES

The light rail system evolving in San Francisco is an example of a typical semi-metro type light rail system incorporating the upgrading of a streetcar network, the reequipping of the vehicle fleet, and the construction of a downtown subway. These actions are generally in accordance with current practice on a number of European systems.

CITY DESCRIPTION

San Francisco is a densely built city situated at the end of the San Francisco Peninsula. It is almost square in shape, with seven-mile sides, but with the downtown area in the northeast corner of the city around the original port and ferry terminal. San Francisco is a major commercial center, and the central city of the much larger Bay Area community. Its dense development is one of the reasons for the strong transit riding habit in San Francisco.

TRANSIT IN SAN FRANCISCO

San Francisco has a long history of transit development. It was the first city on the West Coast to offer urban transit service. The first horse streetcar line was opened in 1860. Over the years, this line was followed by steam streetcars, the famous cablecar lines, electric streetcars, and more recently, by the BART system. The principal transit agency is the San Francisco Municipal Railway, known as the Muni, which operates a mixed fleet of over 1000 buses, trolleybuses, streetcars and cablecars. The San Francisco streetcar system is the third largest in the United States, after Boston and Philadelphia. Each segment of this diverse, multi-modal transit fleet performs a special role.

The cablecar system is confined to three lines operating over steeply graded routes in the older part of the city. Due to the high labor requirements (two men per vehicle), this system is extremely costly to operate, and is retained primarily as a historical monument contributing to the city image.

The trolleybus network consists of a number of major radial lines constructed between 1948 and 1952 to replace a number of streetcar routes. A major reason for selecting trolleybuses was the existence of the old streetcar electrical installation which greatly reduced the installation cost. The present fleet of 333 trolleybuses is about to be replaced with new vehicles manufactured by Flyer Industries of Canada. A number of possible trolleybus line extensions and diesel bus route conversions are presently being considered, primarily along routes which are already largely electrified or are well patronized routes operating over steeply graded streets.

The streetcar system consists of an arterial line running diagonally halfway across the city and branching into five separate routes. These routes were retained after the abandonment of the major part of the San Francisco streetcar system, because they pass through two major tunnels which could not be converted to bus operation.

The BART system operates a line serving a single corridor with nine stations between the downtown area and the southwest part of the city. Regional services into San Francisco are provided by BART trains from the East Bay; by the Alameda-Contra Costa County Transit District buses from the East Bay; and by the Golden Gate Transit District buses and ferry boats serving the suburbs to the north of the city. The Southern Pacific provides a conventional railroad commuter service to communities as far south as San Jose, a distance of 45 miles. The Greyhound Bus Company also provides service to communities south of San Francisco. Apart from BART, none of these regional transit agencies provides transit service within San Francisco.

The Muni system charges a 25 cent flat fare, and grants free transfer privileges. The transfer is valid for a period of two hours and twenty minutes from the time of first boarding, and permits multiple transfers or stopovers on any trip in a continuous direction. The transfer is not valid for a reversal of direction or a round trip. Fares are collected using the traditional North American fare box system. In the past two years, a monthly pass costing $11 has been introduced. This pass has proved popular with the riding public and has increased the rate at which passengers board the vehicles. At a rate of 44 times the single trip farebox fare, the pass would appear to be overpriced by European standards. Nevertheless, it is an important step toward streamlining the fare collection system.

BART has its own fare collection system, based on magnetic cards and automatic fare collection barrier machines. Passengers transferring from one system to another are given a fare discount by means of a somewhat complex two part transfer system. There is presently no coordination of fares between any other transit operators providing regional services out of San Francisco. In the fiscal year 1973-1974, the Muni deficit was approximately $35 million, which was funded from San Francisco tax revenues. The recent availability of funds from revenue sharing and from federal transit operating assistance has tended to ease the burden of the transit system on the city's taxpayers.

Table 13. San Francisco Transit Statistics

<table>
<tr><th></th><th>Existing LRT</th><th>Bus and Trolleybus</th></tr>
<tr><td>Number of vehicles</td><td>115 PCC
100 Boeing LRV on order</td><td>880</td></tr>
<tr><td>Length of double track length (miles/km)</td><td>19/30</td><td></td></tr>
<tr><td>Annual passengers (millions)</td><td>16.8</td><td>90.9</td></tr>
<tr><td>Annual vehicle – miles/km (millions)</td><td>3.3/5.3</td><td>21.3/34.3</td></tr>
<tr><td>LRT network coverage – partial – certain major lines only</td><td></td><td></td></tr>
<tr><td><table>
<tr><th></th><th>Existing</th><th>Future Muni Metro</th></tr>
<tr><td>LRT right-of-way type</td><td></td><td></td></tr>
<tr><td>Subway</td><td>18%</td><td>36%</td></tr>
<tr><td>Reserved</td><td>9%</td><td>20%</td></tr>
<tr><td>Mixed Traffic</td><td>73%</td><td>44%</td></tr>
</table></td><td></td><td></td></tr>
<tr><td>Community transit habit – 158 trips/capita/year*</td><td></td><td></td></tr>
<tr><td colspan="3">*Based on Muni ridership and city population only.</td></tr>
</table>

THE LIGHT RAIL SYSTEM

In 1947, the Muni rail system consisted of a network of approximately 150 miles of double track, on which almost 700 streetcars provided most of the city transit service. A succession of conversions to bus operation left the city with its present system: a single line-haul line of approximately 19 miles (30 km) of double track with five branches (Figure 24), over which 115 post-war PCC cars operate. In 1974, the streetcar part of the Muni system carried 15 percent of the passenger trips and operated 13 percent of the vehicle miles. The light rail system provides service only in certain corridors in the city; alternative bus routes are usually available. The Muni system may thus be classed as a system offering only partial coverage.

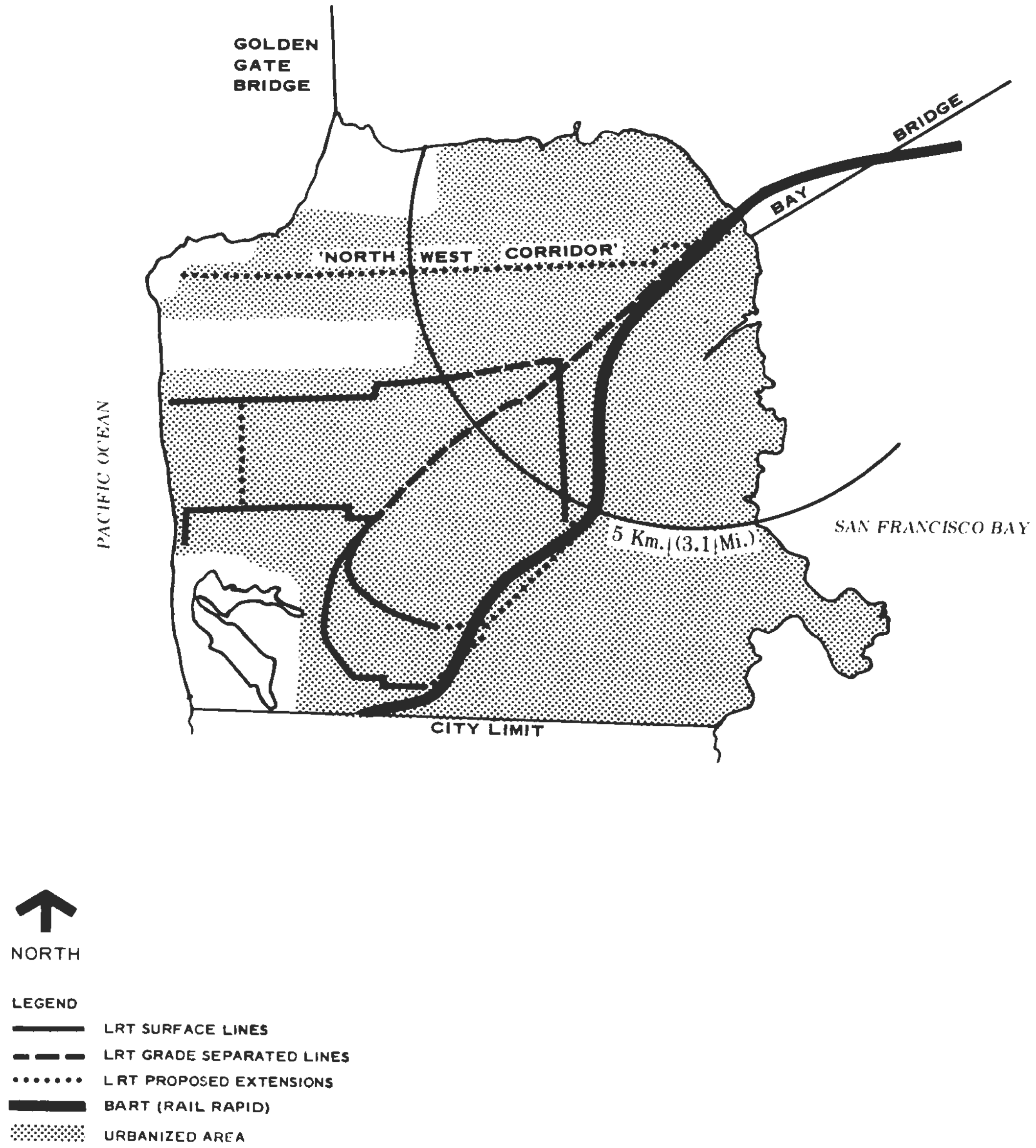


Figure 24. San Francisco System

Apart from some neighborhood bus lines which feed the rail lines, there is no general policy for using feeder buses to support the existing Muni rail system. The primary reason is that in the peak hour, there is no spare capacity on the existing rail system. A number of transit lines for LRT have been striped on city streets to speed up service and protect the streetcars from delay due to traffic backup.

In 1962, a bond issue was approved by the voters of San Francisco and neighboring counties to finance the BART regional rail rapid transit system. As part of the BART system, a subway is being constructed beneath Market Street to accommodate the San Francisco streetcar lines on the line-haul portion of their routes. This subway has now been completed throughout the central part of San Francisco. It is about five miles in length with eight stations, of which four are two-level stations shared by the Muni and BART systems. Because the two systems use different track gauges, there is no track connection between them.

As the design of the streetcar subway evolved, it became apparent that a new generation of streetcars would be required to operate on the new subway system. This need for new equipment in San Francisco and similar problems in Boston led to the development of the Boeing light rail vehicle.

As the plans for the upgraded system developed, it also became clear that most of the existing streetcar system was worn out, and that much of the track and overhead dated from the original installations in the 1920s and earlier. Consequently, in 1972, a major transit improvement program was initiated, funded in large part by the federal government. This program includes not only the acquisition of 100 Boeing LRVs, but also the rerailing and improvement of most of the remaining surface streetcar trackage, the construction of new storage and maintenance facilities, and the complete renovation of the entire power supply system for both the light rail vehicles and trolleybuses. When this program is completed, the Muni light rail system will be given the name Muni Metro as a symbol of its new identity. Figure 25 shows the Van Ness LRT station under construction, while Figure 26 shows a section of newly constructed median trackage built to replace mixed traffic operation. This work was carried out without cessation of streetcar service.

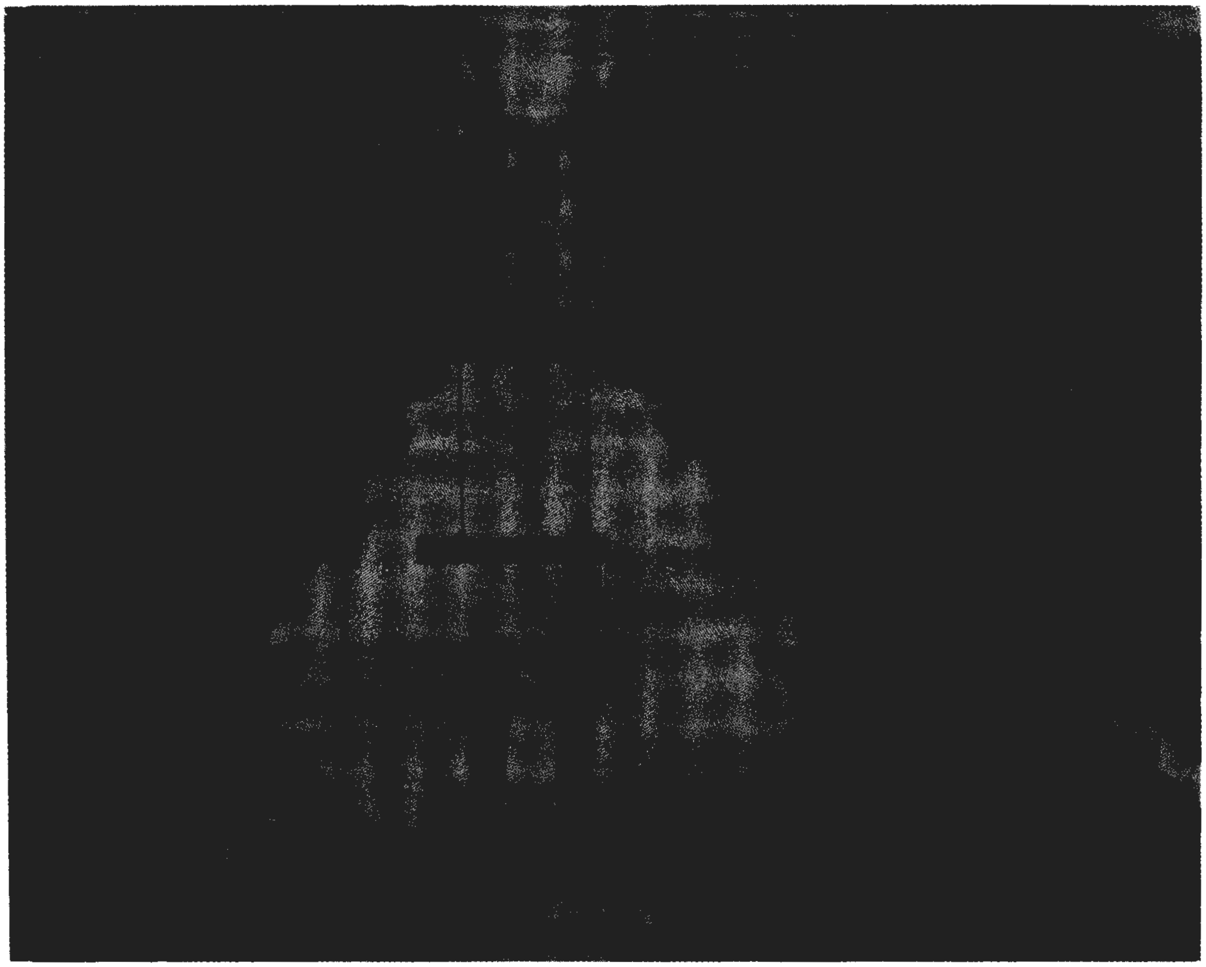


Figure 25. Van Ness Station Under Construction

Figure 26. New Median Trackage – Judah Street

The delivery of the new light rail vehicles will commence in 1977. As these cars are delivered, they will be put into service in stages, one line at a time. An important feature is that in the subway section, they will load and unload passengers from floor height platforms. Through the use of retractable steps, these vehicles can also load and unload passengers at street level.

MUNI METRO OPERATIONS

The Muni Metro System will operate five distinct lines, as at present. The subway section of the network will be operated under the protection of an automatic speed control system using track circuits and onboard cab signals. One impact will be to increase the permissible train headway compared to the present streetcar operation, making it necessary to couple the vehicles together where routes converge at subway portals to achieve sufficient line capacity. The system bottleneck will be the stub-end station at the Embarcadero, where all cars must be reversed through a double crossover. Plans have been developed to convert this stub-end station to a loop, thereby eliminating the bottleneck. Fare boxes will continue to be used on the surface sections, but coin operated turnstiles are being considered for use in the subway stations. Due to the retention of the fare box system, one crewman will be needed to collect fares on each car, even when the cars are running in multiple unit trains.

PLANNING AND POLICIES

The current improvement program includes two minor extensions, connecting the K and M lines by way of the Balboa Park BART station. These extensions will consist of just over a mile of new trackage, most of it on the street. The purpose of this new loop line is to increase patronage at the outer ends of the existing routes by providing a reverse direction flow to the BART station. Access to the storage and maintenance yard will also be improved by the provision of this alternative route. Other minor line extensions are also planned, but construction is unlikely in the near future.

In 1974, BART completed a study of rapid transit extension into the northwest part of the city. This area is densely populated and has very high transit potential. At present, it is served by a diesel bus route operating at headways of less than two minutes in the peak period, with the buses still crush-loaded. The study recommended the construction of an LRT line of the Muni Metro type to serve this corridor, approximately half of it in subway and half on the surface. However, the plan was not well received, either by the city or by the community along the route for a number of reasons:

- Most of the route lies in residential areas, consisting mostly of closely built single-family dwellings. The community is fearful that transit construction will stimulate a demand for redevelopment and commercial intrusion.
- The eleven years of construction disruption attributed to BART on Market Street have dimmed for the time being the prospects for further subway construction in San Francisco.
- The savings in trip time through the construction of the Muni Metro line would not be great enough to give a major return for the substantial subway construction cost.
- The cost overruns and continuing operational problems with the BART system, and the still unproven reception of the Muni Metro operation, are causing a reappraisal of the role of rapid transit at this time.

Consequently, the northwest corridor project has been temporarily shelved.

SIMILAR SYSTEMS

The San Francisco Muni Metro system, when completed in 1979, will be an excellent example of a straightforward semi-metro system. It is conceptually very similar to the Boston LRT, constructed almost 80 years before. It is also similar to European LRT systems which are constructing extensive grade separations but which do not intend to convert to rail rapid transit at some future date. Such systems include Ludwigshafen, Mannheim, Hannover, Frankfurt, Bern, and others. The new Edmonton system is conceptually similar to the Muni Metro, except that neither mixed traffic operations nor low level platforms are planned.

EDMONTON – EUROPEAN TECHNOLOGY TRANSPLANTED

In 1974, the city of Edmonton in Alberta, Canada, began construction of the first segment of the first new light rail system in North America since World War II. The technology for this system is an almost exact copy of that developed almost ten years ago for Frankfurt, West Germany, and adapted, where necessary, for Edmonton's severe climate. The undramatic and businesslike manner in which the light rail project is being implemented, and the use of foreign equipment, where necessary, are two aspects of particular interest.

CITY DESCRIPTION

Edmonton is situated in the northern Great Plains of Canada just east of the Rocky Mountains. With a metropolitan area population of over 500,000 people, it is the capital of the province of Alberta, and contains a well developed central core. In addition, a number of regional centers have developed around shopping centers in the suburban parts of the city. There are also a number of other major trip generators such as the University of Alberta, the Technical College, and industrial areas, located away from the city core.

TRANSIT IN EDMONTON

The city of Edmonton transportation department currently provides transit service with a mixed fleet of buses and trolleybuses. The trolleybus system is being refurbished and expanded. At present, the combined system carries almost 19 percent of all trips within the metropolitan area. The transit network is structured around a number of transportation centers, either shopping centers or other major trip generators, which are connected by express buses or trolleybus lines. The feeder and express services are generally scheduled to meet at transportation centers, thus minimizing system transfer penalties despite relatively long headways.

Table 14. Edmonton Transit Statistics

	Future LRT	Existing Bus Systems
Number of vehicles	14 6-axle U2 cars	405
Length of double track (miles/km)	4.5/7.2	
Annual passengers (millions)	43.5	
LRT network coverage – single radial corridor		
LRT right-of-way type – 22% subway 78% reserved		
Community transit habit – 98 trips/capita/year		

THE LIGHT RAIL PROJECT

Almost ten years ago, the city transportation department was established to coordinate and operate transportation in Edmonton and to develop a long-range transportation plan. This plan included substantial input from the public, including city neighborhood groups. The major theme throughout the plan is that automobile use should be deemphasized and that every effort should be made to make transit attractive. The present transit network is developing much as set out in the plan. One of the policies in the plan states that as patronage on the express links between transportation centers developed, consideration should be given to converting these lines to a guideway system on an incremental basis.

In 1972, detailed planning commenced for the construction of a rail line between downtown and the northeast part of the city. The original planning was based on the Toronto type rail rapid system. However, it was found that cost savings could be realized if grade crossings were permitted, and that system expansion options would be more extensive with light rail. The mode selected was the type of light rail in operation on the A Line network in Frankfurt, West Germany. This starter rail line is approximately four and one half miles long, with a total of five stations. The CBD section of the line includes approximately one mile of subway, while the rest of the route is a surface line operating in a wide median between two railroad tracks. Grade crossings will be controlled by barriers already in existence for the parallel railroad track.

Construction began in 1974. Approximately half a mile of subway line is of cut-and-cover construction, and half a mile requires twin bore tunnel. This work was nearly completed by the end of 1975. A major feature of the construction schedule was its tight planning to minimize surface disruption. Substantial advance warning was given to offices and businesses along the route as to when streets would be closed and for how long. This practice lessened the inconvenience usually caused by subway construction. It is estimated that the first line will be ready for traffic in 1978 (Figure 27).

The fourteen cars required to operate the initial line will be the DuWag U2 type originally developed in the 1960s for Frankfurt. They are standard 6-axle articulated cars which seat 64 passengers. The components for the initial order for cars will be imported from West Germany, with the final assembly and finishing work done in Edmonton. The purchase agreement includes provision that future cars for system expansion may be manufactured under license in Canada. A major incentive for the adoption of light rail is that the high speed and reliability of the service are expected to attract considerable additional patronage. Moreover, the fourteen light rail cars will allow reassignment of some 35 buses otherwise required for this route.

Alternative fare collection systems are currently under review to determine what system should be used on the LRT line. Since there are only five stations on the starter segment, the coin turnstile system will probably be used.

Approximately 66 percent of the project is funded by the province of Alberta with the balance from local city funds. The starter line is estimated to cost approximately $60 million including interest charges and inflation. Patronage is expected to be about 5000 passengers per peak hour, peak direction, with variable length trains operating at five minute headways.

PLANNING AND POLICIES

The Edmonton transportation plan envisages the eventual construction of a full network of transit lines serving all major transit corridors in the city. Studies are currently underway to determine the feasibility of future network extensions, and to establish preliminary alignments, station sites, feeder services and implementation priorities. Various rights-of-way are being investigated, including median operation and a transit mall through the university campus. The pace of construction for this network will depend on the public's reaction to the initial line, the rate of growth of transit ridership, city-wide, and funding availability.

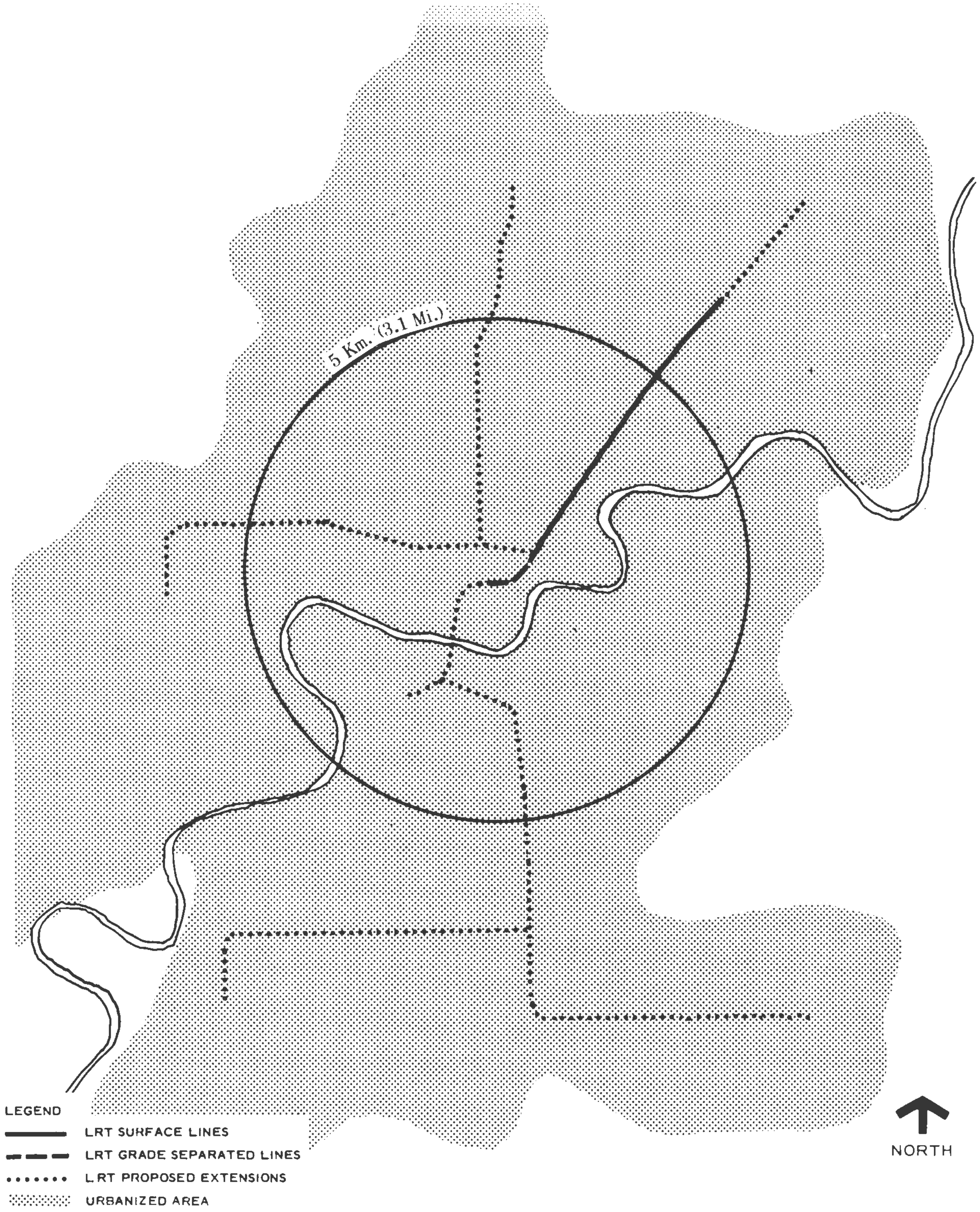


Figure 27. Proposed Edmonton System

SIMILAR SYSTEMS

The Edmonton LRT will be a semi-metro operation, almost identical to the Frankfurt A Lines. In terms of its speed and the characteristics of its surface line operation, it will be similar to the present Shaker Heights operation.

TYNE & WEAR – A MAJOR NEW LRT SYSTEM

The Tyne & Wear project at Newcastle, England is the largest entirely new light rail system under construction in the western world. Prior to the selection of light rail for this system, extensive analyses were made of bus and passenger railroad alternatives. The technology selected for Tyne & Wear is based on the best of the current European practice, with a number of modifications intended to optimize performance.

CITY DESCRIPTION

The Tyne & Wear region is an urbanized area centered in Newcastle on the northeast coast of England. The population of the metropolitan area is approximately 1.25 million. For several centuries, the area has been a center of coal mining, and more recently of general heavy industry. With the decline of coal-based industry in the past few years, service industries have expanded, a trend much accelerated by the transfer of some government offices to Newcastle.

TRANSIT ON TYNESIDE

Between 1920 and 1965, trends in British urban transit followed a course similar to those in the U.S. By 1970, the 42 trolleybus systems in Britain had closed and the 180 odd streetcar systems were reduced to two lines retained as tourist attractions. By 1965, many cities were operating their own bus services, often resulting in several cities running publicly owned bus systems within one metropolitan area. There was also a great number of independent bus operators. The transit systems generally operated without service or fare coordination among themselves or with the state railway system.

In the late 1960s, Passenger Transport Authorities were set up in all major British metropolitan areas to integrate and improve public transit. These authorities acted through Passenger Transport Executives (PTEs), who were responsible for planning and operating transit in their jurisdictions. The first task of the newly established PTEs was to prepare long-range transportation plans for their regions. These plans, in most cases, call for continued reliance on bus systems, with varying degrees of upgrading and coordination of rail services.

The Tyne & Wear PTE inherited within its region several city bus systems, various suburban and rural bus lines, three passenger ferry services across the River Tyne, and a network of decaying suburban railway passenger services. At the present time, apart of its three ferryboat operations, the Tyne & Wear PTE operates an all-bus system only. In addition, it finances the operating deficit of a network of suburban railways, which are operated by the state railway system on a provision-of-service contract. The rail network links most of the major population centers in the region to Newcastle. However, the rail service has been without necessary investment for many years, and is now greatly run down. A few years ago, the electric trains which operated the service were replaced by diesel multiple unit trains. Most of the stations have remained essentially unimproved since the day they were built over a century ago. More seriously, the rail services focus on the central railway station, and offer only one somewhat inconvenient stop to serve central Newcastle. The future of these rail services becomes the central issue in the development of the regional transportation plan.

Table 15. Tyne & Wear Transit Statistics

	Future LRT	Present Bus
Number of vehicles	97 6-axle	50 2-axle single deck 750 double deck
Length of double track (miles/km)	34/55	
LRT network coverage – regional trunk lines only		
LRT right-of-way type – 100% reserved or exclusive		

THE LIGHT RAIL PROJECT

During the development of the long-range transportation plan, a number of alternatives were considered. They included the modernization and retention of the existing rail services, the development of express bus transit using busways constructed along the existing railways, the development of light rail transit, or the continuation of existing services and trends. According to the PTE General Manager, these studies showed that buses offered a readily available mode, while rail required the introduction of many technological and operational elements never used before in Britain. The bus option was therefore very attractive. However, the studies showed that the bus option could not perform the required transit service necessary to attract a sufficiently large mode split in favor of transit.[12] Therefore, the PTE decided to develop a light rail system, making maximum use of existing rail rights-of-way.

The plan adopted for the Tyne & Wear Metro is a 55 km (34 mile) network, of which 42 km (26 miles) are on existing railroads (almost entirely grade separated), and 13 km (8 miles) will be new construction (see Figure 28). The major part of the new construction consists of two intersecting subways in the central part of Newcastle, designed to provide better access and coverage in the CBD area than at the existing central station. A similar but shorter subway will pass beneath the center of Gateshead, a nearby community. Several other small detours are made from existing railroad alignments, where necessary, to secure more accessible station locations. Much of the railroad right-of-way to be used for this system already carries passenger train service using diesel multiple unit trains with headways around 20 minutes during most of the day.

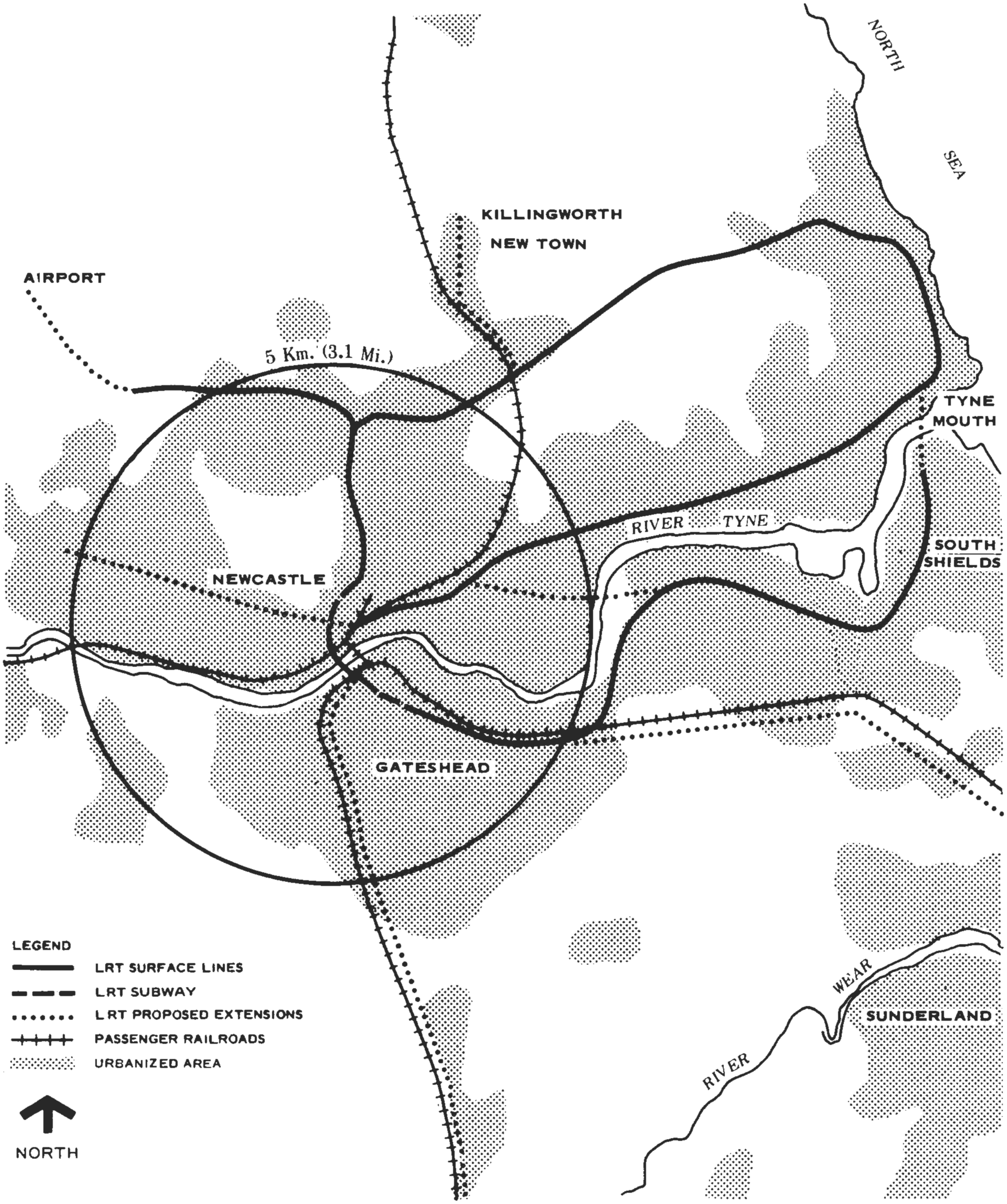


Figure 28. Proposed Tyne & Wear System

Major objectives of the metro plan are to improve accessibility to the rail system by doubling the number of stations and to maintain the same average speed per trip by using high performance, lightweight electric rolling stock. For this reason, the various existing types of railroad equipment used in Britain were rejected, and the decision was made to develop a new lightweight car based on the design of the DuWag Type B car. The car itself was designed and constructed by Metro-Cammell, the principal British manufacturer of rail equipment. Two prototype cars have been constructed and are being tested on the system's test track. The 84-seat, 6-axle articulated Tyne & Wear cars will operate either singly or in trains of up to three cars. Figures 29 and 30 show one of the prototype cars and some experimental track construction at the Backworth test track in 1975.

The overriding design principle of the system is to minimize costs through the use of the simplest possible design standards. Signalling will be of the simple, two-aspect block system. Stations will conform to European light rail practice, consisting of simple platforms and shelters, except in the CBD where conventional subway stations will be constructed.

A significant departure from current light rail practice was the selection of 1500 volts DC for the overhead power supply. The choice was made after considering alternative systems using 750 or 1000 volts DC. It was found that considerable savings in installation costs could be derived from the selection of this system. Moreover, the selection of this voltage is expected

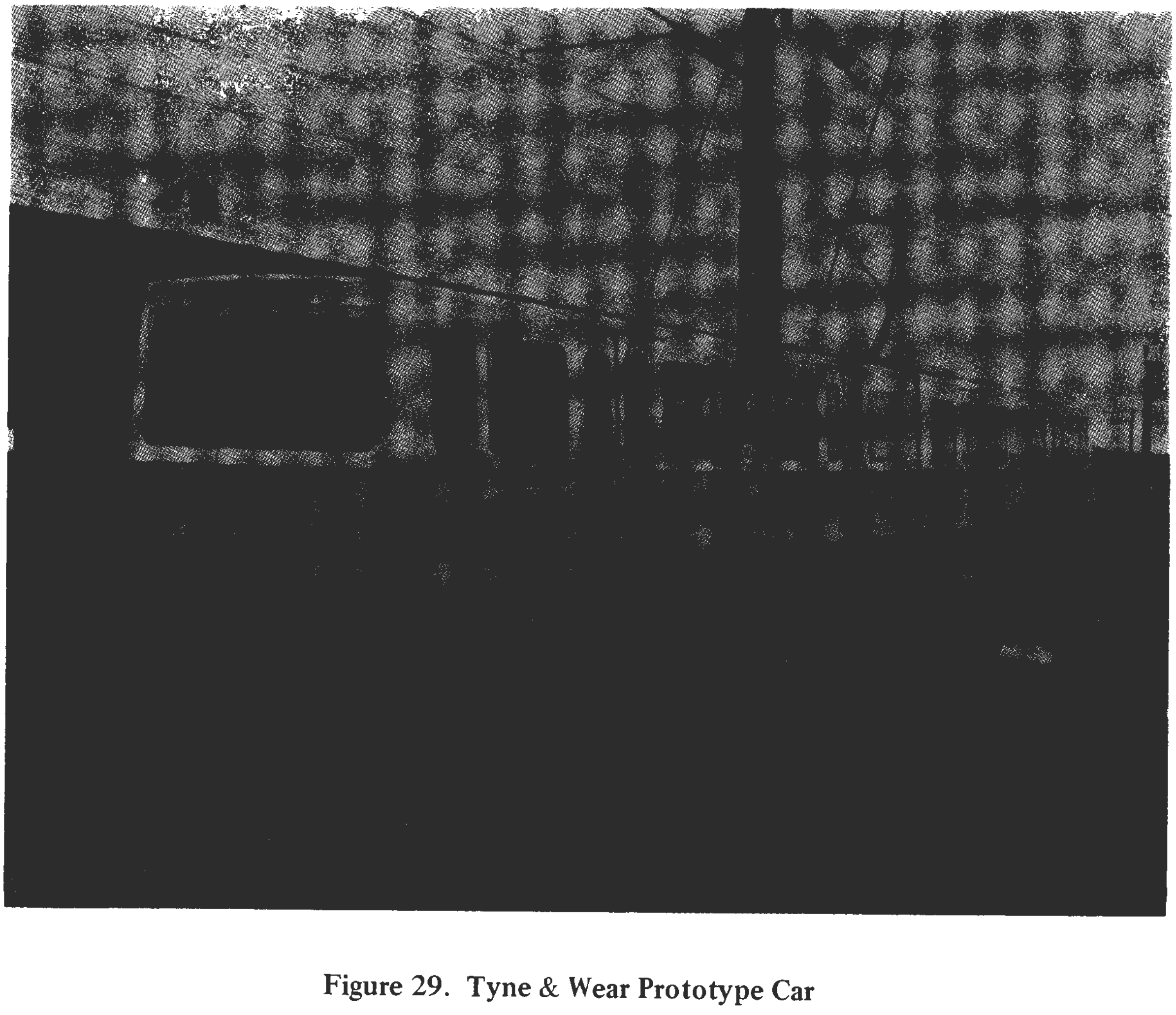


Figure 29. Tyne & Wear Prototype Car

Figure 30. Experimental Track Construction

to show an energy saving of 3-1/2 percent compared to a 1000 volt DC system. Standard 750 volt traction motors are used, connected in series, but insulated for 1500 volts for safety reasons.

On certain sections of the route, freight trains will continue to use the right-of-way. In one location where freight traffic does not exceed two short trains per day, joint track use is proposed. At another point in the system where the line carries substantial freight traffic, an additional "freight only" track will be laid beside the metro tracks.

The European self-service fare collection system will be introduced in Britain by the Tyne & Wear system. The proposed fare structure will be a variable rate based on distance, with tickets purchased from machines. Train operators will have no responsibility for fare collection. The layout of the prototype cars would make a fare box collection system impossible. Passengers will be required to cancel their tickets, and the system will be enforced by selective inspection. Since there is no precedent for the self-service fare collection in Britain, the laws under which the Tyne & Wear Metro is being constructed include a special provision permitting its use, and authorizing the PTE to enforce it. Prior to the introduction of the self-service system, the PTE is encouraging the maximum use of passes by means of advertising and cost incentives.

By mid-1975, the estimated cost of the project was approximately $280 million. With the British inflation rate currently in excess of 20 percent per year, this figure is likely to be greatly increased before the system is in operation. Construction began in late 1974; the first segment of the system is planned to operate in 1978. Completion of the entire first stage is planned for 1980.

SIMILAR SYSTEMS

Although several new systems are now under construction or are being planned, none represents such a thorough reappraisal of light rail technology as was done for the Tyne & Wear Metro. Through its use of high level platforms and the emphasis on high quality right-of-way, Tyne & Wear is similar to the Frankfurt A Lines. However, the car technology is more closely based on the DuWag B Type car developed for Cologne and adopted for several other west European systems.

PLANNING TRENDS

The decline and virtual elimination of streetcars was a worldwide trend not unique to the U.S. In Britain, France, Spain, Canada and Scandinavia, the streetcar was almost completely replaced by buses, while in Belgium, Holland, Germany, Switzerland and Austria where it remains the primary urban transit mode, many smaller networks were closed, and large networks were cut back. Even in some cities heavily dependent on streetcars such as Amsterdam, there was a strong movement to eliminate them.

The change to a more favorable attitude towards LRT is now widespread, and in many cities where LRT exists, improvements are planned or being made. Exceptions are found in a few cities which already have a commitment to another mode (Hamburg) or which are operating small and inefficient systems more economically served by buses.

A major part of the LRT improvement effort is directed towards preferential treatment for on-street LRT operations. Where possible, emphasis is placed on the removal of conflicting traffic from LRT trackways which is a low cost, undramatic treatment of particular appeal in times of economic hardship. New systems, major network changes or extensions to existing systems have stressed improved levels of service often achieved through partial grade separation.

The planning approach to LRT reflects the planning concepts of the period in which it was done. For instance, the planning of the early 1960s stressed the pre-metro concepts typified by Brussels. Many such systems were planned even in cities as small as Bielefeld (pop. 320,000). In more recent times, the development of new LRVs, the reappraisal of growth projections, and improved transportation planning techniques have stressed the semi-metro concept. By the mid-1970s, even this concept was being questioned, and alternative, low investment concepts began to attract attention.

A further trend on most LRT systems has been towards the operation of smaller fleets of larger vehicles. The significant exceptions to this trend, Gothenburg, The Hague, Toronto, continue to use smaller vehicles, and trains of vehicles wherever possible.

CHAPTER 4

RIGHTS-OF-WAY AND STATIONS

The basic distinction between light rail and rail rapid transit is the former's potential to take advantage of a wide variety of rights-of-way. A broad spectrum of potential station configurations may be used. This versatility creates the potential for reduced capital investment, less environmental impact and faster construction than is possible with rail rapid transit. LRT's attractiveness as a transit mode lies largely in the flexible manner in which it can exploit right-of-way (ROW) opportunities, and in the cost savings which can accrue from the selection of appropriate design treatments.

TYPES OF LRT RIGHTS-OF-WAY

LRT systems may be characterized by their rights-of-way which largely determine the system's performance: the more separated the right-of-way from conflicts with other traffic, the higher the potential schedule speeds for a given alignment and station spacing. However, achieving higher standards of exclusiveness often requires considerably greater capital expenditure for subway or elevated guideways.

In Chapter 1, the influence of right-of-way on the classification and performance of transit modes is outlined. The distinguishing feature of the light rail transit mode is its capability to operate on all three of the basic categories of right-of-way: Category A, fully controlled, grade separated right-of-way, also referred to as *exclusive, private,* or *separated*; Category B, partially controlled right-of-way also referred to as *semi-exclusive*; and Category C, surface streets with mixed traffic, also referred to as *shared*.

- On *exclusive* right-of-way, LRT operation is fully controllable; vehicular or pedestrian crossings are prohibited. Segments of an LRT network may use this category; however, rail rapid systems such as the San Francisco BART and the Washington Metro can operate only on fully exclusive rights-of-way.
- On *semi-exclusive* right-of-way, LRT operation is separated from other traffic except at grade crossings. This category is very broad. It includes operations with reserved transit lanes sometimes shared with buses, and curbed street medians. Rights-of-way with grade crossings at a range of spacings are included in this category.
- On *shared* right-of-way, LRT operates in mixed traffic with autos and buses. This type of operation is characteristic of streetcar service and should be limited in application to qualify a system for light rail operation.

An LRT network may contain segments of each category of right-of-way. The predominant right-of-way found in present and proposed LRT systems is semi-exclusive (Category B). However, cost and the desired level of service will govern the percentage of each category in any particular system. Examination of selected European and North American networks, summarized in Table 16, illustrates the variation in quality of LRT rights-of-way from city to city and its impact on system-wide average speeds.

Table 16. 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.

VERTICAL PROFILE CONSIDERATIONS

A second distinguishing feature of LRT is its latitude to be operated within a range of alternative vertical profiles along segments of route, i.e., from at-grade installations along streets or arterials to full grade separation on aerial or in subway. While, as expected, the specific vertical profile will affect performance, LRT has an intrinsic system flexibility which makes it possible to match, in varying instances, right-of-way, vertical profile and desired performance more cost effectively than other transit. In developing a particular category of LRT right-of-way, three basic vertical alignment alternatives can be used.

- With an *elevated* profile, LRT operates on a structure or embankment above ground level. Elevated LRT almost always implies a fully controlled right-of-way for that portion of track.
- With an *at-grade* profile, LRT operates at ground level on shared, partially controlled, or fully controlled right-of-way. In the partially controlled ROW, curbs, barriers, turn prohibitions, special signals and grade separation at important intersections may be incorporated.
- With a *depressed* profile, LRT operates below ground level either in open cut or in subway structure. This treatment may be used on sections sensitive to visual or noise intrusion, or on sections of otherwise at-grade right-of-way where closely spaced intersections would prohibit desired safe, higher speed operation. In subway, the space above would be readily available for other uses, although air space over open cuts have been used for other purposes. Depressed alignment always provides controlled right-of-way.

The vertical alignment need not be constant, but can vary among these four basic alternatives in response to right-of-way opportunities and operational requirements. Thus a line which is basically at grade might include short stretches above or below grade, as for an overpass or short subway, respectively.

LIGHT RAIL NETWORK LOCATION OPTIONS

The rights-of-way available for LRT systems can be developed in various combinations with the alternative profile options to provide a wide variety of design treatments which offer a comprehensive set of cost and performance options. Table 17 illustrates how the use of specific design treatments in various rights-of-way result in a variety of cost, performance and right-of-way category options. Of special interest are at-grade treatments which allow semi-exclusive operations at generally minimum initial cost. Grade separation using elevated or depressed profiles permits exclusive operation with a high level of service, but is substantially more costly and may be justified only for corridors with sufficiently high demand levels. Clearly, the three right-of-way categories represent three different combinations of system performance/investment cost relationships. The right-of-way type, even more than the type of technology, influences the characteristics of LRT and other transit modes.

Table 17. Light Rail Transit Locational Opportunities

Right-of-Way Location	Design Treatment	Right-of-Way Category	Relative Cost*	Performance Levels**
Street	At grade – shared	C	Low	3
	At grade – partially controlled	B	Low/medium	2
	Elevated	A	Medium/high	1
	Depressed	A	High	1
Freeway	At grade – median	A	Low/medium	1
	At grade – beside	A	Medium/high	1
	Elevated	A	Medium/high	1
Railroad all at grade	Abandoned	B C	Low/medium	1
	Joint use of track	B C	Low/medium	1
	Separate track	B C	Medium/high	1
Open Space/Parkland	At grade	A B	Low/medium	2
	Depressed	A B	Medium/high	1
	Elevated	A	Medium/high	1
Utility easement	At grade	A B	Low/medium	1
New right-of-way	At grade	A B	Medium/high	2
No right-of-way	Depressed in subway	A	High	1

*Actual costs associated with each type of design treatment are discussed in Chapter 8.

**Performance Level 1 is typical of that achievable by bus or rail transit on fully controlled right-of-way. Performance Level 2 designates the level achieved by most modern LRT installations, i.e., somewhat inferior to rail rapid transit, but a marked improvement over streetcar operations. Performance Level 3 is typical of that achieved by transit in mixed traffic. Generally, the performance level describes average speed, train size and frequency of service. (See Chapter 7 for additional discussion.)

STREETCAR/LRT OPERATION IN MIXED TRAFFIC

The operation of rail vehicles on streets in mixed traffic is a typical feature of streetcar systems. In most modern LRT systems, parts of the right-of-way are separated from traffic, but often some sections are in mixed street traffic (Figure 31).

The performance and service quality of rail transit in street traffic can vary greatly, depending on street design and the control of traffic. Without special provisions for transit, streetcars operate under many of the same handicaps as buses in mixed traffic, with the

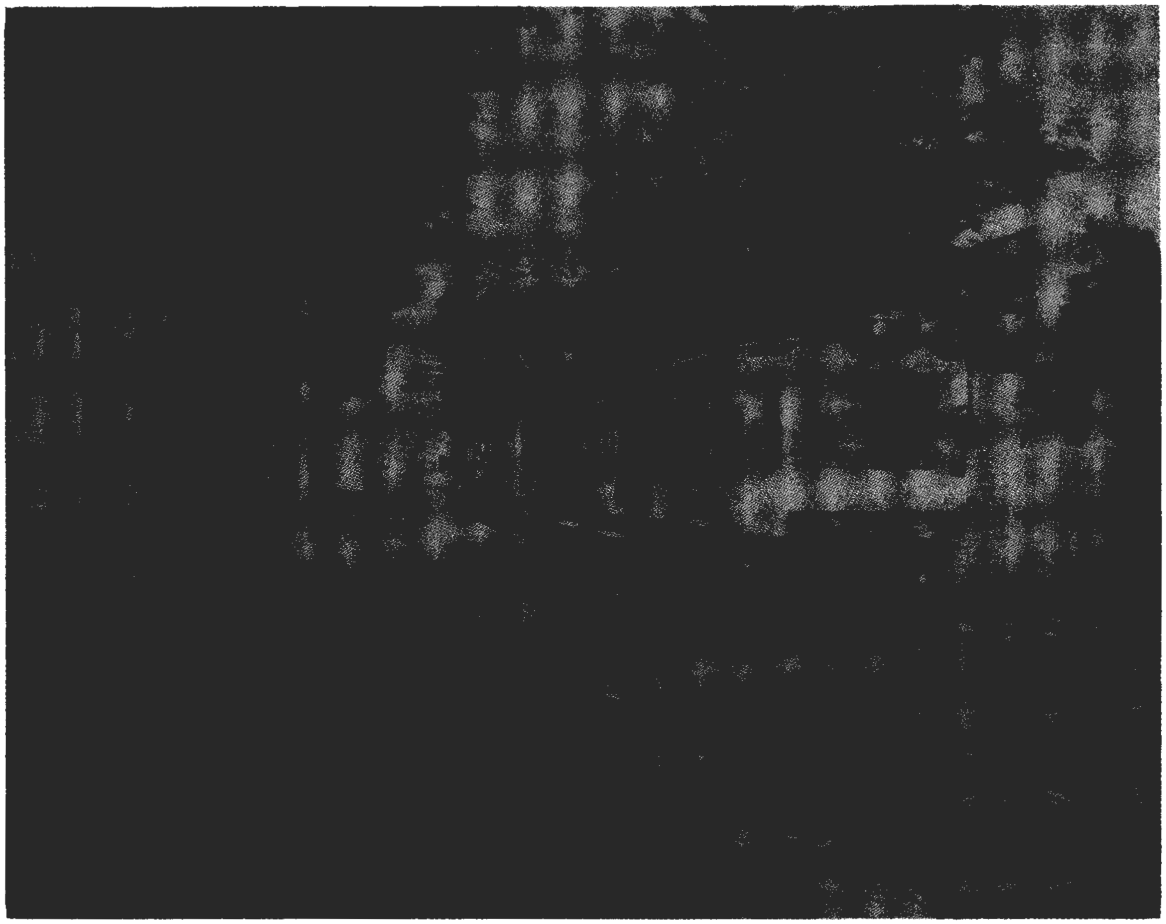


Figure 31. New LRVs Running in the Street in Bonn

additional disadvantage of lower maneuverability resulting in even greater delays. This condition was a major factor in promoting the elimination of streetcars from many cities. Some cities, however, upgraded their streetcar operations to LRT levels of performance by providing some exclusivity to the rights-of-way. In recent years, a trend has developed to upgrade the performance of streetcar operations through less capital intensive methods, such as regulatory measures which minimize the conflicts between rail and auto traffic (Figure 32).

A number of these new traffic management concepts and techniques aimed at minimizing delays to rail vehicles at intersections have been used on existing lines and new extensions of street trackage in Gothenburg, Amsterdam, The Hague, Zurich and most West German cities which operate LRT. The techniques include:

- Prohibition of left turns for auto traffic at minor intersections
- Provision of a special auto left turn signal phase at major intersections
- Provision of a special signal phase for turning LRT vehicles which is often actuated by the approaching vehicle
- Locating LRT stops alternately before and after successive intersections (coordinated signalization allows the LRT vehicles to proceed through both intersections without stopping)

- Elimination of curb parking along street sections with frequent congestion

- Use of sophisticated design and extensive pavement markings to allow joint use of the right-of-way and to separate the modes at transit stops, intersection approaches and turning areas.

Designing techniques for traffic management involving auto and transit modes is only one part of the solution; the other part, often more difficult to achieve, is their implementation. Cooperation from municipal traffic and engineering departments, city police and other agencies outside the domain of the transit agency is required. The progress made in implementing traffic management policies in West Germany has been achieved largely through the introduction of the so-called "Acceleration Programs" for priority treatment of transit vehicles. These programs are coordinated by specially formed committees consisting of representatives of public utility commissions, police, municipal street departments, transit agencies, chambers of commerce and automobile associations.

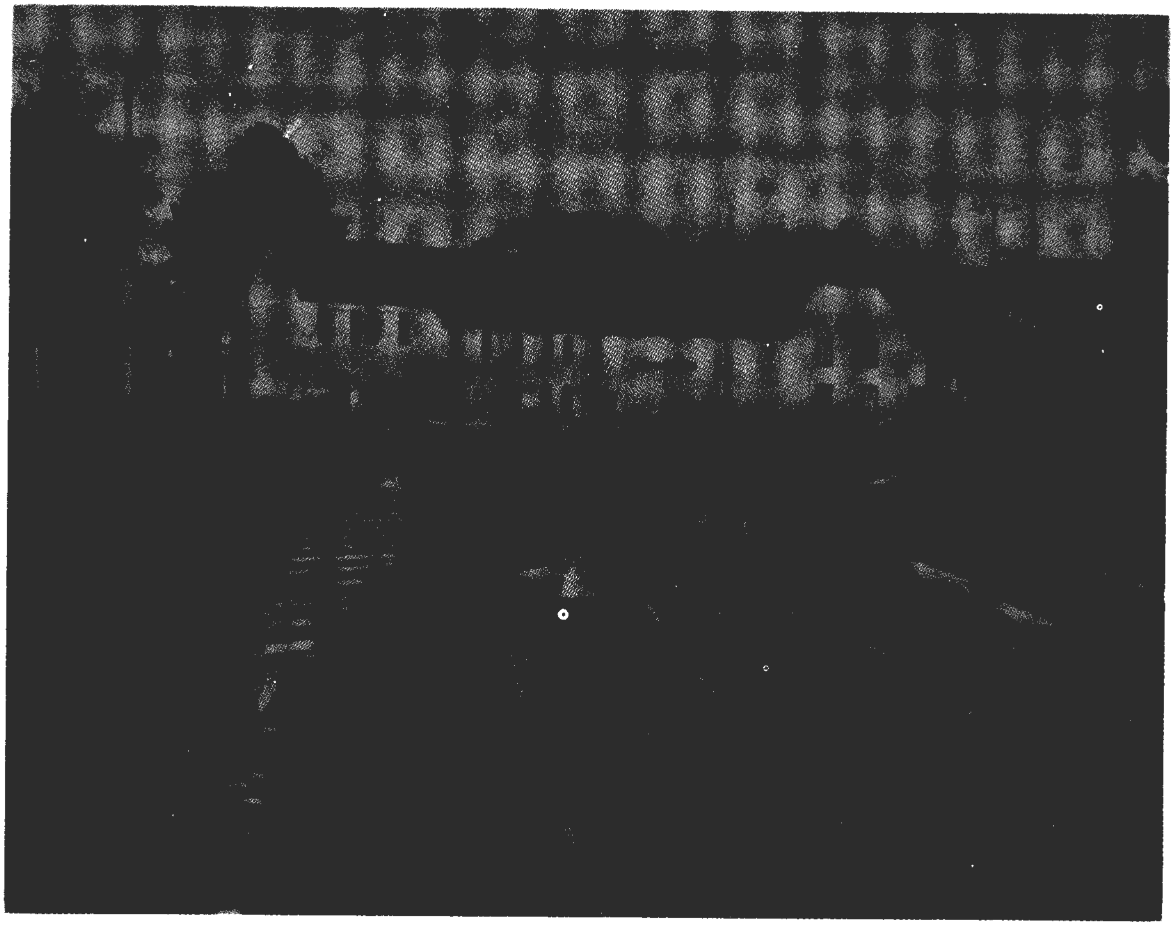


Figure 32. New Streetcar Line in Krefeld (Note Striping Detail)

RESERVED TRANSIT LANES IN STREETS

A further improvement in light rail operation in street or arterial rights-of-way is achievable by providing reserved transit lanes in which automotive traffic is prohibited.* These lanes are separated by pavement markings or mountable curbing only. The effectiveness of these techniques depends on their conspicuousness, public understanding of the markings, and local enforcement policies. Common treatments include:

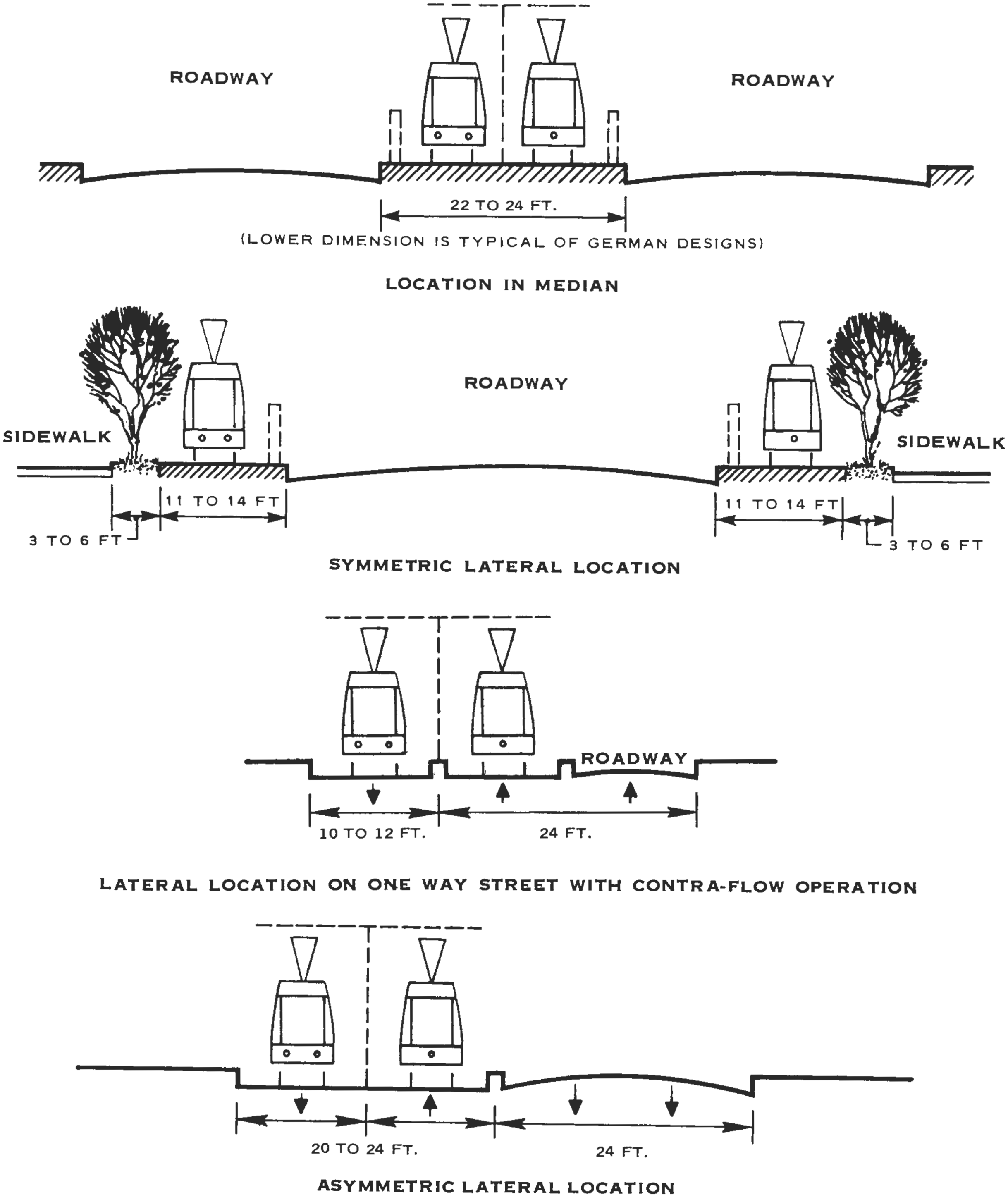
- Solid lines separating track areas from other lanes, as at The Hague and Zurich
- Diagonal striping across the right-of-way as at Hannover, Gothenburg and San Francisco
- Mountable concrete or asphalt curbing on the right-of-way edges (Figure 33).

Figure 33. LRT on Mountable Median Delineated by Low Curbs, Zurich

---

*Since street vehicular capacity is reduced when LRT trackage is installed in street right-of-way, some disruption and increase in congestion on neighboring streets may be anticipated. This effect is likely to be felt more in the heavily used streets of the CBD, but some mitigation would take place as some drivers divert to LRT.

The position of track in the street varies among cities and among locations within the same system. While most systems have tracks in the middle of the street, some asymmetrical designs also exist (e.g., Pittsburgh, Philadelphia, Brussels, Belgrade, Hannover). Figure 34 shows some of the more common arrangements of LRT within street rights-of-way.



LOCATION IN MEDIAN

SYMMETRIC LATERAL LOCATION

LATERAL LOCATION ON ONE WAY STREET WITH CONTRA-FLOW OPERATION

ASYMMETRIC LATERAL LOCATION

NOTE: DIMENSIONS ARE TYPICAL OF WEST GERMAN DESIGNS

Figure 34. Common Arrangements of LRT Within Street Rights-of-Way

In some cities, buses may share all or portions of reserved LRT right-of-way (Figure 35). Where bus and light rail vehicles share the transit lanes, the lane width must be greater than that for light rail vehicles only, due to the lower tracking accuracy of a bus. Figure 36 indicates West German practices regarding the minimum width of LRT medians of various designs.

Compared with light rail vehicles operating in mixed traffic, reserved LRT lanes in streets with minimal physical separation offer the following advantages and disadvantages:

- Advantages
    - Higher service quality
    - Slightly lower operating costs
    - Higher passenger comfort due to fewer stops in traffic
    - Increased safety
    - Slightly better visual identification
    - Greater passenger attraction
- Disadvantages
    - Enforcement required
    - Possible only where at least two or three lanes per direction or a total of four driving lanes, are available
    - Slightly higher maintenance cost.

DEDICATED STREET RIGHT-OF-WAY

Where at least three traffic lanes are available in each direction or a median exists, further upgrading of LRT performance is achievable by operating LRT in the two center traffic lanes or median protected from auto and pedestrian traffic.* This may be done by:

- The use of full curbs and raised median areas
- Separation of the tracks by bushes and plantings (see Figure 37)
- Separation of the tracks by fencing or concrete barrier walls.

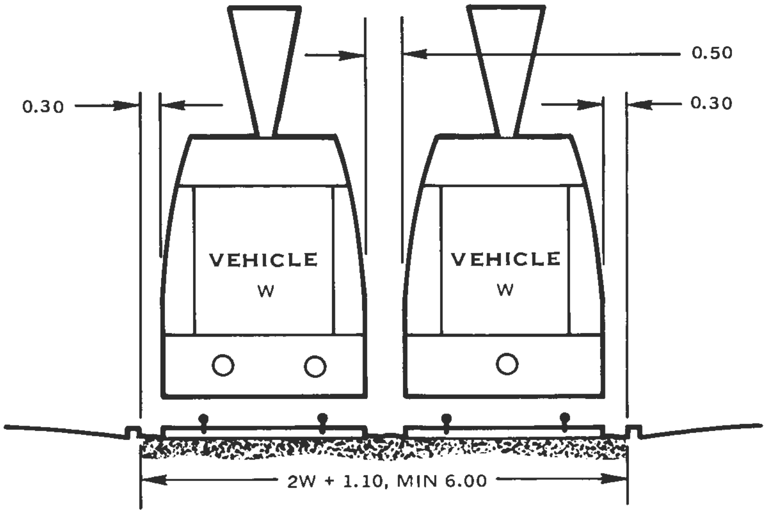
---

*Since street vehicular capacity is reduced when LRT trackage is installed in street right-of-way, some disruption and increase in congestion on neighboring streets may be anticipated. This effect is likely to be felt more in the heavily used streets of the CBD, but some mitigation would take place as some drivers divert to LRT.

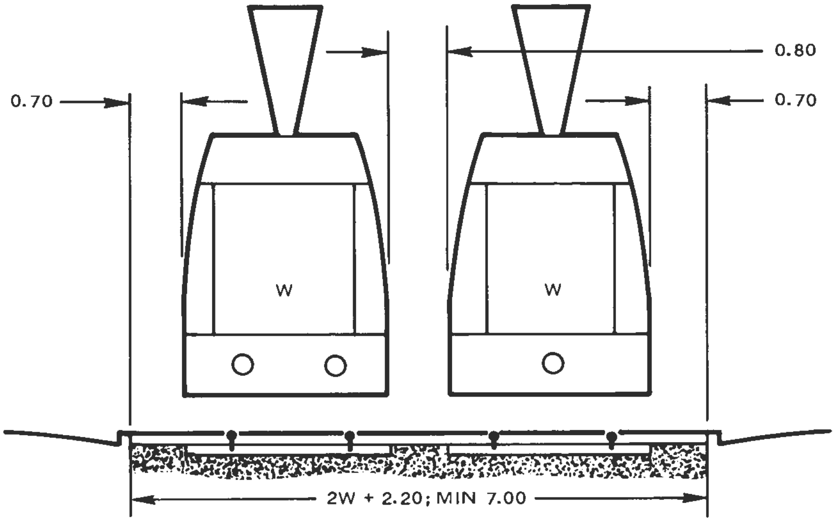
Figure 35. Bus and Light Rail Transit Lane in Bonn

LRT median operation requires sufficient width to accommodate passenger waiting and boarding areas at stations. If the right-of-way is sufficiently wide, landscaping may be employed between passenger stops. More commonly, stops can be accommodated by offsetting stop locations in each direction and by introducing a gentle "S" curve in the horizontal track alignment (Figures 38 and 39).

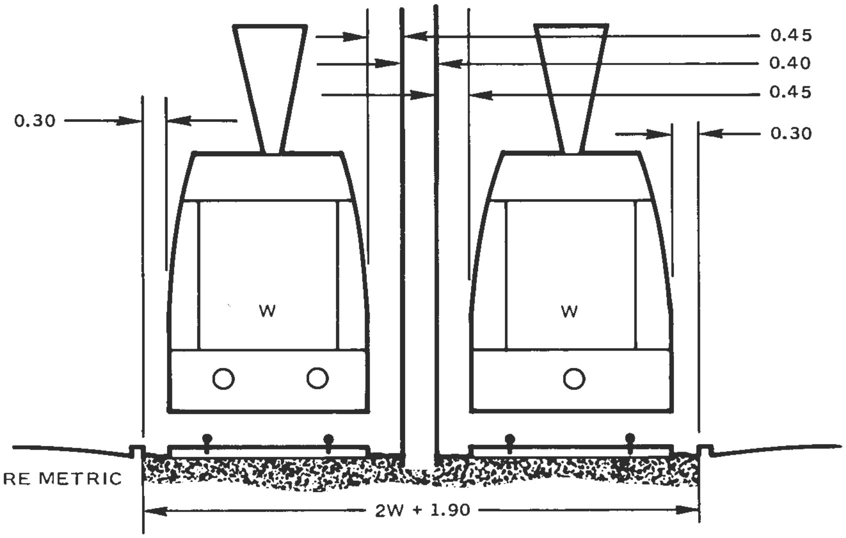
Dedicated street right-of-way installations offer significant opportunities for improved LRT service. Operating speed may be increased over mixed traffic and reserved lane operations, since the risk of traffic interference and safety hazards are minimized. Average schedule speeds will not reach those possible on exclusive rights-of-way, but may be twice the speeds obtained over mixed traffic or reserved lane sections. Typically, average speeds for street operation in dedicated right-of-way without preemption of traffic signals vary from 11 to 15 mph with 20 mph speeds attained over some sections. On dedicated rights-of-way with protected grade crossings in outlying areas, average speeds of 20 to 25 mph may be reached. Shaker Heights rapid transit operates PCC streetcars 17 to 24 mph, depending upon the time of day, over a four mile section in the median strip of an arterial street crossing eleven non-preempted grade crossings with 0.3 mile station spacing.



WITH LATERAL OVERHEAD WIRE SUSPENSION



JOINT UTILIZATION WITH BUSES (MODERATE SPEEDS ONLY)



NOTE: DIMENSIONS ARE METRIC

CENTER POLE FOR OVERHEAD WIRE SUSPENSION

Figure 36. Minimum Widths of Curbed Medians for Light Rail Tracks
(West German Practice)

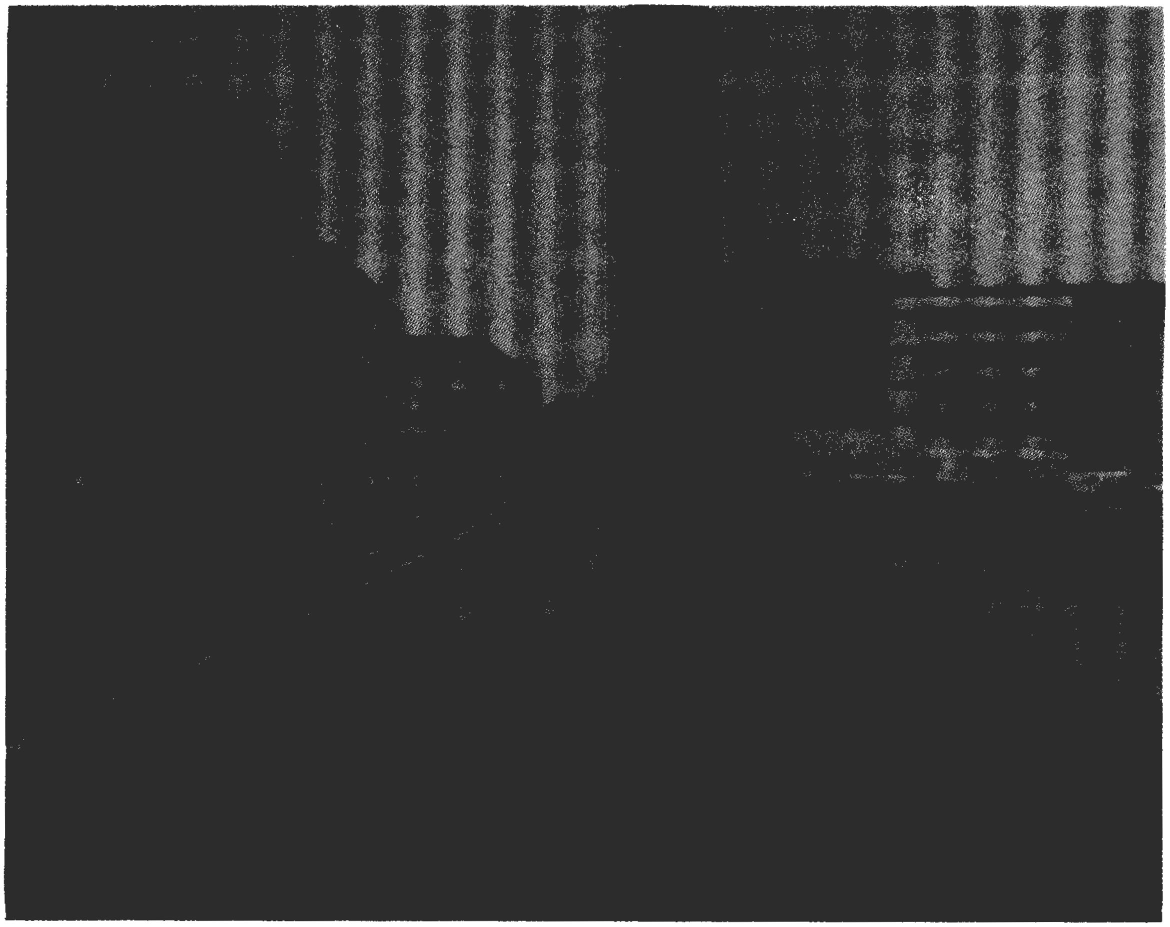
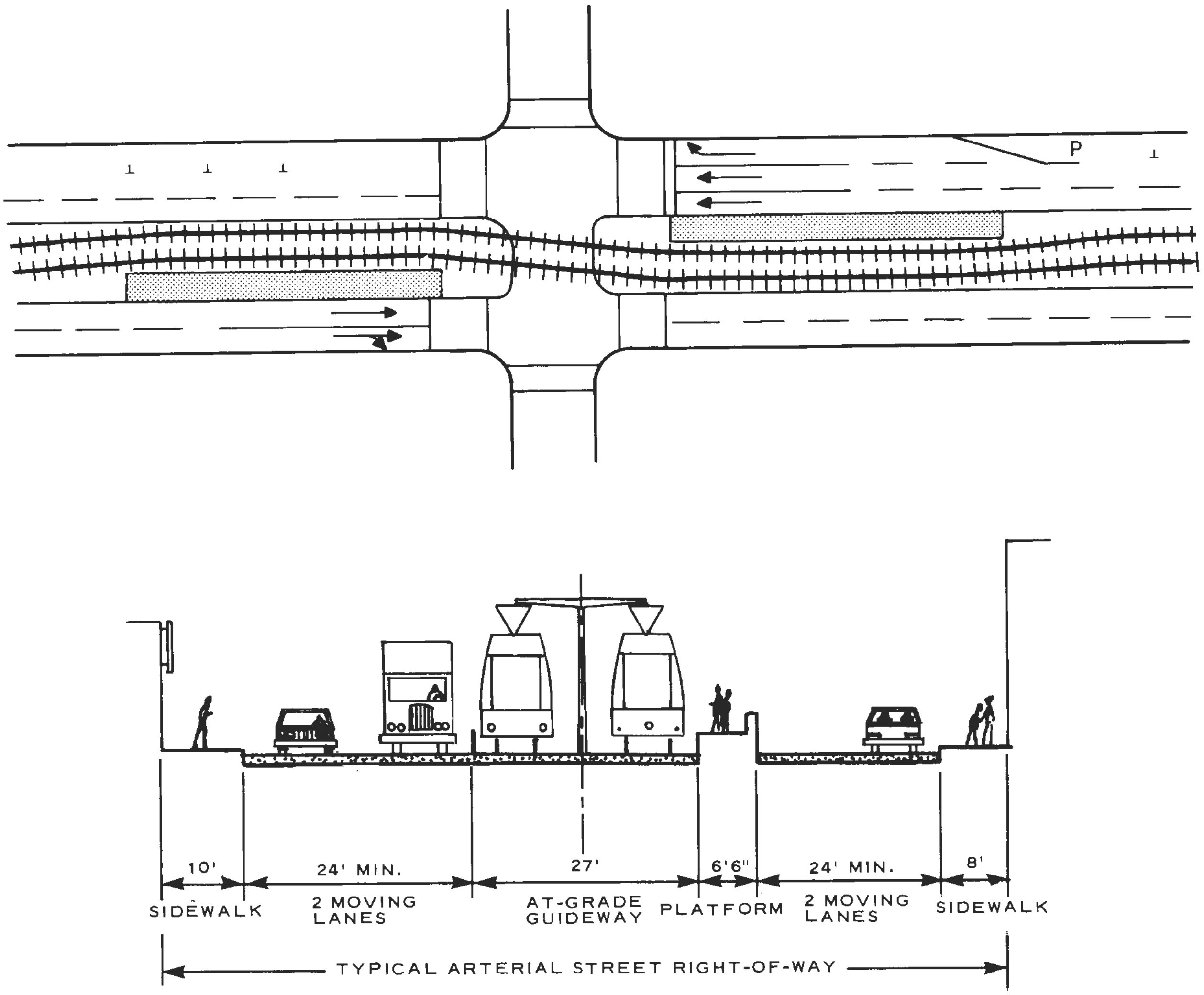


Figure 37. Separation of LRT Tracks and Traffic Lanes by Bushes in Brunswick

Key policy factors governing average speed characteristics are allowable speed limits between stations and through intersections. Experience in North American and European cities is mixed regarding specifications of these speeds. Most European cities permit a maximum speed of 10 kph faster than that for the parallel street traffic. Slower speeds are typically required at intersections. In Pittsburgh, vehicles are required to slow to five mph to traverse intersections. In San Francisco, streetcars are governed by the applicable provisions of the traffic code when running on streets.



CROSS SECTION
SEGMENT A–A

Figure 38. LRT Stop in Narrow Median With Offset Tracks and Platforms

For at-grade operations on arterial street rights-of-way, a number of measures may be used to increase average LRT operating speeds including:

- Elimination of parallel conflicts with automotive traffic, particularly at left turn lanes
- Elimination of conflicts with automotive traffic at intersecting cross streets through signal preemption strategies
- Better door design and fare collection arrangements to provide rapid boarding and alighting of large passenger volumes.

Figure 39. Offset Stop with "S" Curve in Track Alignment in Brunswick

Arterial installation of LRT may also include landscaping to minimize visual impacts of the transit right-of-way. The often mentioned negative aspect of LRT, overhead power wires and their supporting structures, may be mitigated by tall plantings (Figure 40) or by joint use with street lighting poles.

Barrier rails and concrete barriers are seldom used along medians on existing systems, except in locations where a line passes through an identifiable hazard area. This reluctance may be attributed to the aesthetic appearance of such barriers, the undesirable psychological impact of such barriers on city streets, and potential operating and maintenance inconvenience due to incomplete access in the LRT right-of-way. Experience on existing installations suggests that the barriers' marginal increase in LRT safety is less important than the loss of mid-street refuges. Some cities use a low fence or thorny plantings to discourage jay walkers.

Figure 40. Tall Plantings Mitigate Impact of Overhead Wires and Support Structures in Zurich Pedestrian Mall

San Francisco is upgrading the street surface right-of-way, where practical, by using concrete curbs. Some lightly used intersections will be closed; traffic signal controls will be installed on others to give priority to light rail vehicles. Many cities in Europe have been implementing similar techniques to improve operations on arterial streets since the mid-1960s.

LRT MALLS

Some European cities have light rail transit malls free from private automotive traffic where streets in the downtown area are narrow. On such streets, the LRT right-of-way is typically delineated by curbs or markings, but may be freely crossed by pedestrians, as with an ordinary street. Transit operators have found that such malls facilitate LRT operation by removing vehicular traffic interference and allowing ready access to the transit system. They are also popular with the business community. In cities such as Bremen and Mannheim, where many routes focus on the main downtown streets, LRT malls have provided an alternative to subway construction. Speeds on LRT malls are lower than on streets, for both safety and environmental reasons. Typically, 16 mph (25 kph) is the maximum speed permitted through pedestrian zones. Figure 41 illustrates an LRT mall at Bremen.

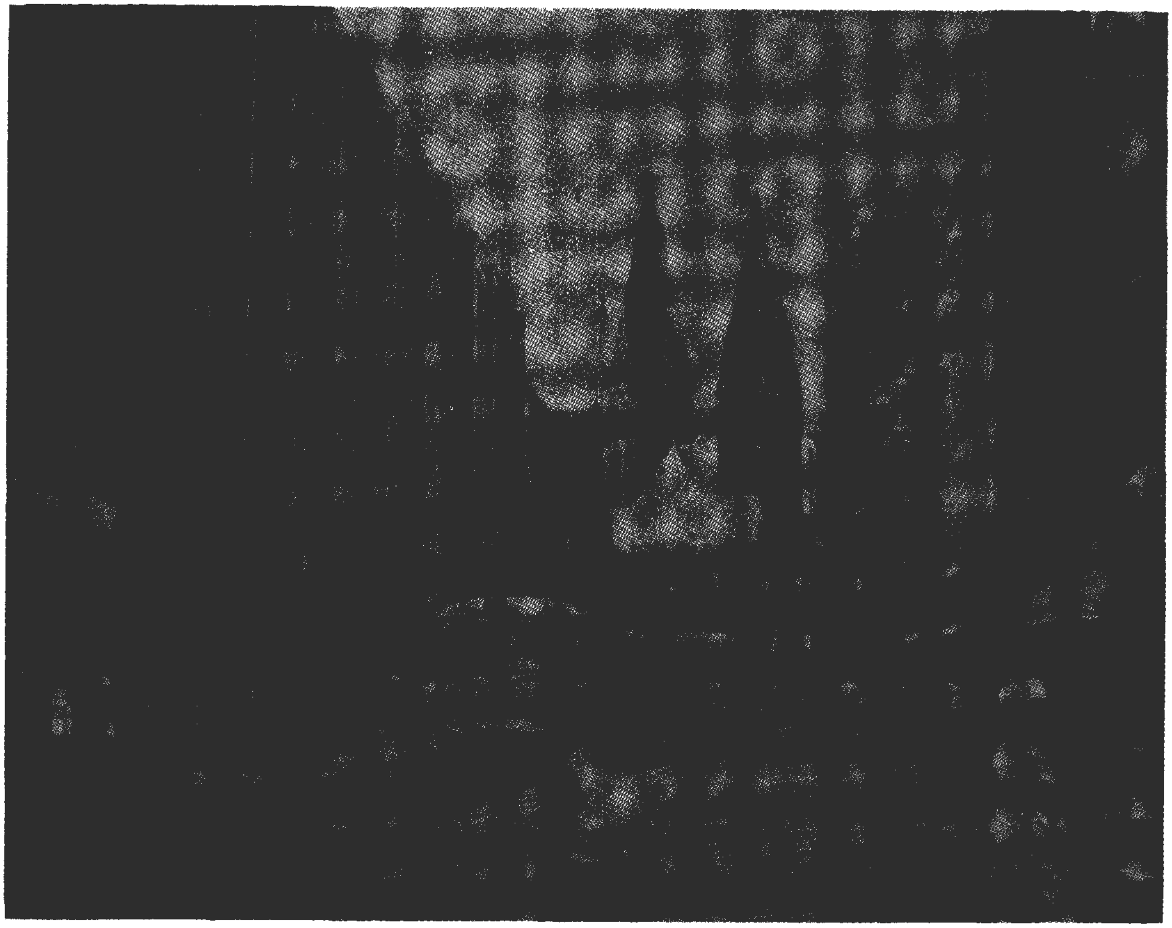


Figure 41. LRT Mall in Bremen

PRIORITY TREATMENT AT INTERSECTIONS

The most critical points on LRT lines are usually street intersections. It is at these locations that turning movements, pedestrian crossings and the merging of lines create the greatest conflicts and delay. Therefore, an important element in the process of providing effective LRT operation is to assure its priority treatment at such intersections, which can be achieved in one (or a combination) of the following ways.

- Signal preemption
- Elimination of left turns for automobiles when both parallel and transverse vehicular roadways interact with the transitway.
- Prohibition of cross traffic
- Grade separation of the transit right-of-way.

In European cities such as Rotterdam, Dusseldorf and Hannover, the first three types of priority are used singly or in combination where grade separation is not provided. Special signal systems, together with certain traffic movement prohibitions, represent a low investment means of providing priority at intersections, although they are usually not as effective as full separation.

Where no priority is given at intersections, delays for transit vehicles may often be reduced significantly by locating alternate stops at the near or far side of intersections in a pattern coordinated with the traffic signal system. Such an operation is found on Eschersheimer Strasse in Frankfurt, where light rail operates in the street median and crosses a number of complex intersections. However, such measures cannot entirely eliminate delays caused by traffic signals.

Crossing protection may range from none provided, which is common on streetcar systems; to fixed cycle traffic signals; to full positive crossing control equipped with preemption and gates, interlocked with the train control system. With positive crossing protection, operations may in effect approach the quality provided by full grade separation.

Full grade separation at vehicular intersections may be provided by underpass or overpass of either the transitway or the highway. Considering the transitway, the underpass is most common (Gothenburg, Stuttgart, Rotterdam) since the sequence of downgrade, upgrade is more efficient for operations and maintenance of speed; also, underpasses are visually and physically unobtrusive. Since LRT vehicles can negotiate grades of up to 10 percent, an underpass does not require excessive length. Less steep grades may be required if later conversion to rapid transit is considered.

Where geometric conditions and other factors are conducive, a transitway overpass can be effectively employed at major intersections or longer line sections (Cologne, Belgrade and Rotterdam). Although they are not visually suitable as underpasses, LRT overpasses and viaducts present less visual intrusion compared with major elevated highways. The design features of overpasses or viaducts may be made compatible with future rapid transit design standards. In certain instances, less impact might be achieved by adjusting the cross vehicular way to pass over or under the at-grade transitway.

SEPARATE AT-GRADE ALIGNMENT

Although streets do provide access to many generators likely to be served by an LRT system, the street pattern may not represent the most efficient LRT network, particularly in high density areas and along heavily travelled radial arterials. Under these circumstances, the performance of LRT can be enhanced by location on an independent right-of-way, aligned and designed to suit the specific needs and objectives of the transit service. Such LRT, used for short segments or for entire routes, may parallel existing arterial streets (Rotterdam, Media Line in Philadelphia), may be located on railroad right-of-way (Boston, Gothenburg, Cologne), on freeways or in parks (Cologne, Stuttgart, Belgrade, The Hague).

RAILROAD RIGHTS-OF-WAY

Existing railroad rights-of-way in urban areas represent a unique opportunity for the development of light rail lines. However, many design problems must be addressed for which standard design guidelines have yet to be developed.

Railroad rights-of-way are often attractive for transit use for a variety of reasons. Some are available in the inner suburban zone of a city where other right-of-way opportunities are scarce, highways are heavily used, and alternatives are costly. Some may be found in locations where the introduction of light rail would have little adverse environmental impact. They are usually wide enough for two and sometimes more tracks, and have suitable alignment standards. Unfortunately, at times the railroad right-of-way is located far from heavily travelled corridors and centers of urban activity. Its attractiveness to walk-in patronage may be less than other more central routes and its use for LRT alignments would entail sizable additional feeder facilities. Nevertheless, railroad rights-of-way suitable for LRT operation have frequently attracted planners' attention. Costs of acquisition or use of needed portions of these rights-of-way may be consequential, if under heavy use.

Railroads have often perceived the addition of transit on their rights-of-way as a severe operational problem and a liability from which they stand to derive no benefits. As a result, many unresolved jurisdictional and operational problems inherent in implementing LRT in railroad corridors must yet be resolved before effective use can be made of railroad right-of-way for LRT deployments.

Conversion of Abandoned Railroad Rights-of-Way

The conversion of existing railroad trackage is the simplest and least costly form of right-of-way adaptation to LRT use. It uses abandoned or relinquished railroad trackage without interference from other railroad traffic. Often this right-of-way traverses decaying neighborhoods and may have little utility to a new LRT line. In the newer cities in the western and midwestern United States, abandoned or extremely low use railroad trackage, i.e., one or two trains a day, may be found traversing central areas. Use by LRT of this type of right-of-way is often appealing but requires careful design and operational planning if there are frequent at-grade street crossings carrying heavy automobile traffic.

Improvements of exclusive operations of LRT on existing rail rights-of-way would not require unique measures, since impact on adjacent land uses would not be modified greatly over the prior situation, and railroad operations would not have to be accommodated. Many LRT lines have been built on railroad rights-of-way or have replaced railroads, particularly in recent years when abandonments have been common. In Europe, recent line extensions in Karlsruhe, Bielefeld and Gothenburg have been constructed on abandoned railroad rights-of-way, and parts of the Tyne & Wear system will replace existing diesel-hauled passenger railroad operation. In North America, part of the Lindenwold rail rapid transit line and the Boston Riverside LRT line were constructed on abandoned railroad rights-of-way.

Joint Use of Railroad Tracks

Railroad freight and LRT operations sharing the same trackage introduces a number of severe operational and safety problems due to conflicting movements. Joint use is not a practical concept when the two systems operate frequently. For instance, frequent freight movements would seriously inconvenience LRT service at almost any time of day. On the other hand, when the railroad is very lightly used and the institutional issues can be resolved, joint use is worthy of evaluation.

A number of physical design problems must be resolved if joint use or at-grade crossing of railroads is planned.

- Railroad tracks in the U.S. are rarely electrified. There are exceptions, particularly in the Northeast; elsewhere, non-electrified track is the rule. Presence of electrification requires special attention to design, clearance and safety problems.
- The contact wire must conform to railroad clearance. In the U.S., this clearance is generally 22 feet, 3 feet higher than the reach of the Boeing car pantograph. However, higher pantograph reach is feasible.

- Passenger platforms at stations must be either low level or conform to railroad clearance. Regarding lateral clearances, each state has legal clearance requirements covering railroad facilities. In addition, each railroad has its own clearance rules which may be more stringent. Edges of high level platforms have to be 5 feet 9 inches to 8 feet 6 inches from track centerline depending on the state and the platform conditions. Hence, gauntleted or bypass track would be needed in stations with high level platforms.
- Structures and grades intended for joint use would need to meet railroad standards, adding to their cost. The size and cost of grade separations would be greatly increased unless bypass trackage was used to route rail operations around LRT grade separations.
- The expectation of cost savings through the use of existing track is seldom realistic, due to the poor state of track usually found on lightly used railroads.
- High railroad axle loads can be detrimental to LRT trackage, and will increase maintenance requirements.
- The wheel profile for LRT, designed for running on shallow groove girder rail, differs from railroad wheel profiles. On a new LRT system, railroad wheels and deep groove rails could be used.
- Light rail and rail freight have different stopping characteristics and hence different grade crossing protection requirements.

In Europe, shared trackage was once widely used, permitting the local streetcar network to act as a distribution system around the city wherever track gauge was compatible. Light electric locomotives usually worked freight traffic, and trains were seldom long. In recent years, the tendency to distribute rail freight from a central yard by road has reduced the importance of shared track use, and it is now less common. In Cologne, approximately 5 km of LRT line in the western suburbs is operated over a private railroad right-of-way which carries about 20 freight trains daily. The LRT operation is controlled by railroad signals. Movable frog switches are used to accommodate the shallow flanged LRT wheels. The regional LRT line to Bonn also provides freight service to wayside communities. On both lines, off-peak headways are 20 minutes or more. Parts of the Frankfurt, Karlsruhe, and Stuttgart systems also share some trackage with freight operations. These systems all use low platforms. In each case, trains are operated by transit company crews. Stuttgart, a narrow gauge system, uses mixed gauge track on its freight route (Figure 42). In England, one branch of the Tyne & Wear system will be shared with freight operation on joint use tracks. On this system, the LRT cars will have railroad profile wheels.

In the U.S., joint use operation was once common, particularly on interurban lines. On many of these lines, freight became the major source of revenue. The non-standard Pennsylvania Trolley Gauge was adopted by some towns to *prevent* railroads from using their

Figure 42. Joint Use Track, Mixed Gauge, in Stuttgart

streets for rail freight activities. Surviving examples of joint use operations include the South Shore Line in Chicago and the Yakima streetcar system. Several recent transit studies, including those for Dayton, Rochester, Vancouver, and Portland, included proposals for joint use of LRT and railroad trackage.

Separate At-Grade Trackage on Railroad Rights-of-Way

The use of separate at-grade trackage for LRT and rail operations within a common right-of-way avoids many of the institutional, operational and engineering problems arising from joint track use. Most railroad rights-of-way can be adapted for additional tracks. In some instances, the construction of LRT will require shifting the existing track, rearranging railroad spurs for access to facilities located along the right-of-way, and perhaps some localized right-of-way widening for transit station facilities. The land uses along most railroads often permit some localized rights-of-way widening without undue impacts. In Washington, D.C., the rail rapid transit system has made use of railroad rights-of-way along a northern route. In this instance, the railroad tracks were relocated to the outside extensions of the existing right-of-way and the rail rapid track constructed between them. This allowed the railroad to maintain spur lines for freight service to customers adajcent to the tracks without grade crossings. Railroad spur tracks crossing of LRT right-of-way would be feasible provided clearance and signal interlocking were installed. The Cleveland rail rapid system crosses a railroad spur at grade.

Multiple use of rail corridors are common in Europe. In North America, the new LRT line in Edmonton is being constructed at grade in a railroad right-of-way, while in Los Angeles a recent LRT study included a shared at-grade right-of-way with separate tracks.

Grade Separated LRT Trackage on Railroad Right-of-Way

The most costly use of railroad right-of-way occurs when rail to rail grade separation is required. Recent rail rapid transit projects such as BART and WMATA have extensive lengths of aerial trackage on railroad rights of way. In some cases, such elevated sections are required to traverse numerous cross streets, but in others, lack of right-of-way or the need to accommodate existing or future spur tracks required grade separation.

In some recent proposals in which rail corridors were selected for use by LRT, the railroads have demanded totally elevated trackage to permit siding access to property fronting the tracks, even where no such sidings now exist. The result has been LRT cost estimates far in excess of those generally associated with building in a rail corridor. For spur tracks giving access to lineside industry, at-grade crossings with proper interlocking are technically feasible, and offer a less costly alternative. However, safety aspects and the impact on the reliability of the LRT operations need to be carefully reviewed before adopting such design concepts.

Where an LRT line is to cross an active railroad, grade separation should generally be considered. The length and frequency of railroad trains and the probability of delay to LRT would have a bearing on the conclusion. Because 22 to 25 feet of clearance is needed to pass over a railroad right-of-way (compared to only 14 to 16 feet over a street), railroad overpasses are both longer and more costly than street overpasses. Since institutional problems associated with developing LRT in railroad rights-of-way overshadow the technical problems, it might be desirable to begin establishing, in a cooperative process with the railroads, the procedures and standards for joint use of the rights-of-way.

FREEWAY RIGHTS-OF-WAY

Exclusive operation of LRT within freeway rights-of-way may be achieved by the use of the median or spaces on either side of the freeway between the shoulder and the edge of the right-of-way. Examples of transit operations within freeway medians include double tracked LRT lines on sections of the Ruhr expressway at Essen, a recent LRT extension in Cologne built in the median of a future freeway, and freeway median rapid transit operations in Chicago, San Francisco, Washington, D.C., and elsewhere.

In general, locating alignments within freeway medians is a viable alternative mainly in newer outlying freeways or where older freeways have a sufficiently wide median. Freeways with a median width of over 36 feet could accommodate at-grade LRT operation (see Figure 43).

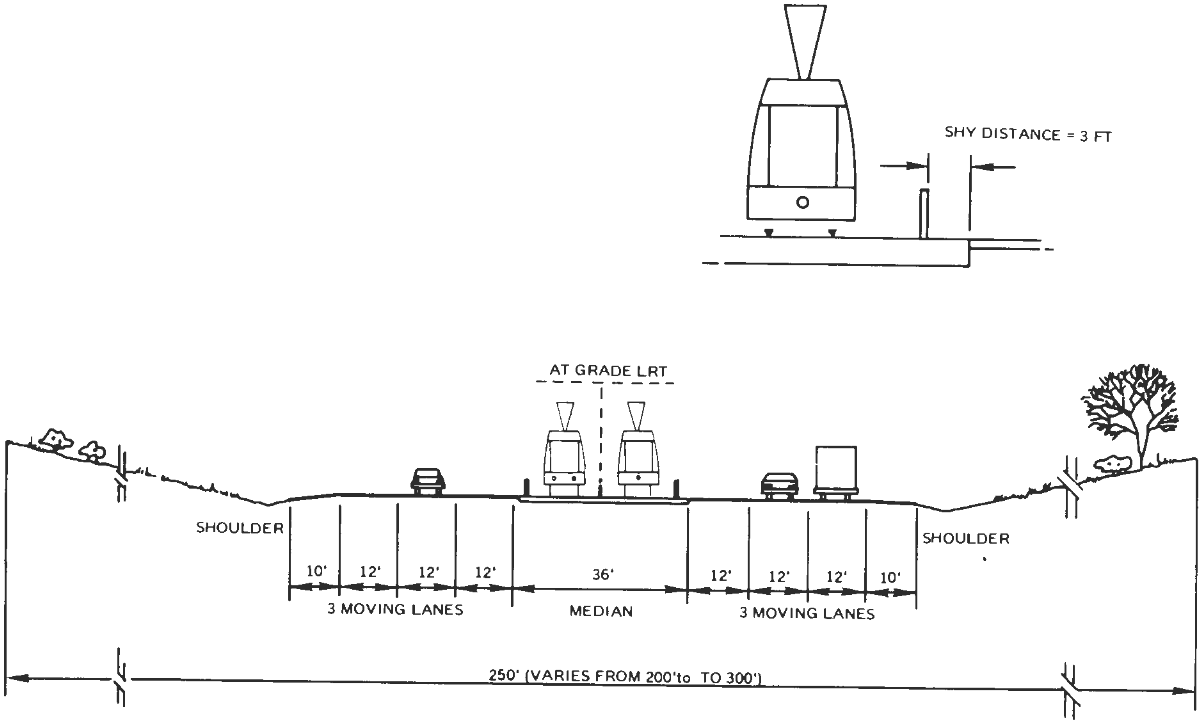


Figure 43. LRT Right-of-Way on Freeway Median

Introducing at-grade LRT in the freeway median poses the following concerns:

- Integration of station and intermodal facilities design with cross street structures, drainage and other freeway elements.
- Integration of alignments and profiles with median elements, including overhead bridge crossing piers.
- Needs for barrier separation of the high speed vehicles and rail traffic, particularly at stations.
- Avoiding modifications to freeway lanes to accommodate station platforms on transit ramps.
- Minimizing interim construction disruptions which may involve at least two freeway lanes.

When sufficient median width is unavailable, LRT may be accommodated on the shoulder or the edge of the right-of-way.* These areas are often side slopes where freeways are either in a depressed or elevated section configuration. The available portion may vary from approximately 20 feet to as much as 100 feet. Conflict with on/off ramps and cross streets may require vertical separation.

---

*Locating LRT by displacing existing traffic lanes is certainly possible in a physical sense but does not appear to be a practical proposition. Therefore, it is not pursued in this analysis.

Basic disadvantages of locating LRT on freeways are generally difficult pedestrian access and poor access from parking. Provision for free circulation of feeder lines at the freeway locations often requires complex and costly ancillary intermodal facilities. A thorough evaluation of freeway right-of-way opportunities cannot be made in the abstract. The practicality of locating LRT within the freeway right-of-way is determined largely by local geometrics and other physical constraints. The feasibility of a particular location can only be made after careful evaluation of all pertinent engineering and environmental factors for that specific site.

SPECIAL LRT TREATMENTS

When exclusive right-of-way is employed to increase the level of service through high density locations or bottlenecks of an LRT system, aerial and subway sections are required. The physical requirements of these structures are virtually identical with those of rail rapid transit. Figures 44 and 45 illustrate a typical column location and cross section for aerial structures. Figure 100 (Chapter 8) illustrates typical sections for subway structures. However, major need of aerial structures or tunnels can eliminate most of the cost advantages of an LRT system.

Downtown distribution routes for light rail are sometimes accomplished by use of subway. In the United States, Boston, Newark and Philadelphia employ subway sections in their LRT systems and San Francisco is building one.

Subways for LRT are generally constructed in the same manner as rail rapid subways. Cut-and-cover is the most common construction practice, although bored tunnels are used also. On existing systems, light rail vehicles are often narrower than rail rapid vehicles. Narrower tunnels may be used unless the system is built to pre-metro standards. Clearance for overhead wires and pantograph is required in LRT subways. Figure 46 contrasts two subways designed respectively for light rail and rail rapid in West Germany. In bored tunnels, the pantograph fits within the curvature of the roof, and no additional size is necessary. Both BART (rail rapid) and Muni (Light rail) use the same size tunnels in San Francisco.

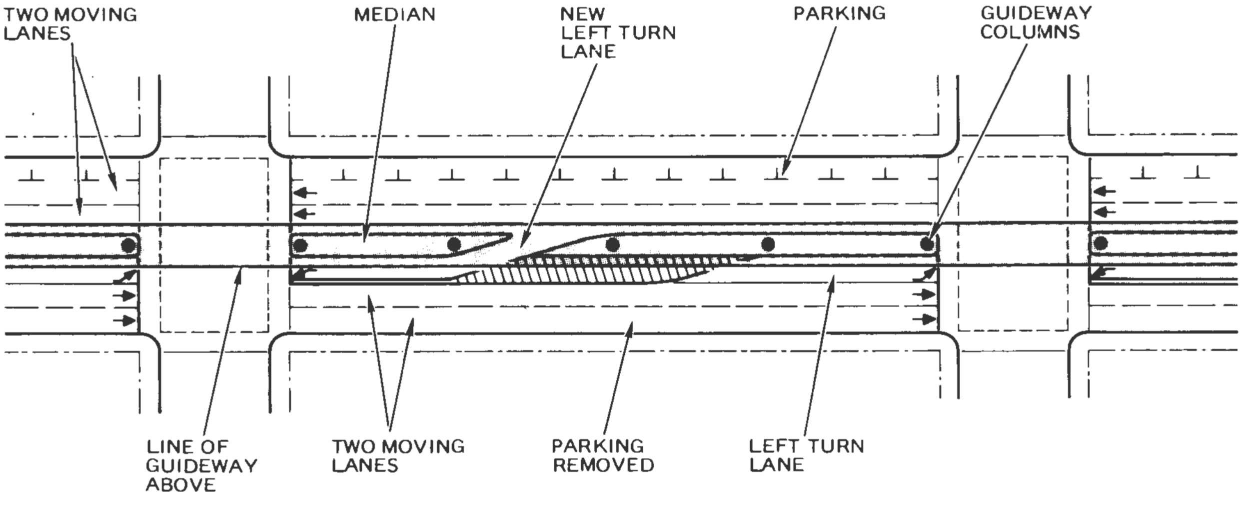


Figure 44. Arterial Street – Plan View of Aerial Guideway Columns and Median

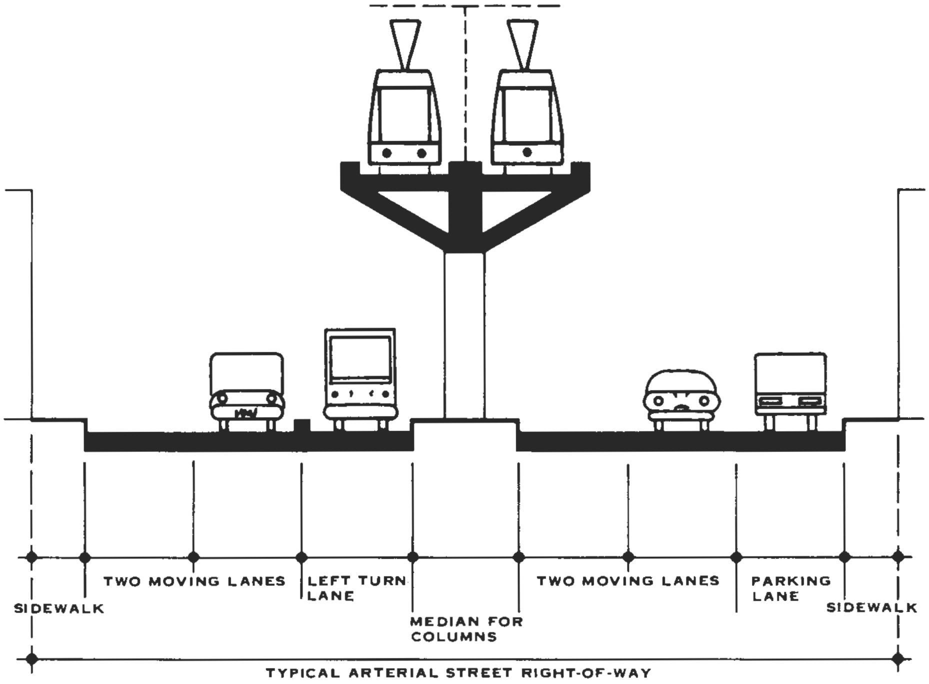
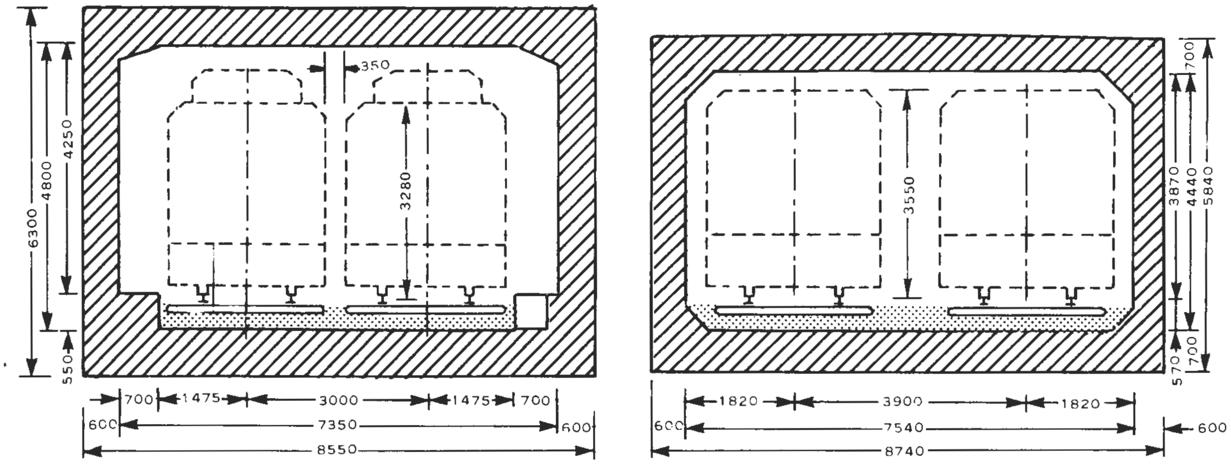


Figure 45. Arterial Street – Section View of Aerial Guideway in Median



FRANKFURT U-BAHN
(Light Rail)

NURNBERG U-BAHN
(Rail Rapid)

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

Figure 46. Typical Cut-and-Cover Tunnel Cross Section

Considerably lower costs for LRT subways can be achieved if reduced alignment standards or track crossings at grade are adopted. In such cases, restriction of running speed due to curvature and crossing interlocking would be necessary, although the travel speed and regularity of service will still be vastly superior to surface operation on uncontrolled right-of-way.

An evaluation of the decision to build to lower standards at lower cost, and in most cases, considerably sooner than it would be possible with higher investment, can only be made with knowledge of planned future developments. The possibility of lower costs and earlier completion of the facilities are certainly highly attractive in the short term, and the penalties appear to be minimal. However, these savings could prove very costly on a premetro system if they became an impediment to the conversion to rail rapid at some future time.

USE OF OTHER RIGHTS-OF-WAY

Physically, LRT lines can be located in or along many kinds of existing terrain, but it is only practical to do so in the rare instances where the right-of-way opportunity coincides with an LRT corridor. In Newark, the LRT line is placed in an old canal bed which naturally provided a high degree of exclusive right-of-way for the system. Rochester also built a subway in a canal right-of-way.

Electric power transmission lines traverse many cities. Light rail could be combined with these facilities as was done in the past era of rail transit. This type of application has been considered for a northeast rail line in Toronto.

In most large cities, there are extensive open space and park systems, many of them linear. Subject to certain design and environmental requirements, parks can sometimes provide transit rights-of-way. Moreover the construction of LRT in landscaped medians can introduce green space into a street. The New Orleans system (Figure 47) is one of the best known examples of this treatment. Landscaped medians are also common in Europe, particularly the Netherlands, where rose bushes provide landscaping and a barrier.

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 the LRT routes. Station configurations vary from streetside curb stops similar to bus stops, to elaborate subway stations with grade separated access, mezzanine levels and fare collection. In general, however, all LRT stations can be divided into two basic categories: at-grade and controlled access (usually grade separated).

AT-GRADE STATIONS

At-grade stations are commonly used on at-grade right-of-way sections, both within streets and in separate alignments (arterial or railroad right-of-way). They consist of a paved area, often raised somewhat above rail height, to facilitate boarding, a shelter, and such amenities as information displays, benches, telephones, newsstands. There are a number of different designs for such stations which can be built at minimum cost. (See Chapters 8 and 10).

Figure 47. New Orleans Landscaped Median

The simplest configuration is used in streetcar type operations in the center of the street. Boarding/alighting is directly from/onto the street. This type of stop is not recommended, because passengers are not physically protected from auto traffic. However if there is no other solution, protection can be provided by a "signal island," which has a signal for auto traffic prior to the stop area, as shown in Figure 48. The signal is actuated by the vehicles approaching the stop.

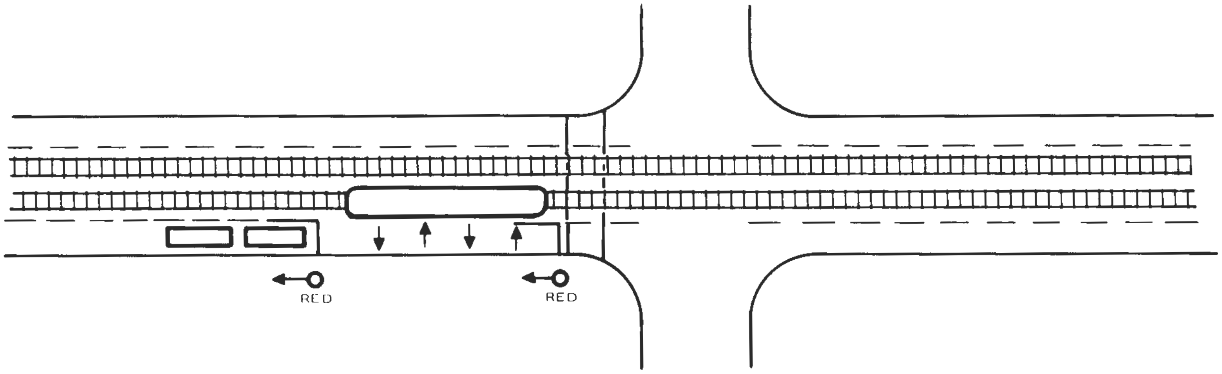


Figure 48. Signal Island Station

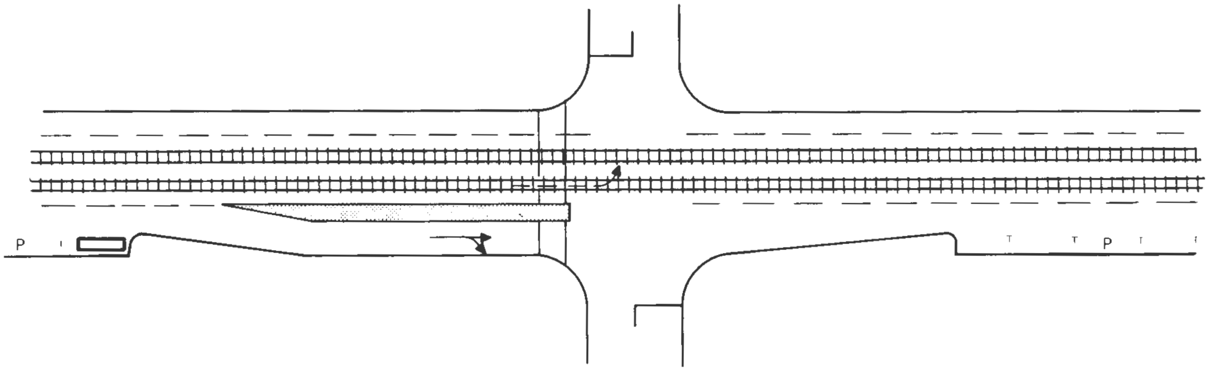
A better solution is provision of a raised island, preferably with an attenuation barrier in the direction of oncoming auto traffic. The island, which should be of adequate width to safely accommodate the projected passenger volumes (at least 5 feet [1.5 m] in West Germany) provides physical protection for waiting passengers, reduces delays to other traffic (autos may pass the stop during vehicle boarding), and facilitates stepping into and out of rail vehicles, thus speeding up their operation. Wherever the necessary width can be obtained, curbed islands should be provided for stations.

Figure 49 represents a near-side station with the island width obtained by discontinuing the parking lane at the intersection approach. Left turns by automobiles may be allowed from the track lane, but only if the volume of that movement is light, so that interference with light rail vehicles is minimal. In most cases, left turns would be prohibited.

Heavy volumes of left turning traffic can be handled in two different ways, as shown in Figures 50 and 51. The design in Figure 50 has higher capacity for left turns than that in Figure 51, but it involves a weaving of auto movements with rail vehicles prior to the intersection. The design shown in Figure 51 requires a full three-phase signal to eliminate vehicular conflicts with the platforms located at the far side of the intersection. This design features the same cross section width for the left turn lanes upstream of the intersection as for the curbed island. Therefore, it requires less street width than the design in Figure 50. Several other variations of LRT station and intersection designs are possible.

In recent years, LRT stations in a number of cities have been placed in such areas as pedestrian squares and shopping malls. In most cases, crossing of tracks is allowed everywhere, since light rail vehicles in the malls operate at low speeds only. The safety experience of this type of operation has been extremely good. The track area is sometimes slightly depressed and separated by low curbs to warn pedestrians and facilitate boarding. An effective method of designating stop areas is the use of textured pavement, usually squares in two colors.

Major transfer stations for surface transit are located in large pedestrian areas, separated from automobile traffic. Short walking distances between vehicles of different routes are generally provided. Also in this case, pedestrian crossing of tracks and roadways is unrestricted. Figure 52 shows a major transfer station in Dusseldorf for both buses and LRT. If vehicle speeds are higher or pedestrian volumes are very heavy, controlled pedestrian crossing, via overpasses or underpasses is generally used.



NOTE: IN SPECIAL CASES, LIGHT VOLUME LEFT-TURNING TRAFFIC MAY BE ALLOWED FROM TRACK LANE (SEE DASHED ARROW)

Figure 49. Near-Side Station With Curbed Island (No Left Turn)

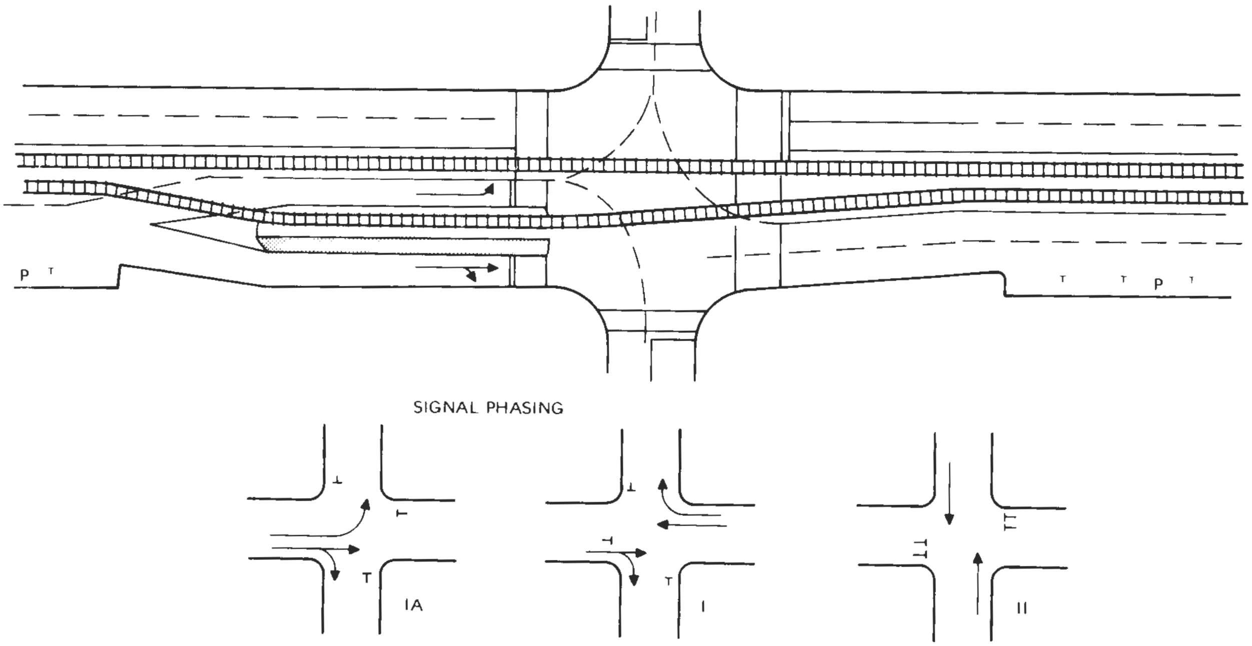


Figure 50. Near-Side Curbed Island Station (Special Left Turn Lane)

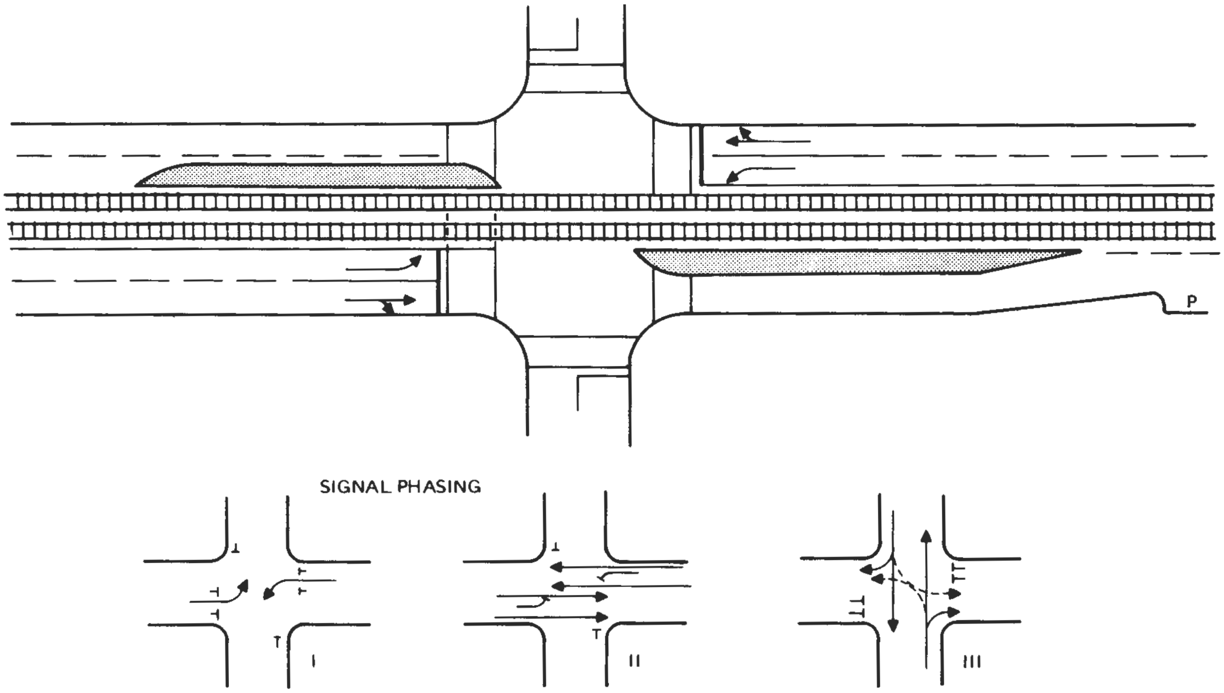


Figure 51. Far-Side Curbed Island Station (Left Turns Separated Through Signal Phasing)

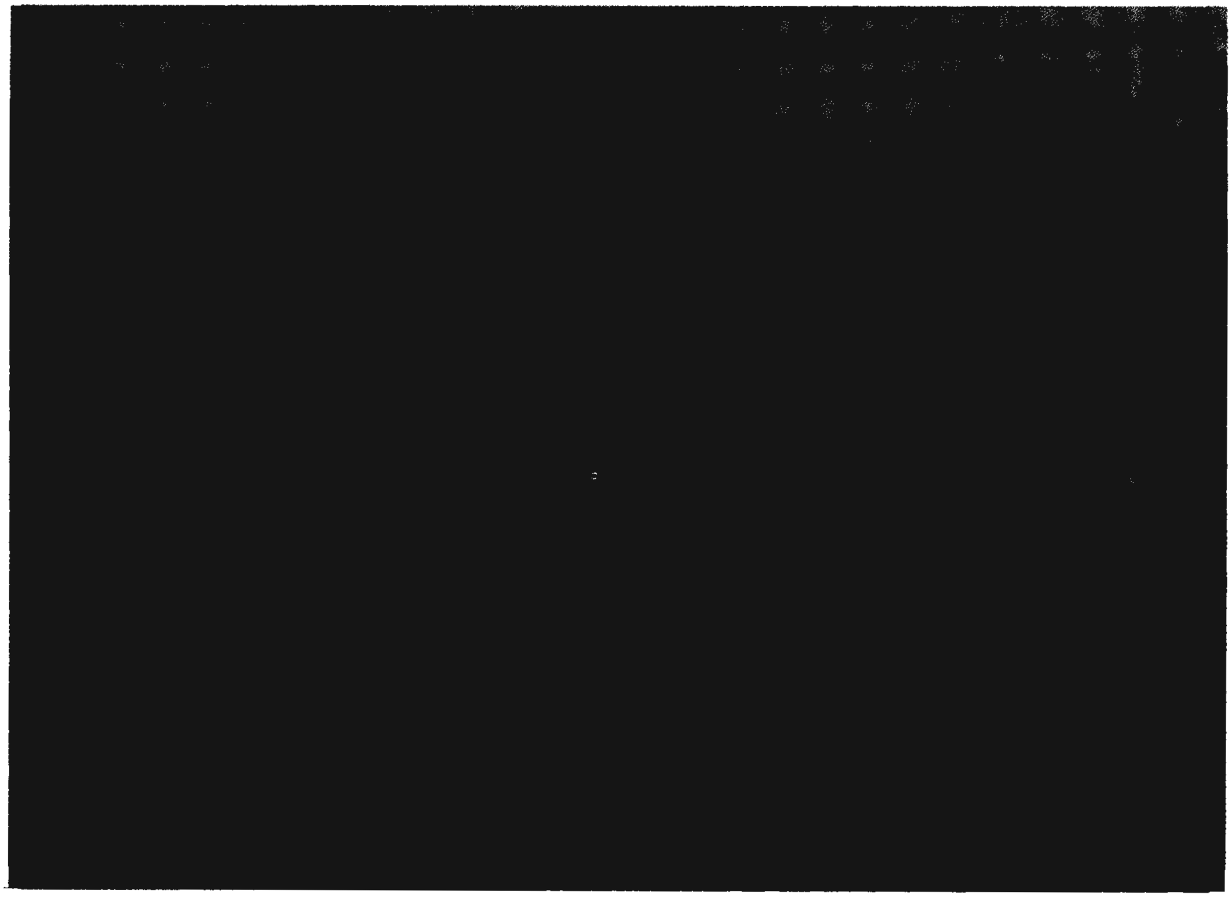


Figure 52. Central Light Rail/Bus Terminal and Transfer Station at Dusseldorf

An innovative feature of some light rail stations has been the construction of large mezzanine areas beneath the tracks and street. These areas often contain shops and other facilities, with stairway and escalator connections to the sidewalks and platforms. This type of station permits safe, traffic-free pedestrian circulation, while avoiding the cost of placing the LRT system underground. Such stations are, in effect, an inversion of conventional subway stations. With depressed mezzanine light rail stations, the tracks are at grade in the street, over the passenger circulating area. Stations of this type exist in numerous cities, such as Brunswick, Krefeld, Karlsruhe and Zurich.

CONTROLLED ACCESS STATIONS

Controlled access stations are usually grade separated from streets. In some cases, they are at grade but with grade separated pedestrian access to one or both platforms (Figures 53 and 54). In most cases, they are designed so that in-station fare collection control can be introduced. In some cases, such control is in regular operation. In others, it is applied during peak hours only, or it is planned for the future.

Since access to this type of station is restricted, i.e., unlike most low level surface street platforms which can be approached from practically all directions, it is possible here to use high level platforms (Figure 55). These platforms allow easier and faster vehicle loading and accessibility for the handicapped. However, on lines using the high level platforms, all

Figure 53. View of LRT Station Between Tracks

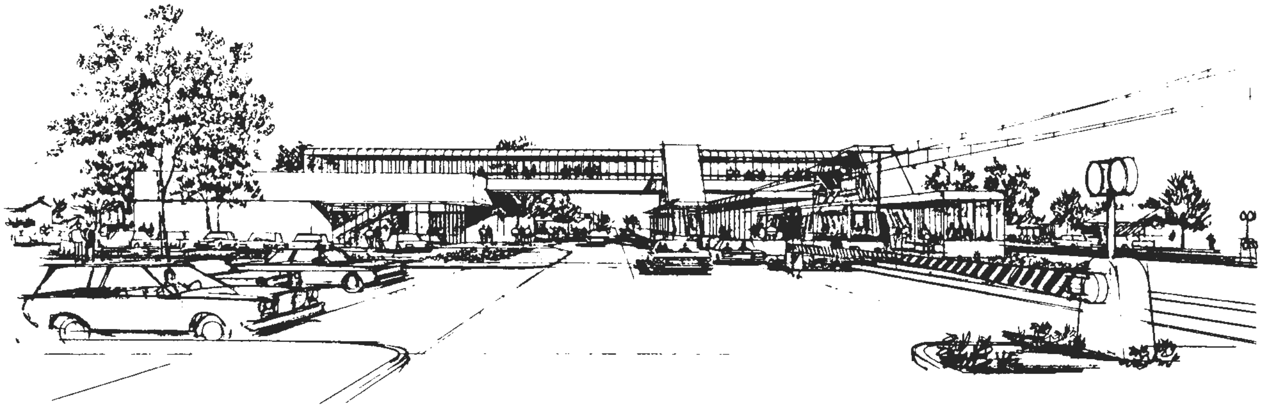


Figure 54. LRT Station in Median With Grade Separated Access

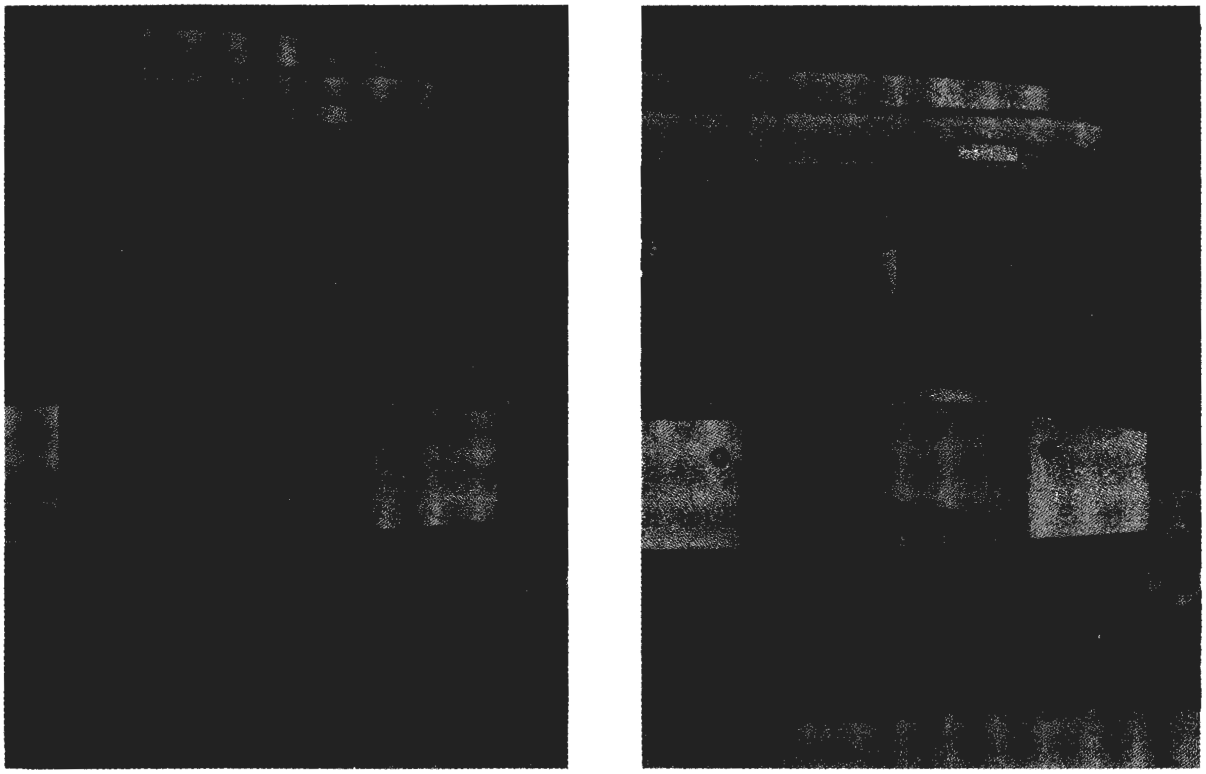
vehicles must be of a design that accommodates this station feature. On some LRT lines, all stations have high level loading; on these lines, the vehicles can be boarded as in rail rapid transit practice. On some other lines, high level loading platforms are used only on certain sections usually in tunnels (e.g., Hannover) or on aerial structures. On these lines, vehicles must be equipped with movable steps to accommodate loading from both high and low level platforms (Figure 56).

Figure 55. Station With Raised Platform in Bremen

Platform length depends on the length of operating units (one, two or more cars per train) and on how many trains utilize the station simultaneously. The minimum length is usually for two 4-axle cars with simultaneous loading, i.e., in excess of 100 feet (30 m). For modern LRT systems, accommodation of at least two 6-axle cars is a more typical standard; it requires in excess of 160 feet (60 m). The longest station platforms are for three 8-axle or four 6-axle cars, with an overall length of approximately 300 to 330 feet (90 to 100 m).

In pre-metro installations, the stations must be designed for the ultimate use, i.e., rail rapid transit. Compatibility of operation with LRT initially, with rail rapid transit ultimately, and even their combination during the transition, presents some interesting problems which require careful consideration.

Several solutions to this problem of transition can be used. In Brussels, a section of the platform sufficient to accommodate two single unit cars is low level, while the remainder is at a higher level. Passenger boarding and alighting on the low level platform is then identical to that in the street. When rapid transit vehicles are introduced in the future, joint operation with light rail will call for stopping at different sections of the platform. Eventually when total conversion takes place, the low part of the platform will be reconstructed to the high level platform, which is indented sufficiently to allow wider vehicles. An objectionable feature of this solution is that the platforms presently used are rather short and narrow, frequently causing congestion at boarding and alighting, while most of the platform length remains



SOURCE: *THIS IS LIGHT RAIL TRANSIT*

Figure 56. Movable Steps for High or Low Level Loading

unused. The principal advantage of the Brussels solution to the platform dilemma is that it permits the transit property to operate vehicles from the surface LRT systems into the subway as soon as the first segment is completed. Meanwhile, work can continue on extending the subway.

Frankfurt has developed a different solution. Light rail vehicles have been equipped with a movable step so that in street operation, passengers can board from the street level. In the stations, medium height platforms are used. There the movable step is not required, and passengers step directly onto the platform. On the newer transit vehicles, passengers can step directly onto the platform. At some stations where the platform height is lower (because freight cars are sometimes transported on this line), passengers step down one or more steps. Eventually the floor of the vehicles around doors will be raised so that all steps are eliminated. In addition to this level adjustment, the older light rail vehicles have an added protrusion on their sides which is level with the intermediate platform to prevent a gap between the vehicles and the platform due to their narrower body. This element is not aesthetically pleasing, but the whole solution is technically satisfactory and safe. Figure 57 shows such a vehicle in a Frankfurt subway station.

In Hannover, two prototype 6-axle cars were ordered from two different manufacturers (DuWag and LHB). They incorporated several novel features for operation at both low level street stations and high level platforms in subway stations by automatic step adjustment and opening of doors at either level. The width of cars was compatible with the future grade separated line clearances. Based on testing and experience with these two cars, the city later ordered 100 8-axle vehicles from DuWag with the same features.

Figure 57. Station for LRT and Rail Rapid Transit Joint Use in Frankfurt

Since light rail lines generally operate with smaller units and higher frequency than rail rapid transit, simultaneous loading of several vehicles or short trains at stations is essential for speed of operation, capacity and reliability of service. In most cities, simultaneous stopping of vehicles at stations is employed, even if light rail vehicles operate under full block signal control. At stations, double signals allow stopping of two or more vehicles at the same time. To avoid confusion of passengers waiting for particular vehicles, automated systems have been introduced (Philadelphia, Cologne and Brussels) which, prior to the arrival of each vehicle, display on the platform its destination and its stopping position along the platform.

Since conventional LRT systems generally use on-board fare collection or fully automated self-service fare systems, stations are not designed with special facilities for processing boarding passengers; street level or simple elevated platforms often suffice. However, premetro and some heavily used LRT systems do require stations compatible with rapid transit operations, so that a mezzanine level is added. The mezzanine can also be efficiently utilized as a pedestrian street underpass (at subway stations) or overpass (at aerial stations). The three-level stations have higher capacity, but they are costlier.

The security needs for light rail stations vary as to the degree of complexity of the type of station. Underground stations could require constant surveillance, intense lighting and a sophisticated communications system. For elevated stations or shelters which are of minimal construction and located in busy surroundings, security measures could be minimized.

CHAPTER 5

LIGHT RAIL VEHICLES

The assessment of a transit mode requires a basic understanding of its technology. The evolution and variation in the technology of LRT needs to be understood both in the contemporary setting, and in relation to its streetcar predecessors. There are certain design, operation, and performance features of LRT vehicles which should be recognized as unique to this mode. The characteristics of the vehicle and its components (subsystems) play a significant role in the assessment of LRT's service attributes, and its impacts on cost, safety, environment, and community acceptance.

A wide range of light rail vehicles are planned or in operation around the world. Some of the vehicles were built at the beginning of the century and are still in daily use (Lisbon, Vienna); others are modern, high performance vehicles now in the design, construction and delivery stages. Vehicles vary in size from the small, 2-axle standard European cars to modern designs over 100 feet in length, and operate on tracks of different gauges.

Although a degree of standardization has been achieved, at least for vehicles produced by one manufacturer or within one country, almost every major LRT system in Western Europe now operates custom designed vehicles. Preference for local manufacturers plays an important role in this situation. In Eastern Europe and Russia, centralized economic planning has resulted in a higher degree of vehicle standardization. Table 18 summarizes the principal LRV manufacturers and the car designs built by them in recent years. This table, though far from complete, indicates the great variety of LRVs produced in recent years.

The state of the art of light rail vehicles and their subsystems is outlined here to a level relevant for transportation planning. Basic differences in vehicle design, operation and performance are discussed as they relate to the technology and design options of subsystems, their costs, safety, and systems' operations. Detailed descriptions of vehicle subsystems are generally not given, nor is this chapter intended as a reference for detailed vehicle design.

Vehicles are classified according to their body configuration and methods of operation. Characteristics of a number of new vehicles are discussed focusing on intended types of operation, their significant features, and the advantages or disadvantages of using a particular vehicle in varying system applications.

CLASSIFICATION OF LRT VEHICLES

BODY CONFIGURATION

Light rail vehicles are normally classified by the number of axles and number of articulations. On most modern designs, the number of axles relates to the vehicle's articulation: 4-axle vehicles are non-articulated, 6-axle vehicles have one articulation, and 8-axle vehicles have two articulations. Basic body configurations are as follows:

- The *non-articulated* vehicle generally has 4 axles, arranged in two trucks. Before World War II, most European cars (particularly German) were non-articulated with two axles. Cars with three axles and a mechanical steering mechanism were also used in Europe, but are now largely replaced by larger

Table 18. 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)	Antwerp, 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

articulated vehicles. Today, all new non-articulated cars are of the 4-axle, 2 truck type. The vast majority of vehicles built before the late 1950s, including the U.S. PCC car, were non-articulated.

- The *single articulated* vehicle is composed of two body sections connected by a joint which allows pivotal movement in both the horizontal and vertical planes. This design makes it possible to build longer cars than non-articulated designs, without loss of curve negotiating capability. Passengers have free access through the vehicle articulation joint. Most single articulated cars have three trucks (6 axles) with one truck under the joint. Some single articulated vehicles have less than six axles, such as the 4-axle Bremen and Munich cars, which use a vertically constrained articulation, and the 4-axle Stuttgart cars, which have articulated bodies mounted on a rigid underframe. Several other nonstandard designs have been developed, usually by rebuilding and adapting existing equipment. For example, the 5-axle West German MAN vehicle is essentially a car and semi-trailer, with the latter supported on a 2-axle truck.

- The *double articulated* vehicle is composed of three body sections, with the center shorter than the end sections. Two joints similar to those on single articulated cars allow pivotal movement in the horizontal and vertical planes. Most double articulated vehicles have four trucks (8 axles), with two of the trucks centered under the joints. Double articulated vehicles are widely used in Western Europe, both on surface and semi-metro LRT systems. In many cases, six-axle, single articulated cars have been converted to eight-axle, double articulated cars by adding a center section. A number of six-axle, double articulated vehicles have been built, most notably for Zurich. Several multiple articulated designs have also been built, such as the Philadelphia Liberty Liners and the 12-axle cars in Mannheim.

- *Trailers* are vehicles without a driving control position, and can only be operated coupled with another vehicle. They may be either powered or unpowered. In general, a trailer is designed to be operated with a specific type of motor car to ensure geometric and dynamic compatibility. Trailer cars are generally 2- or 4-axle, non-articulated.

A great number of variations in configuration have been developed for LRVs. Many of these were experimental, or the result of rebuilding programs, and are not significant to the mainstream of LRT technology. Figure 58 shows the most important configurations used on LRT systems. Designs 2 and 3 are the most significant to LRT in North America.

The first articulated vehicles were developed in the U.S. (Cleveland, 1893) and were subsequently tried on numerous streetcar, interurban, and rail rapid systems. Articulated cars did not achieve great popularity in the U.S., due to the primitive technology of the time and fare collection practices. A number of vehicle designs well in advance of contemporary European practice were developed in the U.S., including the Key System articulated cars of

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

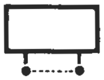
6-AXLE ARTICULATED. THIS IS THE MOST COMMON CONFIGURATION FOR MODERN CARS WHERE WIDTH AND CURVATURE DO NOT IMPOSE SEVERE CONSTRAINTS. FIRST DEVELOPED IN 1890'S FOR CLEVELAND. IS USED FOR BOEING LRV. DUWAG B TYPE AND U2, TYNE & WEAR, AND MANY OTHERS.

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

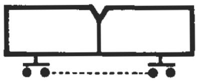


2-AXLE PIVOTAL. PIVOTAL AXLES, WITH A MECHANICAL LINKAGE USED IN BRITAIN AND ELSEWHERE. HAS RESEARCH SIGNIFICANCE.

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 58. Basic Light Rail Vehicle Configurations

1936, and the 1941 Electroliners still running on the Philadelphia Norristown line. The virtual abandonment of the mode halted development in the U.S. The mass production of articulated cars in Germany began in 1956. Their main advantages are a reduction in overhang for short radius turns (requiring less clearance than long, non-articulated vehicles), increased individual vehicle capacity, and better passenger distribution onboard.

METHOD OF OPERATION

Vehicles may also be classified according to their method of operation.

- *Single unit* – These vehicles are designed to operate without coupling to another vehicle. In emergencies, and sometimes in normal operations, single unit vehicles can be coupled to other cars.
- *Multiple unit* – These vehicles are designed to operate in trains usually not longer than three units. Existing LRT systems do not operate more than 3-car trains although this is possible where the power supply and stations have adequate capacity.
- *Single direction* – These vehicles are designed to operate in one direction only. Doors are placed on only one side (generally the right side for right-handed operation). Single direction operation requires a turnaround loop or "Y" at turn back points. Advantages of single direction operation include fewer doors, more seats and reduced controls cost. Single direction operation is preferred where trailers are used; vehicles cannot turn back at crossovers, a major handicap in subways. They are, therefore, being phased out in semi-metro systems.
- *Bi-directional* – These vehicles can operate in either direction. The car is essentially symmetrical, with doors on both sides and controls at each end. Due to the additional doors, there is a reduction in the available passenger seating space. The main advantage of these vehicles is that turnbacks can be made at crossovers, which is important for cars with larger turning radii and in subways. An added advantage is that the vehicle can service side or center island loading platforms.
- *Low level loading* – Most LRVs load passengers from low level platforms, or street level. Loading is generally considered to be low level if the platform is less than 10 inches (254 mm) from the top of the rail head. Many systems use curb height platforms (6 to 8 inches).
- *High level loading* – Some LRVs are designed to permit loading from high level platforms. Such platforms are either flush with, or one step down from, vehicle floor level. In general, LRT vehicles have floor heights of less than 3.28 feet (1000 mm). Some recent DuWag designs and the Boeing LRV for San Francisco have movable steps which permit loading from either high or low level platforms.

DESIGN PRINCIPLES

THE TREND TO LARGER VEHICLES

The design of light rail vehicles has evolved from small, 2-axle and 4-axle streetcars to larger and faster cars with single or double articulation. This change has not been haphazard. It stems from realizations that changes in the characteristics of Western European cities, in the economics of urban transportation, and in the evolving competition with the automobile require substantial technological innovation to maintain, if not to strengthen, the role of rail transit. Fundamentally, the new LRT designs sought to produce faster, quieter and more comfortable vehicles than their streetcar predecessors. They also sought to provide a simple solution to the need to improve the productivity of operating personnel, and thus keep operating costs in check. Finally, they dealt with the problem of providing, in the fastest and least costly way, an effective improvement in public transit that would support the preservation of the quality of life in cities as it existed at that time. Specifically, these major objectives were approached as follows:

To improve the economic picture, larger vehicles were required, because:

- Operator productivity is improved on a larger vehicle, i.e., the cost of one operator can be apportioned to many more riders.*
- Up to 60 percent of vehicle cost is in electrical work. The cost per seat is reduced when a set of electrical components is made to serve a larger number of passengers.
- The electronic controls used on some of these vehicles help reduce energy consumption, hence operating costs. Choppers are more efficient and could be easily adapted to power regeneration, i.e., saving power by recovering energy from the vehicle while it comes to a stop.
- Maintenance costs are reduced when a smaller fleet of larger vehicles provides the same service as a larger fleet of small vehicles.
- Long vehicles give higher capacity per unit train length, due to fewer coupling gaps and driver console dead space.
- Larger vehicles increase the passenger carrying capacity of the transit line.

---

*However, in considering the utility of larger vehicles for North American cities, it is helpful to recall that the diurnal distribution of travel demand, i.e., number of peak hours and intensity of travel during peak hours, is not necessarily the same as that of the West European cities that feature LRT service. Accordingly, a shorter peak hour period, typical of North American practice, would cause the larger vehicles to operate with lighter passenger loads during off-peak hours for longer periods during the day. Thus, the savings in operating costs due to the increased productivity of the driver would be offset somewhat by the higher energy costs caused by the operation of larger vehicles.

To increase the speed of operation:

- The use of fare collection not onboard the vehicle was adopted, primarily as the self-service fare collection system. This method removed the obstacle to the use of multi-door, fast loading, high capacity vehicles.
- Powerful motors and lightweight vehicle bodies were used to increase both cruise speeds as well as acceleration capabilities.

To improve the ride quality and its style:

- Sophisticated motor and brake controls were introduced to reduce discomfort during starting and stopping.
- Improved car body design was used to reduce interior noise. Improved suspension to decrease vibration, and air conditioning were introduced to maintain passenger comfort.
- Larger vehicles were used, improving passenger security. Unattended trailer cars were subject to problems of passenger security and vandalism. Large vehicles eliminated the need for trailer operation during the low patronage, high vandalism evening period, but retained reserve capacity for unexpected loads.

These design guidelines have influenced contemporary LRT vehicle design as discussed below.

BODY CONFIGURATION

Light rail vehicles, particularly in Europe, often must operate on existing streetcar lines where clearances are restricted and tight turns prevail. Almost all LRT vehicles can negotiate curves of 83 feet (25m). Due to narrow clearance between track centerlines in Europe, many of the vehicles are necessarily very narrow. With the problems of tight curves and restricted clearance, articulation is the only way to increase a single unit's length, and hence its capacity. Articulation allows the distance between trucks to remain short, providing the capability to negotiate the tight curves. The use of double articulated vehicles further increases capacity without infringing on clearance restrictions.

METHODS OF OPERATION

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. Multiple unit operation requires longer station platforms to accommodate the longer trains. Problems with fare collection (unless self-service) and vandalism can be encountered if trailing units are unattended. However, a problem with articulated vehicles is their propulsion: mono-motor trucks cannot readily be used under body joints. Therefore, articulated vehicles have only end trucks powered except when bi-motor trucks are used or the articulation is located between trucks.

DIRECTION OF OPERATION

The first streetcars introduced at the beginning of the century were almost always designed for bi-directional operation. This allowed operation on simple track layouts with easy turnbacks. As streetcar systems evolved, single direction operation became popular.

Greater car reliability reduced the requirement for turnbacks, and maximizing seating became an important goal. Most systems in the U.S., and many in Europe, use single direction cars. However, the recent trend to subway construction, train operation, and larger cars had led to the return of the bi-directional car. Bi-directional vehicles are preferred for underground operation since they can turn back at a simple crossover track. Another advantage of bi-directional operation is that loading is possible from either island or side platforms.

Some disadvantages of bi-directional operation are that doors are required on both sides of the vehicle, which tends to reduce the seating capacity of the vehicle. Costs for doors are increased and reliability decreased, since there are twice as many door mechanisms (recent experience shows that these devices are particularly prone to failure). Another disadvantage is that two operators' consoles are required, which also reduce passenger capacity by approximately three or four standing passengers and increase the technical complexity of the car. The latter increases vehicle cost. Also, some protection or locking devices must be provided for the unattended control station.

In general, most smaller LRT systems, and those without subways, now use single direction operation, and will continue to do so. Larger systems, particularly those with subways, or requiring high capacity, are tending to switch to bi-directional cars.

PASSENGER LOADING TECHNIQUES

Recent LRV designs have been heavily influenced by the reform of passenger loading techniques. These reforms have enhanced the acceptance of large, articulated LRVs in Europe after their indifferent reception in the U.S. many years earlier. The following vehicle features affect passenger loading.

Steps

On any transit vehicle, steps provide a significant obstacle to efficient, fast passenger loading. Low level loading requires three steps for some vehicles (lower floor height) and four steps for others. As the number of steps is increased, floor space inside the vehicle is lost. For street loading, the first step can be of considerable height. One solution is to make the first step a folding or retractable step, thereby reducing the number of steps inside the vehicle. A retractable bottom step often has been used, both in historical and modern designs, to facilitate street loading on a vehicle that also uses low level platforms.

Some recent LRV designs (Edmonton, Tyne & Wear) use only high level loading, more commonly found on rail rapid systems. On other systems which use high level loading, movable steps are provided. When the steps are in the "up" position (e.g., Boeing LRV for San Francisco), the step well disappears; high level, no-step boarding can take place. On the DuWag Type B car, both retractable and movable steps are provided.

A further consideration is the impact of step design on the suitability of the vehicle to operate from a third rail power pick-up. Most contemporary LRT designs are not able to do this because of their steps. Certain designs such as the DuWag B car and the Tyne & Wear car are able to operate on tracks with third rail power supply. The B car has a retractable bottom step which could be retracted in third rail operation, while the Tyne & Wear car had no steps at all.

High and Low Level Loading

Several recent LRV designs allow for both high and low level loading (Table 19). High level loading has advantages where large volumes of passengers are involved, such as on

Table 19. LRV Designs with High and Low Level Loading

Car Type	Configuration
Boeing LRV	Single articulated
DuWag P8	Double articulated
DuWag Hannover 6000	Double articulated
DuWag B Type	Single articulated

modern LRT subways. The main technical disadvantage of providing both high and low level loading is that movable steps must be provided which add more complexity and cost to the car and adversely affect overall reliability.

Doors

Doors are generally of three types: folding, sliding and plug. The folding door takes up some space inside the vehicle so that available boarding width is reduced. However, folding doors can be electrically operated, thus eliminating the need for a separate pneumatic system. Passenger pressure from inside the vehicle against the door pushes it in its direction of closure, thus providing greater safety against inadvertent door opening. Although folding doors are simpler devices than sliding or plug doors, they have a tendency to flutter at high speeds. DuWag has developed a lock to prevent this problem.

The sliding door runs on runners and opens into a recess within the double wall of the car. Typically found on rail rapid transit vehicles it is reliable, but bulky and not suited to LRVs loading from low platforms.

The plug door is now used on some European buses and LRVs. The door is supported on hinge arms. When opened, it is moved out and away from the vehicle side and then slides parallel to the vehicle axis. The door does not require space inside the vehicle when opened, and thus does not restrict the boarding width. Because pressure towards the interior of the vehicle is required to keep the door closed, it is sometimes considered less safe.

In West Germany where self-service fare systems are used, doors are equipped with passenger-operated pushbutton controls located inside and outside the vehicle. The pushbuttons are interlocked with a switch which must be activated by the operator. The switch is inhibited if the vehicle is moving. Such door control precludes the need for all doors to be operated at once or for the vehicle operator to select the proper door to be opened, thus saving heat and air conditioning and decreasing boarding and alighting time.

Modern LRV door closure control is similar to elevator practice. Pressure sensitive steps, sensitive door edges and photo cells are used. For automatic closure, photoelectric cells can be used. If the light beam is not interrupted for four seconds, the doors close. This method can save time during the boarding process, because the doors close immediately when it is clear. On a long car, the end doors always get more use, since passengers are frequently waiting beyond the car when it stops. Double end doors are advantageous for this reason.

Where movable steps are installed, DuWag designed cars use a two piece door. The top part is a conventional plug or following door, the bottom part is part of the step mechanism, and only operates when the steps are lowered. By contrast the Boeing LRV uses a full height plug door. When the movable step Boeing LRV opens its door at a high level platform, the plug door must open into the space between the car and the platform, a procedure which has caused considerable design problems. The P8 car, which is also built with and without movable steps, uses a full door only on the low level loading design.

Platform height has other impacts on car door design. LRVs designed only to load from high level platforms have no constraints on car door locations. By contrast, vehicles designed to load from low level platforms must have doors located away from the vehicle trucks. In this event, the doors are generally not located in the optimum positions. For instance, a vehicle such as the DuWag B car, designed for low level loading, has six doors per side, which is excessive for a vehicle about 100 feet in length. By contrast, the Tyne & Wear car, utilizing generally similar components to the DuWag Type B car, but designed to load only from high level platforms, has only four doors per side in a car of slightly greater length. This reduces car costs, and increases the vehicle seating capacity without appreciable impact on passenger flow. Other factors which have an impact on door design and location are the type of service (which determines the relative importance of doors and seats) and type of fare collection.

FARE COLLECTION

Early American articulated rail cars used various combinations of entry and exit doors, and on-board barriers separating paid from unpaid areas. In many cases, two conductors were required to collect fares on a single articulated car, removing much of the potential benefits from its operation.

Fare collection was an important factor in the development of modern articulated cars in Germany. Previously, each car had a conductor, so that the common motor car/trailer unit had a crew of three men. The articulated cars, 6- or 8-axle, were operated with one conductor only, using the driver to check prepaid tickets at his door. The crew was thus reduced to two men with appreciable saving.

With the introduction of self-service fare during the 1960s, the conductor(s) was no longer needed, so that that particular advantage of articulated cars disappeared. However, their popularity continued to increase, because the presence of the driver in the vehicle is preferable to operation of unmanned trailers. Thus, the self-service fare collection did not affect the trend toward articulated vehicles. Instead, it had the benefit of faster loading which was equally beneficial to all vehicle types.

SEATS

To balance the demands of passenger comfort, cost and vandal resistance, a large number of vehicle designs are provided with molded plastic contoured seats, including thin plastic covered foam pads. Upholstered seats, covered with leatherette materials, are also used, but less commonly. Seats supported on floor stanchions make cleaning the floor difficult. One solution is to cantilever the seats from the side wall, as in the Boeing LRV. A German design recommendation is that seats be attached to the side wall with the aisle sides hung from the ceiling by steel tubes, which serve double duty as hand holds for standees.

Seats can be arranged parallel or sideways. Wider cars may have 2 + 2 across seating. European vehicles, which generally are narrower, often have a 1 + 2 across seating, particularly on narrow gauge systems. A larger ratio of standees to seats may be tolerated if trip distances and/or travel times are short.

The seat arrangement in relation to the doors and aisle widths is important in passenger loading, unloading and capacity. For example, wider aisles provide greater access through crowded vehicles, therefore decreasing the amount of time a passenger needs to reach a door to alight. The same is true in passenger loading, because passengers can move into the spaces between doors faster, therefore reducing queues at boarding. The effects of inadequate width found even in the Boeing vehicle (the widest modern LRV) are illustrated in the Boston vehicle by the adoption of three-across seating to secure an aisle of adequate width for standees.

DIMENSIONS

Table 23 gives the dimensions of ten of the more significant modern LRV designs. Articulation makes longer vehicles possible. As one would expect, vehicle height remains essentially constant, being a function of truck size and human height. Vehicle width data shows that double articulated cars are generally narrower than other types.

Since LRT vehicles have evolved from streetcars (many are still being operated in Europe as streetcars), narrower widths have been required due to restricted clearances between tracks and narrow rights-of-way. Rail rapid transit cars and LRVs for new systems are generally wider than current LRT models. Where LRVs of different width are operated on lines with platforms, the narrower width LRV presents a problem in "bridging the gap" to the loading platform at the rail transit station. In Frankfurt where such an operation occurs, a protruding skirt which is level with the platform has been added to the sides of the LRV to take up the gap (Figure 18). Narrow vehicles are generally not relevant for new systems. Vehicles designed for rail rapid transit range in width from approximately 8.5 to 10.5 feet (2.6 to 3.2m). Greater vehicle width can increase passenger capacity per vehicle unit length by up to 30 percent. The widest new LRT vehicle is the Boeing LRV, but even it is narrower than most rail rapid transit cars. The U.S. PCC car was built to many widths. Some systems used 9 foot wide PCC cars. Narrow LRT vehicles are found only in Europe, and here only for historical reasons. Most lines developed from horsedrawn streetcars, and at no time was it convenient to change the gauge or track spacing.

The Tyne & Wear and DuWag Type B single articulated vehicles are the longest in their class and are comparable in length to the longest double articulated design. Both of these vehicles have very large capacities and large turn radii, and illustrate that where maintaining narrow width is not required by operational considerations, a long single articulated car may be used in lieu of a double articulated car of the same length.

WEIGHT

Table 20 shows the spectrum of vehicle empty weight and weight per unit floor area for a selection of LRVs. Correlations exist between the cost of transit vehicles and the vehicle weight or the weight per unit floor area. A trend to increased weight per unit area is observed as articulation is added. The weight per unit of vehicle floor area increases as vehicle length increases due to requirement of greater longitudinal strength, and the weight associated with the articulation joint and track.

Increased vehicle capacity per unit length can also be obtained by increasing the width. Because vehicle strength is not as critical in the transverse as in the longitudinal direction, increased width also permits a decrease in vehicle weight per unit area, and possibly a reduction in cost. This suggests that a wider LRT vehicle may be more appropriate and less costly for the conditions prevailing in the U.S.

Table 20. Spectrum of Empty Vehicle Weight

Body Configuration	Example	Empty Vehicle Weight		Empty Vehicle Weight Per Area	
		1000's lbs	1000's kg	lbs/ft^2	kg/m^2
Non-articulated	U.S. PCC Car	40	18	100	490
	Canadian LRV	53	24	107	520
Single articulated	Boeing LRV	66	30	107	520
	DuWag U2	66	30	100	490
	DuWag B Type	86	39	111	540
	Tyne & Wear	86	39	109	530
Double articulated	DuWag P8	75	34	109	530
	Hannover 6000	86	39	135	612

Source: *Lea Transit Compendium: Light Rail Transit*

VEHICLE PERFORMANCE

The performance of transit vehicles is generally described by their capacity, turn radii, grade climbing capability, speed, acceleration, and braking. The statistics of vehicle performance are shown in Table 23.

VEHICLE CAPACITY

A wide variety of standards are used by different manufacturers and transit operators to estimate vehicle capacity. Since, for a given design, a vehicle has a fixed amount of head space due to doors, operating consoles and seats, the total capacity depends primarily on the available floor area. Passenger occupancy of this space may vary between 5 and 1.5 square feet per person according to the desired design standard.[13] The DuWag design standard is 2.7 feet^2 (0.25 m^2) per standing passenger, a standard which may not fit the needs of U.S. transit. Vehicle capacity for several LRVs is shown in Table 21.

GRADE CLIMBING

The grade climbing ability of LRVs is a function of their power, weight on drive wheels, and the critical coefficient of friction. Non-articulated vehicles should be able to climb grades in the range of 10 percent. Articulated units generally have lower capabilities. This lower climbing capability is due to unpowered wheels at the articulation.

SPEED, ACCELERATION AND DECELERATION

Table 23 shows the speed range and average acceleration capabilities of some modern LRVs. The lesser acceleration shown for the articulated vehicles is due mainly to the reduction of the number of powered wheels. The loss of adhesive weight is particularly significant on 8-axle vehicles. Mono-motor trucks help to maintain traction under all conditions, because the same motor powers both axles of a common truck. Hence, traction is reduced only if both axles on a common truck begin to slide. The Boeing LRV is designed to achieve constant performance under varying conditions of load by incorporating a means to adjust automatically

Table 21. Vehicle Capacity

Body Configuration	Examples	Total Design Capacity* (Passenger Spaces)	Number of Seats
Non-articulated	U.S. PCC Car	118	48
	Canadian LRV	131	42
Single articulated	Boeing LRV	152	52 - 67
	DuWag U2	162	64
	DuWag B Type	180	72
Double articulated	DuWag P8	170	62
	Hannover 6000	150	46

*Based on 2.7 feet^2 (0.25 m^2) per standee

Source: *Lea Transit Compendium: Light Rail Transit*

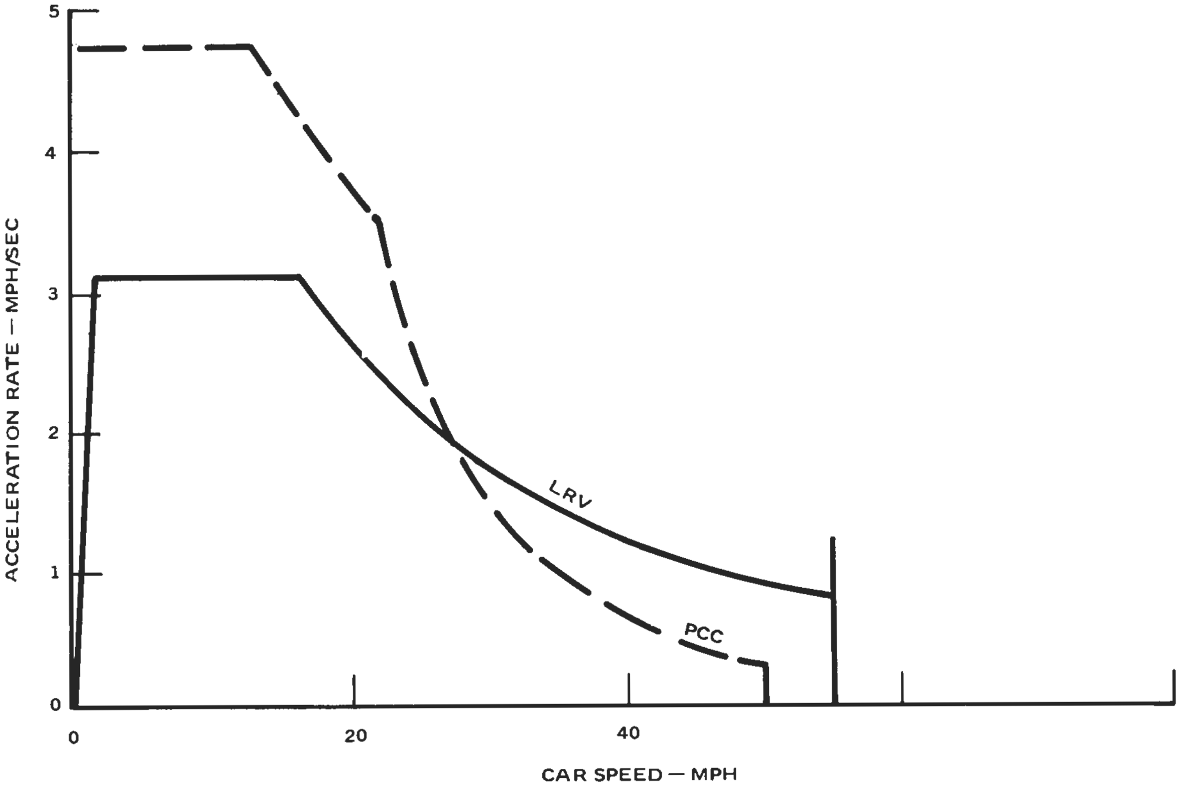
for varying loads and by using anti-slip control. Accelerations greater than 4.6 to 5.2 feet/second^2 (1.4 to 1.6 m/second^2) generally would not be applied in regular service, because standing passengers might lose their balance.

Figure 59 shows the acceleration versus speed curves for the Boeing LRV and the PCC car. Although the PCC car has a higher peak acceleration, the Boeing car maintains a higher average acceleration. Thus, the Boeing LRV can attain a speed of 50 mph in about the same time the PCC car could reach 36 mph. By comparison, the Canadian light rail vehicle is very highly powered (two 164 kw motors), and attains a speed of 30 mph in 12 seconds and 50 mph in 30 seconds.

BRAKING

Table 22 summarizes the average braking performance of some significant LRVs. During dynamic braking when the motors are used to slow the vehicle, the unpowered wheels at the articulation do not assist in braking. Consequently, articulated vehicles tend to have poorer braking rates. Magnetic track brakes, which are normally installed on every truck, enable emergency braking rates of articulated vehicles to equal those of non-articulated vehicles. Thus safety is not reduced due to the articulation feature, because magnetic track brakes are universally used. Almost all modern LRV designs have emergency braking rates around 9.8 feet per second^2 (3 m/second^2).

The comparative emergency stopping distance for LRVs and rubber tired vehicles is of interest, because it indicates why light rail can be designed to operate on street rights-of-way. Figure 60 shows the design emergency stopping distance for autos on dry and wet pavement, and for the Boeing LRV on dry rail without sanding. Under the worst conditions (oil, soap or ice), the LRT stopping distance will increase by 33 percent without sand. Sanding will reduce this amount. On oil or ice, rubber tired vehicles suffer substantially degraded performance.



LEGEND

– – – PRESIDENTS' CONFERENCE COMMITTEE CAR (PCC)

—— BOEING LIGHT RAIL VEHICLE (LRV)

NOTE: AVERAGE PASSENGER LOAD

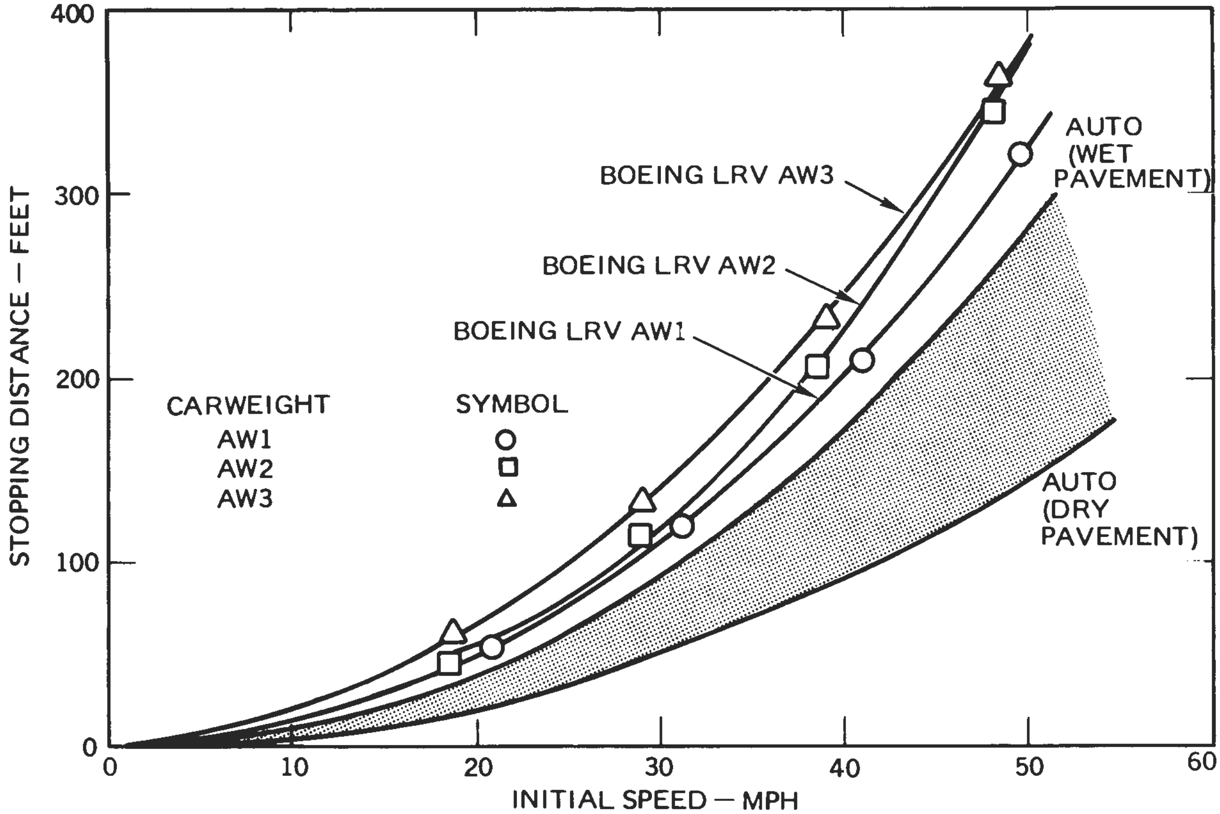
SOURCE: M. Lenow, Boeing Vertol Company

Figure 59. Light Rail Vehicle Acceleration Curves

Table 22. Spectrum of Normal and Emergency Braking

Body Configuration	Examples	Service Deceleration		Maximum Emergency Deceleration	
		ft/s^2	m/s^2	ft/s^2	m/s^2
Non-articulated	U.S. PCC Car	4.6	1.4	9.5	2.9
	Canadian LRV	5.2	1.6	10.3	3.1
Single-articulated	Boeing LRV	5.2	1.6	8.9	2.7
	DuWag U2	3.9	1.2	9.9	3.0
	DuWag B Type	3.9	1.2	9.9	3.0
Double articulated	DuWag P8	3.9	1.2	9.8	3.0
	Hannover 6000	3.9	1.2	9.8	3.0

Source: *Lea Transit Compendium: Light Rail Transit*



SOURCES: BOEING VERTOL COMPANY (TEST DATA)
<u>TRAFFIC ENGINEERING HANDBOOK</u>, INSTITUTE OF TRAFFIC ENGINEERS

Figure 60. Emergency Stopping Distance

VEHICLE SUBSYSTEMS

Each LRT vehicle contains certain components (subsystems) which are important to the evaluation of candidate vehicles from the point of view of performance, reliability and cost. These subsystems include trucks, wheels, drives and motors, braking, heating and air conditioning, and pneumatic systems.

TRUCKS

The vehicle body is supported by trucks which contain the wheels, motors and brakes. The trucks also transmit the vehicle weight to the rail. They insulate the passenger carrying structure from vibration caused by the motion of the vehicle on the rail by "suspending" the wheel axles from the truck and then the truck from the vehicle body. The entire process is known as suspension. Primary suspension of the axles from the truck is provided by either metal or rubber chevron springs. Current designs use rubber chevron springs which yield a higher alignment accuracy between the two axles and reduce noise levels.

A secondary suspension, consisting of metal springs or airbags, is required to insulate the car body from vibration and noise generated by track irregularities. If air suspension is used, a pneumatic system is required to maintain the correct air pressure in the bag. This device tends to increase the complexity, cost and weight of the vehicle. If air suspension is used, however, traction, braking and vehicle level can be adjusted automatically to varying vehicle passenger loads.

WHEELS

Resilient wheels are used in all new LRT vehicle designs. Their chief advantages are reductions in noise (squealing) on short radius turns, and in wheel wear. Resilient wheels work like a cracked bell; they refuse to resonate. The wheel developed for the PCC car, the "super resilient" wheel, is a much softer wheel than the common European Bochum 54 wheel. The latter is available in North America as the Penn-Cushion wheel, and has been fitted experimentally to some PCC cars. The wheel selected for the Boeing LRV, the Acousta-flex wheel, is regarded as considerably stiffer than either of these two. However, the balance of advantages and disadvantages suggests that the marginal increase in noise attributable to a stiffer wheel is more than compensated for by the advantages of such a wheel. By contrast, the wheels used on rail rapid transit systems have no resilience at all.

Resilient wheels are not without disadvantages. At higher speeds, they can become unbalanced. Consequently there have been efforts to develop stiffer wheels, such as the Acousta-flex. Resilient wheels may increase the rate of rail corrugation, and hence the need for track grinding. The value of resilient wheels has been recently proven by DuWag in an experiment with the new DuWag Type B car. Eighteen of the cars were fitted without the standard resilient wheels to determine if track wear could be reduced as a result. Because wheel screech was unacceptable on curves, all future cars designed will continue to use conventional resilient wheels.

DRIVES AND MOTORS

Traction motors are almost always mounted on the trucks. A bi-motor truck carries two motors, with each axle being driven by a *separate* motor. Its disadvantages are that one wheel set (two wheels rigidly mounted on one axle) can slip with respect to the other; maintenance, cost and truck weight is increased; and both the truck design and motor speed control are more complex. The motors on the bi-motor truck can be transversely mounted using right angle drives.

Mono-motor trucks use only one motor to drive both axles. Mono-motors are always mounted longitudinally and connected to the axle with a right angle drive.

The present trend is toward the use of mono-motor trucks, particularly in West Germany. All DuWag and Schindler trucks are mono-motor, as are those of the Boeing LRV. The main advantage of the mono-motor truck is that all four wheels are driven by the same source, thus reducing the chance of wheel slip. Mono-motor trucks tend to marginally increase floor height. However, mono-motors require less maintenance and reduce truck weight, and hence vehicle weight. Their design is somewhat simpler, and therefore they are less costly.

The PCC car utilizes bi-motor trucks, as do all of the current European PCC designs. The Tatra cars, which are based upon the PCC cars, also have bi-motor trucks.

Motors are generally coupled to the gearbox by a Cardan shaft with rubber couplings. The rubber coupling is an important factor in noise reduction. Some vehicles use a two-stage gearbox, while others have a single-stage hypoid gearbox (i.e., a type of automotive gearing).

BRAKING

The braking system used on light rail vehicles is particularly significant, because it is one of the features which distinguishes the mode from other rail modes and enables it to operate safely in the proximity of street traffic without reliance on automatic track protection. Three different and independent braking subsystems are used on light rail cars.

Dynamic brakes are the principal means of normal deceleration from high speeds. They operate by using the traction motors as generators (much in the same way as an automobile can be braked by putting it in low gear). This technique is common to most electric transit and permits frequent or continuous braking without overheating, and with a minimum of mechanical brake wear. During braking, the motors are independent of outside power sources. The electrical current produced by dynamic braking (the motors are now acting as electric generators) may be returned to the overhead power supply. This procedure is regenerative braking. Alternatively, the electric power may be dissipated in resistors located beneath the floor or on the vehicle roof. In many designs, these resistors are incorporated into the vehicle heating system. Regenerative braking has not proved attractive on light rail systems in the past, but the achievable 10 to 30 percent savings in power may cause it to be more popular as power costs increase. It does, however, add approximately 20 percent to the initial cost of the brake subsystem. In regions where the heating season is long, the power savings will never make it attractive, since heating power not obtained from the resistors must come from the contact wire.

Dynamic braking becomes ineffective at low speeds and must be supplemented by a mechanical or friction braking system to bring the vehicle to a halt. On modern designs, the mechanical brakes usually consist of disc brakes located on the vehicle axles, although automotive drive, drum, and tread brakes are also used on older designs. These brakes may be pneumatically or hydraulically operated and are usually spring-loaded so that they are applied even in the event of power failure. They also function automatically as parking brakes. The mechanical brakes are blended (i.e., braking shifts smoothly from one procedure to the next as speed decreases) to achieve continuous jerk-free operation through the entire operating speed range. In modern traction/braking systems, the braking force can automatically compensate for changes in vehicle load by means of pressure feed-back from the air suspension system. A heavier vehicle will require a larger stopping force to come to a halt in a given time or distance. Some modern vehicles also have a slip/spin prevention subsystem to interrupt vehicle braking if sliding begins to occur. (It is much like the intermittent braking force one applies in an automobile when stopping on wet or slippery pavement.) This device is also important to prevent flat spots in the wheel treads. Since both the dynamic and mechanical brakes are limited by the coefficient of friction between the steel wheels and rail, an automatic rail sander can be provided to give reliable service braking in wet or icy conditions. This device simply releases a small amount of sand on the rails in front of the wheels.

The third braking system is the electromagnetic track brake, used to prevent rollback when starting on an upgrade, and more significantly, as an emergency brake. It is the availability of this brake which gives light rail cars their outstanding braking capability. The brake consists of a block of electromagnets suspended from the truck frame between the wheels, just above the rails. When actuated, these brakes grip the track, producing a powerful retardation which is largely independent of the vehicle load or wet or icy track. The track brakes are operated from the onboard auxiliary power supply, and are independent of the overhead line power. The track brake was developed in the 1920s, and is now required by law in Europe on rail transit systems with at-grade operation or non-continuous signalling.

MOTOR AND DYNAMIC BRAKING CONTROL

The motors of LRT vehicles are controlled (i.e., acceleration, cruise speed and deceleration) by regulating the motor current and voltage. Two techniques are used: the traditional rheostatic approach and, more recently, by electronic solid state methods.

In the rheostatic methods, the current is applied to the motor via a number of resistors arranged in a lattice pattern. The power supplied to the motor is varied by changing the effective circuit resistance by adding or subtracting incremental resistances. The main disadvantages of rheostatic control are that energy is wasted in the resistors and that forced air cooling is sometimes required to keep the resistors from overheating. The main advantages of rheostatic control are that it is well established, has a history of reliability, the units are fairly rugged, and most maintenance shops have personnel well acquainted with its repair.

Cam devices are generally used to remotely vary the closing and opening of relay contacts for the resistors. These cams can be hand operated or motor driven. Alternatively, the resistors may be switches using electromagnetic devices. The operator may, through a handle or pedal, command the desired acceleration of the vehicle. A feedback signal is used to compare the accelerator command signal with motor speed, completing a closed loop control of vehicle acceleration. Similarly, a braking pedal which overrides the accelerator controls the braking resistors.

More recently, solid state thyristor choppers have been used to control LRT motors. The power to the motor is "chopped" or broken into pulses at the rate of a few hundred per second. The resulting power fed to the motor is proportional to the duration of the power pulses, providing a continuously variable control of the motor.

An advantage of the chopper control is that regenerative as well as dynamic rheostatic braking can be achieved. It is also possible to provide very accurate control of performance. Among its disadvantages are the requirement for sophisticated electronic maintenance. Vehicles incorporating chopper control do not always permit multiple unit operation with cars using rheostatic control. Choppers also generate electromagnetic waves which can cause interference with control and communications circuits and therefore require shielding. Chopper motor controls add approximately 6 percent to vehicle costs. If regenerative braking is included, theoretical energy savings for chopper control may range as high as 20 to 30 percent.

HEATING AND AIR CONDITIONING

Heating is generally supplied by directing the forced air cooling from the starting and braking resistors to the inside of the car, supplemented as necessary by power from the contact wire. During summertime, the fans are reversed to blow the heat away from the vehicle. Air conditioning on LRVs is mainly a North American requirement. Very few West German or other European systems have air conditioned vehicles. Mannheim, one of the few systems using air conditioned vehicles, recently took delivery of 20 new cars with air conditioning and will specify it for all future new equipment.

PNEUMATIC SYSTEMS

The vulnerability of pneumatic systems to interference due to cold is widely known. The use of alcohol in the air lines can reduce this problem. In recent times, the increasing complexity of modern light rail vehicles has resulted in a preference for all electric or electric-hydraulic designs. This design change would improve the cold weather operational reliability of LRT, and probably had some bearing on the selection of the U2 car (an all electric design) for Edmonton.

CURRENT VEHICLE DEVELOPMENTS

As shown in Table 18, many new LRV designs have been developed in Europe and North America in recent years. These designs exhibit considerable diversity in vehicle characteristics. While this diversity serves to demonstrate the capability of LRT to operate under a wide range of conditions, it also led to small purchase orders and relatively high costs as compared with other mass produced vehicular hardware. Although variations of operating conditions and physical constraints between systems prevent complete standardization, there is clearly a need for greater coordination in future LRV procurements.

Vehicles chosen for description here represent a cross section of recent designs in North America and Europe. Each of the selected designs is a modern, high performance car, and has one or more qualities that make it potentially suitable for use on U.S. systems. For each vehicle, the type of application for which it was intended, its development status, and significant features, are addressed. Together with later reviews of performance characteristics, these descriptions are designed to aid preliminary decisions for the selection of vehicles. Table 23 outlines the basic statistics of these vehicles.

THE PRESIDENTS' CONFERENCE COMMITTEE CAR (PCC)

BACKGROUND

The PCC car is not a recent design, nor is it manufactured any more in North America. However, no review of modern LRVs would be complete without a description of this significant vehicle which even today, 40 years after its introduction, continues to influence the design of light rail vehicles. The PCC car was initially developed during the period 1929 to 1935 to replace the aging equipment on America's streetcar systems. The design of the car was a radical departure from practice of that time, motivated by a need for better performance and lower capital and operating costs.[14] A major design goal was to lower manufacturing costs by achieving a high degree of component standardization without losing the ability to adapt to the needs of various properties. PCC cars could be supplied in a variety of sizes and track gauges, with single or bi-directional operation, and various seating arrangements. Figure 61 illustrates a typical PCC car.

Table 23. 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

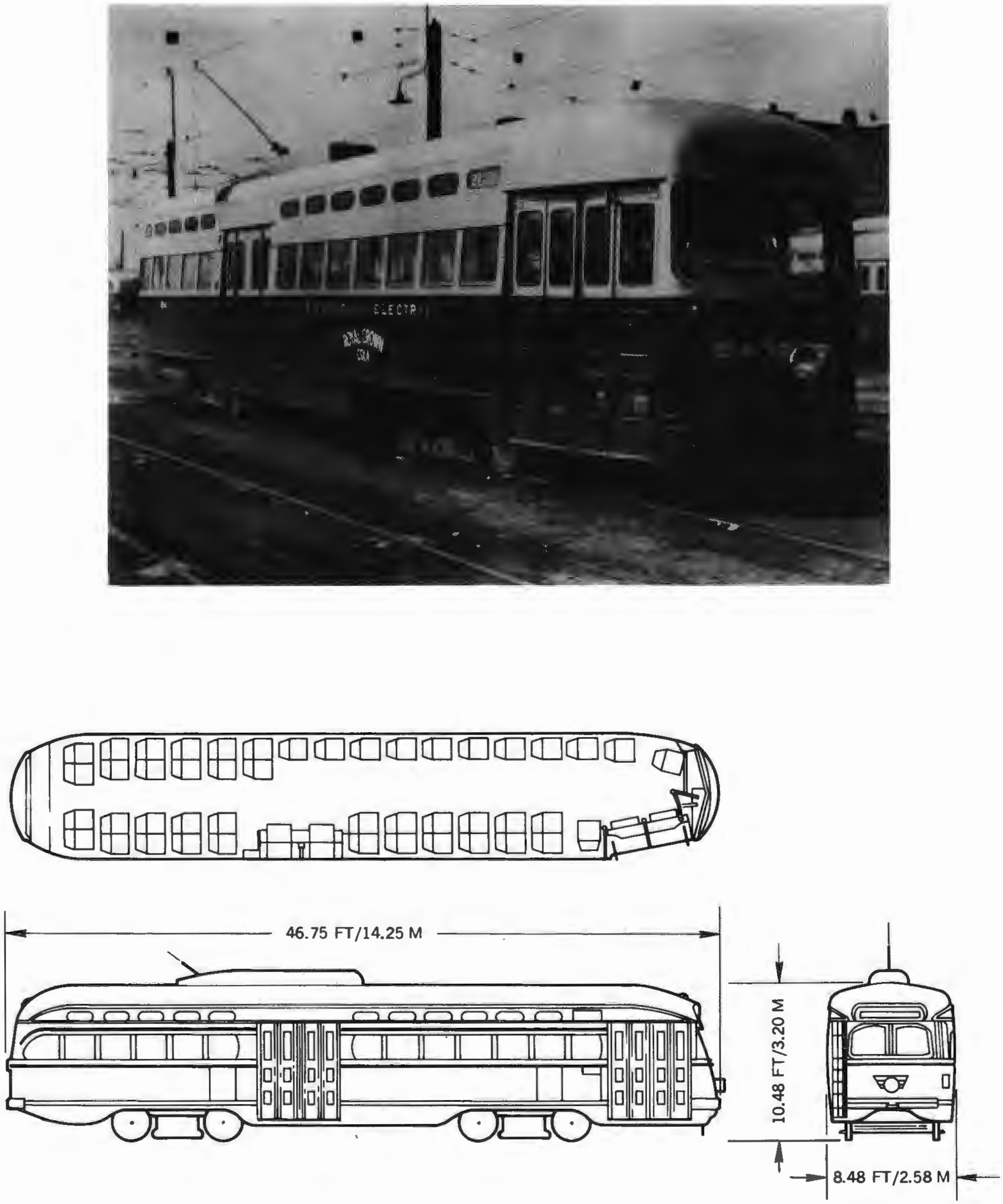


Figure 61. PCC Car

Some 5000 PCC streetcars were built in the United States between 1936 and the mid-1950s. About 1100 streetcars of this design still remain in operation. Systems in North America continuing to use the PCC cars are:

- Massachusetts Bay Transportation Authority (MBTA)
- Shaker Heights Rapid Transit System
- Newark City Subway, Newark, New Jersey
- Southeastern Pennsylvania Transit Authority (SEPTA) – Philadelphia
- PAT – Pittsburgh (see Figure 62)
- San Francisco Municipal Railway
- Toronto Transit Commission
- Mexico City
- Fort Worth Subway
- El Paso-Juarez (temporarily out of service)

Figure 62. Refurbished PCC Car in Pittsburgh – 1975

SIGNIFICANT FEATURES

The PCC car was developed after a long period of study, design and testing. It ultimately incorporated numerous technical improvements, many of them still used in new LRVs today. The more significant advances were the following:

- A new motor/brake controller was developed by Westinghouse Electric and Manufacturing Company and General Electric Company to eliminate the jerkiness of the older type of resistance controller. The PCC controller had 99 contact points and a rotating accelerator moved by a servo-motor.

  The car had three braking systems. Dynamic braking, being independent of adhesion between wheels and rail, is used effectively for deceleration from higher speeds and avoids skidding. At lower speeds when dynamic braking fades out, air brakes were automatically introduced to bring the car to a full stop. Later models eliminated air brakes, substituting a friction brake on the driveshaft. The third system is the magnetic track brake which acts directly on the rails. The track brake is also independent of the vehicle to rail adhesion, giving extremely powerful but jerky retardation. It, therefore, serves as an emergency brake only. The magnetic brake is a characteristic element of all light rail vehicles.

- A resilient wheel was developed to reduce rolling noise and screeching on curves. The wheel was constructed as a sandwich of steel and rubber discs that effectively damped much of the noise and vibration. It was called the *super resilient* wheel, a term used now to distinguish it from later resilient wheel designs.

- A combined rubber and steel spring suspension system was developed to further reduce vibration and noise.

- Hypoid gears (a special spiral bevel gear used in automobiles) encased in oil were used in lieu of the older and noisier spur gears.

- The car body was made as light as possible with major structural members arranged to act as air ducts and channels for wiring and piping.

- The basic car was designed for single direction operation but was arranged so that it could easily be adapted to bi-directional operation.

- Trucks were designed for easy adaption, at nominal cost, to different track gauges.

- High speed, lightweight motors were specifically developed for the car. Four motors were provided (i.e., bi-motor trucks), each mounted with its shaft at right angles to the axle and connected through the hypoid gears.

- Performance was significantly improved. Average acceleration rates as high as 6 feet/second^2 could be obtained, while the maximum rate of 6.97 feet/second^2 was more than twice that of other conventional streetcars of the time. These rates were found to be above the comfort level for standing passengers, and in later years most PCC cars were reset with lower acceleration rates. The cruising speed on level tangent track was 42 mph (67 kph), with a safe maximum of 50 mph (80 kph).
- Costs were 25 percent below the average of other cars of comparable size available at the time.

It is generally accepted that the PCC car represented a major advance in LRV design, an achievement somewhat overshadowed by the general decline in the industry due to other reasons. Even today, designs based on the U.S. PCC car are still being built in Europe. After World War II, the PCC design was introduced in Europe. The firm of La Brugeoise et Nivelles, of Bruges, Belgium began to build PCC cars in 1948, and has continued to do so ever since. During these years, over 700 PCC cars have been built, including vehicles delivered to Antwerp, Brussels, Ghent and The Hague in the 1970s. These new vehicles are considerably modified from the original design, including the experimental use of choppers (The Hague) and the introduction of articulated units. In 1976, 8-axle PCC cars were being built for use on the Brussels network.

TATRA VEHICLES

The Tatra Corporation of Czechoslovakia is one of the two major manufacturers of light rail vehicles in Eastern Europe. The predecessor of the Tatra Corporation was negotiating a license to build the U.S. PCC cars in Czechoslovakia at the outbreak of World War II. The war prevented any progress in this direction, but in the late 1940s, Tatra began production of a vehicle based on PCC designs. Tatra has continued to build vehicles of this type ever since. Each year the design is updated and modernized; recently, several articulated designs have been developed. Two important examples of the present Tatra production are the Tatra T5 and the Tatra KT4.

TATRA T5

Background

The T5 is the latest PCC derived, non-articulated light rail car offered by Tatra. It has four axles, operates only in one direction, and can be used as a single unit or in trains of up to three cars. The vehicle was designed to replace a now obsolete design at the small vehicle end of the Tatra range. It is intended for wide use on systems throughout Eastern Europe. The vehicle can be considered in the economy class, although costs are expected to exceed somewhat those of earlier "T" series models.

Development Status

The Tatra T5 is currently in test service in Czechoslovakia, and was scheduled to begin production in 1975.

Significant Features

The T5 car introduces mono-motor trucks and chopper control to the Tatra range of LRVs. Compared to other non-articulated vehicles, the T5 weighs less per unit of floor area, and has the lowest emergency braking rate. Its minimum turn radius is less than the average for vehicles in its class. As a non-articulated vehicle, it is exceeded in total capacity and overall size only by the Canadian LRV.

The Tatra non-articulated light rail vehicles are austere in appearance and passenger comfort as compared with modern design standards in Western Europe and North America. This accounts, in part, for their lower prices.

TATRA KT4

Background

The Tatra KT4 is a short, single articulated, single direction, four-axle vehicle which can be coupled into trains. The vehicle is supported on two trucks only, similar to designs used in Bremen and Munich. This car is intended to provide high capacity on systems with restricted clearances, mainly in East Germany.

Development Status

Two prototypes were completed and placed in service for testing in 1972: one vehicle in Prague of 4.708 feet (1435 mm) gauge, and one vehicle in Liberec of 3.28 feet (1000 mm) gauge. Full production was expected to begin in 1975, with initial deliveries to East Germany.

Significant Features

This vehicle is the shortest single articulated vehicle, with the exception of the older Bremen four-axle design. It is also one of the narrowest. Because its width is only 7.2 feet (2.2m), its capacity is limited to 117 passengers. Other features are:

- Low ground clearance. A lower first step height of 13 inches (330 mm) is achieved without use of an outside folding or fixed step.
- Drum brakes, rather than the disc brakes found on most modern vehicles.
- Bi-motor trucks, although most modern vehicles use monomotor trucks.
- Lower performance and emergency braking rates than LRVs designed in the West.

CANADIAN LIGHT RAIL VEHICLE

BACKGROUND

The Canadian light rail vehicle (CLRV), the second LRV to be developed in North America, will be a 4-axle, non-articulated car suitable for multiple unit operation. Initially, the CLRV (Figure 63) will replace the aging PCC cars now used in Toronto; it will also provide a vehicle suitable for use on the new LRT lines being considered in Toronto and other cities. Future procurements for this vehicle may require 6-axle articulated and married pair configurations for high performance operation on exclusive rights-of-way.

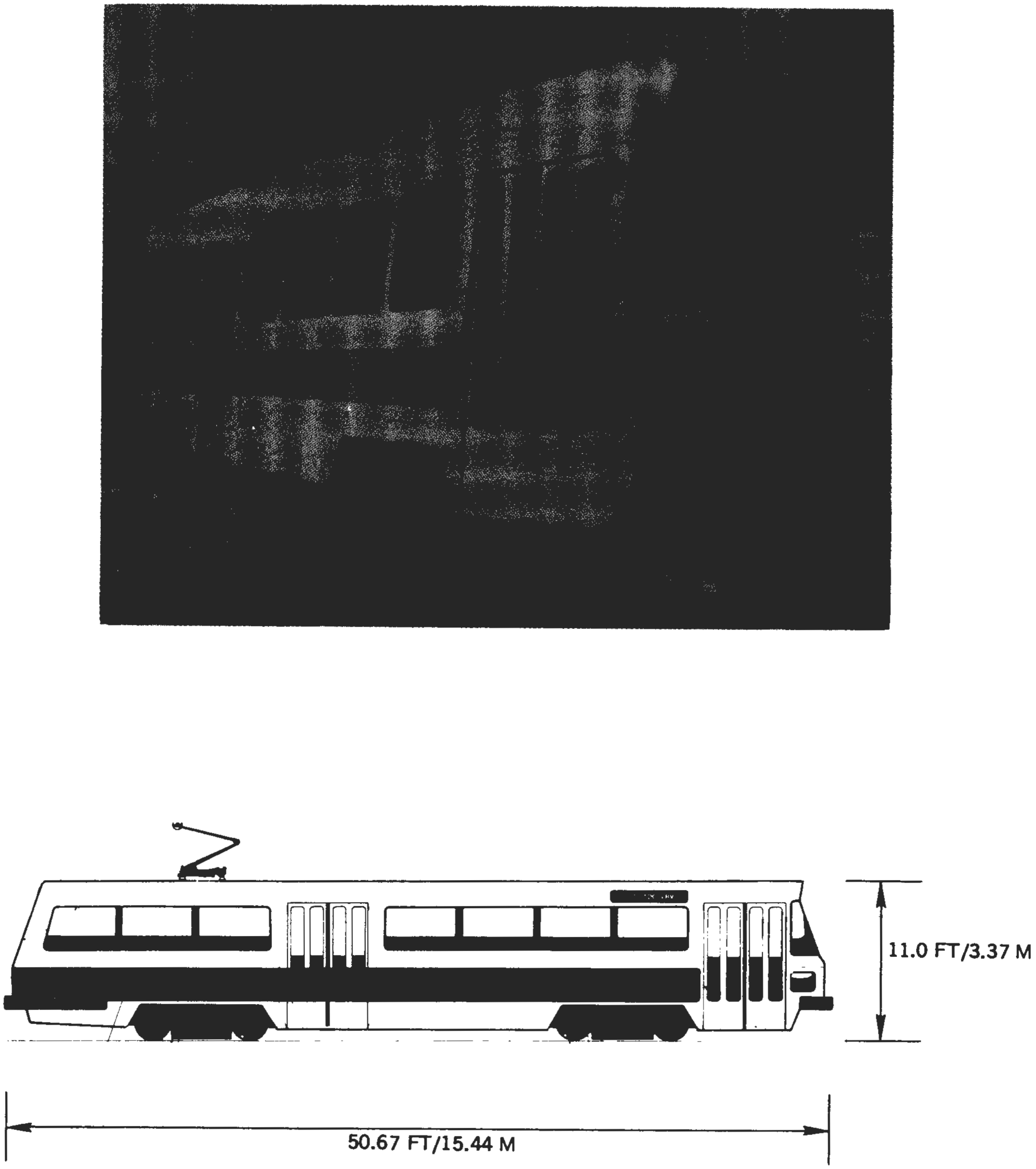


Figure 63. Canadian Light Rail Vehicle

STATUS OF DEVELOPMENT

The Urban Transportation Development Corporation (UTDC) was established by the government of Ontario to develop concepts and hardware for transit systems. The specifications for the Canadian LRV were developed by the UTDC in conjunction with the Toronto Transit Commission. The UTDC will act as a coordinator, subcontracting the detailed development, design and manufacturing work. A contract for vehicle design has been awarded to the Swiss Industrial Company (SIG). Major subsystems, such as brakes, couplers, doors, heating, ventilation and air conditioning, will be supplied by others. In the U.S., the Garrett Company will supply the traction motors and the chopper controls.

The UTDC procurement approach is unusual and involves vesting prime contract responsibility in a small overview staff at UTDC rather than in the principal engineering contractor, SIG. Resolving the assembly or interface problems of this project will require considerable engineering and management skill. But if these problems can be satisfactorily addressed, the results will be of interest as an approach to the development of new transit hardware.

Initial production has been scheduled for the Toronto Transit Commission. Two hundred of the new vehicles will be purchased at a price estimated to be $490,000 (Canadian dollars) by the time they are delivered in 1979. The electronic (chopper) controls add $20,000 to the cost, and trailers could be provided for approximately $100,000 less per unit. The first 10 cars are to be built as prototypes in Switzerland, after which a manufacturer will be selected for the remainder. The first unit is scheduled to be completed in 1977 with delivery of the 200 cars to be completed by mid-1979.

SIGNIFICANT FEATURES

When produced, the Canadian vehicle will be the only new non-articulated design in North America. This design was selected for Toronto for several reasons. It fits the existing maintenance facilities. More frequent service can be given during the non-peak hours while keeping overall operating costs down as compared with more lightly loaded, larger units. Also, the smaller size does not conflict with conventional operator fare collection used on the Toronto system.

The car is designed to reduce noise levels by 10 dBA compared with PCC streetcars. The exterior noise level specification is 75 dBA measured at a distance of 15 feet when the car is traveling at 40 miles per hour. Interior noise is also to be reduced by acoustical treatment of the car structure.

Thyristor chopper motor and brake controls are to be used, as are mono-motor trucks, a feature generally adopted on modern LRVs.

The CLRV for Toronto will have performance characteristics similar to those of the PCC car; however, greater performance capabilities are planned for later versions. The modified Canadian LRV planned for regional transit service will have a power-to-weight ratio (an index of its ability to accelerate rapidly) exceeding that of the Boeing LRV and comparable to the Type B car for Cologne/Bonn. Maximum design speed is 70 mph (113 kph). It will be the highest speed of all current LRT designs, although the version presently being built for Toronto has a top speed of only 50 mph. It has yet to be proven whether the Canadian LRV's greater performance can be utilized in service.

Other features of the current design are:

- Energy absorbing front and rear bumpers
- Axle mounted disc brakes
- Lower first step height than in U.S. and European PCC designs
- Larger overall size than U.S. and European PCC designs
- The largest passenger capacity of any non-articulated vehicles
- Exceptionally high emergency deceleration capability
- A variety of seating patterns.

BOEING LIGHT RAIL VEHICLE

BACKGROUND

In late 1971, the San Francisco Municipal Railway (Muni) sought bids for a six-axle articulated LRV to replace its PCC cars and operate on its new LRT subway. The bids submitted for the 78 car order were rejected. Later, under the sponsorship of the Urban Mass Transportation Administration (UMTA), the transit operators of a number of North American cities (all of which needed a vehicle to replace their PCC cars) assembled a set of common vehicle specifications suitable for each system. The Boeing Vertol Company, the lowest bidder in the competitive bidding, was selected to build the vehicles. Subsequently, San Francisco and Boston placed a joint order for 275 of these cars with Boeing.

The light rail vehicle (Figure 64) produced by Boeing is a 6-axle articulated car. The car body is of all-welded steel construction. The two end trucks are powered by a single motor driving both axles; an unpowered center truck supports the articulation joint. All trucks incorporate axle mounted disc brakes and electro-magnetic track brakes. The Boeing LRV has been designed to provide a smooth and quiet ride with low exterior noise levels.

The vehicle was designed to be the largest size car which could be built within the constraints of the Massachusetts Bay Transportation Authority (MBTA), San Francisco Municipal Railway (Muni) and Southeastern Pennsylvania Transit Authority (SEPTA) systems.[15] The Boeing LRV is designed for multiple unit operation on exclusive and semi-exclusive right-of-way, or in mixed traffic. By adding movable steps, the San Francisco version of the vehicle can operate at both high and low platform stations.

DEVELOPMENT STATUS

In 1973, the Boeing Vertol Company began to build 80 vehicles for the Muni and 150 vehicles for the MBTA. Subsequently, Muni and MBTA ordered additional Boeing LRVs, bringing the total quantity on order to 275. Test vehicles have been operated at MBTA and at the UMTA rail transit track at the U.S. Department of Transportation's Transportation Test Center. The first operational vehicles will be delivered to Boston late in 1976.

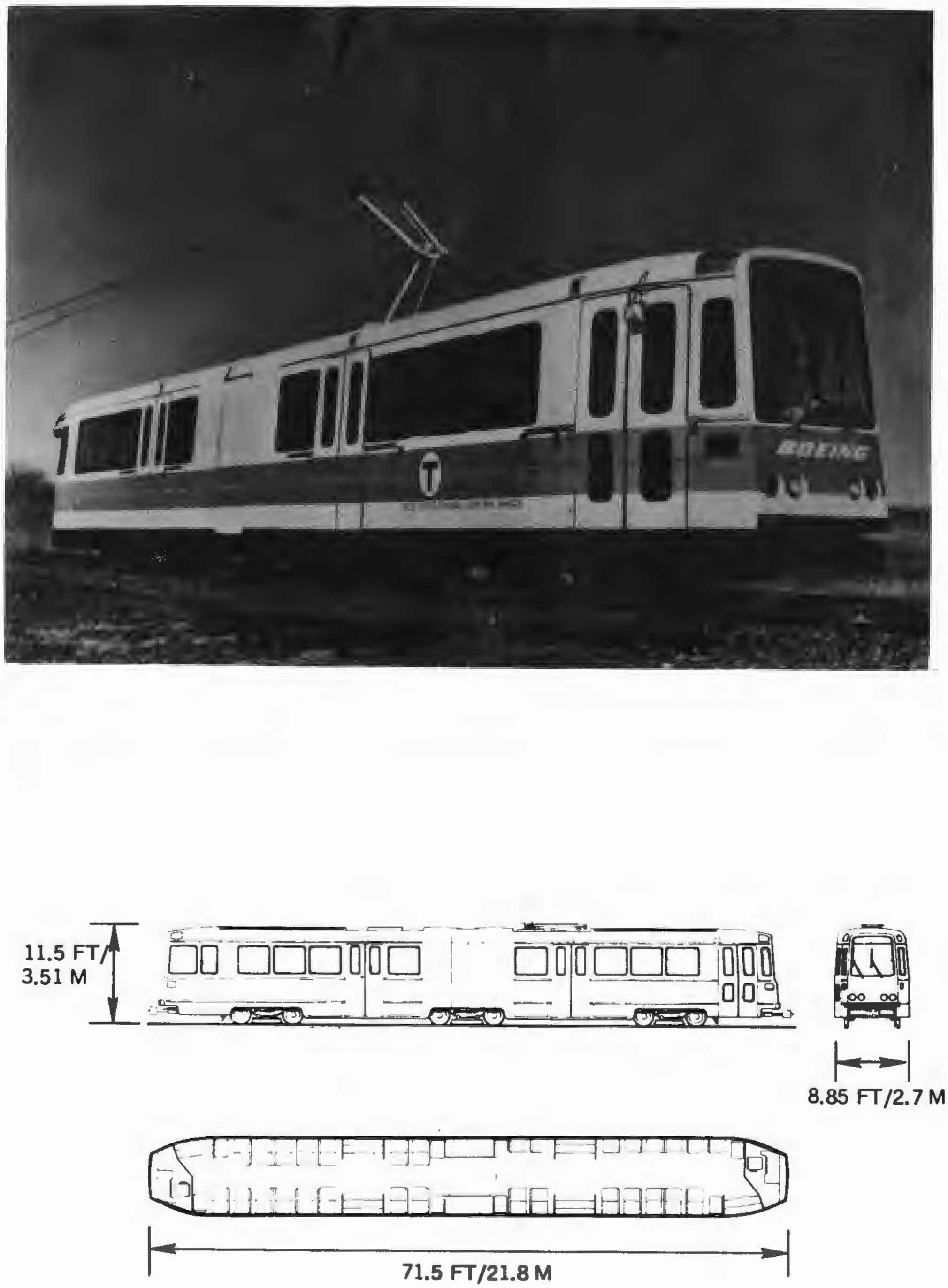


Figure 64. Boeing LRV

SIGNIFICANT FEATURES

The Boeing LRV has been designed to incorporate many recent technological developments. These include:

- Performance profile better suited to modern LRT operations than the U.S. PCC car. Despite a lower initial acceleration than the PCC car, the Boeing LRV sustains its acceleration to higher speeds and can attain 50 mph (80 kph) in about the same time as the PCC car could attain 36 mph (58 kph). The maximum speed of the Boeing LRV (50 mph) is exceeded only by the DuWag B Type car.
- Movable steps for high or low level platform passenger loading (San Francisco vehicles only).
- Advanced electronic motor/brake controls (thyristor chopper) and anti-slip wheel control.
- Cab signals for use in systems employing automatic train protection (San Francisco).
- Automatic compensation of the suspension, propulsion and braking systems to variations in vehicle load.
- Couplers designed to absorb energy in minor collisions.
- Plug type doors with sensitive edges to avoid entrapment in closing doors.
- Mono-motor trucks to improve adhesion and reduce maintenance.
- The widest current single articulated design, 8.9 feet (2.7m).
- High capacity (68 seats, up to 151 passengers standing).

DUWAG VEHICLES

DuWag of Dusseldorf, West Germany, has been the leading manufacturer of light rail vehicles in Western Europe since the mid-1950s. Many cities in West Germany (except the Bavarian cities and Bremen) operate DuWag vehicles. Rotterdam in Holland, and Vienna, Graz, Linz, Innsbruck in Austria have purchased vehicles from DuWag or from a local manufacturer building cars under license from DuWag. Edmonton, Canada has also ordered cars from DuWag; Vancouver, British Columbia has acquired a second hand DuWag car (originally built in 1970 for Hannover) for operation on a demonstration test track. DuWag began building articulated LRVs in 1956. Ever since their introduction, articulated cars have formed the major part of DuWag's production. In recent years, DuWag orders have increasingly shifted toward 8-axle, double articulated vehicles, including large orders for Frankfurt, Dusseldorf and Hannover. DuWag is also building some central sections for conversion of 6-axle into 8-axle cars. Although DuWag produces many types of car, considerable component standardization is practiced. DuWag components are also sold to other car builders. Four DuWag recent designs are described here.

DUWAG U2

Background

During the 1960s, Frankfurt began building an LRT subway and associated at-grade approach lines, now known as the "A" lines. Unlike the rest of the Frankfurt network, these lines required no street level loading, and did not exhibit the sharp curvature of the then existing system. A new LRV was designed to operate on this system (the DuWag U2).

The U2 (Figure 65) is a six-axle, articulated, bi-directional vehicle designed for use on exclusive and semi-exclusive rights-of-way. Intermediate level platforms are used on the segments where the U2 is operated, and eventual conversion to high level platforms is planned.

DEVELOPMENT STATUS

Delivery started in 1968, and 64 vehicles are now in use in Frankfurt. Additional U2 cars are presently being delivered. The new LRT system being constructed at Edmonton, Canada, requires 14 cars to operate its first line. A small order of this size clearly called for the use of an existing proven design. The U2 order for Edmonton is the first DuWag sale in North American market.

Significant Features

At 8.69 feet (2.65m), the U2 is wider than most other West German designs. This width is now the standard for new West German LRT systems, and is used on the Cologne and Rhein Ruhr systems. Other noteworthy features of the U2 car are:

- Compatible coupling systems with the newer DuWag P8 car, also designed for the Frankfurt LRT system so that the U2 and P8 can operate together in an emergency.
- Untapered ends, reflecting its design for use on a system without tight curves.
- Doors with sensitive edges and photocell protection to prevent passenger entrapment.
- Multiple unit operation in trains of 1 to 4 cars.
- Mono-motor trucks.
- Anti-slip wheel control.
- Semi-automatic speed control.
- Relatively large minimum horizontal turn radius (82 feet [25m]). This radius is not a disadvantage on the systems for which the U2 was designed. However, it would preclude the use of this vehicle on systems requiring very tight turns.
- All-electric subsystems, giving enhanced reliability in cold climates.

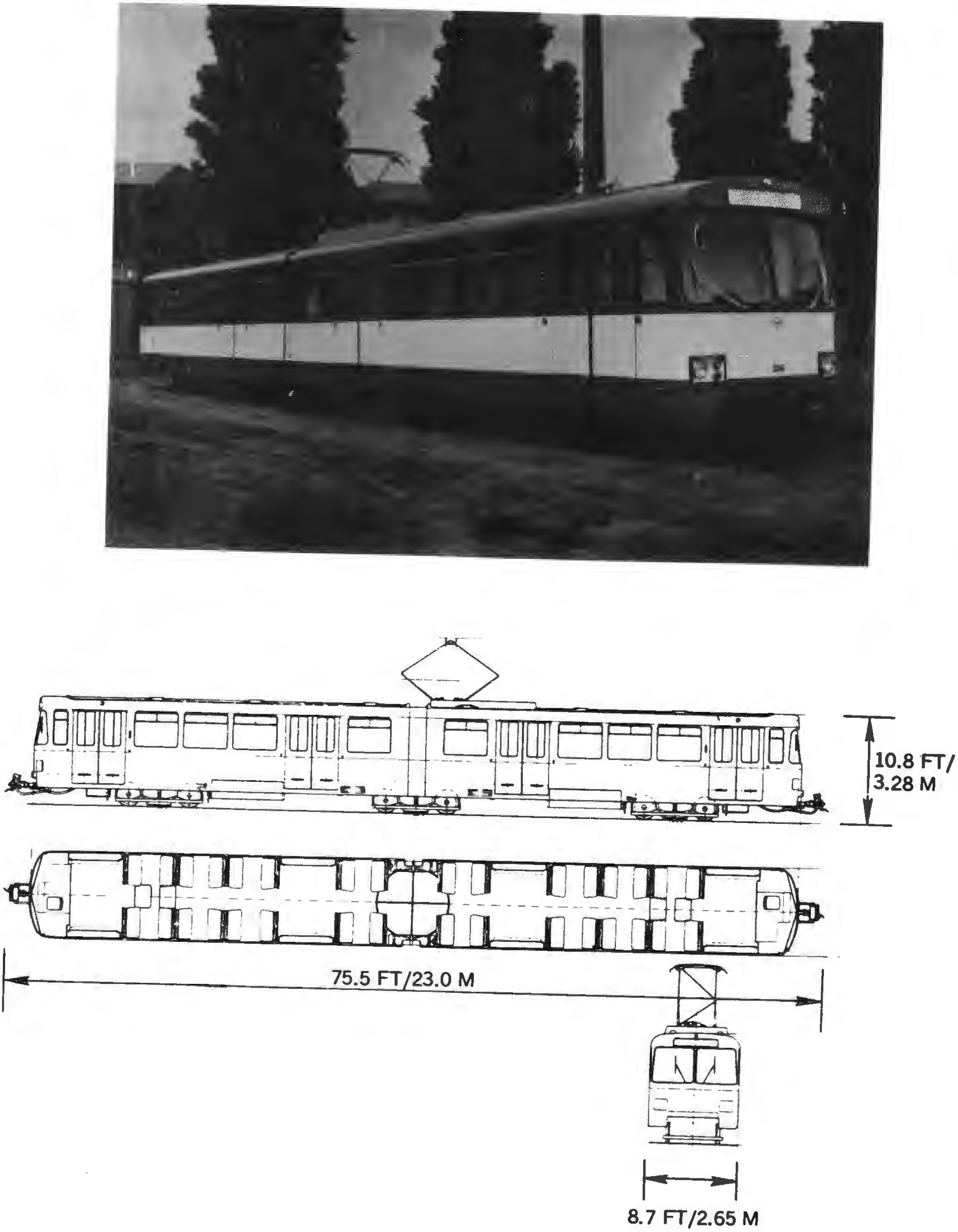


Figure 65. DuWag U2

DUWAG P8

Background

The continuing development of the Frankfurt LRT system led to the need for cars able to operate on both streetcar sections of the system and on new subway lines having high level platforms. The P8 car was designed to fill this need. The P8 is an 8-axle, double articulated, bi-directional vehicle designed for multiple unit operation. Up to three vehicles can be coupled and operated as a train. It can be equipped with movable steps for low or high platform use. The narrow P8 (7.71 feet [2.35m]) is used on the Frankfurt "B" lines, where curvature and tracking spacing on surface segments do not permit operation of the DuWag U2 cars.

Development Status

From 1972 to 1974, 100 vehicles were purchased and are now in operation. Cars used on surface lines only do not have the movable step option, with consequent simplification of door and step mechanisms.

Significant Features

The DuWag P8 vehicle has the following special characteristics:

- Movable steps for high or low level passenger loading (some cars only).
- A high first step, 15.8 inches (400 mm), requiring low level platforms for surface operation.
- Doors with sensitive edges and photocell protection.
- Coupling system compatible with the U2 so that they can be operated together in case of emergency.
- Conventional resistance traction controls operated by semi-automatic electronic devices. The feature includes automatic control of pre-set speed and anti-slip wheel control.
- Automatic train protection on some cars (cab signals).
- A minimum turn radius of 56 feet (17m) made possible by the double articulation. A relatively long car, the P8's greater length is necessary to achieve high passenger capacity in a narrow vehicle.
- A large capacity. It is exceeded in total capacity by the DuWag Type B and Tyne & Wear single articulated vehicles.
- Performance somewhat less than most modern LRVs due to the low power motors (two each at 120 kw) and heavier empty weight, 75,000 lbs (34,000 kg).

DUWAG TYPE B

Background

In 1970-1971, the cities of Cologne and Bonn decided to develop an LRV to operate on their subway and surface LRT systems and on the two 23 mile electric railways that link the systems. This required a high speed LRV capable of multiple unit operation and operation on streetcar sections of the system. The resulting DuWag Type B car (Figure 66) is a 6-axle single articulated vehicle. It is bi-directional and can be coupled into trains of up to three units. The B car is probably the most significant of all present European designs, since it has the capability of high speed operation. It has now been selected for several other European systems, including the Rhein-Ruhr Stadtbahn, the Rheinbahn (Dusseldorf), and the new Utrecht system. It is the prototype for other vehicles, such as the meter gauge M car by DuWag and the British Tyne & Wear car, which use many common components. The Type B is the fastest LRV in Europe.

Development Status

The first cars were delivered to Cologne in 1973. Since then, deliveries have been made to Bonn, Cologne, and the Rhein-Ruhr. It is anticipated that up to 500 vehicles may eventually be built.

Significant Features

The B car represents a significant step in the evolution of LRVs, incorporating numerous design refinements, as follows:

- Movable steps are incorporated so that passengers may board from high or low platforms.
- The vehicle is the fastest LRT vehicle in West Germany, 62 mph (100 kph). It is also faster than any German rail rapid vehicle.
- Automatic couplers are provided with heating provisions to preclude problems from ice formation.
- Vehicle performance (i.e., velocity and acceleration capability) is among the highest for all articulated LRT vehicles in operation, exceeding that of the Boeing LRV. The Gothenburg and Melbourne ASEA cars are designed for higher acceleration.
- Seated and total passenger capacity is the largest for all LRT vehicle designs, except for the Tyne & Wear car which is derived from the Type B design, and the special purpose designs used in Mannheim and Freiburg.
- The mono-motor trucks utilize the largest motor of any of the current LRT vehicles, 235 kw per motor. The larger rating is required to achieve the extremely high performance.
- This vehicle, together with the Tyne & Wear car, is the longest and heaviest of the single articulated LRT vehicles, with a weight per unit floor area somewhat greater than that of the Boeing LRV.
- The B car has six doors per side.

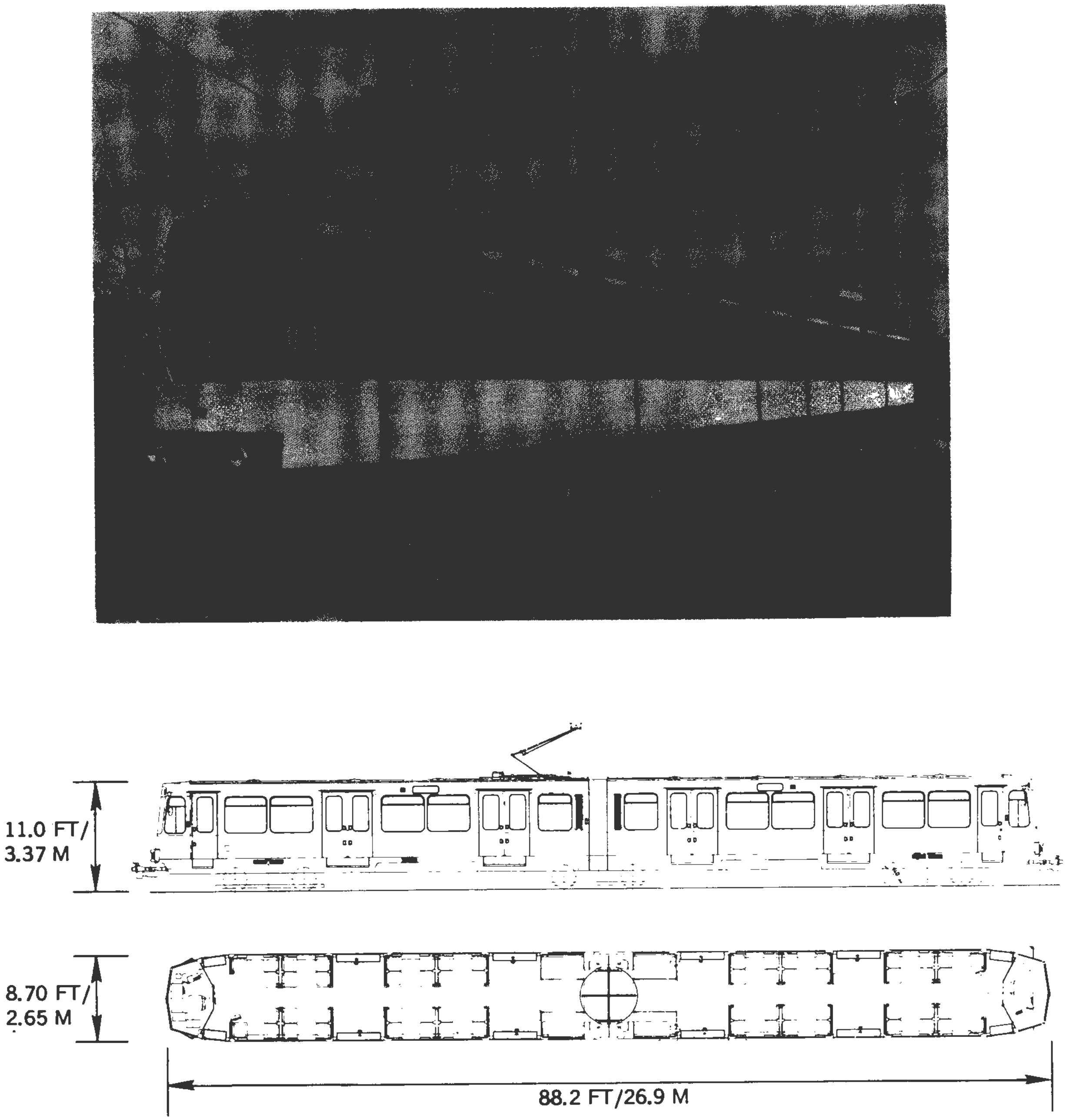


Figure 66. DuWag Type B

- As with other large single articulated cars, it requires a relatively large turn radius. It can be used on third rail electrified lines when equipped with a pick-up shoe.

HANNOVER 6000 VEHICLE

Background

In the early 1970s, Hannover began constructing a light rail subway system, and ordered two 6-axle prototype cars, one from DuWag, and one from Linke-Hoffman-Busch (LHB). After extensive testing, the DuWag design was selected, and an order for 100 cars placed. The production cars included many modifications, including an increase in length to 8-axles and the adoption of chopper controls, the first such installation on West German LRVs. The original DuWag prototype was renovated and sold to the Bureau of Transit Services in Vancouver, B.C., where it is scheduled to operate on a demonstration track.

Development Status

Delivery of the 100 vehicles to Hannover is nearing completion. The initial subway was opened in 1975, and additional subway extensions are in progress. It is anticipated that additional cars will be ordered.

Significant Features

The Hannover 6000 is an 8-axle, double articulated, bi-directional vehicle designed for subway and surface use with low and high level platforms. Designed specifically for use on existing surface routes where side clearances require the narrow width, it is 7.9 feet (2.4m) wide. The 8-axle design was selected to permit use of a long car within these constraints. Other important characteristics are:

- Movable steps for high and low level platform passenger loading.
- Advanced electronic (thyristor chopper) semi-automatic propulsion and braking control. This is a federally sponsored project intended to determine whether such control should be adopted in other West German systems.
- Disc brakes.
- Relatively high first step height, 15.3 inches (388 mm), requiring low level platforms on surface operations.
- The highest empty vehicle weight of any double articulated vehicle. With the greater weight and power of 2 x 216 kw, performance is somewhat less than the average LRT vehicle, and poorer than both the Boeing and Canadian LRVs.
- The maximum speed of 50 mph (80 kph) is the same as that of the Boeing LRV, Tyne & Wear, and DuWag U2 but less than the DuWag B. However, it is one of the fastest double articulated vehicles.
- A relatively short turning radius of 57.4 feet (17.5m).

- High total vehicle capacity compared to all other LRT vehicles due to its larger floor area and relatively low ratio of seated to standing passengers.
- Multiple unit operation capability.

TYNE & WEAR CAR

BACKGROUND

In 1974-1975, the firm of Metro Cammell in England built two prototype cars to operate on the new Tyne & Wear LRT system. The Tyne & Wear car (Figure 67) is a 6-axle, single articulated, bi-directional unit. It can be operated singly or in multiple units of up to four vehicles. The body is of lightweight aluminum alloy construction on a welded steel underframe. With the exception of its high level loading feature, the vehicle is similar to the DuWag Type B car. It is being built specifically for the LRT system at Newcastle, the first new LRT system in the United Kingdom. All streetcar systems, except one in Blackpool, were abandoned in the United Kingdom after World War II.

The car incorporates many imported components, such as DuWag trucks and couplers and Siemens control equipment. The vehicle is assembled in Britain into British-built bodies. The design emphasizes the use of the best proven components developed for other LRT vehicles. The vehicle features magnetic rail brakes intended for emergency use. These brakes will permit safe operation over future extensions which will include at-grade street crossings. Cars are equipped with radio communication to a central control station.

DEVELOPMENT STATUS

Construction of the network began in 1974. As part of an R&D program, two prototype cars were constructed. These cars were delivered to the Backworth test track, and are now undergoing tests prior to placing orders for the rest of the cars. A fleet of 90 cars will be required by 1980. The test cars were designed and built in less than two years, and are estimated to cost $600,000.

SIGNIFICANT FEATURES

The Tyne & Wear LRT vehicle has been designed primarily with proven components. The design features include:

- Passenger loading only from high level platforms (the new Edmonton system also has this feature).
- Lighter and more powerful cars than conventional British rail commuter rolling stock to achieve higher performance.
- Total vehicle power (370 kw) exceeded only by the DuWag Type B (470 kw).
- Total empty weight at the highest end of the spectrum, equal to the DuWag Type B (the reason for its lower performance).
- Width standard with DuWag U2 and B cars (8.69 feet [2.65m]).
- Untapered nose due to lack of curvature restrictions on new system.

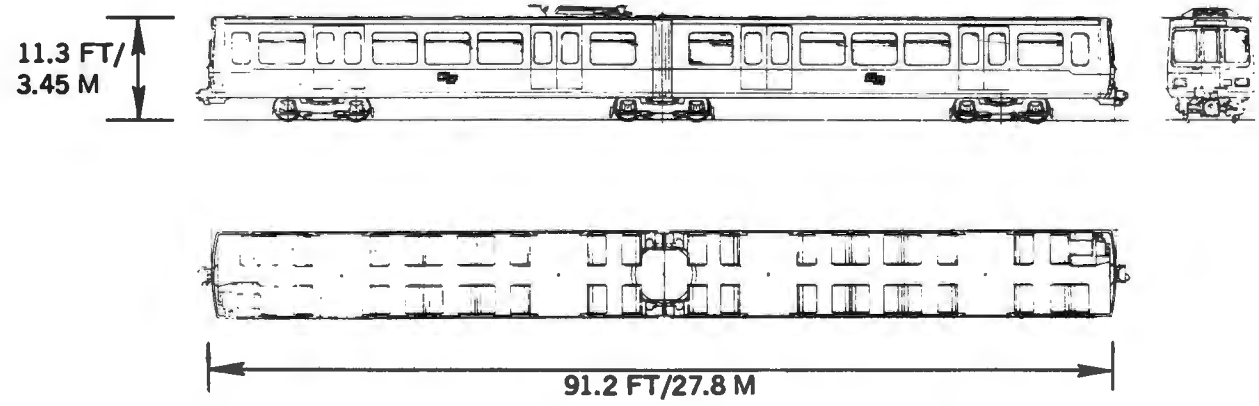


Figure 67. Tyne & Wear Car

- A 1500 watt DC power supply system selected to reduce costs of the overhead wire system and substations. The Tyne & Wear cars are the only new LRT vehicles using this higher voltage, which was formerly common on interurban systems. The use of 1500 volts DC on a two motor car permits standard 750 volt motors to be used when connected permanently in series.

THE CITADIS PROJECT

In 1975, the French Ministry of Transport, in an open letter to eight major provincial cities, suggested they consider LRT as a transit mode to meet their long-term transit development needs. The Citadis Project is an R&D program to develop a French LRV. It is a conventional six-axle configuration, but with the vehicle floor depressed to curb level between trucks to gain the benefits of high level loading without resorting to movable steps or system-wide high platforms. The penalties of this design are that the vehicle has steps onboard at each truck, and that the subsystems normally placed under the floor must be located elsewhere. Whether this radical design will prove to be a breakthrough is not yet clear. Similar designs were used on streetcar systems in the past, particularly in the U.S.

VEHICLE STANDARDIZATION

Standardization of vehicle design, or at least the standardization of certain key dimensions, is probably the biggest single issue which needs to be addressed by the LRV supplier industry. If there is to be a reestablishment of LRT systems in North America and a continuing refurbishment of the remaining existing systems, then the issue of standard vehicle dimensions which would permit interchangeability of vehicles between systems is of primary importance.

One of the major failures of the European LRT industry has been its inability to adopt standard vehicle dimensions with the result that a profusion of vehicles is in use, all of them narrower than optimum for a modern transit system. These systems began as horsedrawn streetcar systems at a time when wide vehicles and widely spaced tracks would have been an unjustifiable extravagance. As stated by Von Rohr, "... *complete standardization has not and cannot yet be achieved, because local conditions are too different and also because fixation of a car design for a long time would seriously hamper technical progress and development. The VOV Rail Vehicle Committee therefore will limit its future work to standardization of equipment parts and groups for such cars and will give recommendations only for basic dimensions.*"[16]

From discussions with European transit operators and a survey of the present status of LRT planning in the U.S., the following issues are clear:

- Most systems now in the planning stage or planning network expansion require only a few cars initially and cannot afford to sponsor new designs and start-up costs.
- It will be desirable for vehicles to move from one LRT system to another in future years, in response to fleet renewal and system expansion programs.
- Where high level platforms are used, the variations in vehicle width acceptable for low level loading streetcars become unacceptable.

- Once tunnels and other structures have been constructed too narrow, the option to operate wider vehicles in the future is lost.

As an example of the inflexibility which failure to standardize has caused, Table 24 shows the vehicle widths from various North American rail rapid transit systems. As a result of these varying widths, if a certain system wishes to expand its fleet to meet a patronage increase or to operate a small line extension, it cannot place an "add-on" order to some other system's fleet order in the manner that, say, Boston and San Francisco are cooperating in the purchase of the Boeing LRV.

The basis for vehicle width is the width requirement for four across seating plus an adequate width of aisle. Aisle width is necessary to carry occasional surges in passenger load, and to permit onboard circulation of passengers when a standee load is being carried. The Boeing LRV to be supplied to Boston is being equipped with three across seating to achieve what is considered to be adequate aisle width. As a result, the comfort standard for all passengers has been lowered by the elimination of some potential seating.

A degree of standardization already exists in contemporary LRV designs. The Boeing LRV (2.7 meters), Tyne & Wear car, DuWag B Type, DuWag U2, (2.65 meters) and the Melbourne car (2.59 meters) already form the nucleus of a standard group of cars. If a standard width of 8.5 to 8.9 feet (2.6 to 2.7 meters) were to be adopted, it should be borne in mind that it is generally too narrow and undesirable for a system of the pre-metro type.

A separate issue from the standardization of vehicle dimensions is the interchangeability of vehicle parts. The DuWag company, which builds or designs about 90 percent of light rail vehicles for West Germany, uses three basic truck designs. Vehicle steps, doors, control systems, brakes and traction mechanisms can all be made standard in widely differing car designs. The common conversion of 6-axle cars to 8-axle cars is an example of standardization being exploited. The PCC car, though a standard design, has been built to numerous widths, gauges and configurations, while still retaining extensive use of component standardization.

Table 24. Widths of Rail Rapid Transit Cars in North America

BART	10 feet 6 inches
Boston	8 feet 3 inches/9 feet 0 inch/9 feet 10 inches/10 feet 0 inch
Chicago	8 feet 10 inches/9 feet 4 inches
Cleveland	10 feet 0 inch/10 feet 5 inches
Mexico City	8 feet 2-1/2 inches
Montreal	8 feet 3 inches
New York CTA	9 feet 0 inch/10 feet 0 inch
New York PATH	9 feet 3 inches/9 feet 4 inches
Philadelphia	9 feet 1 inch/10 feet 0 inch
Toronto	10 feet 4 inches
Washington, D.C.	10 feet 2 inches
Boeing LRV	8 feet 10 inches

Source: *Lea Transit Compendium: Heavy Rail Transit*

CHAPTER 6

TRACK, POWER AND VEHICLE CONTROL SYSTEMS

The development and state of the art of track, power and vehicle control systems of existing light rail transit systems are presented to give a general understanding of the engineering requirements involved in the planning of new LRT systems and the expansion or improvement of existing systems.

TRACK

The track is the structure on which the transit vehicle is supported. Its basic elements are rail, rail fasteners, ties and ballast. The methods for constructing track vary depending on the type of roadbed. The major considerations for the basic, most common types of roadbed are discussed.

RAIL

Two types of rail are used on LRT systems: T-rail and girder rail (Figure 68). The selection of rail weight for an LRT line is based on axle load, design stiffness of track, electrical requirements, cost and availability. Rail is rolled in a series of sizes, and classified by weight in pounds per yard.

T-rail is normally used on conventional railroads and rail rapid transit systems, and is available in a range of weights. It is used for non-paved track and on structures.

Girder rail is available in several weights and cross sections. The principal variations are shallow grooved (for streetcar wheels), deep grooved (for railroad profile wheels), and broad or narrow based. Girder rail is used in pavement. The groove provides a permanent flangeway for the wheel, and the greater depth of the rail provides the stiffness necessary to preserve the pavement.

Selection of rail weights in the U.S. has been governed by availability and other considerations related to ease of procurement. At San Francisco, 100 lb/yard T-rail is being used for new Muni track; girder rail used in paved track is 104 and 128 lb/yard.

Modern LRT, rail rapid transit and railroad systems almost invariably use welded rails in track construction. Welded rail provides a quieter and smoother ride, requires less maintenance, and eliminates the need for electrical rail bonding at joints.

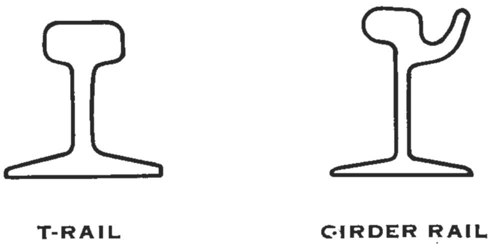


Figure 68. Sections of Rail Used for LRT

RAIL FASTENERS

Rail fasteners provide vertical and lateral stability to the rail and restrain it from movement in the longitudinal direction. For railroads and transit systems, the most commonly used rail fastener in the United States is the cut-spike, plate-rail anchor combination. It is used to fasten T-rails on timber ties placed on ballast.

For rails supported on a concrete invert, fasteners have been developed consisting of a steel plate supported on an elastomeric pad anchored directly to the concrete. This direction fixation fastener provides electrical isolation and acoustical and vibration dampening, in addition to vertical, lateral and longitudinal rail support. Direct fastening is now used on almost all transit systems where track is constructed on structures.

The most common method to support girder rail uses the cut-spike, plate-rail anchor combination. The street pavement is placed on top of the ties and ballast to the height of the girder rail section. In the United States, girder rails are often supported by and fastened to pavement subbase.

TIES

Ties transfer the load from the rail to the ballast and maintain the track gauge. Both concrete and wood ties are widely available. Wood ties are most common in the United States, with Europe favoring concrete ties on their new transit systems. Steel ties are generally no longer used. In Holland, concrete blocks with steel tie rods are now standard for new construction of non-paved track. The spacing of the ties on the roadbed is very important since it influences the distribution of contact pressures between track and ballast and indirectly the track and wheel maintenance. At San Francisco, ties are generally 22 to 24 inches apart on the Muni system.

BALLAST

Ballast is a layer of coarse granular material which allows water to filter through and off the track bed. Another purpose of the ballast is to anchor the track in place. Sometimes, ballast is laid on a lower layer of a finer material (sub-ballast) that serves as an impermeable barrier between the ballast and the subgrade. The sub-ballast also keeps water from building up on the subgrade. Should the subgrade become saturated, its load bearing capacity can be reduced, and track alignment and resilience will deteriorate.

TRACK CONSTRUCTION

There are three basic types of track used on light rail systems: open track, fixed track and paved track. Track construction varies widely, depending on the types of roadbed, ties and rail fastening systems. A basic design principle is to incorporate some flexibility in the track structure. This flexibility permits the track to deform under traffic load, and to absorb, rather than transmit, noise and vibrations.

OPEN TRACK

The simplest and most common form of track on modern LRT systems is known as open track; it is identical to track used on railroads. This track consists of rails supported on ties and ballast. T-rail is normally used. Open track is generally the most resilient, since its construction form makes provision for extensive movement under load. It is also easy to maintain and the quietest form makes provision for extensive movement under load. It is also easy to maintain and the quietest form of track. It is used wherever possible on LRT systems, and in some instances may be used on structures and in tunnels.

FIXED TRACK

This track form is normally used only on structures or in tunnels. T-rail is almost invariably used and is bolted directly to the structure. To damp the potential acoustical and vibration problems, flexible elastomeric pads and special tie plates are placed between the rail and the structure. This form of track construction is used extensively on rail rapid systems, which normally have a higher proportion of their network in elevated or tunnel structures.

PAVED TRACK

Paved track is required wherever LRT shares its right-of-way with rubber-tired vehicles, such as grade crossings, pedestrian malls, and transit ways shared with buses. Paved track is also used on narrow street medians where ballasted track would be untidy and accumulate trash. Such an installation has just been completed on Judah Street in San Francisco, and is also common in Europe.

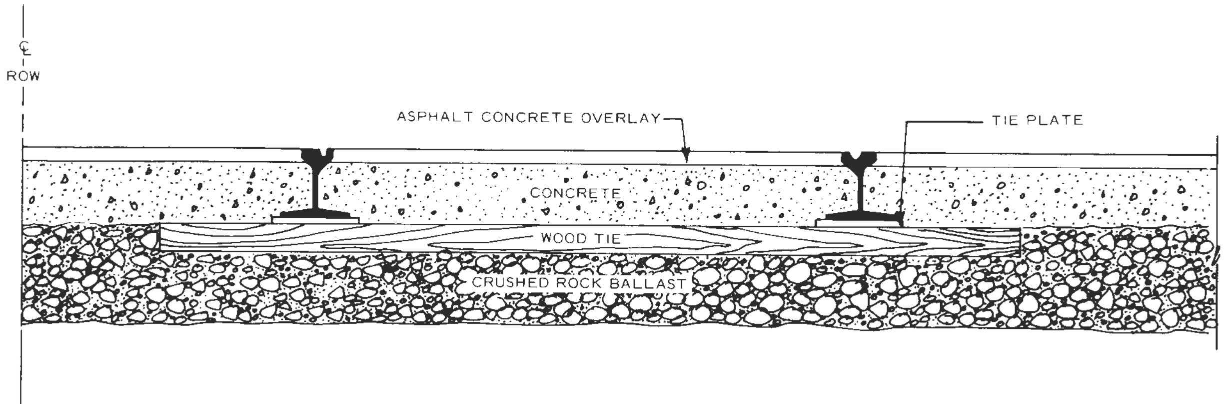
When constructing paved track, the desire to provide a resilient track and the need to provide a rigid pavement base conflict. Two basic design approaches have been adapted to this problem.

In North America, paved track is constructed in basically the same manner as open track, using ties, ballast, and, generally, girder rail. When the track construction, compaction and alignment is completed, some form of pavement is placed over the ties up to the rail head. Sometimes an asphalt concrete overlay is used (Figure 69). In some installations, the rails are set directly onto a reinforced concrete base, without ties. In either case, the track is rigidly attached to the pavement, and any vibration produced is transmitted to the pavement. The resulting track is somewhat noisy, and if the pavement is of insufficient strength, it may be damaged by the subsequent vibration and movement of the rails.

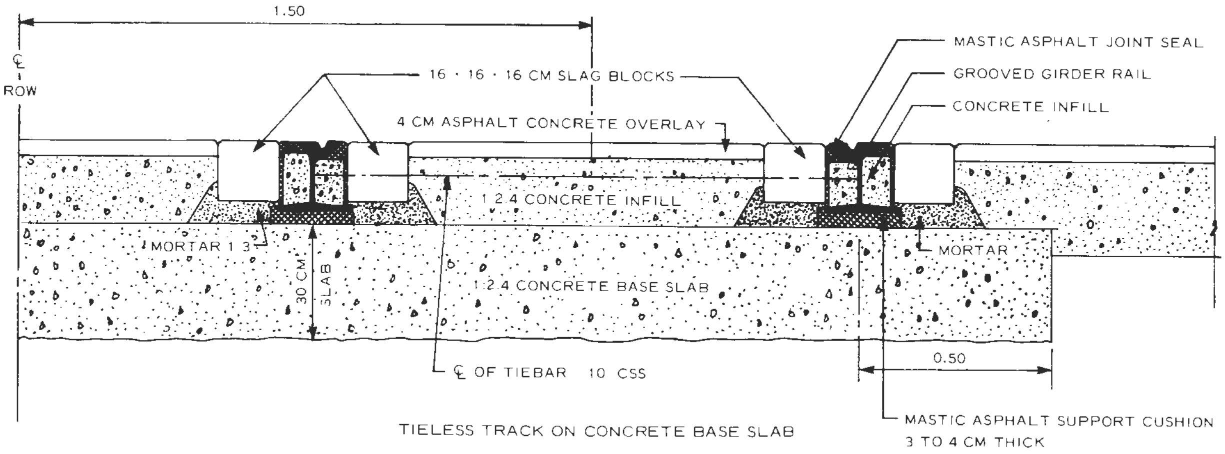
In Europe, an entirely different form of track has evolved for use in pavement. It is commonly referred to as tieless track. In conventional track, the function of the ties is to spread the load of the train onto the ballast, to hold the gauge of the track, and to prevent the track from buckling under thermal stresses. Because the axle loads of LRT vehicles are less than those experienced in conventional railroad operation, the load may be transferred to the track base directly, if a rail with a broader base is used.

European girder rail is rolled with a broad base, usually about 18 cm (7 inches), and is commonly laid directly, without ties, either on ballast or onto a concrete base slab (Figure 69). To maintain track gauge, a tiebar connecting the rails is installed approximately every 10 feet.

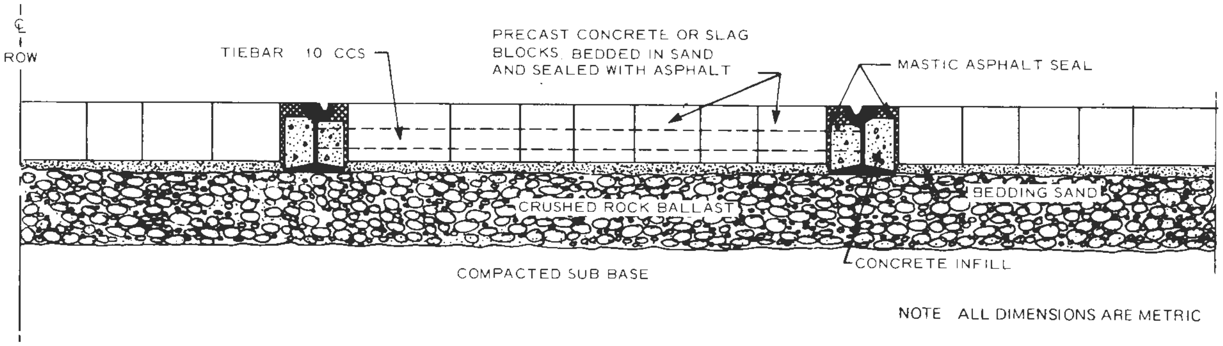
Since tieless track is invariably constructed with the rails not rigidly attached to the adjoining pavement, noise and vibration are reduced and pavement life is increased. These effects are achieved by "floating" the rails in a jacket of mastic asphalt, which has the property of absorbing vibrations while supporting the weight of trains and thermal expansion stresses without permanent distortion. High friction slag blocks are placed between the mastic asphalt and the pavement itself. The blocks provide a firm edge between the pavement and the flexible joint, and a high friction surface to assist the traction of rubber-tired vehicles traveling along the trackway. In the Netherlands, blocks made of copper slag are normally used adjacent to the rails and the rest of the track area is paved with conventional asphalt or concrete material. In Germany, it is more common to pave the entire area with slag or concrete blocks which are specially precast for this purpose. The effectiveness of this form of



NORTH AMERICAN PAVED TRACK



TIELESS TRACK ON CONCRETE BASE SLAB



TIELESS TRACK ON BALLAST BASE

Figure 69. Paved Track Sections

track construction is particularly noticeable when visiting a city which uses tieless track set rigidly in concrete. The disadvantages of noise and vibration of rigid paved track are particularly obvious in Zurich, a city which has not yet adopted decoupled track in its new construction program. Hannover has adopted a simpler form, dispensing with the blocks and paving to rail head in concrete. However, care is taken to see that the rails are "floating" in mastic asphalt.

Whether tieless track is placed on a slab base or a ballast base depends on the design stiffness of the adjoining pavement. In general, the slab based track is now more commonly used. Tieless track may be laid directly on well compacted natural sub-base. In The Hague, the ground conditions are such that track is laid onto the natural sandy sub-base. Where it is used in unpaved areas, it is essential that the track be ballasted up to the rail head to resist buckling due to thermal stresses. Figures 70 and 71 illustrate the two basic types of tieless track under construction in Europe.

TRACK GAUGE AND TOLERANCES

Track gauge influences vehicle stability and ride comfort. The standard gauge in rail rapid transit and light rail transit systems is 4 feet, 8-1/2 inches, (1.436 m). This gauge is common in Europe and North America. Many European systems use 1.0 m (3.281 feet) gauge and a few have adopted unusual gauges, such as the 1.1 m (3.609 feet) at Brunswick. In the United States, parts of the SEPTA system, Pittsburgh and New Orleans use non-standard gauges.

Figure 70. Construction of Tieless Track in Europe

Figure 71. Tieless Track in Europe

When selecting a gauge, it is important to consider the adaptability of existing maintenance and construction equipment, and rail vehicles from a railroad which might be used to deliver materials to the system. The establishment of a dual gauge system or transfer points will entail extra capital costs or labor handling expenses. Where LRT systems of different gauges interface, mixed gauge track is sometimes used (Krefeld, Mulheim, Stuttgart [Figure 42]).

Two methods commonly used to improve ride quality are to maintain a smooth "top of rail" profile and true wheels. The rail surface may be ground to remove any corrugation or irregularities which cause noise, passenger discomfort and create high impact stresses in the track or vehicles. Wheel truing to remove flat spots and irregularities is a regular part of LRV maintenance. It is accomplished by grinding or by wheel lathe.

On most modern LRT systems, the car wheels and rails are ground regularly. Track grinding or scrubbing machines can travel at schedule speeds; or alternatively, this work can be done outside peak hours.

TURNOUTS

The turnout is the track and equipment assembly which enables a branch track to turn out from a tangent track. It consists of movable switch rails at the point where divergence commences, a frog at the point where the rails cross, and associated tracks between these points. Figure 72 shows a typical turnout assembly using T-rail.

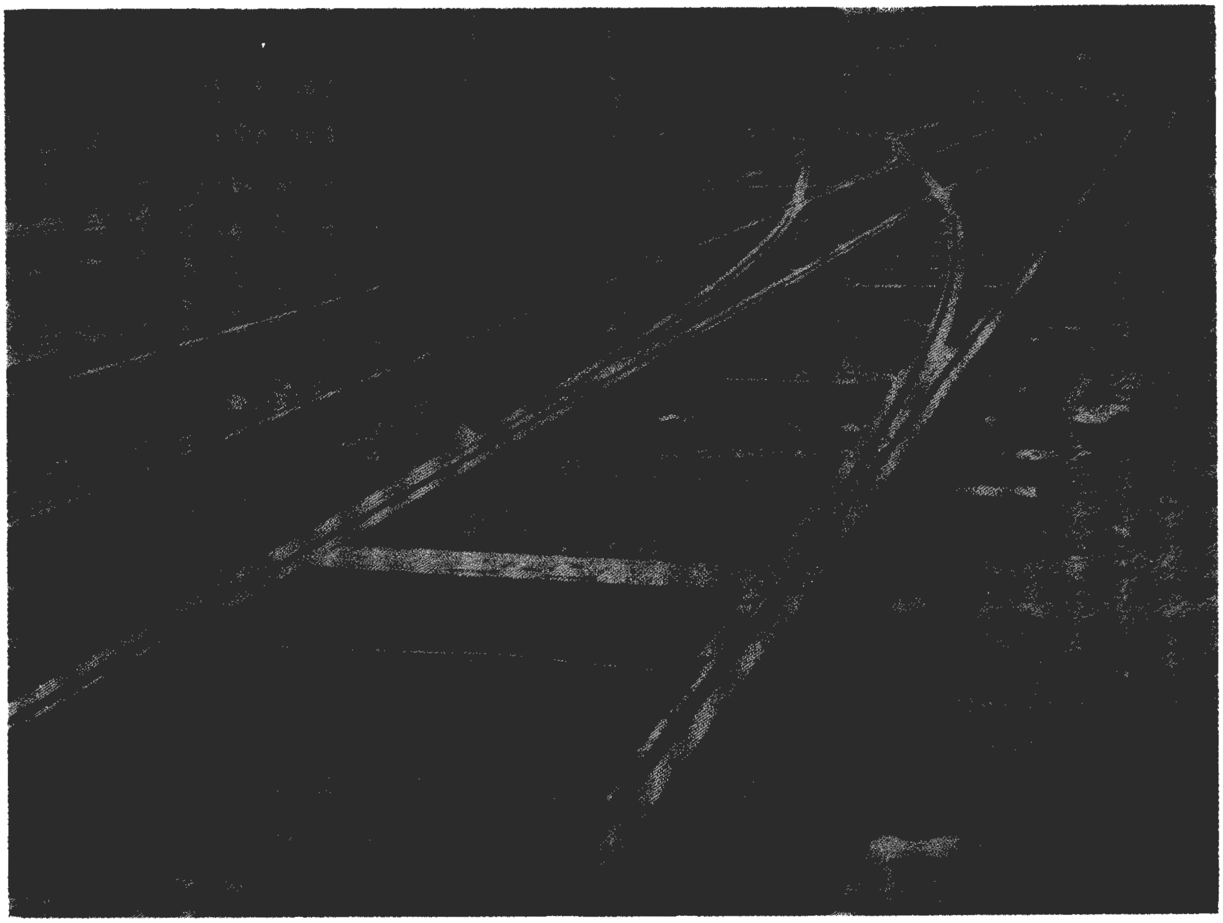


Figure 72. Light Rail Turnout

Two types of switches are used on LRT systems. In open track and where T-rail is used, the conventional railroad split switch is installed. This switch comes with a selection of turnout angles, making it suitable for low or high speed operation. Split switches can be designed to accommodate all speeds of interest to LRT operation. On paved track and girder rail track, tongue and mate switches are used.

TONGUE AND MATE SWITCH

The predominant switch found in streetcar systems is the single point or tongue and mate switch. It has a single movable point, the tongue. The opposite rail has a fixed point, the switch mate, through which a flanged wheel can pass on either the tangent or turnout track. The tongue is usually placed on the inside of the curve.

The main advantages of the tongue and mate switch are its simplicity, lower cost, and reduced maintenance. Since switch points in paved track require frequent inspection and cleaning, this is a major consideration. The main disadvantage is that it cannot be used for high speed applications where smaller turnout angles are necessary, and where operation on the wheel flange through the fixed elements is not adequate.

SPLIT SWITCH

The split switch is a conventional railroad switch with two movable points. This switch is used on LRT lines on reserved rights-of-way where higher speeds are encountered and conventional T-rail is used. The split switch, throughout which a wheel operates on its tread rather than flange, can be designed for operation at any speed. There is generally no speed restriction on the tangent track, particularly if a facing point lock is provided. Numerous refinements have been made to the basic split switch. Movable frogs are used on some LRT systems to provide continuity in the track through the frog, so that there is no gap in the track. This increases the cost of the turnout, but improves ride quality and reduces wear.

SWITCH OPERATION AND CONTROL

The simplest form of switch operation is the spring switch. The switch is held biased in one position by means of a spring. In the trailing direction (when the frog is crossed before the switch), wheel pressure forces the spring to permit passage through the switch. After passage, the points return to their original position. In the facing direction (when the switch is traversed before the frog), the vehicle will always go in the direction in which the switch is lined by the spring. In some installations, a dash pot is used to momentarily hold the points and reduce wear on the vehicle wheel flanges and switch point. Spring switches permit passing on single track, and turn backs at the end of the double track without any further switch control.

Where positive switch operation is required, motors, solenoids and air cylinders may be used to set switch points. The most frequent manner of actuating the motor or solenoid is through contactors placed parallel to the contact wire. Switch position is determined by car propulsion power mode (on or off) at the moment the pantograph passes the contact. Although this type of switch control is simple and inexpensive, its main disadvantage is that the operator must properly manipulate power to actuate the switch machine. This can conflict with the requirement of the signalling system on track subject to signal control, and is now being superseded by new switch control techniques on many systems.

A new technique for switch control uses an inductive loop in the roadbed to receive a coded signal from the car. The coded signal carried aboard a car can be preset so that all switches for a particular route are automatically set. These coded signals can also be used for traffic light preemption, setting destination indicators in stations, and transmitting the position of the train to a central control room, depending on the particular technique selected.

An example of one widely used system is that being adopted by the Karlsruhe LRT system. Existing overhead wire contactors are being converted to a new automatic switch lining system. The system seems simple in concept and reliable in operation. The failure of an individual installation does not disrupt the system, because the failed switch can still be operated manually. The system consists of a car-borne transmitter which signals wayside detectors. Each route uses a different frequency to set the switches. Three detectors are used. The first receives the car signal and aligns the turnout if the approach circuit is clear. The second detector confirms that the route is set and the switch is locked, so that the car can proceed. If the turnout is not clear, the car will be given a slow down command by this detector. The third detector provides a backup system in the event of a turnout mechanical failure, an obstructed switch point or other cause. In the event of such failures, the detector directly actuates the car emergency brakes which bring the car to a halt before reaching the switch.

The installation will increase the effectiveness of LRT operation in Karlsruhe. It will also provide additional safety by ensuring proper turnout alignment before vehicle passage, and by eliminating the potential for vehicle collision at turnouts. The installation also permits faster operation through turnouts, previously restricted to 15 kph. Under the new system, cars may operate at speeds up to 35 kph through turnouts if track alignment permits. The manufacturer (Siemens) claims that the third detector emergency backup system will only be activated about once a year on the entire system. Switches are normally equipped for manual operation in the event of a failure of the operating mechanism.

PROPULSION POWER SUPPLY SYSTEMS – DISTRIBUTION AND PICKUP

DISTRIBUTION SYSTEMS

A major consideration in sizing the power distribution system is power requirement per train and headway. The current carrying capacity must deliver adequate power for the greatest length train anticipated at the shortest headway.

The characteristics of the transportation system determine the type of power distribution suitable for it. Most modern electrified railroads are electrified using single phase AC high voltage electric power. Line voltages of 25 to 50 kv are normally used on this type of system, not only in the U.S. but worldwide. However, LRT, rail rapid transit, and some railroads (portions of the Penn Central and the Long Island Railroad) are powered by direct current (DC) at relatively low voltage, generally 600 to 650 volts. The main reason for the different forms of electric power used by LRT versus most mainline railroads stems from differences in their operating characteristics. On mainline railroads, the distribution system must cover large distances; to reduce power losses, high voltage AC current is preferred. Rectification and stepping down of voltages to a range suitable for powering traction motors are also accomplished without undue penalty because of the large size of the powered vehicles and/or locomotives. By contrast on LRT the distribution distances are much smaller, and losses in distribution of electric power are therefore less. The equipment necessary for rectification and stepping down of voltage is more difficult to package within the confines of the smaller transit vehicles. These factors favor the distribution of electric power to LRT installations at low voltage in direct current form.

On systems powered with direct current, the fixed distribution installation is fairly complex involving transformer substations and a substantial feeder system. Since the current is delivered at lower voltage, frequent feeder points and an extensive feeder distribution system are required. On the other hand, the onboard power system is correspondingly simple, since the DC traction motor has characteristics ideal for transit use. The voltage of a DC power supply system is governed by vehicle requirements. It is not practical to transform DC voltage in the manner of AC power supply. As a result, rail systems which are short and intensively used and which operate lightweight equipment with numerous starts and stops are invariably electrified on the DC system.

A basic principle of power supply design is to enable the system to operate even when segments of the system fail. Figure 73 illustrates a layout concept for a typical low voltage (600 to 1500 volts) DC power conversion and primary distribution system.

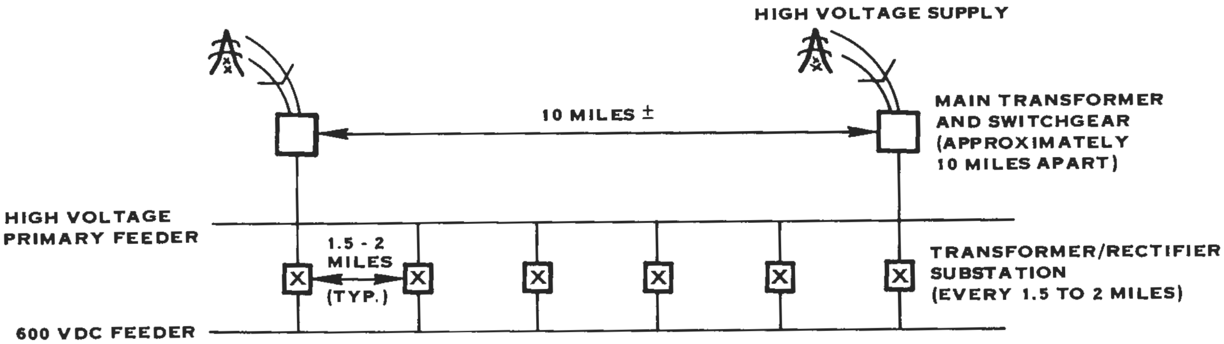


Figure 73. Power Distribution and Conversion System

Power from the public supply is tapped at regular intervals, generally of several miles. Each supply tap is from a different zone of the public supply system, thereby reducing the chance of multiple supply point losses in the event of a partial failure of the public system. The incoming power is transformed to the primary feeder voltage and fed into the primary feeder system for the transit network. This feeder system supplies the line substations, and can bridge any one of the public supply points in the event of a power failure. The primary feeder typically operates at a relatively high voltage, such as 33 kv. The primary feeder cables may or may not follow the transit routes, and can generally be placed in underground ducts. At shorter intervals throughout the system, the primary feeder connects to transformer/rectifier substations. Here the power is transformed to the operating voltage and converted to direct current, normally 600 volts. There is a tendency to use higher operating voltages on new transit systems, some equipment now being designed for 750 volts. However, most existing LRT systems use 600 volt DC power. Since previous LRT systems were generally conversions from conventional streetcar systems, there were considerable cost factors which discouraged a change in operating voltage. However, for an entirely new system, it would be appropriate to study the use of a higher voltage to reduce electrical component sizes and increase operating efficiency and substation spacing. The likely alternative voltages would be 750 to 1500 volts DC.

The selection of the 1500 volt DC power supply system for the new Tyne & Wear system is particularly significant, because it is consistent with these trends which were interrupted by the financial failure of the electric transit industry, and because it was selected only after a comprehensive survey of alternative power supply systems. Most of the components already developed and standard in the LRT industry can be used with this power system with relatively little modification. Moreover, 1500 volts is generally regarded as the highest operating voltage which can be used with a third rail distribution system, and does not require appreciably different clearances when used in tunnels or under structures. 1500 volts DC is widely used on railroads in Europe, particularly suburban railroads.

OVERHEAD PICKUP SYSTEMS

The operation of LRT at grade requires that an overhead power supply system be used, at least for the at-grade sections of the network. Light rail vehicles collect power from the overhead contact wire by means of a trolley pole or a pantograph. The trolley pole system was used extensively on streetcar systems, but is now being phased out in favor of the pantograph. The advantages of the pantograph include its greater current collection capacity, its freedom from dewirement, its ability to be used in either direction, and its ability to negotiate horizontal angle points in the contact wire. The pickup conductor shoe of the pantograph, being longer, has more area for wear, hence a longer lifetime than trolley shoes.

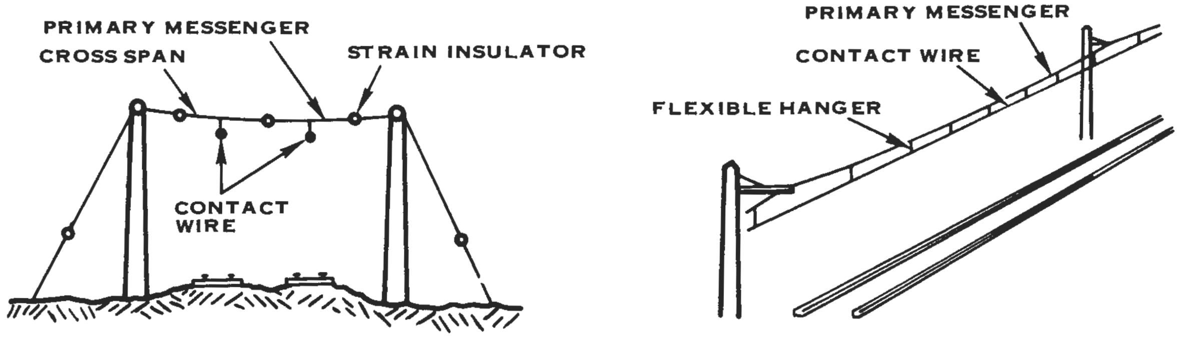
Another advantage of the pantograph is that it is preferred for tunnel operation, because dewired trolley poles are difficult to rewire underground.

Pantographs are usually fabricated in a symmetrical diamond arrangement of jointed steel tubing. Many recent LRT designs now use an asymmetric, single jointed arrangement which is less expensive. One or two contact shoes may be provided, the latter ensuring better contact with more area, and hence less power loss from contact resistance. The pantograph is supported by springs and exerts a pressure against the contact wire of 10 to 20 pounds.

The pantograph may be used with either a single contact wire or with the multi-wire catenary system. The overhead contact system design differs depending upon whether it is to be used with a trolley pole or a pantograph pickup system. However, the two may operate on a common system during changeover if compatible components are used. Overhead designed for pantograph use normally follows a slight zigzag alignment, so that the contact point with the pantograph is not constant. This distributes wear over the pantograph contact surface, and prevents the buildup of high temperatures. Consequently, although the contact area on the pantograph is less than for a trolley pole, its current carrying capacity is actually higher. In addition, pantographs are often designed with more than one shoe, to further increase their current carrying capacity.

Types of Catenary

There are two basic designs used for LRT overhead: single contact wire or multi-wire catenary (Figure 74). On streetcar systems and on some modern LRT systems a single contact wire is used with support points at approximately 100 feet (Figure 75). This system is light, simple and inconspicuous (compared with multi-wire catenary), but requires frequent supports and is of limited current carrying capacity. The wire is made of a bronze alloy whose conductivity is approximately 40 percent of that of annealed copper, which is too soft and could wear out rapidly. The largest size contact wire used for LRT weighs approximately one pound per foot.



SIMPLE CROSS SPAN-SIMPLE CONTACT WIRE

SIMPLE CATENARY SUSPENSION

Figure 74. Simple Contact Wire and Catenary Systems

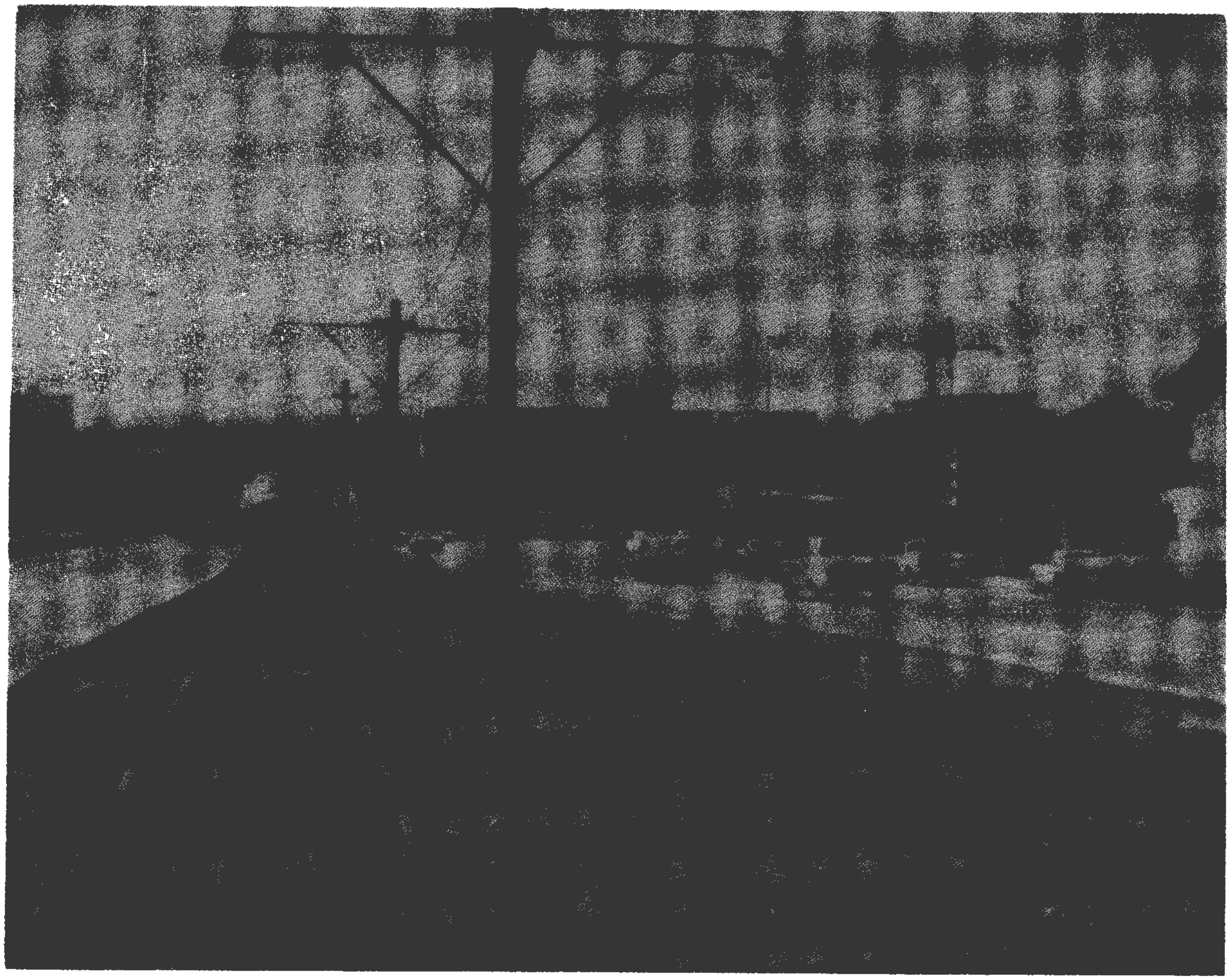


Figure 75. Power Distribution of Muni at San Francisco

On many European installations, two contact wires are placed side by side on intensively used sections of track to provide sufficient electrical capacity. The single contact wire system is generally not used on high speed lines, due to the sag inherent in this type of construction, and the varying stiffness of the wire at different locations through its span.

The alternative overhead system is the multi-wire catenary (Figure 74). A catenary system is normally used on new installations and on high speed lines, because it has superior electrical properties and requires fewer support poles. The catenary consists of one or more support wires known as messengers which support and maintain a contact wire in an approximately level profile (Figure 76).

In low voltage LRT systems, the messengers are made of hard-drawn copper. The catenary system has some flexibility throughout the length of its span, producing a uniform rate of wear and reducing the possibility of arcing. Moreover, the metallic cross section of the catenary is generally several times greater than that of the contact wire itself, which increases the current carrying capacity of the system. Since this latter factor can be critical on modern LRT systems, this greater current capacity is an important consideration. Catenaries are usually tensioned with weights, which secures constant tension and eliminates thermal sag.

Figure 76. Catenary Power Distribution at The Hague

Both single contact wire and catenary systems may be supported by poles placed centrally between the tracks or outside the tracks. An important consideration when constructing overhead within the street right-of-way is to secure joint use of these poles for both overhead support and street lighting.

In streets, the supports for the contact wires can be anchored to buildings and utility poles. The support spacings are relatively close, and catenaries are not required. However, along reserved rights-of-way, support poles are needed; a tradeoff must be made between the greater number of support poles required by a simple contact wire and the more complex suspension of the catenary.

While the methods of suspending the overhead wire system are the same for trolleys or pantographs, there are basic differences in the construction and alignment of the contact wire. For example, in trolley operation, the contact wire must move toward the inside of a curve so that the trolley shoe remains tangent to the contact wire. For operation with pantographs, this alignment on curves is not necessary.

Overhead Special Work

The overhead system at track turnouts and crossings is generally referred to as special work. Where the overhead is designed for trolley pole operation, a simple overhead turnout with no moving parts is required. For pantograph operation, no overhead turnout is required since the pantograph has a wide pick-up shoe. The ends of the pantograph are typically turned down to prevent its snagging on converging or diverging wire. Where overhead designed for pantograph operation crosses at right angles, special precautions must be taken to prevent the possibility of the pantograph snagging on the intersecting wire.

Clearance Requirements

Both trolley poles and pantographs are designed to operate over a wide range of contact wire heights. The Boeing LRV pantograph has an operating range of between 12 and 19 feet above top of the rail. Since it is not practical to design the overhead for operation at the minimum pantograph operating height, the lowest possible contact wire height must therefore be in excess of 12 feet. On the LRT system currently under construction in San Francisco, the minimum design height for the contact wire in tunnels is 12 feet, 7-1/2 inches above rail. Additional height is required for the depth of the catenary itself, and for the catenary support system. It is preferable to have a height of 2 feet available on new construction between the height of the contact wire and the tunnel socket to avoid an unduly constrained design. On European LRT subways, a common design of overhead is to use an insulated arm to support the contact wire. (See Figure 18.) This arm is attached to a dashpot which is bolted to the ceiling of the tunnel. This system ensures the flexibility necessary in a catenary system, and provides it in the minimum possible depth. Depths of less than 12 inches are possible between the contact wire and tunnel socket if such a system is used.

On new LRT systems where circular bored tunnels are used, the maximum diameter of the tunnel normally is not governed by the height of the vehicle and contact wire system, but by the width of the vehicle and the safety walkway. In tunnels constructed by the cut-and-cover method, however, the width and height of the tunnel are independent of each other. In such cases, the location and clearances for the contact wire become the determining factor for inside tunnel height.

Visual Design Principles

In communities which have operating experiences with electric transit, the presence of the overhead contact wires is seldom perceived by the public as being a major issue. Nevertheless, it is essential that particular attention be directed during the design stage to the appearance of the contact wire system. Developments in electrical conductors and insulators and the heightened understanding of the principles of visual design permit a far more enlightened approach to this problem than was possible in streetcar times.

Most European systems are devoting increasing effort to the appearance of their overhead systems, and some have developed outstanding design standards. The small and recently renovated Brunswick system has been particularly successful in its approach to this problem (Figure 77).

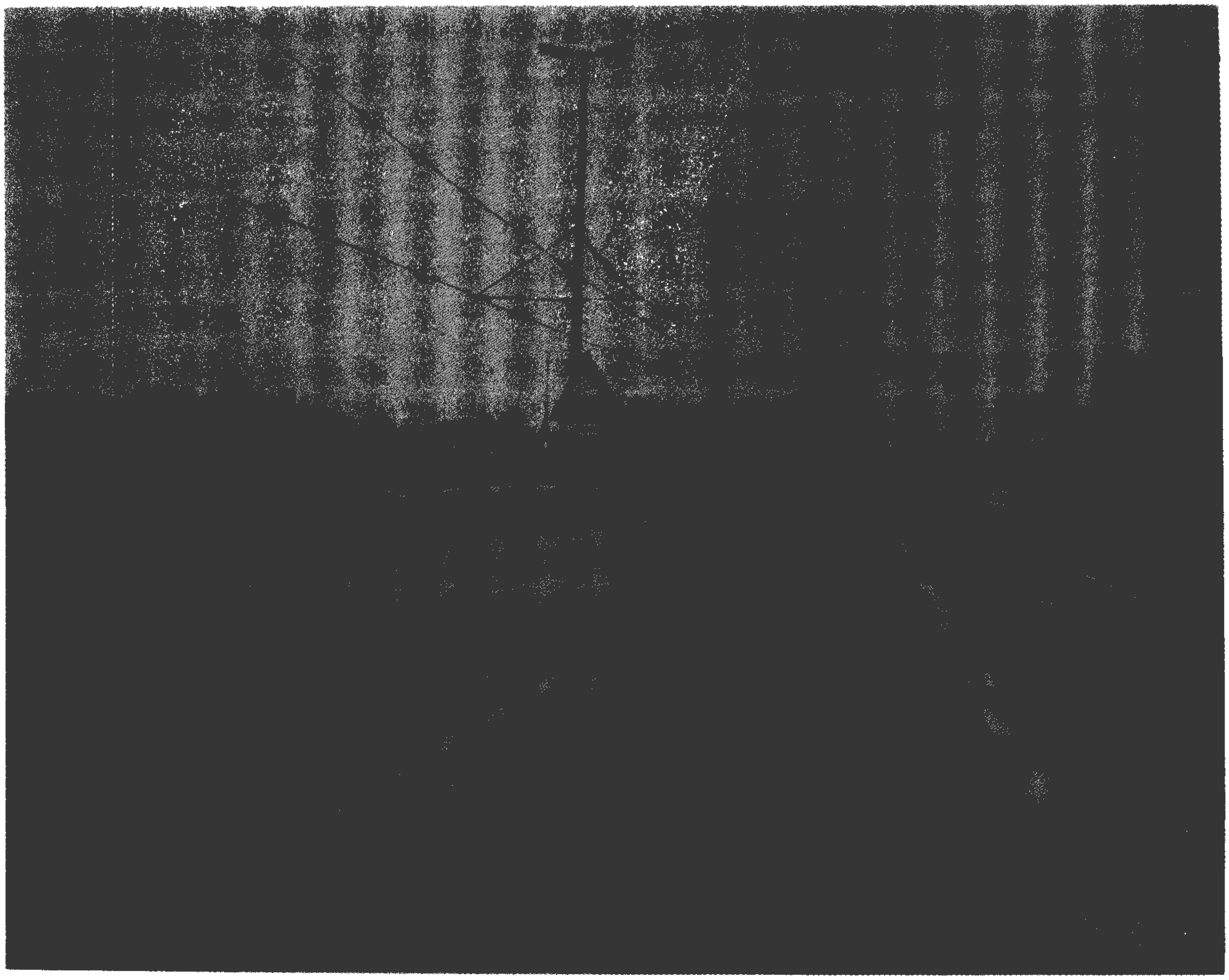


Figure 77. Overhead System at Brunswick

The significant design concepts to be considered in the design of LRT overhead power supply include the following:

- All circuitry non-essential to power pickup should be placed in underground conduits. This generally includes the power feeder cables, signalling circuits and communication lines.
- Wires are conspicuous primarily in silhouette. Therefore, trees and structures that disrupt the wired silhouette should complement any landscaping concept (see Figure 40).
- Poles are readily acceptable in the street scene for lighting and traffic signals. It is essential to combine multiple uses within the same poles to avoid unnecessary proliferation. The pole spacing requirements for street lighting and for light rail are similar.
- The use of existing structures to support the wires can form a cheaper and less conspicuous substitute for poles.
- Cantilever support arms of tapered tube design without stays or straps, similar to street light arms, are less intrusive.

THIRD RAIL SYSTEMS

Third rail is not generally used for LRT operations and is only suitable for exclusive right-of-way installations with high level platforms. Clearance problems may arise on sharp curves and with the low level fixed or retractable steps of vehicles or their under floor equipment.

The third rail system has certain advantages: it has a greater electrical cross-section, and can therefore be used with fewer feeders, or longer trains than overhead systems (most overhead wire systems are limited to three or four car trains), and it is less conspicuous for sections of line above ground.

COMBINATION PANTOGRAPH AND THIRD RAIL

A few rail rapid transit systems in the United States operate with both third rail and pantograph equipment, including the Skokie Swift in Chicago and Boston's line to the airport. In Chicago, the transition from third rail to pantograph (and vice versa) is made while the vehicle is moving. In Boston, the transition is made at the last station before the train emerges from underground. In both cases, the mixed system is used for historical reasons, and no new installations of this type have been built.

However, there may be advantages in equipping LRT systems for both pantograph and third rail pickup, including lower height requirements for tunnel sections, joint operation with rail rapid transit, and more efficient operation over both heavily and lightly traveled lines. On heavily traveled lines, full grade separation and third rail power distribution can be efficiently used to operate long trains. Where the line has grade crossings and shorter trains are used, a lighter duty and less expensive overhead wire system can be utilized.

SIGNALS AND TRAIN CONTROL

The basic philosophy in signalling in LRT is to provide as much signal protection as is feasible and needed to operate on a particular right-of-way. As a general rule, LRT signals are needed:

- At grade crossings, to assign right-of-way between conflicting movements.
- At locations where tracks converge or cross, to prevent conflicting movements. Such signalling is usually connected to the track switches, in which case it is called interlocking.
- On single line track used for two-way travel.
- Where speeds are high or sight distance is restricted.

At all other locations, existing LRT operates under visual/manual control without signals, in the same manner and (if on a public street) under the same laws as buses and automobiles.

VISUAL/MANUAL CONTROL

In visual/manual control, the operator's awareness of the conditions under which he operates his vehicle is limited to his line of sight. Streetcar operations in the United States were conducted in this manner, as are current European systems which operate vehicles on streets mixed with other traffic or in reserved lanes. Some reserved right-of-way operations also use wayside and/or cab signals. In congested areas where train speeds are slow, visual/manual control will probably continue in use, because current fixed block systems do not allow trains to close up on one another, even at slow speeds.

AUTOMATIC TRAIN PROTECTION

Automatic Train Protection (ATP) detects the position of vehicles (trains) in successive track blocks and relays the information to the operator so that he may operate the vehicle safely and prevent collisions. If Automatic Train Stop (ATS) is included, the brakes of the vehicle are automatically applied if the vehicle exceeds the safe speed limits signalled to it. ATP is widely used on both railroads and transit systems, and is extremely reliable. ATP is not used generally on LRT shared or reserved lane rights-of-way. It is used predominantly on exclusive rights-of-way. On restricted rights-of-way, ATP may be used at times, depending upon site-specific conditions. For LRT operations in subway, ATP becomes necessary.

ATP may use wayside or cab signals. Cab signals relay the information on block condition to the operator's console onboard the vehicle. With cab signals, the ATP system displays to the operator the maximum speed instructions. The speed is based on the safe braking distance to the preceding car, possible conflicting train movements or turnout alignment, and the safe operating speed for that section of track. The operator remains in control of the car, subject to his observing the maximum speed displayed and other line of sight conditions. However, if ATS is included and the prescribed speed is exceeded, the brakes will be set automatically. ATS is also referred to as overspeed protection and is commonly used in rail rapid transit.

A common refinement of ATP systems is the use of "permissive close" in operations, which permits the train to close in on the train ahead, provided that it does so at a low, safe speed. It enables operation at very close headways during peak periods or periods of schedule recovery, allowing one train to enter a station immediately behind another. It also permits a train to close in on a disabled train and, thus, to clear the line with little delay. This feature adds to system capacity at critical times by allowing headways slightly greater than the maximum station dwell times. "Permissive close" cannot operate through junctions of two lines, where absolute stops are required.

Should ATP be used on dedicated rights-of-way with at-grade crossings, the traffic signals at each crossing must be interconnected with the system. For high performance LRT service on lines with at-grade crossings, interconnection of the two control systems may be essential to preserve adequate traffic flows on cross streets and overall safety. Preemptive traffic signals can also be tied into an ATP system. Because the progress of each vehicle along the line can be monitored and visually displayed to a dispatcher at a central control station, the ATP system may also be used to monitor schedules. In conjunction with an interlocking system, ATP may also be designed to permit single track, bi-directional operation for emergency or maintenance purposes.

To improve operations, Automatic Vehicle Monitoring (AVM) may also be provided. With this system, each light rail vehicle is equipped with a train code which actuates a trackside induction detector. This detector identifies the car and the route number, transmitting the data to central control and using it to align turnouts and set passenger information display boards at stations.

AUTOMATIC TRAIN OPERATION

Automatic Train Operation (ATO), e.g., BART, is a well established practice on rail rapid systems and has successfully operated on the London, Hamburg and Lindenwold rail rapid transit systems for several years. The operator becomes an attendant, his functions being limited to monitoring vehicle performance and communicating with central control, closing doors, and responding to emergency situations. Exclusive right-of-way and grade separation are required for ATO. The utility of ATO to LRT operations is therefore somewhat limited.

However, it would be possible for appropriately equipped LRVs to operate on lines equipped for ATO.

FULLY AUTOMATED UNMANNED OPERATION

Fully automated unmanned operation enables a train to operate without an onboard operator. At present, fully automated unmanned operation is confined to experimental systems, airport shuttles, and industrial rail lines. Full automation requires exclusive and fully restricted guideways and is not therefore applicable to LRT whose distinguishing characteristic is its *capability* to operate through at-grade conflict points. The type of automation suitable for LRT and the technological and economic circumstances which would promote its application to urban transit are still uncertain at this writing.

EXAMPLES OF LRT CONTROL SYSTEMS

The majority of LRT systems use visual/manual control. However, where systems operate on extensive private rights-of-way or in subways, some form of ATP is used. These systems include:

- Dortmund: wayside signals for one track section
- Philadelphia: wayside, two-aspect signals on portions of the Media Line
- Chicago (Skokie Swift): cab signals
- Frankfurt: block signals in subways
- San Francisco: cab signals
- Brussels: block signals in subway
- Pittsburgh: wayside signals on portions, including all single track sections
- Tyne & Wear: two-aspect wayside signals.

Control systems presently operating at The Hague and Hannover employ a type of automation intended to increase average line speed. Both are discussed more fully, because they lend themselves to limited or localized forms of automation and could be tied into the ATP and ATO systems.

CHAPTER 7

LIGHT RAIL TRANSIT OPERATIONS

The operational flexibility of light rail is one of its major assets. Light rail installations range from streetcar type applications in mixed traffic to completely grade separated, high speed lines with characteristics similar to rail rapid transit. Due to this flexibility, the operational characteristics of LRT cannot be simply quantified using statistics and other findings drawn from existing operating systems unless the data have been related to the specific type of operation.

The information presented in this chapter is drawn from a survey of the broad range of LRT operating characteristics as they are found in various types of installations. Light rail operational practice is presented in three major categories.

General operations – deals with staffing, maintenance, fare collection, access for the handicapped, passenger security and energy consumption. The European trend toward one man operation in articulated car, multiple unit operation is of considerable interest. (For additional details, see Appendix I.) Fare collection techniques are especially pertinent to the study of light rail in view of the effect they may have on the mode's operational characteristics and economic viability. In particular, the European trend toward self-service fare collection with one man operation is noteworthy. The unique aspects of providing access for the handicapped to LRT are considered. Vandalism and security common problems to all transit modes are briefly addressed in the context of characteristic LRT operations and vehicle and station design. A brief review of the energy consumption of LRT and a comparison with consumption by other transit modes is also included.

Level of Service deals with achievable speeds, effects of station spacing, braking capabilities, headways and system capacity. Of particular significance to the category of operational details is the handling of automotive and pedestrian conflicts on non-exclusive rights-of-way, at at-grade intersections and at street level stations. Pertinent safety aspects of LRT operations at these points of conflict are also addressed.

Environmental Impacts deals with noise, impacts on passengers (interior noise levels) and on the surrounding community (exterior noise levels) and the impacts of electric transit vehicles on air quality (compared with those of other modes).

GENERAL OPERATIONS

LRT PERSONNEL PRACTICES

Vehicle Operations

On the surveyed installations, LRT operators generally work under the same rules and conditions as other transit operators. On most systems, platform staff may transfer between modes, if qualified. On most systems, the introduction of larger vehicles, the conversion to one man operation, and the operation of multi-car trains has involved negotiations with the respective labor unions. In the United States, the labor rules governing multiple car operations vary from city to city. Until recently, a shortage of labor assisted the introduction of more productive operation practices on most European systems.

In general, the cost savings arising from the use of more productive equipment have been offset in recent years by increased costs of labor benefits. These have included various combinations of such items as a guarantee of no layoffs, better pay and fringe benefits, and a simplification or reduction in duties. At Zurich, the introduction of two car trains of double articulated cars was accompanied by the elimination of all operator involvement in fare collection. The introduction of better driving positions, automatic switching, mechanical destination signs, and fewer split shifts were used to negotiate the new labor agreements.

Other Staff

If LRT is introduced as a new metropolitan transit operation, a number of specialists who generally cannot be drawn from the ranks of the bus operators, are needed to operate and maintain the new physical plant. These include trackmen, line men and shop personnel with electric vehicle experience.

If a self-service fare collection system is selected, the personnel needed to implement it represent a significant change in staffing (compared to those needed for current fare collection practices). In the initial stages, a high level of ticket inspection would be needed to develop compliance. As the system is expanded and the public becomes familiar with it, the level of inspection may be lowered. At the same time, all unattended vehicles need patrolling to increase passenger and equipment security. Ticket inspection and security patrol functions could be combined along with a broad spectrum of additional responsibilities, such as public assistance and information, and response to emergency situations. As a case in point, at San Francisco, a system of "transit monitors" has been established to curb violence and vandalism on the transit system. Some 40 police cadets in uniform are assigned to this task, with about ten on the system at any one time.

FARE COLLECTION

A variety of fare collection methods and equipment are used on LRT systems. Fares are collected before boarding, after boarding, or in certain combinations of these methods. If fares are collected onboard the vehicle, it must be done by the operator or an attendant (thus increasing costs), or via onboard self-service machines. In either case, a longer time could be required for passengers to board, station dwell times could increase, and average line speeds would decrease. It is possible to expedite LRT movements through stations by providing preticketing areas onboard the vehicle. Some seating and standing space would, however, be lost permanently.

Self-Service Fare Collection

The "no barrier", or "honor" or self-service fare system, as it is usually called, has been used for nearly twenty years throughout Europe. Until recently, this technique aroused no interest in this country. In a transit literature search performed for this study, only one pertinent American reference was identified. In this as yet unpublished report, the feasibility of self-service fare collection was examined for the Metropolitan Atlanta Rapid Transit Authority (MARTA).[17] Comprehensive studies on self-service fare systems appeared in two 1973 papers presented at the 40th International Congress of the International Commission on Economic Policies in Transport.[18] These papers reported a survey of transit operations using honor fare systems and include statistics on policing requirements, cheating, fines and other operational issues.

Self-service fare collection is characterized by the absence of gates for control of passenger entry or exit. For rail rapid transit, this means simpler, turnstile-free stations. It also means that the operator need not monitor fare collection. Entrance and exit through multiple doors becomes feasible without the presence of a second operator. Fare payment is policed by roving inspectors who make periodic checks. In Europe, local laws allow the inspectors to assess and collect substantial fines on violators, usually on the spot.

Major reasons cited by authorities for using the self-service concept include financial savings, reduction in the staff work load, and relief from shortages of staff. Service benefits claimed for honor fare collection are also substantial. Increases in schedule speed of up to 10 percent in Belfast, Brussels, Geneva, Grenoble and Utrecht are cited in the MARTA study.[19] The boarding time in Copenhagen was cut by more than half, from 4.5 to 2.2 seconds, using self-service fare collection. The popularity and workability of the concept are exemplified by the fact that no city has ever dropped the system after having adopted it. A further indication of its popularity in Europe is the fact that according to a 1973 survey, 45 percent of the transit agencies were using self-service fare collection, and 76 percent expected to use it in the future.

Different procedures can be used to implement the self-service fare concept. In many West German cities, monthly passes are available, and single ride tickets may be purchased directly from streetside machines or from the driver. Transactions with the operator slow down the system operation and prevent utilization of the full potential of the concept in reducing travel times. To reduce onboard ticket purchases, substantial discounts (typically 35 percent or more) are offered for prepaid tickets. Usually, the ticket is cancelled when the passenger inserts it in a validation machine upon entering the vehicle. Roving inspectors check for a valid ticket or pass. These tickets are, as a rule, used by over 50 percent of the ridership. This percentage is usually the highest during peak hours when most passengers are regular riders. Time savings is particularly important during these periods.

On the Zurich LRT system, operator responsibility for fare collection has been eliminated. Tickets are available only from machines at stations. Onboard machines are used to cancel the ticket as passengers enter. Here too, roving inspectors check randomly for compliance.

At The Hague, 70 percent of the patrons use heavily discounted, prepaid multi-fare tickets which can be purchased from the transit office. Single trip tickets must be purchased from the operator. However, the installation of ticket vending machines onboard the vehicles and in stations is planned to improve convenience and efficiency.

Many authorities attribute the success of light rail systems in Europe largely to the adoption by most cities of the self-service fare collection system. This system reduces the number of operators required to collect fares onboard, reduces dwell time at stations, and increases operating speeds. These changes, in turn, reduce operating costs through reduction of the number of vehicles required for operation (at higher speeds, fewer vehicles are required for a given route). The reduction in the number of vehicles required is also a capital cost savings.

The success of light rail systems operation in the United States could depend to some degree upon the utilization of self-service fare collection. It is difficult to forecast the practicality of the self-service fare concept in the U.S. In Europe, fare evasion is not the problem that many Americans seem to assume it would be. Roving inspectors typically check less than 5 percent of the patrons, and it is estimated that fraud is less than 1 percent.[20] American experience with self-service gas stations, telephone credit card fraud, locked box newspaper sales, shoplifting, and automatic toll machines were noted in the MARTA study; evasion of payment was cited as amounting to generally less than 1 percent of sales. This figure is comparable to the level of evasion encountered with barrier fare collection, such as the turnstiles used on the New York subway. However, it may be low when compared with recent statistics of increased evasion at automated highway toll booths in Connecticut, Delaware and elsewhere in the U.S. The MARTA study estimated evasion in Atlanta would be 3 percent to 5 percent of daily passengers. Further analysis and research as to the legal ramifications of initiating the self-service fare concept in the United States are also desirable.

Table 25 summarizes the published statistics on self-service fare collection. Supplemental material gathered by the writers of this report in discussion with transit officials in Newcastle, The Hague, Zurich, Stuttgart, Hannover, Mannheim, Frankfurt, Bremen, Cologne/Bonn and Bielefeld is also included.[21]

Conventional American Fare Collection Systems

American streetcar and LRT operations use conventional, onboard fare collection techniques. Exact fare procedures have been widely adopted on most surface transit systems to reduce robberies and speed up boarding, but virtually nothing has been done to reduce the inconvenience to passengers caused by this fare collection method. Technological advances in fare collection equipment have been relatively minor.

Rail rapid fare collection techniques would certainly be of interest to future LRT installations. Up until the mid 1960s, fares were collected usually by the simple coin or token operated turnstile. The Illinois Central Gulf Railroad first introduced automated fare collection for its Chicago suburban service. In recent years, the Lindenwold high speed line at Philadelphia, and then the San Francisco Bay Area Rapid Transit District introduced automated fare collection techniques based upon vending machine principles, electronics and computer technology. These approaches have had problems with reliability and maintainability; a number of the firms involved in making this equipment have now withdrawn from the market. Table 26 summarizes rail rapid fare collection techniques for North American systems.

LRT MAINTENANCE

Storage and Maintenance Facilities

Most existing LRT systems operate a central workshop and several satellite storage yards. As in most other rail transit installations, the storage yards are sized and located to minimize deadhead mileage. They usually contain routine car service and cleaning facilities, as well as basic staff needs.

With the arrival of much new and more complex equipment, many European systems are building, or have just built, new central workshops. Typical installations are those at Stuttgart and Zurich, designed primarily for servicing the rail fleet; but also for handling bus or (at Zurich) trolleybus repairs to maximize plant utilization. A common feature in the main shop is a shallow transfer table (Figure 78) running the length of the building which permits the convenient movement of the large modern cars from bay to bay in the shop.

In the United States, both the Boston and San Francisco LRT operations are preparing for their new Boeing cars by constructing new central workshops for the rail fleet. The San Francisco shops, designed to store and maintain 100 articulated cars, are being built on a site only 300,000 square feet in area.

Table 25. Self-service Fare Collection in European Cities

City	Ticket Availability	Ticket Cancelling	Inspection	Evasion	Comments
Newcastle (Proposed)		On board fare cancelling machines	On train inspectors with on spot fining powers provided by enabling Act of Parliament		Variable fare system
The Hague	Tickets available from driver Substantial discount for use of prepaid multifare tickets (used by 70% of patrons) Plans to install ticket vending machines on cars and at stations	On board fare cancelling machines			
Zurich	Tickets bought only from machines at stations		60 fare inspectors police the honor fare system; check 9% of patrons, fine is 5 francs	0.2% of passengers cheat	Two zone type fare system
Stuttgart	Tickets bought from streetside machines at a discount or from drivers		30 ticket inspectors check 3.6% of passengers; fine is 10 marks	1.5% of passengers cheat	
Hannover	Tickets may be bought from driver or from machine (at a discount). Only 10% of customers buy tickets from driver, 60% use ticket books, 30% purchase passes		Inspectors randomly check 2% of all trips; fine is 20 marks	0.3% are caught	
Mannheim			40 inspectors – check 25% of all trips; fine is 10 marks	Only 2.5% of passengers cheat	
Frankfurt			Inspection is not rigorous; only 0.8% of passengers are checked; fine is 20 marks	2% or more of passengers cheat	Flat fare throughout transit area
Bremen	Tickets may be bought from driver or sidewalk ticket machines (at a discount)		70 inspectors used; also check other system performance		
Cologne/Bonn	Tickets may be purchased from driver except on subway portions where ticket offices are provided.		Inspectors check 5% of passengers; fine is 20 marks	1.6% of passengers cheat	
Bielefeld	Tickets may be bought from driver or curbside machine (at a discount)		8 inspectors; fine is 20 marks	1.5% of passengers cheat	

Table 26. Fare Collection Systems in Use on North American Rapid Transit Systems

Property	Medium	Manner of Collection	Fare Structure
MBTA Boston	Coin-token	Turnstile Fare box on vehicle	Flat fare – zone Pay to enter
CTA Chicago	Coin	Turnstile Station attendant Conductor on train	Flat fare Pay to enter or en route
CTS Cleveland	Coin	Station agent Turnstile Fare box on train	Flat fare Pay to enter
MUCTC Montreal	Ticket Manual dispensing	Turnstile	Flat fare Pay to enter
NYCTA New York	Token	Station Agent Turnstile Conductor on train Coin box	Flat fare – zone Pay to enter or en route
PATH Newark	Coins	Turnstile	Flat fare Pay to enter
PATCO Philadelphia	Magnetic ticket Vending machines Manual Sales	Electronic gate	Flat fare – zone Pay to enter Checkout to exit
BART San Francisco	Magnetic ticket Automatic dispensing	Entry gate Exit gate	Variable fare Buy ticket to enter; subtract fare to exit (automatic)
TTC Toronto	Token-ticket	Station agent Turnstile (token)	Flat fare Pay to enter

Vehicle Maintenance

Modern LRT vehicles rely heavily on complex electronic and electrical equipment. To maintain a high level of fleet utilization, a number of techniques are used to expedite vehicle maintenance and to minimize loss of vehicle availability. Electronic failure diagnosis is used to quickly identify defective components. Electrical and electronic subsystems are detachably mounted on modular panels for ready access and speedy replacement (Figure 79). Removable structural components are used. For instance, the DuWag car used at Frankfurt is equipped with fiberglass end panels to simplify speedy replacement when damaged in traffic accidents.

By cutting the time requirements for routine maintenance and minor repairs, high peak hour availability is achieved. In Stuttgart, 95 percent of the fleet is routinely available for peak hour service. This percentage is typical, rather than an exception.

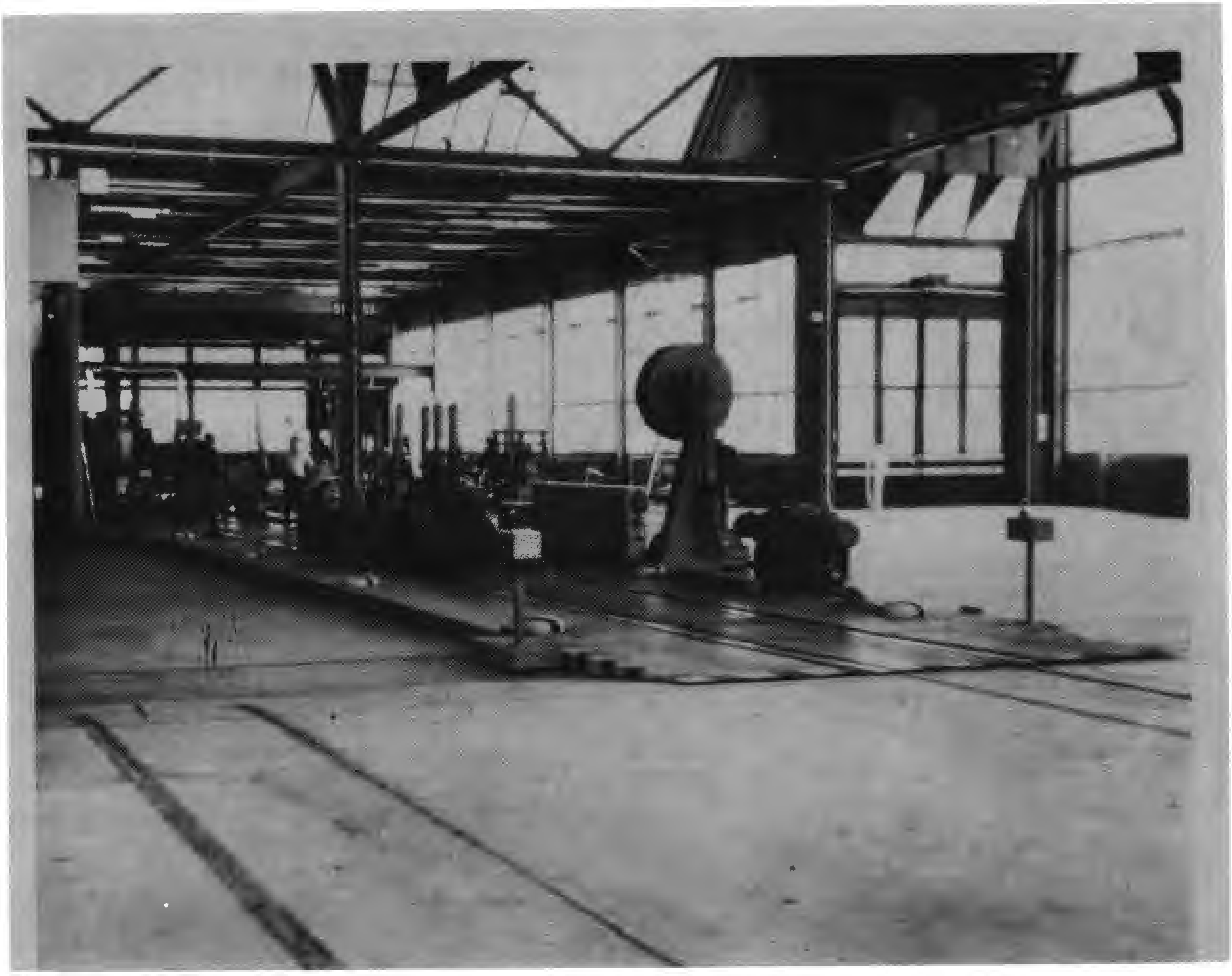


Figure 78. Transfer Table in New Workshop in Zurich

Track Maintenance

Light rail trackage does not require unusual maintenance, compared with that of rail rapid transit. As with other rail installations where ties are used, they need replacement at the rate of 3 to 5 percent per year. Where the trackage is built into the road, as it is in street running and at-grade intersections, most of the track superstructure is protected in the pavement and would have high durability. Many cities have tracks which need no major repairs for 15 to 25 years (Amsterdam, Dusseldorf, Stuttgart). Although LRT has a high utilization rate of the trackage as compared with most conventional rail installations, frequent inspection of the rail on tangent track is not required. However, periodic inspection is desirable at stations and curves where acceleration, braking and side loads add considerable stress to the track.

Track switches, particularly in pavement, require frequent attention. On many systems, switches are inspected on a daily basis. Frequent attention is desirable to prevent accumulation of trash on exclusive rights-of-way of LRT or any other transit mode. On some systems vacuum trains are used, particularly to clean tunnels.

Figure 79. Electronic Subsystem Being Repaired on Light Rail Vehicle in Zurich

An important task is rail grinding to prevent the development of rail corrugations, a major source of LRT noise. On well maintained systems, two approaches are used. Some systems send a "scrubber car" over the whole network at schedule speed every two weeks or so, thereby preventing corrugations from forming. Other systems grind down any corrugations that do occur on an as-needed basis (approximately every six months).

Overhead Maintenance

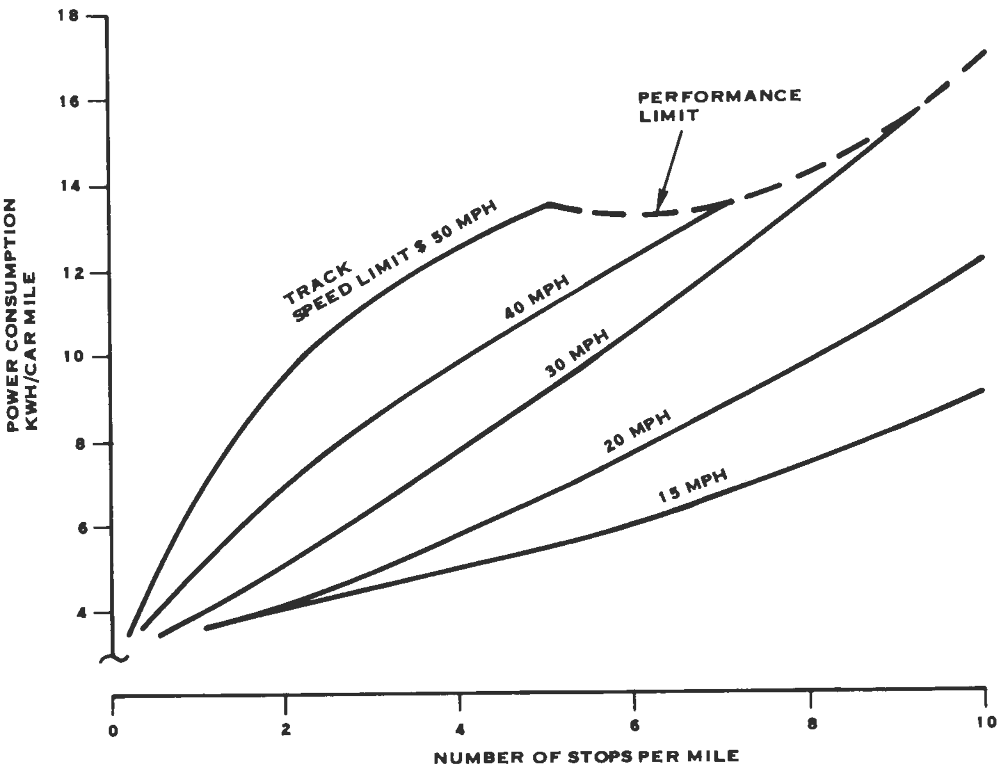
Overhead maintenance is concerned primarily with power supply failures. Most commonly, this results from damage to the contact wire frequently caused by extensive wear or stress by the pantograph or trolley. A variety of temporary wire support techniques are used to enable service to continue until a permanent repair can be made at night.

The power supply and substations need to be designed with sufficient reserve capacity to absorb partial failures with minimal impact on service. Initial installation cost economies intended to reduce this reserve may have adverse consequences on system dependability.

ENERGY CONSUMPTION

The energy consumption of transit vehicles depends on a number of design and operational factors. These include vehicle weight, acceleration and braking rates, the efficiency of the power distribution system and of the vehicle's motors and controls, grades, station stops, and other stoppages or slow-downs experienced en route. Energy consumption can be calculated easily and fairly accurately.

Figure 80 shows estimates of energy consumption for the Boeing light rail vehicle for a range of cruising speeds and for a range of station spacings. The implicit assumption made in developing these data is that the LRT operation is unimpeded by intersection crossings. The results of another series of parametric calculations also for the Boeing LRV are shown in Figure 81. Here, the significant findings are the effects on energy consumption of station spacing and stops at traffic signal controlled intersections. Station stops were varied from 0.1 to 1 mile. An average of eight at-grade intersections per mile were assumed to be randomly spaced. The solid line indicates the energy consumption assuming the LRV has full preemption at all grade crossings, or alternatively, that it operates on a grade separated right-of-way. The dotted line shows the increased energy consumption caused by operating without signal preemption. In this case, a 30 second green phase was assumed in each 60 second light cycle. The light rail vehicles were assumed to arrive at random times at each intersection. Energy consumption typically increased by a factor of two. This amounts to a penalty of 7 to 15 cents per vehicle mile assuming typical power costs. In addition, the low schedule speeds caused by randomly phased signals indicate that preemptive signalling or, at a minimum a form of progressive signalling, is desirable for acceptable LRV performance in line-haul applications.

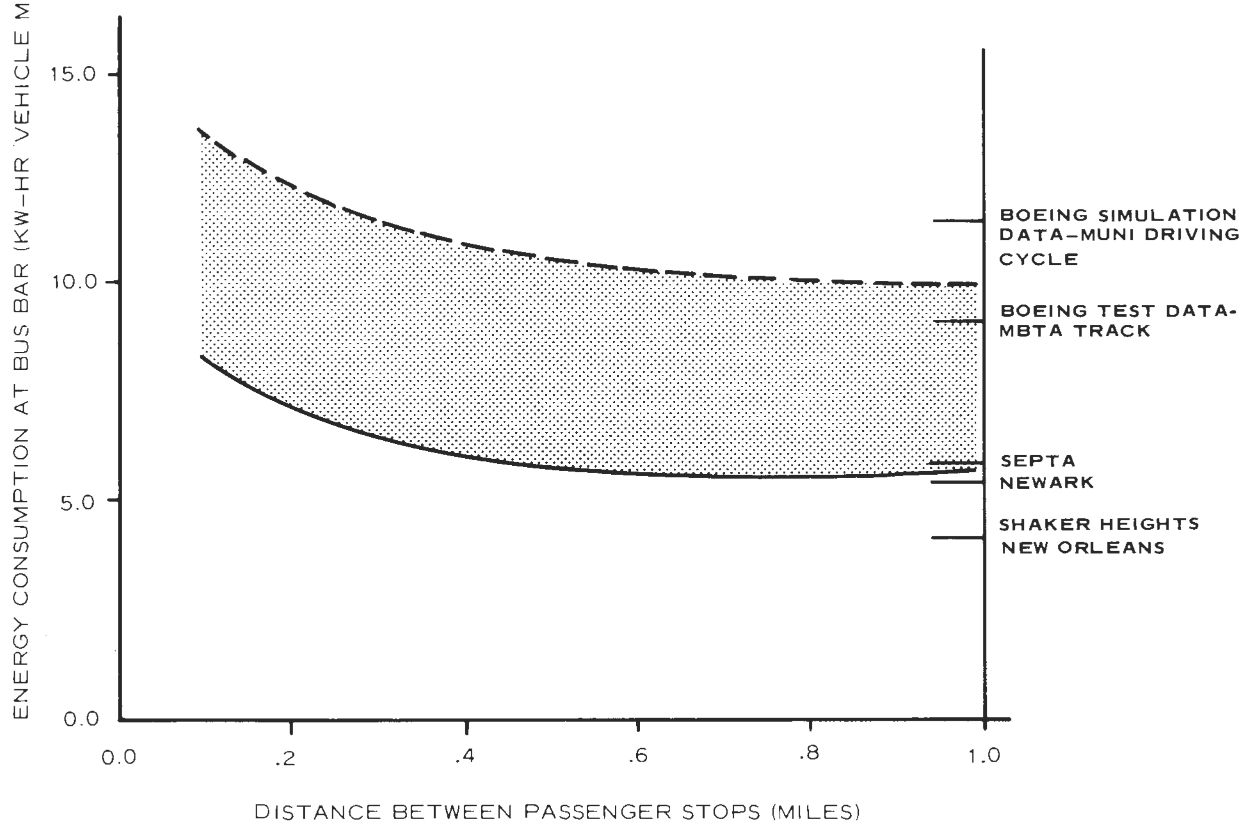


NOTES:

1. 35 KW AUXILIARY LOAD
2. 100 PASSENGER LOAD
3. 15 SECOND STATION STOPS

Source: Boeing Vertol Company

Figure 80. Boeing Light Rail Vehicle Estimated Power Consumption



ASSUMPTIONS

1. MAXIMUM SPEED 50 MPH
2. LEGEND
   - — — — NO PREEMPTION
   - ——— 100% PREEMPTION
3. TRAFFIC SIGNAL AT EACH INTERSECTION (8 PER MILE, RANDOMLY SPACED)
4. SIXTY SECOND SIGNAL CYCLE
5. TWENTY SECOND PASSENGER STOP
6. BOEING LRV

SOURCE: BOEING STANDARD LIGHT RAIL VEHICLE TEST DATA
BOEING VERTOL COMPANY

Figure 81. Relationship Between Energy Consumption and Station Spacing

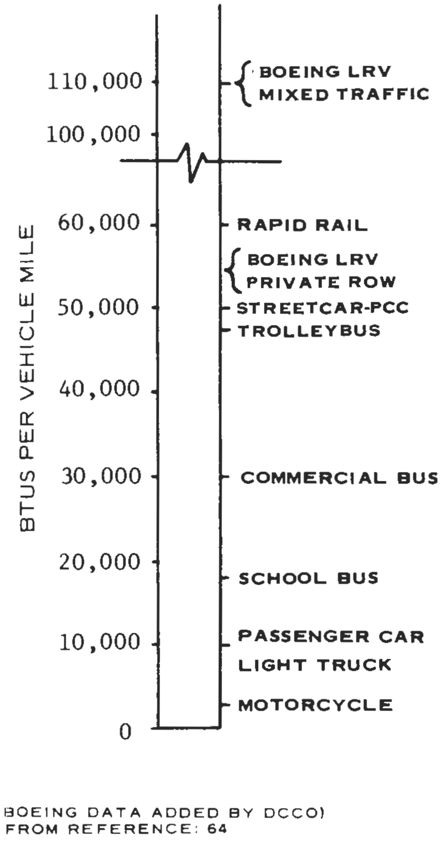
The validity of the simulation can be checked by plotting measured energy consumption from existing transit operations on the right hand scale. An independent calculation of the Boeing LRV on a typical San Francisco Muni driving cycle estimated an energy consumption of 11.68 kilowatt hours (kwh) per vehicle mile.[22] This estimate is at the high end of the graph; the discrepancy is the result of the exceptionally steep grades contained in the Muni run. Actual Boeing test data obtained on a normal grade profile at the Boston MBTA indicated a consumption of 9.52 kwh per car mile for a combined subway-surface run at an average speed of 14.5 mph.[23] Actual PCC energy consumption for typical American systems runs four to five kwh per car mile.[24] This lower range is explained by the lower weight of the PCC car: 69,000 pounds for the Boeing LRV compared with 39,360 pounds for the PCC car. Adjusting the PCC data for weight gives a consumption of 7 to 8.75 kwh per car mile, precisely in the range of the graph shown in Figure 81.

For comparison purposes, Figure 82 shows the energy consumption for buses, rail and other modes with the projected Boeing LRV performance superimposed. The LRV consumes more energy in mixed traffic operation than conventional rail since the cars weigh the same, and stops are much more frequent. However, reductions in the energy consumed by light rail vehicles are achievable with current LRV technology by using regenerative braking (i.e., returning to the line, under certain conditions, the power that would otherwise be dissipated as heat during braking) and with chopper controls. Looking ahead at technologies still in development, the use of energy storage devices, such as flywheels, may reduce energy consumption even further.

On a per vehicle basis, the bus consumes less energy than either the LRT or rail rapid vehicle due to its lower weight. It is difficult to convert the per vehicle energy data into energy consumption per passenger, except for specific operations, due to the large variability in passenger loadings. However, for many observed transit operations, the bus and LRT vehicles are very similar in energy consumption per passenger mile, and rail rapid is the most energy efficient mode per passenger mile.

PROVISIONS FOR THE HANDICAPPED

The provision of access for the handicapped is receiving increasing attention in U.S. transit system design. Recent legislative decisions in Washington, D.C. have stressed transit agencies' obligations to design their equipment to permit access by the handicapped. Proposed modifications to requirements for federal financial assistance for construction purposes include strong requirements of provisions for access for handicapped persons, in particular the wheelchair handicapped.



(BOEING DATA ADDED BY DCCO)
FROM REFERENCE: 64

Figure 82. Energy Consumption for Typical Vehicles

Providing access in light rail vehicles for wheelchair handicapped requires special design treatments. Standard, raised floor level vehicles with stepped entryways suitable for low level loading areas cannot be used if these passengers are to be accommodated. Raised floor vehicles, such as standard buses, present obvious access difficulties to mobility limited persons.

For LRT, mitigation of access problems experienced by the handicapped can be accomplished in two different ways. Either the loading area can be raised to match the vehicle floor height or the vehicle's floor level can be lowered to platform height. Among vehicular designs, two recent developments are noteworthy. One, the Boeing LRV design, incorporates an adjustable height step. In the other, a lowered floor has been incorporated into the conceptual design of the French Citadis articulated car design. Low floor vehicles require additional design effort and expenditure to improve passenger safety and increase the efficiency of interior vehicle space utilization.

Raised station platforms accessible by handicapped via ramps can be used as an alternative with raised floor level LRVs. The raised platforms, however, are costly, may create some safety hazards and may have a negative visual impact.

While either design approach entails some additional cost, the handling of handicapped on LRT would still be achieved more economically than on rail rapid transit where costly elevators must be provided at stations to facilitate access for the handicapped to the platform from street level.

VANDALISM

Vandalism is a problem on European transit, as it is on American systems. As in the U.S., European transit operators are forced to spend increasing sums annually to repair damage caused by vandalism.[25] The following steps are being taken by European LRT operators to control the problem.

- Vandalism is significantly more serious in trailer cars. For this reason, Bremen, Frankfurt and Bielefeld are either phasing out trailers or minimizing their use in the late evening.
- One route at Gothenburg dropped trailers during evening hours because of vandalism.
- Closed circuit TV monitoring is being used in stations at Hannover and Frankfurt.
- Bremen offers a reward for reports leading to the apprehension of persons damaging transit property.
- Hannover is minimizing the use of upholstery for seats.

These approaches generally follow similar practices in the United States. They also point out the significant advantage of driver surveillance which favors articulated cars over multiple unit operation.

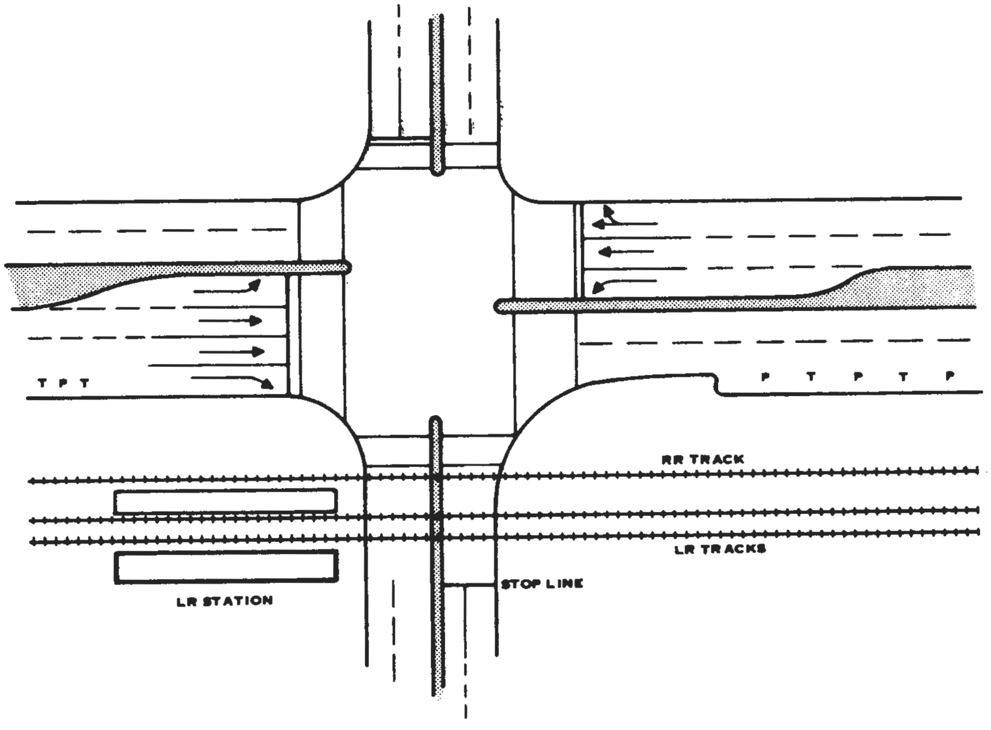
OPERATIONS IN NON-EXCLUSIVE RIGHT-OF-WAY

A distinguishing feature of light rail transit is at-grade operation on parts of its routes. This type of operation has the potential of significant capital cost savings, but it introduces a number of operational ramifications. These operational issues include dealing with automobile cross traffic, pedestrian safety, problems of signal preemption and effects on LRT system speeds.

Grade Crossings

The alignment of LRT routes emphasizes use of public rights-of-way, railroad rights-of-way and minimum use of grade separated structures, i.e., aerial or underground guideways (see Chapter 4). Where surface traffic conditions permit, the LRT alignment may cross intersections at grade. At these crossings, high speed, high frequency, at-grade light rail operations (typical of peak hour service) require some sort of signal or barrier protection device to avoid conflicts with automotive traffic.

Since in many cities it might be possible to locate light rail alignments in existing railroad rights-of-way, a variety of grade crossings would have to be carefully planned for light rail operation. One such case is the location in a railroad right-of-way paralleling a major highway. A schematic of a crossing of this type is shown in Figure 83. At such a grade crossing, the automotive traffic signals should be interlocked with light rail vehicle-actuated signals, and the stop line on the cross street must be located away from the intersection to prevent vehicles from stopping on the tracks. The traffic signal phasing depends on local conditions,



NOTE: SIGNALS FOR RAILROAD AND LIGHT RAIL TRANSIT MUST BE INTERLOCKED WITH SIGNALS CONTROLLING CROSSING MOVEMENTS.

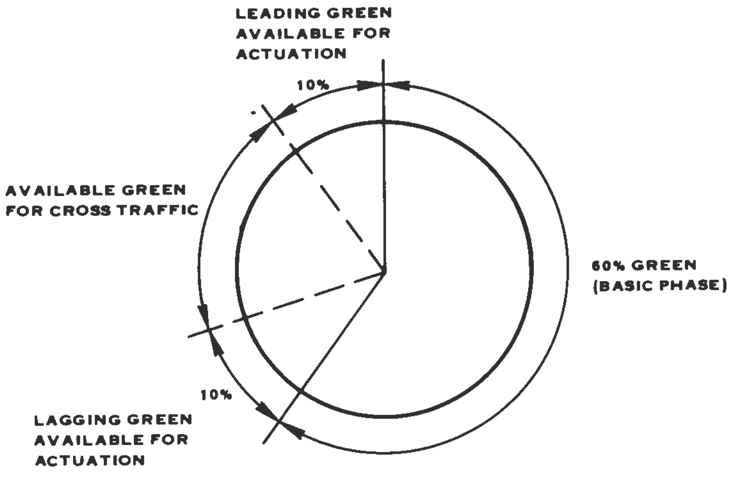
Figure 83. LRT on Railroad Right-of-Way

such as intersection geometry and volumes of individual traffic movements. In the interests of safety, actuation of signals by rail vehicles must allow considerably longer clearance times than at simple street crossings. Some turning movements may have to be eliminated and rerouted to a more convenient location. If a light rail station is located at the intersection, it is easier to provide safe operation due to the reduced operating speeds of the light rail vehicles. Also, the time loss for light rail vehicles is reduced.

A different situation involving potentially more complex conflicts with surface street traffic is found where a light rail line is located on the median strip of an arterial. In this case, conflicts arising from left turns and pedestrian movements, in addition to those created by the cross traffic, must be resolved. Here, light rail traffic signalling should be coordinated with that for parallel automotive traffic. To resolve potential conflicts, some degree of coordination of street traffic and pedestrian crossing signals with LRT controls is needed. In the process, some automobile traffic may be rerouted, and some decrease in vehicular flow through the intersections may be experienced as a result of changes in street traffic signalization. Some parking spaces may be affected, and the availability of some traffic lanes may be lessened. The light rail vehicle, in turn, may be slowed or stopped at these intersections.

The diversity of traffic conditions and street geometrics is so great, however, that generalization regarding these issues are impractical. Each case must be judged on its own merits. The decision regarding grade separation should evolve from a consideration of all operational, economic and environmental factors. Since local conditions at LRT crossings with street traffic vary greatly, the operational control of crossings, required for both capacity and safety reasons, can be one of the following types, given here in the ascending order of LRT service quality.

- Stop or yield signs for cross traffic. These controls are used where traffic volumes and other conditions do not justify installation of traffic signals.[26]
- Standard signal with fixed-time operation. At crossings controlled in this manner, light rail vehicles travel with the other traffic in the same direction. (For handling of left turning traffic, see designs in Chapter 4.)
- Standard fixed time signal with a special phase for light rail vehicles. This type of control may accommodate turning and other movements crossing light rail tracks by separating them in time. This type of signal control allows more movements with higher safety than the preceding one, but the total capacity of the intersection is lower due to the added signal phases.
- Signals actuated by light rail vehicles which can require either leading or lagging green, retaining constant background cycle. This type of signal generates a high probability for light rail vehicles to have a green phase when crossing an intersection, as shown in Figure 84.
- Signal control with full light rail vehicle override (preemption). This type of signal is used for high speed light rail operation crossing minor streets. It eliminates all delays for the LRV, but disrupts other traffic. It is therefore not desirable at intersections where the cross and turning traffic volumes have high volume to capacity ratios.



BASIC SPLIT — 60:40

ON-CALL LEADING — 10%

ON-CALL LAGGING — 10%

TOTAL AVAILABLE GREEN FOR LIGHT RAIL VEHICLE — 80% MAXIMUM

NOTE: NORMALLY, CROSS TRAFFIC HAS 40% GREEN AVAILABLE. CROSS TRAFFIC GREEN CAN DECREASE TO 30% WITH ONE ACTUATION AND TO 20% WITH TWO ACTUATIONS DURING HIGH FREQUENCY SERVICE WHEN ONE LIGHT RAIL VEHICLE ACTUATES LEADING GREEN AND ANOTHER ONE ACTUATES LAGGING GREEN. THIS FORM OF TRAFFIC CONTROL WOULD BE APPLICABLE AT INTERSECTIONS WITH LOW TO MODERATE CROSS TRAFFIC VOLUMES.

Figure 84. Signal Cycle With Light Rail Vehicle Actuation

- Signal control with full light rail vehicle preemption with flashing lights, with or without barriers. The barriers increase safety and driver obedience, since they are very similar to railroad crossings. LRT crossings with full signal override on open streets or highways may affect highway capacity when light rail service is frequent (e.g., 15 to 20 vehicles per hour per direction or more). The reason is that while LRV occupancy times at intersections are short, LRT preemptions interrupt the traffic flow, and may at times, reduce highway capacity. Where barriers are desirable or required, additional degradation of highway capacity could be anticipated, particularly for high frequency light rail transit service.
- Control of LRT/street traffic crossings, accomplished by prohibition of turns, closing of minor crossings, and provision of underpasses/overpasses for LRT at major streets or highways.

Signal actuation techniques vary from the simple operation of a contactor on the overhead wire to the modern Vetag system, by which the preemptive signal is transmitted from the vehicle to an inductive loop antenna embedded in the road surface.

Flashing lights are often used on certain track sections, mainly along arterial medians (Figure 85). These devices are similar to those used for grade protection on mainline railroads. The flashing red lights are actuated by standard railroad track circuits which require the rails to be properly insulated from each other. This method is incompatible with certain

Figure 85. Automated Signals – LRT At-Grade Intersection

types of light rail track construction, such as tieless track, and is generally used in areas where the system runs on standard ballasted ties. In some cases, flashing light systems are operated in conjunction with audible alarms, such as horns or bells.

A standard railroad grade crossing signal and aluminum gate combination may be required at certain intersections for crossing protection (Figure 86).[27] The counter-weighted arms are rotated by an electric motor with the typical time for raising or lowering averaging about ten seconds (some local design standards may require a 20 second delay for gate actuation). As with flashing lights, the movable barrier is actuated by track circuits which detect an approaching vehicle.

The different types of protection devices elicit different responses from the driving public and pedestrians. Recognition of these behavioral aspects will affect the operations of LRT, its level of service and safety. Auto drivers tend to ignore railroad flashing lights. In California, a driver "shall not proceed until he can do so safely" when a clearly visible electrical or mechanical device gives warning of the approach or passage of a train.[28] If there is a crossing gate, the driver is permitted to cross while the warning signals are operating, and the gate is in the process of closing. Thus when crossing gates are used, it is necessary to lock the gate in position while the LRV is still a safe stopping distance away from the intersection. By contrast, when traffic signals are used, most drivers will stop as soon as a red indication appears. The traffic light could thus be expected to promote better driver cooperation than railroad crossing devices and reduce the length of time that the LRT is operating under control of the intersection signal.

Traffic Impacts

High speed, high frequency, at-grade LRT operations may limit parallel and cross street traffic capacity. A calculation carried out for a fairly simple crossing illustrates these effects. If the arrival of light rail vehicles could be fully coordinated (synchronized) with the traffic signals at the intersection, i.e., to arrive when the cross traffic has a red light, it would be possible to avoid any delay in cross traffic (or reduction of cross street traffic capacity). In real installations, however, some LRT vehicles will arrive at the intersection when cross traffic has a green light. If provisions are made to preempt the cross traffic, the green time available for cross traffic would be decreased. The effects on cross traffic become more pronounced as the frequency of LRT crossings increases, as the length of the crossing trains increases (because large trains take more time to traverse the intersection), and for lower LRT speeds. At lower LRT speeds, the effect of train length is more pronounced, imposing one of the practical limits on the length of the LRT trains in mixed traffic operations.

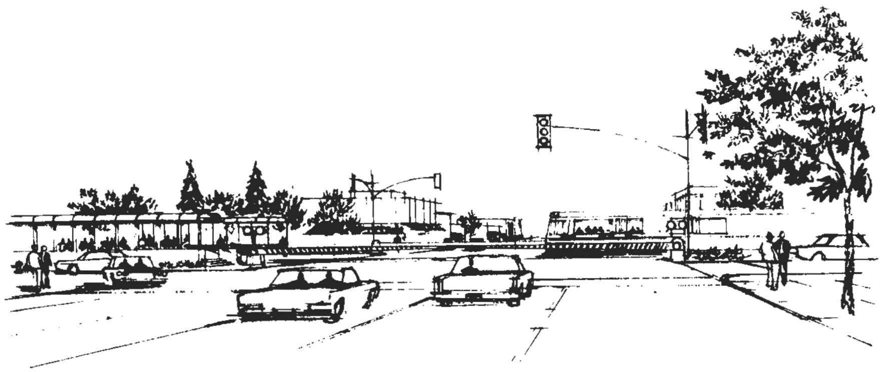


Figure 86. Automated Crossing Gates – LRT At-Grade Intersection

It is reasonable to assume that lesser degrees of preemption would have less impact on the cross highway capacity, but the LRT performance would suffer accordingly, i.e., the random arrival of trains at the intersection would cause random delays, stoppages and overall increases in travel time. An advanced form of traffic control which could coordinate the timing of cross traffic signals with the speed of the light rail vehicle to help synchronize train arrivals with green cycles could do much to improve the mutual operations of both LRT and automobile traffic. While elements of equipment and software required to implement a control of this type are available or easily developed, no systems of this type have as yet been produced or even conceptualized.

When movable barriers are installed, they provide greater intersection safety. They also significantly reduce the traffic volume through the crossing, because about twenty seconds are required to raise or lower the barrier.

LRT alignments are frequently located on highway or arterial medians. An extensive study of this type of operation has been completed recently for the Southern California Rapid Transit District.[29] This study found that for cross streets with traffic volumes from 2,500 to 35,000 cars per day, light rail at-grade operation was feasible for crossing intervals as low as two to three minutes for the higher volume intersections. The study concluded that at-grade LRT operations were feasible at major intersections with crossing volumes as high as 35,000 vehicles per day without significant adverse impact on local traffic capacity or circulation. The preemption of signals in favor of LRT would affect, however, the vehicle platoons developing with progressive signals along the cross street. The study points out that operational strategies, such as street widening for additional turn lanes or the prohibition of left turns, could mitigate some of the negative impacts on motor vehicle movements. However, since the investigation was not carried out at a sufficiently fine level of detail, its conclusions should be regarded as tentative. Detailed study of specific intersections, taking into account the actual street geometrics and other urban environmental factors, are necessary to firmly establish all operational aspects of each specific at-grade intersection.

Coordinated signalization can be used to improve the flow of light rail vehicles as well as buses. It requires that stop spacing be increased so that the LRVs crossing several intersections between the stop spacings can travel with the green band of signal progression. Secondly, each near-side stop should be followed by a far-side stop so that the LRV may cross an additional intersection with the traffic platoon.[30]

Traffic Signal Preemption

One of the key features of modern LRT is its relatively high average operating speed. To accomplish this, LRT operations through at-grade intersections require some preemption of cross traffic, at least during peak hours.

The preemption of traffic signals as a means to upgrade LRT performance is being used increasingly in Europe. The LRT system in Basel has both the greatest number and percentage of traffic signals with priority for LRT. Nuremburg has 138 preemptive signals. Overall statistics needed to estimate the extent of the use of preemption in Europe are not immediately available.

Preemption of traffic lights is most effective at crossings remote from stations. There, the time savings include not only the signal delay, but the 20 to 30 seconds that would also be lost when slowing to a stop at a station and accelerating back to speed. Where traffic lights are used with a typical yellow-red time of 30 seconds and a cycle time of sixty seconds, the average delay at the light is estimated at 7.5 seconds. On the average, the light rail vehicle encounters a green light half the time; the other half it faces a delay as large as 30 seconds. Thus, if preemption is used by manual actuation from a station preceding the signal, only about 7.5 seconds can be saved on the average. Preemption of a stationless crossing can save considerably more time.

A number of techniques are available to preempt at-grade crossings for light rail priority. These techniques include actuation via automatic track circuits, actuation via the pantograph, and actuation via signals transmitted from the vehicle.

Automatic track circuits have been used since the late 1800s to detect the presence of rail vehicles. This technique is straightforward and can be used to actuate flashers, crossing gates or even conventional traffic signals. The track circuit requires that one rail be kept at a low voltage while the other rail is grounded. The track is divided into segments insulated from each other. The steel wheels of a passing train short the circuit between the two rails, providing an indication that a particular track block is occupied, and that a particular signal sequence can therefore be activated.

An intersection traffic control device can also be actuated by means of the pantograph which activates a contactor, which in turn operates the traffic signal. Several LRT systems have replaced this type of control with the more versatile inductive loop system.

Use of a signal transmitted from the vehicle and received by inductive loop antennae buried in the roadway (similar to the loops used to activate street traffic signals) is an innovative approach to signal preemption, remote operation of switches and general traffic management.[31] In Europe, such a system, known by the trade name Vetag,* has been devised and is used for light rail and bus applications.[32]

---

*Other techniques designed to accomplish the same functions that do not rely on automation have been used or tested for a number of years. For instance, switches have been operated via signals actuated manually by the LRV operator. Procedures for identifying and locating rail vehicles or buses via radio frequency signals, optical scanners or other technological means have been used in various applications or have been the object of considerable testing. There is little doubt that they could be adapted to full advantage on future LRT installations. The Vetag system is described in some detail, because it is one of the first technological developments specifically keyed to LRT requirements.

Vetag consists of three basic units: an interrogator installed alongside the road, a detection loop embedded in the road surface under the rails as well as in pavement, and a transponder fitted underneath each vehicle. The interrogator sends out pulses through the detection loop at a fixed rate. When a transponder-equipped vehicle passes over the loop, the transponder is activated and returns a signal to the interrogator by way of the detection loop. This signal identifies the type of vehicle, the route number and vehicle identification number. The signal may be sent to a control center or computer or used to operate traffic lights or switch points. In the "automatic" mode, all traffic lights along the route may be made to automatically respond to requests from the transponder to ensure priority for public transit at highway intersections.

In The Hague, a grade crossing improvement program has been recently undertaken, relying in part on the Vetag system. This system is also being employed on the Amsterdam light rail system. The Vetag equipment detects, identifies and positively locates selected vehicles in a stream of road traffic. It is, therefore, well adapted to the automation of LRT or streetcar signalling which must operate without external supervision.

Pedestrian Crossings

A major task in planning LRT is the preservation of pedestrian circulation across LRT routes. Potential restraints on pedestrian movements occur principally along median trackage (Figures 87 and 88). In other cases such as railroad rights-of-way, pedestrian crossings may be generally prohibited except at key locations where they are provided by grade separation. Where LRT operates in mixed traffic in a streetcar mode, no new pedestrian restraints are introduced, and conventional crosswalk practices can be followed.

As a general design goal, pedestrian crossing facilities over a new median LRT line should be as closely spaced as they were before construction. In actual practice, it is sometimes necessary to consolidate pedestrian crossings without serious loss of pedestrian freedom.

Figure 87. LRT Vehicular Barriers At Grade

Figure 88. LRT Pedestrian Barriers At Grade

At vehicular grade crossings, pedestrian crossings are easily implemented. In some LRT alignments, minor street closures are needed with full signalization at the remaining intersections. Such treatments are not necessarily adequate for pedestrians. In Europe, a widely used crossing is the "zee" design which channels pedestrians crossing the tracks toward the oncoming light rail vehicle by the use of a barrier fence (Figure 89). High intensity lighting and visual or audible warnings can also be provided to increase pedestrian safety.

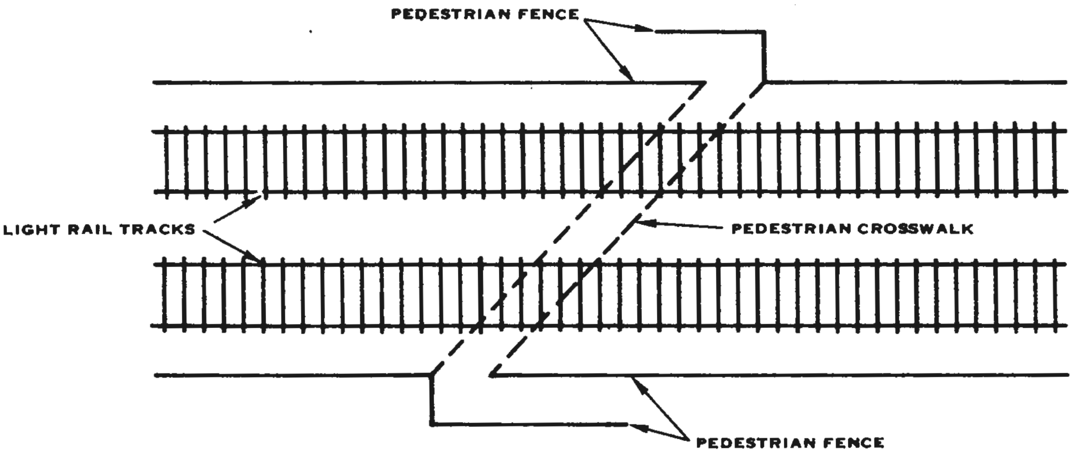


Figure 89. "Zee" Pedestrian Crossing of Light Rail Tracks

In operation, when the zee crossing is unoccupied, the LRT would pass through at full service speed. Otherwise, when potential hazards are perceived, speeds would be reduced accordingly. Of course, incidents of mischief or trespassing are always possible. Means to avoid these occurrences might be required. For instance, sufficiently long lines of sight may be provided to permit safe stopping or automatic closing of gates.

A further area of pedestrian conflict is at stations. Where low platforms are used, pedestrian movement on the tracks is possible. A fence *between* the tracks is sometimes required at stations. It is significant that the Frankfurt LRT system, one of the few not using fences between tracks at stations, also lists pedestrian accidents as the second most prevalent type of accident on its LRT system.

SERVICE QUALITY

The level of service offered by a light rail system is a major determinant of its public acceptance and patronage. Factors relevant to the quality of service are acceleration and braking limitations, station stops, speed, headway and capacity.

Acceleration and Braking Limitations

Service acceleration levels for LRT vehicles range from 2.5 to 6 feet per second^2, with an average of about 3.5 feet per second^2.[33] The slower articulated vehicles operate at the lower end of the acceleration scale, a deliberate choice to limit acceleration in the interest of comfort and safety. In addition, articulated vehicles have fewer powered axles and are, therefore, limited in the tractive effort which they can deliver. For all transit modes, the critical constraints to high stop/start performance are the passengers' upper tolerance limits of jerking, acceleration and deceleration rates.

Standard railroad train deceleration rates can be as low as 1.4 feet per second^2.[34] Light rail service deceleration rates are typically 5 feet per second^2; an emergency deceleration rate is available (using magnetic track brakes) of 6 to 8 feet per second^2 or higher.[35] Figure 90 shows the significant reduction in stopping distance this implies. The superior braking capability of LRT makes it possible to consider operation in mixed traffic where automobile decelerations are typically about 8 feet per second^2.[36] The magnetic track brakes, which are relied on for emergency stops, are not fail-safe in the traditional railroad sense, since they depend on available electric power. Therefore, the proper deceleration value used to size the minimum headway between vehicles is somewhat subject to judgement and traditional practice.

Effects of Station Spacings

For light rail vehicle operating with frequent starts and stops, acceleration/deceleration levels may have more impact on schedule speed than that of maximum speed to determine schedule speed. Figure 91 compares the attainable schedule speed for a vehicle with an average acceleration and braking rate of 6 feet per second^2 and a maximum speed of 45 mph with that of a vehicle with an average acceleration and braking rate of 3 feet per second^2 and a maximum speed of 60 mph. The curves illustrate the point. However, when stations are over a mile apart, high cruise speed becomes more important.

In studying the utility of European vehicles to American environment, the network configuration must be considered. Many estern American cities with widely spaced stations could use high speed LRT. Completely different performance characteristics than are common for typical European applications would be required.

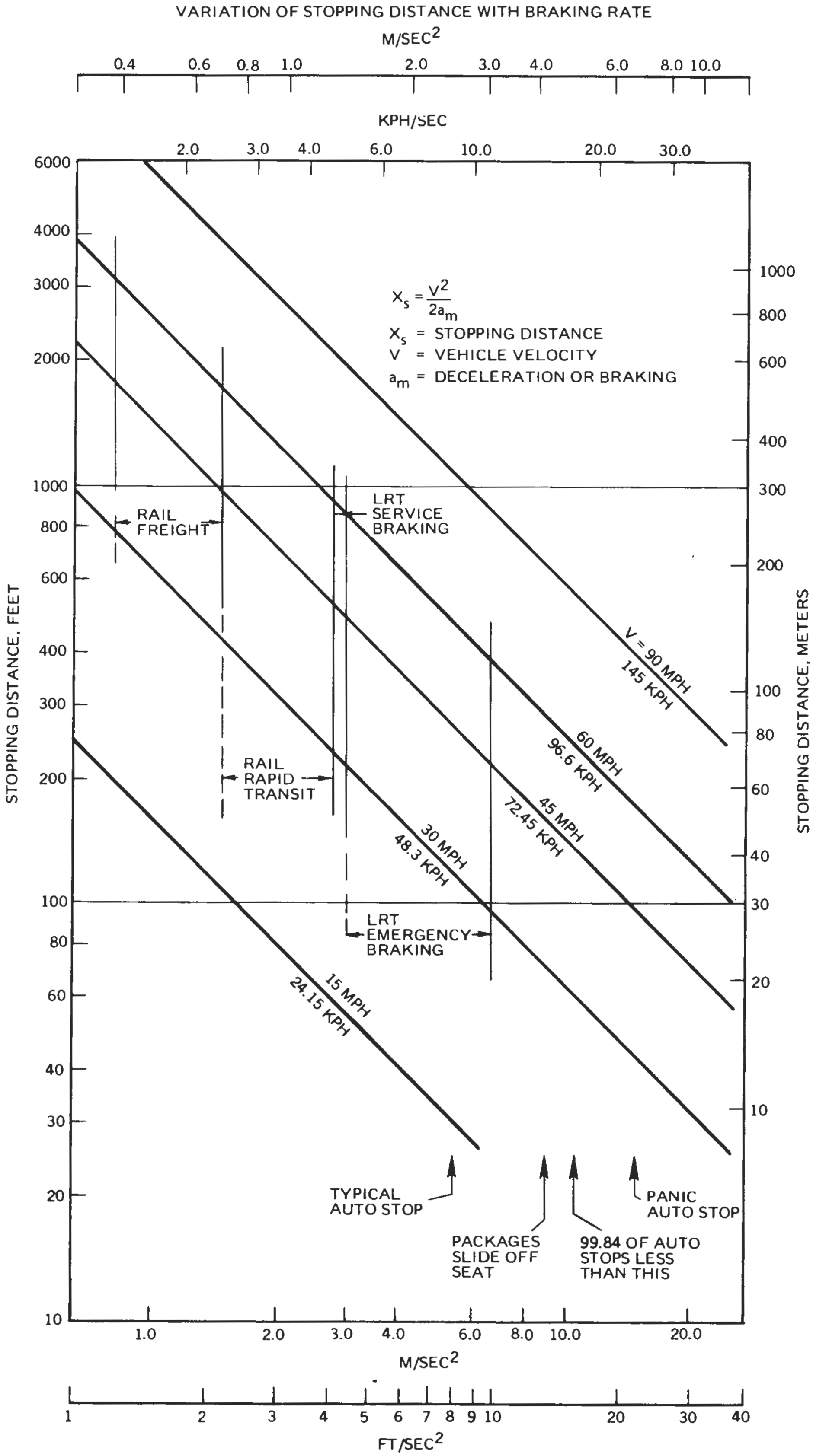


Figure 90. Typical Braking Rates (Deceleration Rates) ft/sec²

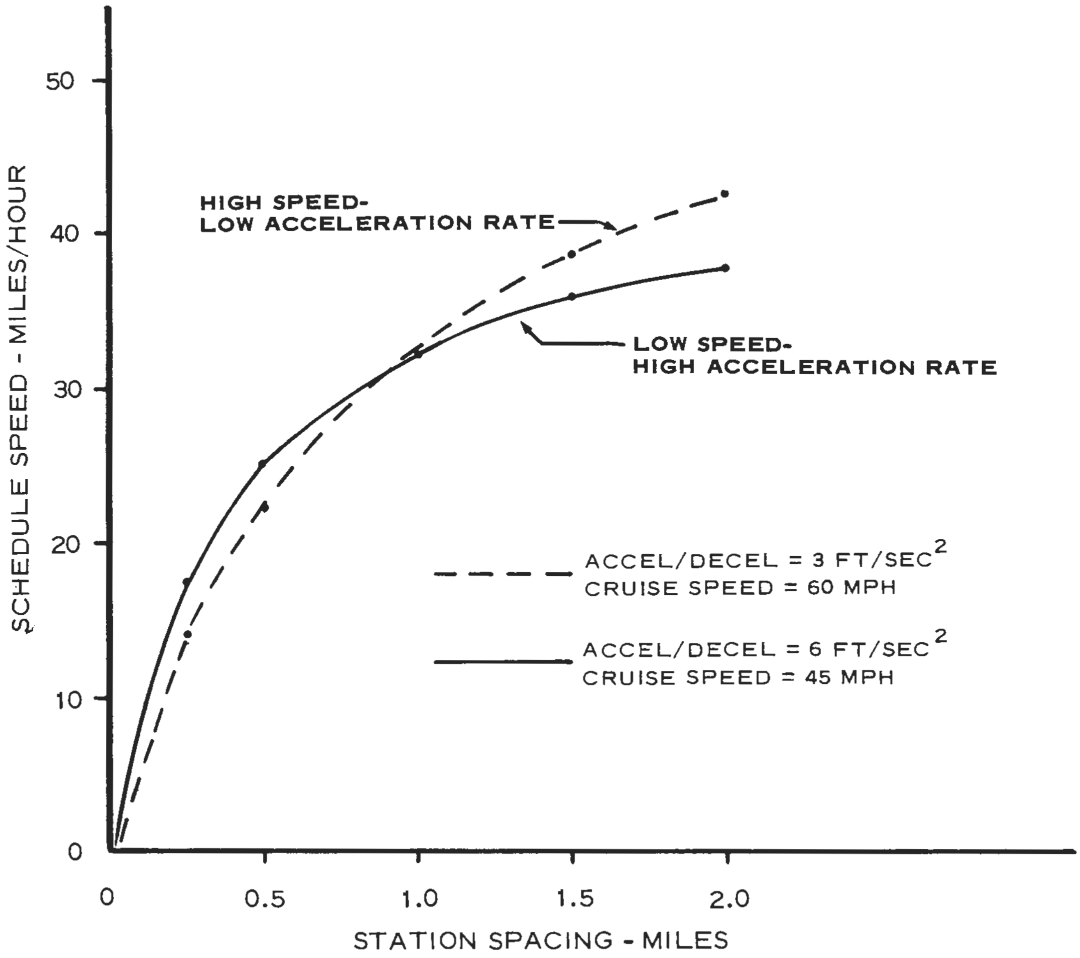
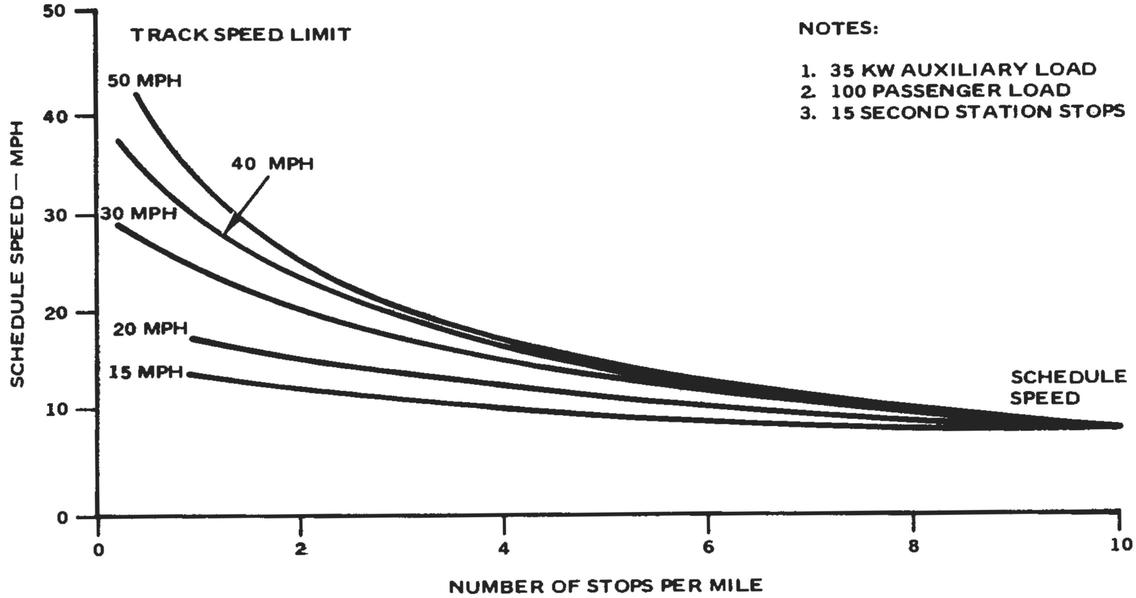


Figure 91. Effects of Acceleration, Braking and Maximum Speed on Schedule Speeds

Figure 92 shows the impact of station spacing on the performance of the Boeing light rail vehicle for operation on a completely grade separated right-of-way. Figure 93 shows the results of different degrees of grade separation on the performance of the same vehicle. The top curve is equivalent to the 50 mph line in Figure 92 with the exception that different dwell times at stations have been assumed. The middle curve shows maximum performance achievable for operation on a median strip with intersections every quarter mile. It was assumed that at fifty percent of the intersections the LRT would preempt traffic signals, while at the remainder the signals would operate randomly. The lower curve shows the same median operation with no signal preemption. Also shown is the ten mile per hour speed, characteristic of operation of light rail in mixed traffic. From the figure, it is clear that with typical half mile station spacings, a completely grade separated system can operate with a schedule speed of 26.5 mph. For median strip operation with 50 percent signal preemption, the schedule speed drops to 21 mph, while with no preemption, the schedule speed is 18.5 mph. By comparison, operation in mixed traffic cannot achieve a speed better than about 10 mph. This is another illustration of the importance of a private right-of-way for light rail performance. While some of the operational, high performance LRT systems approach the higher speed ranges, the overall statistics suggest that, on the average, LRT systems operate in the 10 to 15 mph range.



Source: Boeing-Vertol Company

Figure 92. Performance of Boeing Light Rail Vehicle

Table 27 shows typical station spacings for light rail systems.[37] Most spacings are in the range from a quarter to a half mile.

LRT Speeds

As a rule, most European systems restrict LRT speeds to auto limits except for operation on fully protected, private rights-of-way. Table 28 provides typical speed constraints for some European light rail systems.

Schedule speeds on operating LRT systems vary widely. The schedule speed for a number of European LRT systems in 1963 were reported as 8.0 mph (12.9 kph).[38] Since that time, considerable development of LRT has taken place. Cologne LRT speeds average 10 to 13 mph (16 to 21 kph) in street traffic, 15 to 20 mph (24 to 32 kph) for median strip operation, and up to 25 mph (40 kph) on private right-of-way without crossings.[39] The Brussels system reported a schedule speed of 10.5 mph (16.9 kph) in 1975 for its light rail system.[40] In Bremen, the schedule speed of new sections of LRT lines is 15 to 17 mph (24 to 28 kph) compared with the previous speed of 11.6 mph (18.6 kph).

Examples can be found of drastic improvements in schedule speeds made by providing separate rights-of-way. In 1973, Amsterdam separated its entire route No. 1 of 5.9 miles (9.5 km) from other traffic by concrete curbs, and established 17 traffic lights along the route as priority signals. Speeds had averaged 4 mph (6 kph) in the peripheral areas; autos average 9 mph (15 kph). After conversion to LRT, the average schedule speed was raised to 10 mph (17 kph) or 1 mph (2 kph) higher than averaged by private autos.[41]

At Cleveland, Shaker Heights Rapid Transit operates PCC streetcars in a light rail mode with average schedule speeds of 23 to 24 mph (37 to 39 kph) over the ten mile (16 km) line during peak periods. The first six miles (10 km) have stations spaced one mile apart; on the last four miles (6 km), the spacing is 0.3 mile (0.5 km). Over the last four miles (6 km), the trains operate in the median strip of an arterial street, crossing eleven non-preempted grade crossings. The average speed ranges from 17 to 24 mph (27 to 39 kph) depending on the time of day.[42]

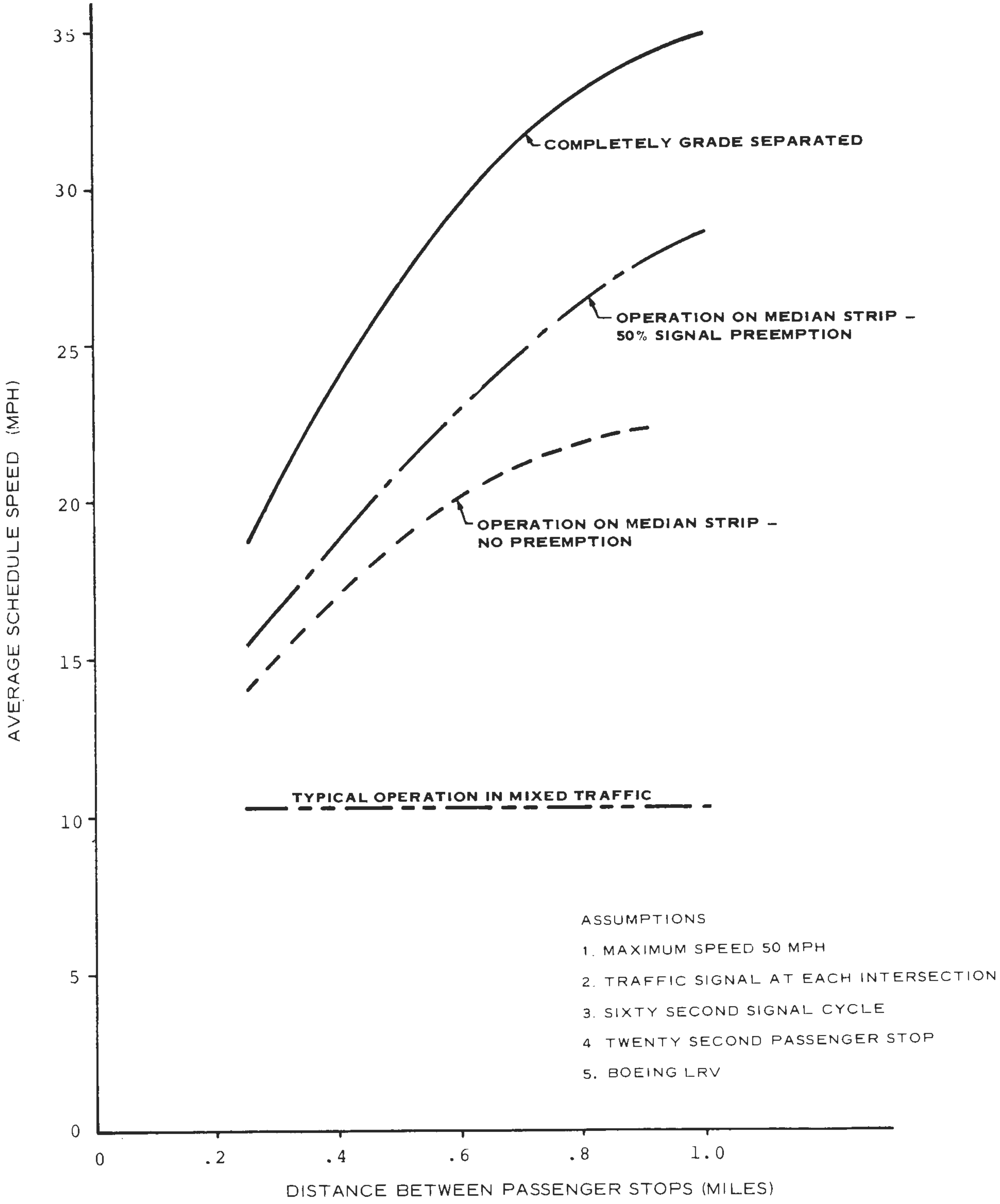


Figure 93. Relationship Between Average Schedule Speed and Station Spacing

Table 27. Typical Light Rail Station Spacings

City	Average Station Spacing	
	Miles	Km
Cologne	0.41	0.66
Hannover	0.37	0.60
Frankfurt	0.34	0.54
Nuremberg	0.32	0.51
Stuttgart	0.32	0.51
Bochum	0.31	0.49
Dortmund	0.31	0.49
Brussels	0.30	0.48
Bremen	0.29	0.47
Kassel	0.26	0.42
Basel, Brunswick, Heidelberg	0.25	0.40
Bern, Gothenburg	0.22	0.35
Antwerp	0.20	0.32
Ghent	0.18	0.29

Table 28. 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)

Figure 94 summarizes the range of speeds achievable for the three extremes of rail operation: streetcar operation in mixed traffic, light rail operation with private right-of-way and some at-grade crossings, and rail rapid operation on a completely exclusive right-of-way. Also shown are typical speeds for rail rapid systems and for bus operations in mixed traffic.[43] Light rail speeds over a spectrum ranging from that of a bus in mixed traffic to that attained by rapid rail systems.

Headways

Figure 95 shows typical minimum headways for light rail and other systems. With automatic block signalling systems, headways are limited to about 90 to 120 seconds. Shorter headways of 30 to 60 seconds are possible under manual control but would be practical only at lower speeds.[44]

Speed has a major impact upon headway. Figure 96 shows theoretical headways calculated for a block signal system with 3.2 feet per second deceleration rate and a safety factor of 1.35, i.e., allowing 35 percent greater stopping distance than is provided under the worst conditions, as is the practice in railroad operations. The upper curve includes automatic emergency stopping in the event that the operator should violate a red signal. The lower curve does not provide this extra protection. Although headways greater than 90 seconds are usually cited, it is clear that shorter headways are realizable if lower speeds are accepted.

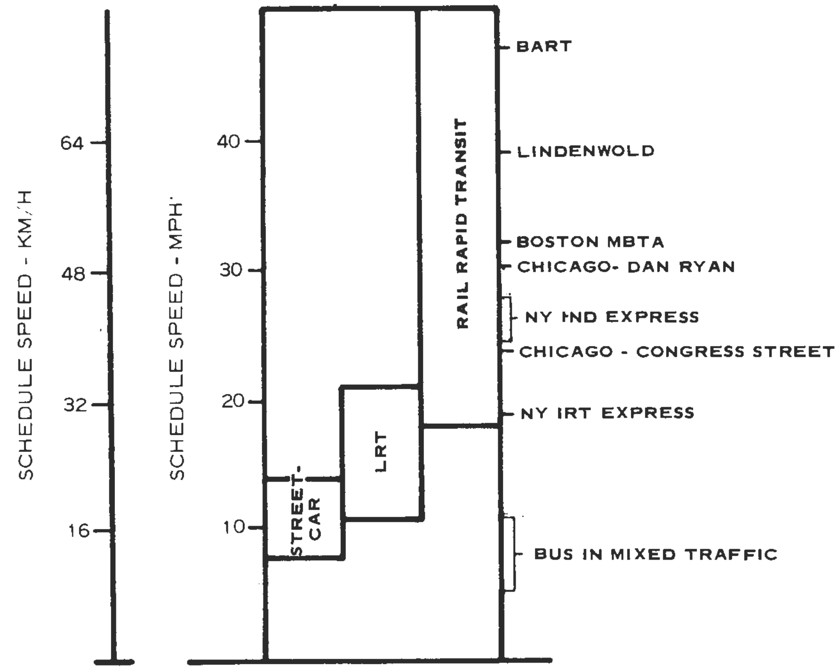


Figure 94. Range of LRT Schedule Speeds and Representative Schedule Speeds of U.S. Transit Service

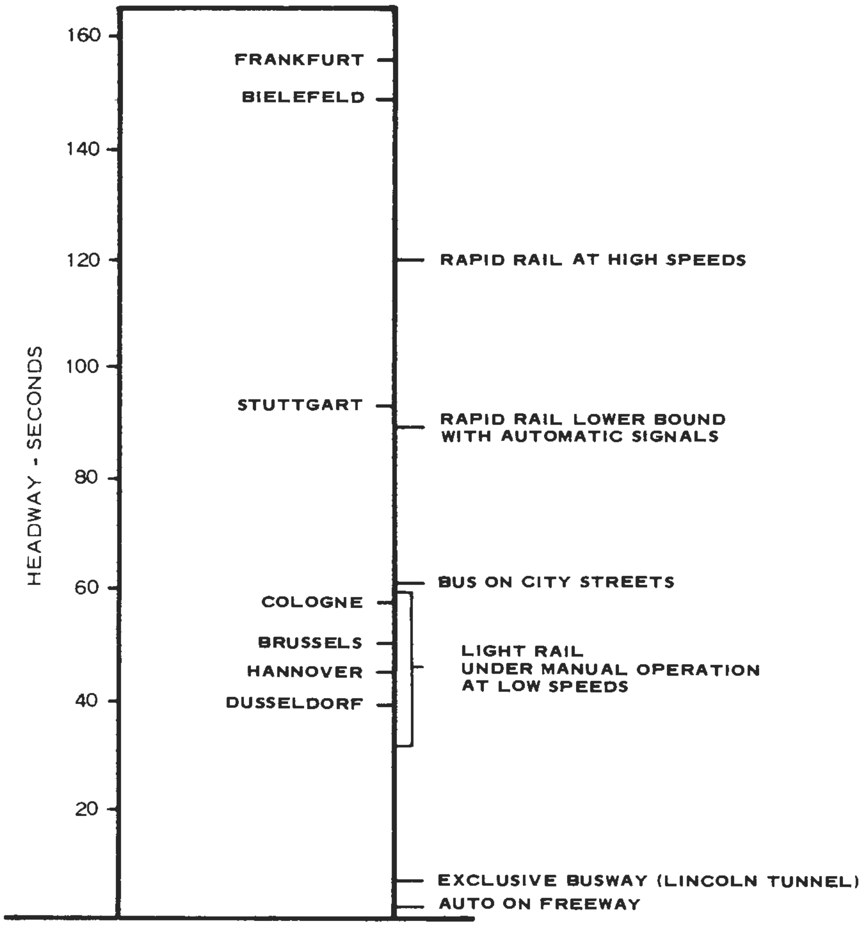


Figure 95. Observed Minimum Headways on Different Transit Systems and Modes

Capacity

The passenger carrying capacity of LRT is often the primary operational parameter of interest to planners. In particular, attention is focused on the relative carrying capacity of light rail systems vis-a-vis alternative modes. The seated capacity of buses on city streets will saturate in the range of 2,000 to 3,000 passengers per hour (pph). Express busways on reserved freeway lanes operating at headways as low as 37 seconds can handle 4,000 to 5,000 pph. If station stops are made periodically instead of a pure nonstop express service, the capacity is lower. At the upper extreme, peak hour volumes of 25,000 passengers per hour have been reported on the I-495 contra-flow bus lane approaching the Lincoln Tunnel at New York from New Jersey with headways of only six seconds and no station stops until reaching the Port Authority Terminal.[45] Carrying capacities in this range are not common for most bus operations. The Lincoln Tunnel values are realized mainly because this system utilizes an extremely large bus terminal for passenger boarding and alighting. This facility permits simultaneous boarding/alighting of many buses, thereby preventing the queueing of arriving buses.

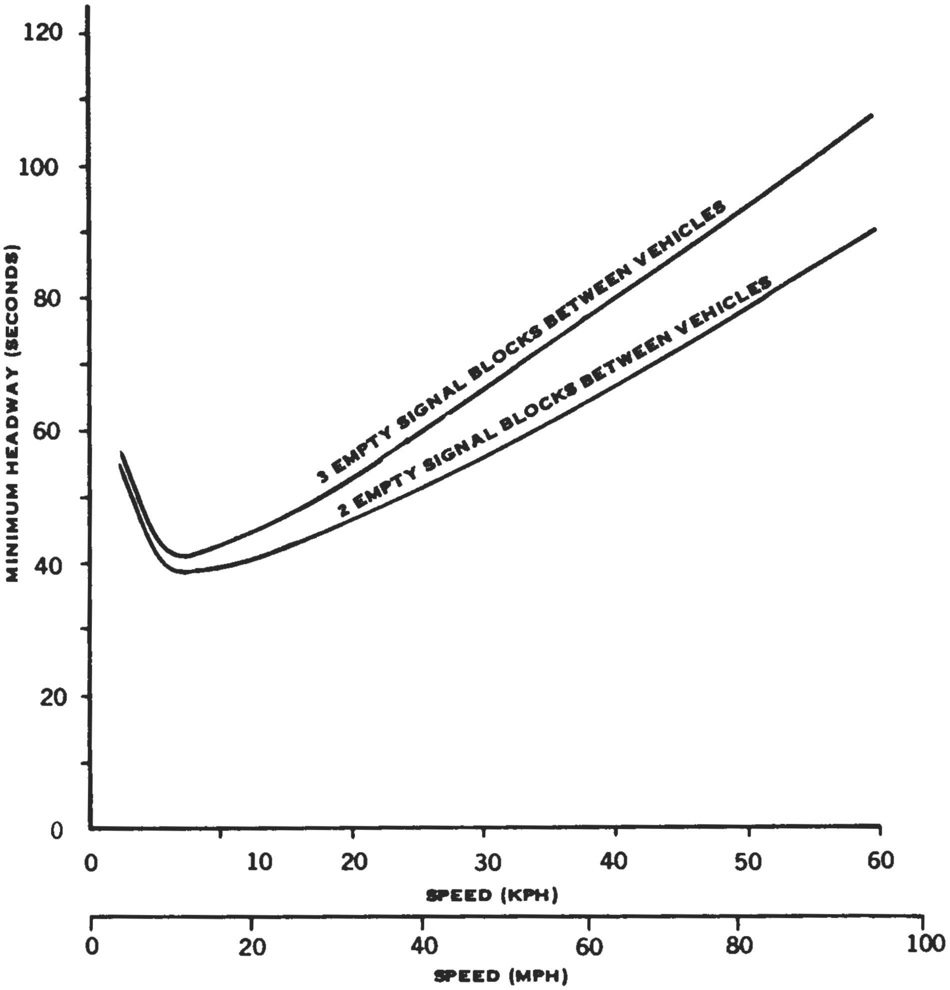


Figure 96. Effects of Operating Speed on Minimum Headways

As with all other fixed guideway transit, the passenger carrying capacity of LRT depends on vehicle size, train length and headway. However, the realizable LRT capacities also depend on design and policy considerations which reflect specific local constraints of at-grade operations and type of right-of-way. LRT train consists are usually limited to a maximum of three or four cars. There are several reasons that longer trains are not used. The major one is that longer consists could not operate on city streets without simultaneously occupying more than one intersection when traversing short blocks. Other reasons for limiting the consist size include clearing at-grade intersections rapidly and the desirability or need to limit platform length at the stations. The Canadian light rail vehicle will be designed to operate in eight car trains, but that feature is not currently planned to be utilized in operation.

Headways for light rail systems can also vary. For operation under the control of a block signalling system, as is common in rail rapid transit, 120 second headways are typical. At these headways, a high speed LRT system operating on mainly reserved rights-of-way with three unit Boeing vehicle trains would have a line capacity slightly in excess of 6,000 seated and 19,000 total passengers per hour. Under single vehicle manual operation at lower speeds, closer headways are certainly feasible. At 60 second headways, single Boeing LRV units have a capacity of 4,000 seated and 13,000 total passengers per hour.

It is not uncommon to find European systems with headways as low as one minute along sections of track which are shared by a number of different routes. Total capacities (seated plus standing) as high as 20,000 passengers per hour can thus be noted regardless of the mode of operation, i.e., streetcar or LRT. For example, in the central area of Basel, one section is shared by six different lines with a capacity of 14,500 passengers per hour at 60 seconds headway. Table 29 gives maximum line section capacities for selected light rail systems.[46] Fairly large hourly capacities are shown, but there is little correlation with the percent of private right-of-way. As suggested above, the streetcar operations, largely on shared rights-of-way, may match the carrying capacity of the higher performance of largely private right-of-way LRT systems. However, there is a significant difference in speed and reliability which affect both service quality and performance efficiency. The higher speed and reliability of the LRT will result in more passenger-miles per hour and per employee than is possible with the lower speed streetcar type of operation.

Many existing LRT lines operate with peak hour volumes as low as 2,000 persons. New lines projected to operate at such low volumes cannot be easily justified, even if low cost rights-of-way were available. In most cases, LRT is designed for peak hour volumes of 4,000 to 10,000 persons, but the mode is capable of serving up to 20,000 persons per hour.

Table 29. 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.

Such volumes usually occur on the network sections on which several routes converge. For volumes above 10,000 persons per hour, special operational measures are usually necessary, such as simultaneous stopping of several vehicles, fast fare collection and tight schedule control along routes.

As an intermediate capacity system, LRT overlaps the application areas of buses operating on exclusive bus facilities, and automated light guide transit systems. The intermediate range, particularly between peak hour volumes of 4,000 and 14,000 passengers per hour, offers significant application potential in both medium and large urban areas throughout the United States.

Safety

Except for conditions arising from operation in shared and semi-exclusive rights-of-way (categories B and C), the safety aspects of LRT operation might be expected to be similar to those of conventional rail transit. That differences exist in the safety environments experienced by these two rail transit modes must be recognized in planning. Maintaining the safety of operations in non-exclusive rights-of-way should be recognized as a significant aspect of LRT system design. Particular care is required in addressing the safety aspects of at-grade operations in shared or reserved rights-of-way, at intersection crossings, and at street level platform stations. While it is clear that these safety issues do not arise in the fully grade separated right-of-way of rail rapid transit, the differences with the safety of streetcar operations are less obvious. Since modern LRVs are intended, for the most part, to operate faster and frequently, the segregation of other vehicular traffic and pedestrians from the transitway becomes a more demanding design challenge than in the earlier days of streetcar operations.

However, there is a scarcity of applicable historical data to help describe the safety of modern LRT operations. Applicable American data is insufficient to develop significant conclusions, while the data available from West European LRT operations needs to be interpreted to render it suitable to the different transit operations and street/highway traffic practices of the United States. For example, data is available for the old New Orleans streetcar operations (Table 30). At this system, as at the Shaker Heights LRT operation, the recent safety record involves mainly minor incidents without fatalities. But the vehicles, the track and the operators are not representative of what would be expected in modern LRT practice. The data shown in Table 30 are therefore, at best, indicative of the type of hazards arising in LRT operations and not of the projected safety statistics or of the severity of mishaps.

The New Orleans cars have only pneumatic brakes (no magnetic or dynamic braking), and the traffic engineering at grade crossings is not advanced. This system operates at low speeds and almost entirely on a reserved boulevard median strip. Over eighty percent of accidents reported occur at intersections, and about two-thirds of these involve left turns.[47] Prohibition of left turns at light rail intersections thus offers the promise of reducing accidents significantly.

Accident data from the San Francisco Muni for 1974 indicate streetcar accident rates per mile are 40 percent higher than those for buses.[48] Data from The Hague indicate a 56 percent higher streetcar accident rate, corroborating the Muni experience.[49] However, due caution must be exercised when examining these statistics. The rates cited include onboard accidents. Hence, it is to be expected that the larger light rail vehicles carrying more passengers than buses would incur more such accidents per vehicle mile. Another factor hidden in the above data is the operation of the different modes. The light rail vehicles and the buses to not operate necessarily in areas of equal congestion. Hence the exposure rate to potential accidents is not the same.

Table 30. New Orleans 1974 Accident Data

Type	Reported Incidents	Frequency (percent)
Light rail vehicle and auto turning left in the same direction	74	38
Light rail vehicle and auto at right angles	44	23
Light rail vehicle and auto turning left in opposite direction	10	5
Sideswipes	11	6
Derailments	17	5

Because applicable statistics are scarce, grade crossing safety *forecasts* for future high performance LRT systems can only be formulated in fairly crude fashion at this time. Safety *goals* for future LRT systems could be *proposed* by interpretive extrapolation from existing safety statistics of railroad at-grade crossings. These goals could then be met by a combination of technology and strategies to control the conflicting movements of LRT vehicles, automobiles and pedestrians. The direct relevance of the railroad crossing experience to planning of LRT facilities is undoubtedly open to question. The speeds of the railroad and LRT are not necessarily the same, and the operating frequency of the transit system certainly would be much higher than that of the railroad. The more frequent exposure of the driving public to an LRT operation may by itself mitigate the accident rate suggested by the railroad statistics drawn, for the most part, from infrequent daily operations. Also, the higher braking rates of light rail vehicles and improved crossing geometrics may significantly improve the accident rate as compared with that observed for railroad crossings. In any event, it does not appear that particularly relevant numerical conclusions regarding the safety of LRT crossing should be drawn from available U.S. railroad crossing statistics.

The safety statistics of existing LRT operations in this country, as discussed before, are equally lacking in relevance for modern LRT installations. Until a detailed and interpretive (to the conditions in the U.S.) analysis of European safety data 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 the infrequently used existing railroad crossings. These goals could be approached by:

- Complete grade separation for LRT crossings of heavily travelled highways, perhaps for those carrying more than 5,000 automobiles per lane per day
- Restriction or elimination of automobile left turn movements at the remaining intersections, when feasible
- LRT speed reductions through intersections (it is difficult to project the desirable speed range, but a rate close to prevailing street speeds might prove advantageous)

- Installation of occupancy detectors to ensure positive slowdown and stop commands to the light rail vehicle when the intersection is occupied by stalled vehicles or pedestrians
- Installation of positive crossing control devices, such as gates, to restrict automobile and pedestrian access through the intersection shortly before and during the passage of the LRT. Railroad experience suggests that gates are twice as effective as flashing lights and six times as effective as stop signs in reducing hazardous events at intersections.[50] However, the appearance, noise, and operation of frequently located railroad type gates could cause adverse environmental and community reaction at some locations. The gates should therefore be used selectively, i.e., where traffic speeds are high and surroundings would not be seriously affected.*

SELECTED LRT ENVIRONMENTAL IMPACTS

INTERIOR NOISE LEVELS

Noise levels can be measured and described in numerous ways. It is common to describe the noise inside or outside transit vehicles in dBA-weighted decibels, which relate the noise level to the sensitivity of the human ear in a simple one number index. Figure 97 indicates the dBA level for interior noise levels in typical transit vehicles along with some common noise sources to provide a subjective correlation. In general, the inside noise level should be between 65 and 75 dBA to permit comfortable conversation.

Figure 97 shows that noise levels in transit vehicles vary widely. Typical interior bus noise levels range from slightly below 70 dBA up to 78 dBA while cruising. This is comparable to noise levels inside many automobiles.[51] When accelerating under full power, however, the inside noise level in an 8-cylinder bus can approach 95 dBA.[52] The Milan Transport Authority has reported values ranging from 67 to 84 dBA for 8-axle articulated light rail cars which have wheels with a layer of rubber insulation.[53] For the PCC cars, values of 77 to 80 dBA have been reported on the newer cars with levels up to 5 dBA greater on older cars.[54] Recent test data on the Boeing cars showed an interior noise level of less than 69 dBA at 40 mph, remaining under 70 dBA at speeds up to 70 mph.[55] (These data suggest that the Boeing vehicle is exceptionally quiet.)

EXTERIOR NOISE LEVELS

Exterior noise is important because of its community impact. From this point of view, rail transit vehicles range from being significantly worse than buses to significantly superior. Noise levels measured at 50 feet from the track range from 70 to 80 dBA for modern, noise engineered systems, to as high as 95 to 100 dBA for the 1900 vintage Chicago elevated system.[56] For both light rail and rail rapid transit systems, track and wheel conditions are major factors in determining noise level. Better maintained systems can have noise levels superior to buses and some automobiles, while on poorly maintained rapid transit systems, the noise level can become quite bothersome.[57] Exterior noise levels of a variety of vehicles are illustrated in Figure 98.

---

*In some states, e.g., California, gates may be required as a matter of policy by the agency responsible for safety (Public Utilities Commission or equivalent).

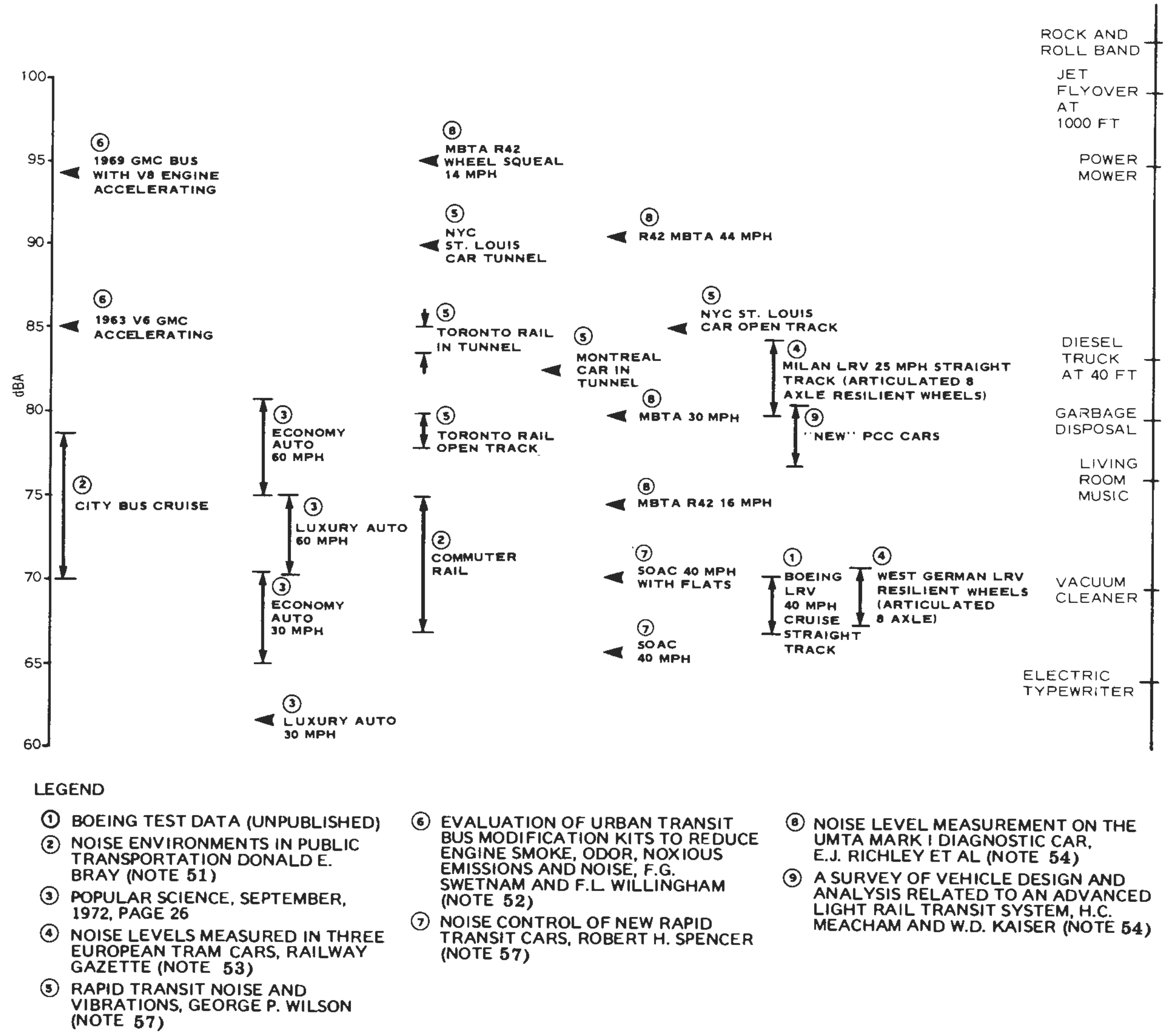


Figure 97. Interior Noise Levels

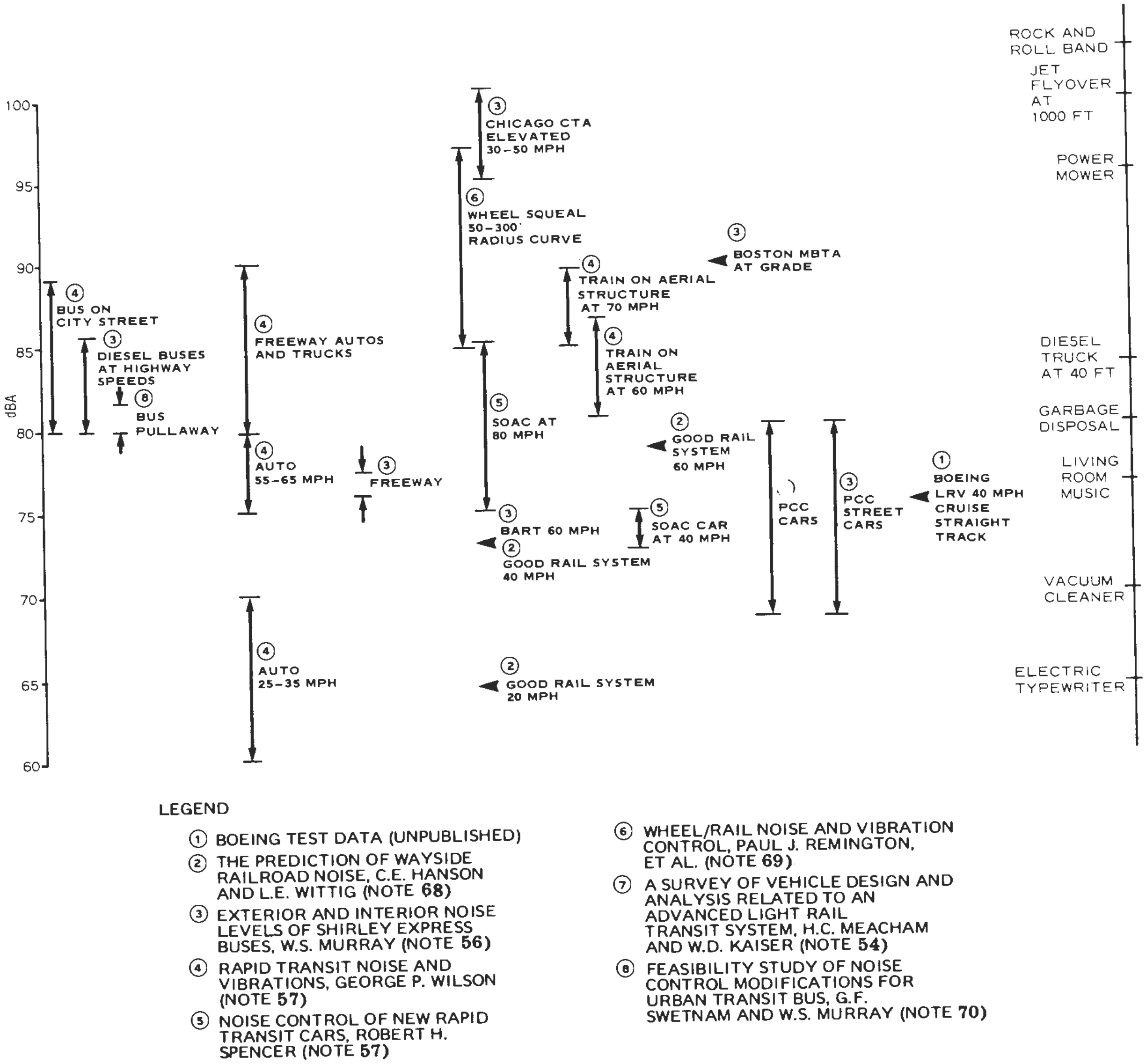


Figure 98. Exterior Noise at 50 Feet dBA

Wheel squeal is the most serious exterior noise problem for steel wheeled vehicles, remaining a problem on curves with radii up to 700 feet. This squeal is caused by metal sliding on metal as the wheel flange and running surfaces slide around tight radius turns. Wheel screech has been measured at 97 dBA at MBTA.[58] Other reports cite increases in noise on curves of 15 to 30 dBA.[59]

Resilient wheels incorporate a damping material between the wheel rim and hub to damp out the wheel squeal. Boeing tests with the Acousta-Flex wheel indicated substantial improvement; noise was reduced by 20 to 30 dBA.[60] Since metal to metal contact is minimal on straight track, resilient wheels have negligible impact on noise level on uncurved portions of the route. Commercial resilient wheels being used today include the Acousta-Flex wheel manufactured by the Standard Steel Company, the Bochum wheel sold in the U.S. by Penn Machine Company, the Krupp wheel (used by DuWag), and the SAB wheel. Tests on a 140 foot radius track with Acousta-Flex resilient wheels showed reductions of 20 to 25 dBA.[61] Values of 15 to 20 dBA reduction on curves are reported for the other designs.[62]

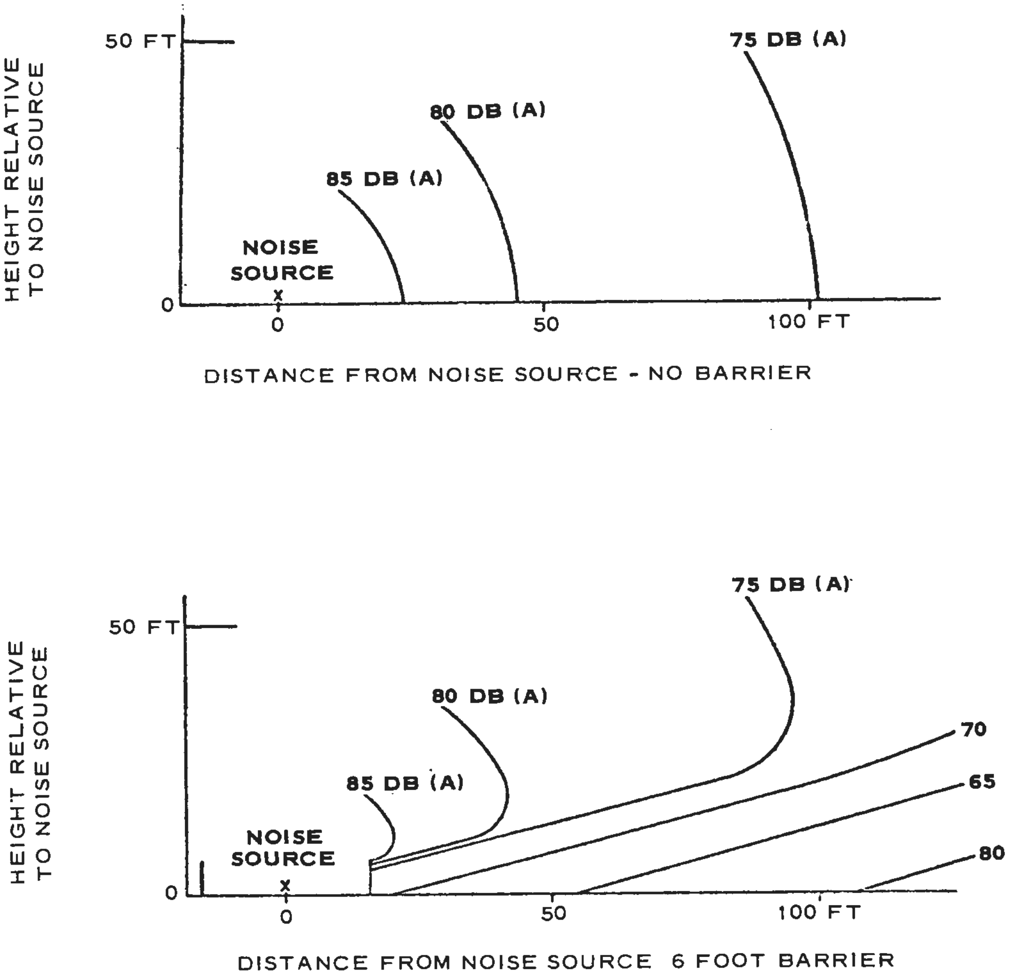
The use of lubricant (usually oil) on the inside surface of rails has also proved effective for reducing screech on curves. One method of lubrication is that found on the Cologne/Bonn system where an automatic track oiler has been developed.[63] This device, which cuts down on rail wear, is installed in the trackage wherever a problem is anticipated from train noise. It consists of an oil pump operated by a signal emitted by the passing train. The oil pump injects a small amount of oil through a series of horizontal holes on the inner side of the head of the outside rail just before a train passes. The surplus oil runs down the side of the rail head and drains into a small trough, from which it is returned through a filter for reuse. The installation of this particular lubricating equipment has cut down on the amount of waste oil spilled onto the ground and also on the maintenance required by lubricating devices. The oil consumption is such that filling is required only once every nine months.

In a related development at Zurich, near one of the storage yards where many complaints about noise were being received, a system of water lubrication was installed. A small amount of water released into a rail groove has proved to be an extremely effective way of controlling noise on track curves.[64]

Exterior noise levels also depend on vehicle speed. For example, noise levels at 50 feet from the Boeing LRV increase by 5 to 10 dBA as speeds increase from 20 to 50 mph.[65] Since this increase represents a significantly greater community noise impact potential, it is relevant in the evaluation of high speed operations on arterial streets. On the other hand, reduced vehicle speed is an effective noise mitigation technique for operations in noise sensitive areas.

NOISE EFFECTS ON LAND USE

The noise level standards promulgated by the U.S. Department of Transportation, Federal Highway Administration are summarized in Table 31. These standards provide a basis for assessing the order of magnitude of the cited transit noise levels, but local ordinances should be checked as well. For developed non-residential areas, transit noise not generally exceeding 75 dBA at the building front (approximately 50 feet for a major arterial right-of-way) would meet the standard. (The Boeing vehicle would meet this specification for speeds up to 50 mph.[66]) For noise sensitive areas, an effective means of reducing at-grade transit system noise by 8 to 12 dBA is to construct a four to six foot acoustic barrier adjacent to the track. The effect on noise of introducing a barrier wall in the vicinity of the transit alignment is illustrated in Figure 99. Note that transit noise at 50 feet is typically reduced from nearly 80 dBA to 65 to 70 dBA by this treatment.



THE SHIELDING TO BE EXPECTED FROM
6 FT. HIGH BARRIERS ALONG A TWIN-TRACK RAIL SYSTEM

Figure 99. Noise Abatement by Acoustic Barriers

Table 31. Design Noise Level/Land Use Relationships

Design Noise Level – L_{10}	Description of Land Use Category
60 dBA (exterior)	Tracts of lands in which serenity and quiet are of extraordinary significance and serve an important public need, and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose. Such areas could include amphitheaters, particular parks or open spaces which are dedicated or recognized by appropriate local officials for activities requiring special qualities of serenity and quiet.
70 dBA (exterior)	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals, picnic areas, recreation areas, playgrounds, active sports areas, and parks.
75 dBA (exterior)	Developed lands, properties or activities not included in the categories above.
55 dBA (interior)	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals and auditoriums.

Source: U.S. Department of Transportation PPM 90-2.

LRT AIR POLLUTANT EMISSIONS

Electric transit vehicles do not directly produce significant levels of air pollution. Their major contribution to air pollution stems from additional loads placed upon the power plants serving the system. This source can be physically removed from critical areas, and is potentially more readily controlled. Table 32 provides estimates for the emission factors for a variety of vehicles. The factors for electric vehicles refer to the emissions from a power plant burning fuel oil. The data are for an electric propulsion system delivering the same output horsepower as a diesel bus.

The range of values for diesel powered buses reflects significant changes in emissions characteristics of newer transit coaches and varying test conditions. Due to the nature of the diesel engine, different parameters are involved in producing emissions. Diesel engines run at higher efficiencies and temperatures using more oxygen than do light duty gasoline engines. Therefore, they produce less carbon monoxide (CO) and hydrocarbons (HC) and more nitrogen oxides (NO_X) on a per vehicle mile basis, than do light duty vehicles. One of the major parameters affecting these emissions is the fuel injection system. In 1970, a new fuel injector was introduced to help reduce diesel engine emissions.

Since an LRV can weigh over three times as much as a bus, its emissions on a vehicle mile basis would be several times as large as given in the table. However, the normalized approach shown in Table 32 provides a better estimate of the relative emission levels for equal productivity. For an electric vehicle, CO and HC levels are insignificant as are emissions of sulfur dioxide. The use of coal would reduce oxides of nitrogen to about a fifth of the level cited, but would increase sulfur levels and add significant particulate emissions.

Table 32. Air Pollutant Emission Factors* (grams per mile)

	CO	HC	NO_x
California Air Resources Board[1] tests of diesel bus	4.8	3.9	28.6
EPA heavy duty vehicle[2]	20.4	3.4	––
Argonne heavy duty vehicle[3]	32.5	––	––
EPA bus test[4]			
Arterial	15.0	3.8	––
Downtown	28.8	7.2	––
Department of Transportation[5]			
Express bus	10.5	11.7	––
Other	10.9	14.7	––
Electric vehicle of same[6]	0.0	0.2	6.3 (plus 3.3 SO_2)

*Emission produced at power plants and not in the streets.

Sources:

(1) California Steambus Project *Final Report.* January, 1973

(2) U.S. Environmental Protection Agency, *Compilation of Air Pollutant Emission Factors.* Second Edition, September, 1973.

(3) Argonne National Laboratory, *Handbook of Air Pollutant Emissions from Transportation Systems.* Prepared for Illinois Institute for Environmental Quality, December 1973.

(4) Communication with Mr. D. Syskowski, citing preliminary data for 1971 model year coach supplied by General Motors Corporation.

(5) D.B. Sanders and T.A. Reynen, *Characteristics of Urban Transportation Systems.* May, 1974.

(6) R.E. Bolz and G.L. Tyre, *CRC Handbook of Tables for Applied Engineering Sciences.* Assumes heating value of 147,000 B/gallon, power plant efficiency of 40% transmission line losses of 10%, and an oil fuelled power plant with fuel with 0.35% sulfur.

CHAPTER 8

COST CONSIDERATIONS

An up-to-date review of capital and operating costs for light rail transit is essential to evaluate this mode's economic viability. Costs are also key factors in assessing how LRT compares with other transit modes. To assist in these evaluations, the available capital and operating cost data for light rail transit are summarized here, and the basis for estimating costs for planning and analysis of alternatives is described.

No attempt has been made to obtain European facilities capital cost data, because construction cost information from the United States is readily available and directly applicable. Capital cost data from a number of authoritative U.S. sources have been cross-checked and correlated. A quantitative basis was derived for assessing the considerable impact of light rail operations and right-of-way characteristics upon system costs.

Operating costs based upon current experience of both European and American cities are presented. Most of the light rail systems in Europe today operate partly in mixed traffic and at low speeds. Statistical records do not segregate the various levels of light rail operation. Data for European systems must, therefore, be used with discretion in planning new LRT systems for U.S. cities. An approach is presented here which uses statistical data to project the cost impact of changes in operating characteristics. Mathematical models are used at times for O&M cost projections. The characteristics of such a model are briefly described to highlight the significant parameters affecting the costs.

The cost figures discussed are presented specifically to illustrate differences between alternative operating policies and transit modes. Neither the capital nor the operating costs of a transit system can be generalized, because varying site and facility conditions, labor agreements, regional structure and other factors have an impact on system costs. There is no alternative to basing definitive cost estimates on sound preliminary engineering which includes the assessment of right-of-way facilities and the projected operating characteristics. The unit prices, average costs per route mile and operating costs presented herein must, therefore, be used with discretion.

CAPITAL COSTS

The following basic cost elements are included as a matter of accepted practice in the calculation of transit capital costs.

DEVELOPMENT COSTS

The development costs of a transit project cover those activities required to confidently move from specifications generated in the definition phase to a point where adequate documentation exists to begin the detailed design and production of vehicles and possibly other vital electromechanical subsystems.

Since light rail transit principally involves the use of "off the shelf" technology, development costs should be minimal. There may be some investment in further testing of train control and communication systems. However, control equipment development costs are normally included in the suppliers' production cost. Since the Boeing and Canadian light rail vehicles, the only LRT equipment produced or about to be produced in North America is still considered to be in the development stage at this writing, some activity in further vehicle testing may be warranted. European operational equipment, e.g., the DuWag U2 car, would also require a minimum of pre-operational testing to establish compliance with American transit practice.

RIGHT-OF-WAY

While it is generally considered desirable to locate light rail lines within established rights-of-way to minimize displacement and community disruption, it is likely that there will be specific instances where insufficient right-of-way width is available. Additional right-of-way must be purchased in such instances; these costs must be charged to the total capital investment for the system. In some instances, costs may also be incurred in obtaining rights to operate in railroad rights-of-way. These operating rights, or air rights as applicable, must also be accounted for. Right-of-way for stations and parking facilities must be estimated as a separate item and can generally be determined on a cost per acre or cost per car space basis by applying average unit cost for commercial, industrial, or residential units being displaced. Where the proposed route impinges upon existing structures, the cost of their relocation is a major element of the right-of-way costs. In addition, the costs of relocating individuals displaced from their homes by construction must also be considered.

GUIDEWAYS

For light rail, as for the other guideway transit modes, the guideways constitute a major part of the total system costs. Guideway costs per route mile are difficult to generalize, because they are affected significantly by the route's vertical and horizontal alignments. The impact of subway, at-grade and aerial alignments is far more significant to costing than specific details of structural design and architectural concept. An adequate amount of site specific data is needed to establish these costs with reasonable certainty. Vertical and horizontal alignments must be established on the basis of urban design constraints and projected operations plans for the system.

Unit costs based on preliminary design sections may be computed for different categories of guideways, but the costs will vary substantially due to differences in site conditions and the construction process may, in some cases, alter significantly cost projections based on unit cost data only. If it is necessary to construct the guideway in a heavily congested area, the difficulties imposed by working around existing utilities and structures and by diverting traffic will immensely complicate the task and augment the cost..

The major guideway categories used in classifying costs are as follows:

- Aerial
- Underground
    - In shallow tunnels (cut-and-cover construction)
    - In mined or bored tunnels
- Surface
    - At grade on special rights-of-way such as railroad, median or freeway (off-street)
    - On embankments or in cuts
    - At grade (on-street).

Costs in each one of these categories may vary considerably depending upon specific off- or on-street conditions that would affect the detail design of the structure and the construction sequence. Figure 100 illustrates typical guideway sections for aerial, underground, and at-grade conditions for light rail and other fixed guideway transit modes.

Items in the unit costs for at-grade, on-street guideways include pavement removal, utility and drainage adjustment, base construction, trackwork and restoration of pavement. Unit costs for off-street guideways on an embankment or at grade include earthworks, subbase, drainage, trackwork, fencing and landscaping.

Items included in the unit cost of aerial structures include foundations, footings, columns, superstructure, drains, trackwork, utility adjustments, restoration of streets and landscaping.

Items included in the unit costs of underground sections include pavement removal, underpinning, maintenance and relocation of utilities, excavation, shoring and dewatering, concrete tunnel structure and trackwork. Alternatively, underground sections may involve hard rock or soft ground tunneling.

TRACKWORK

Trackwork costs include the acquisition and installation of track, including turnouts and crossovers. Unit costs may be developed on a per mile basis without a detailed track layout by assuming allowances for switches, crossovers and other special trackwork.

TRACTION POWER

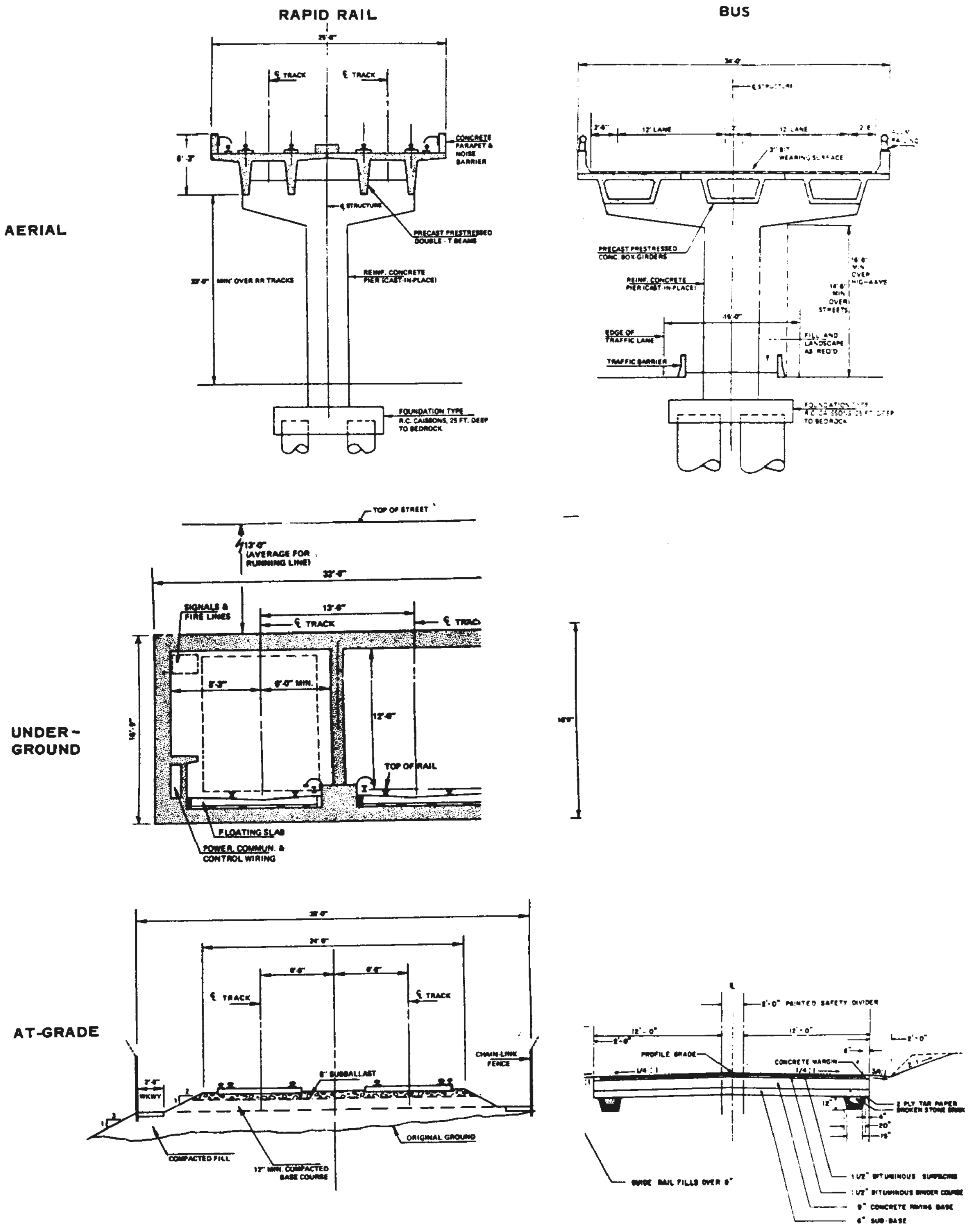
This item includes all costs involved in the supply of power to the vehicles. It includes the power supply system (either third rail or overhead), power distribution and substations. Traction power costs are readily estimated on a lineal unit cost basis.

CONTROL AND COMMUNICATION SYSTEMS

Cost elements of the control and communications subsystems may include signal light preemptive devices, automatic train protection, two-way radio, a public address system, emergency telephones, surveillance, and some level of central control capability. Since they will have a significant impact upon costs, the required degree of sophistication of these subsystems should be determined by detailed systems analysis. For preliminary planning, communications and control costs are generally expressed on lineal unit cost basis with a per vehicle allowance for any required onboard equipment.

STATIONS AND INTERMODAL FACILITIES

The station costing procedures follow a pattern similar to that used for guideways. Parking requirements are usually estimated separately and added to stations with park-and-ride facilities. Stations may be categorized for purposes of costing into several types which cover virtually all sites and passenger volume situations. Typical design drawings showing basic circulation patterns, platform lengths, and other basic requirements must be developed for each station classification. Costs can then be derived using order of magnitude estimating procedures.



00. Typical Guideway Sections for Alternative Transit Modes Comparison of Sections

Major effects on station costs are the vertical position of the station and its location. Typical station sites and vertical locations are listed below:

- At grade in the median of a street with or without a shelter
- At grade alongside a railroad, freeway or street with track and platform at grade and a mezzanine above or below track grade
- Aerial in the protected median of an arterial street with guideway and platform aerial and a mezzanine area above the platforms
- Aerial alongside a railroad, freeway or street with guideways and platform aerial and access area at grade
- Subway with direct street access to platform level
- Subway with separate mezzanine and platform levels.

A major determinant of a station's cost is its physical dimensions. Expected passenger volumes, fare collection techniques and train composition have a direct effect on station physical dimensions. For purposes of costing, stations can be classified in three categories described by passenger volumes:

- Low volume shelters or stations handling under 1000 passengers per hour in the peak hour
- Medium volume shelters or stations handling 1000 to 4000 passengers per hour in the peak hour
- High volume stations handling 4000 or more passengers per hour in the peak hour.

Station costs are also influenced by auxiliary equipment requirements; location of platform (side or center); elevation of platform (high or low); security requirements and architectural treatment. A lump sum cost can be established for each station type for planning purposes.

MAINTENANCE AND STORAGE FACILITIES

Maintenance and storage yards and shops, central control housing facilities, and any special administrative facilities constitute the principal support facilities for a light rail system. Reliable cost data can be established for these facilities. The principal items of construction for maintenance and storage facilities include site preparation, earthworks, drainage and utilities, buildings and shops, shop equipment, cleaning equipment, parts storage, staff facilities, yard equipment, yard lead structures, yard control trackwork, electrification, landscaping, and security. These costs can generally be estimated from conceptual layouts.

VEHICLES

Light rail vehicles are currently being produced in Europe and North America. A range of cost data is available for estimation purposes, but should be used with care because of inflation uncertainties. Variability in the sophistication of various vehicle subsystems also contributes to the spread of these cost data.

To help in the interpretation of vehicle costs, it is often useful to normalize data for various vehicles with respect to some of their common features, such as vehicle weight, number of seats or floor surface area. However, vehicle cost per seat or cost per passenger are not well suited for cost comparisons, because seating configurations and loading restrictions vary greatly from system to system. The best units of comparison are costs per square foot or costs per unit weight, with the former providing the best correlation of available cost data.

It is significant that over the past few years vehicle costs have been escalating at a far greater rate than most other capital cost items. 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. The increases represent more than the effects of inflation. As transit operators have demanded improved performance, greater passenger comfort and improved maintainability of the newer equipment, the number, complexity and cost of the various components carried onboard the LRV have increased. The larger increases in costs as stated in terms of dollars per square foot of floor space are indicative of this trend.

The Boeing light rail vehicles currently being produced for Boston have a contract price of approximately $330,000 per unit.[71] The vehicles being produced for San Francisco without air conditioning and with a different seating configuration have a contract price of approximately $300,000 per unit (for the San Francisco system).[72] Based upon this figure, the San Francisco vehicles cost $500 per square foot.

The Canadian Urban Transportation Development Corporation (UTDC) is presently developing a smaller 51-foot non-articulated, 4-axle light rail vehicle. The Toronto Transit Commission will purchase 200 of these vehicles at an estimated cost of $363,000 each in 1975 dollars.[73] UTDC plans to manufacture unpowered trailer vehicles which will be offered at a cost of approximately $100,000 less than the powered cars. The Canadian light rail vehicle has a cost of approximately $880 per square foot based upon the above price. It is expected that future orders will cost more, probably as high as $490,000 for vehicles delivered in 1979.

European cars of comparable complexity to the American products sell for similar amounts. Thus, new DuWag 8-axle M cars are being constructed for Bielefeld, Germany at a cost of approximately 1 million marks ($426,000),[74] or approximately $5.70 per pound or $620 per square foot. The DuWag U2 cars bought for Edmonton, Canada, are priced at $540,000 when escalated to 1977 costs.

Future procurements for Boeing vehicles are likely to bear a significantly higher price tag than the San Francisco and Muni purchases due to inflationary pressures and an overall reassessment of production costs in the light of the experience gained from the San Francisco and Boston procurements. As the Boeing Company continues to gain experience on its LRV, it is quite conceivable that the future cost of this vehicle may reach $700 per square foot.

Lower cost vehicles are available on the market. Tatra T3 vehicles, for instance, whose design derives from the PCC car, are reported to cost in the range of $100,000,[75] but this price cannot be confirmed since the vehicles do not operate in Western Europe and recent manufacturer's bids are not available. Another recent version of the PCC car, at The Hague, was priced at $174,000 in 1975.[76] Stated in terms of cost per unit floor area ($627/square foot), or weight ($4.88/pound), the cost of this vehicle does not appear to be out of line with that of the larger vehicles. In comparing the costs of the smaller and cheaper cars with the costs of modern light rail vehicles, it might be noted that the former are lighter (as low as 60 percent of the weight of the heavier Boeing LRV, for instance), carry much less sophisticated equipment, offer inferior passenger comfort and accommodations, and have considerably lower driver productivities. As the manufacturers of these cars have moved to larger vehicles to improve driver productivity, their costs have increased accordingly.

FEEDER SYSTEMS

Light rail and other types of fixed guideway transit will have costs associated with provision of feeder services to the fixed guideway stations. These costs, including vehicles, shelters, communications equipment and other support facilities, must be considered when comparing one transit alternative with another.

ENGINEERING AND ADMINISTRATION

This item includes all costs incurred by the agency in the course of implementation of the transit facility. Direct costs in connection with administration of the project during its design and construction phases will amount to from three to five percent of the total capital cost. Costs of design, detailing and construction supervision will amount to approximately ten to twelve percent of all capital cost. An average of approximately fifteen percent of the total capital costs should be allowed to cover all engineering and project administration costs.

CONTINGENCIES

In all conceptual estimates there are unpredictable costs which may arise due to the preliminary nature of the design and the early state of project definition. The basic purpose of a contingency allowance is to provide for these unpredictable items of cost at the time of estimate. For order of magnitude cost estimates of the type described herein, a contingency of 25 to 35 percent of direct capital costs should be applied, depending upon the degree of preliminary planning anticipated. An allowance for inflation is not included in these figures.

RANGES OF UNIT CAPITAL COSTS

Capital cost data from three independent sources are compared in Table 33. The first column summarizes unit costs developed by De Leuw, Cather & Company for a specific project in 1974.[77] Because actual alignments were under consideration and site conditions were known, the range of order of magnitude cost shown for each major item of construction is relatively narrow.

The second column summarizes ranges of unit costs for construction of light rail systems presented by George R. Beetle in a paper delivered to the Transportation Research Board National Conference on Light Rail Transit in June, 1975.[78] Since the unit prices presented in this column are not site specific, the ranges are wider. The De Leuw, Cather cost ranges for aerial guideway and underground construction fall within the Beetle ranges.

A set of unit costs developed by Thomas K. Dyer, Inc. for UMTA's Office of Research and Development and reported in July, 1975, is presented in the third column of the table.[79] The Dyer costs present a wider range for aerial guideway costs and a narrower range for underground construction costs than shown by Beetle. The fourth column of the table summarizes similar unit cost data developed by Dyer for rail rapid transit during the same project for UMTA.

While there are differences between numbers in specific categories, the overall cost picture which emerges from these separate cost estimates is remarkably similar. In general, the costs in the first column which were obtained for a specific application tend to have a narrower range than the Beetle and Dyer figures which were meant to be general "rules of thumb." There is significant variation in the areas of electrification and command and control. Since the cost of electrification depends primarily on the number and length of trains operating over 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

Table 33. Comparative Unit Capital Costs for Light Rail Transit and Rail Rapid Transit (RRT) (In Thousands of Dollars)

Cost Element	De Leuw 1974 LRT*	Beetle 1975 LRT**	Dyer 1975 LRT***	Dyer 1975 RRT****
Guideways (per mile)				
Dual aerial	6,200-8,000	10,000-15,000	2,820-17,150	2,800-17,150
Dual at grade (grade separated)	3,000	2,000-5,300	1,000-2,430	1,150-3,780
Dual at grade (grade crossing)	1,000	340	500-1,000	–
Dual underground	24,000	18,000-35,000	29,130-33,730	29,130-33,730
Trackwork (per mile)	900	540	750-1,000	750-1,000
Stations				
Aerial } medium to high passenger-volumes	1,300-2,100	5,000	190-4,560	700-5,160
At grade	1,500-1,800	–	2,770	350-4,150
Underground	6,500-12,500	5,000-15,000	440-7,560	870-8,000
Low level platform } low and medium passenger-volumes	60-120	75	20-60	–
High level platform	–	110	–	–
Traction Power (per mile)				
Third rail	1,800	–	–	700-850
Overhead wire	–	490	1,100-1,300	–
Controls				
Block (per mile)	1,300	190	210-410	690-2,650
Grade crossings (per crossing)	60	25-100	50-200	–
Maintenance Facilities (Per Vehicle)	100	60	126-454 (assuming 100 vehicles)	80-281 (assuming 100 vehicles)
Vehicles (each)	350-500	450	320	350
Engineering and Administrative	15%	15%	15%	15%
Contingencies	25%	25%	25%	25%

*Reference 77
**Reference 78
***Reference 79
****Reference 79

the high figures would be more representative. The De Leuw, Cather figures for command and control assume a highly sophisticated automatic block system with a significant provision for central traffic management. The other figures are more representative of a "bare bones" block safety system with widely spaced blocks and no central monitoring capability. Vehicle costs in all cases may be somewhat on the low side in view of recent manufacturers estimates as discussed previously.

The variations in 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 the three independent sources lends credence to the use of these data for estimating purposes. However, it must again be cautioned that use of such data for planning is no substitute for actual field investigations and engineering analyses which would provide more accurate and narrower ranges of unit costs as illustrated in the first column of Table 33.

IMPACT OF OPERATING AND RIGHT-OF-WAY VARIATIONS ON CAPITAL COSTS

Comparison of the LRT and rail rapid transit unit cost ranges shown in Table 33 shows relatively little or no difference between most of the major items of construction. Light rail capital costs depend primarily upon certain characteristics of the system. If the design is for a predominantly grade separated light rail system with sophisticated train control and elaborate station facilities, relatively little difference will be found between the cost of LRT and the cost of conventional rail rapid transit. If the design is more austere with alignments in street medians, at-grade crossings, manual operation, few sophisticated train safety controls and simple passenger shelters, light rail transit costs show a considerable competitive edge.

To illustrate, six alternative systems were costed using the independent cost ranges summarized in Table 33. The six hypothetical light rail systems are summarized below:

- *System 1* (complete grade separation)
  100 percent underground
- *System 2* (complete grade separation)
  20 percent underground
  20 percent elevated
  60 percent at grade; grade separated crossings
- *System 3* (partial grade separation)
  20 percent underground
  20 percent elevated
  20 percent at grade; grade separated crossings
  40 percent at grade; at-grade crossings
- *System 4* (partial grade separation)
  100 percent at grade; grade separated crossings
- *System 5* (complete at grade)
  100 percent at grade; at-grade crossings; existing railroad right-of-way
- *System 6* (complete at grade)
  100 percent at grade; at-grade crossings using existing railroad right-of-way and upgrading track.

For grade separated sections of the above systems, full two-level stations compatible with that type of section, third rail electrification and block signalling were assumed. For non-grade separated sections, simple shelters, overhead electrification and at-grade crossing protection without block headway regulation were assumed. An exception was System 4, for which grade separated construction was assumed in conjunction with simple shelters, overhead electrification and simple signalling more commonly associated with operations with grade crossings. Shelter or station spacing was assumed to be one per route mile, and fleet size was apportioned on the basis of three vehicles per route mile. In addition, costs per route mile for a comparable rail rapid transit system were estimated for Systems 1 and 2 using the Dyer unit cost data. The results of the above computations are illustrated graphically in Figure 101.

For System 1 which is entirely underground, the median costs were $58 million per mile for LRT versus $57 million per mile for rail rapid transit. Similarly for System 2 which is completely grade separated and only partially underground, the median costs were $23 million per mile for LRT versus $29 million per mile for rail rapid transit. This comparison dramatically illustrates that for comparable fully grade separated, high performance design, there is relatively little difference in cost per route mile between light rail and rail rapid transit.

Realistically, light rail transit costs on a system-wide basis are likely to average somewhere in the range between $15 million and $30 million per mile as for System 3, which includes a combination of elevated, underground and at-grade construction.

Significant cost savings are possible by exploiting the ability of LRT to operate totally at grade along streets or existing railroad rights-of-way. For Systems 5 and 6 with simple shelters and at-grade crossings, costs as low as three to eight million dollars per route mile become achievable.

CAPITAL COSTS COMPARISON

There have been no light rail projects constructed in the United States* in recent years for which actual capital costs can be shown. However, there have been several rail rapid transit projects which serve to illustrate the correlation between the hypothetical costs per mile discussed above and actual construction costs. The above analysis illustrated that for a similar set of operating and right-of-way conditions, the costs of light rail and rail rapid transit are not dissimilar. Thus, a review of rail rapid transit systems on a cost per mile basis is useful.

Figure 102 illustrates (symbolically with a dot in lieu of the actual cost spread experienced during the life of each project) the cost per route of sixteen rail rapid transit projects which have been constructed in North America since 1945.[80] To illustrate the impact over time of construction cost escalation on these projects, the *Engineering News-Record* construction cost index, a measure not used for actual cost estimating but only as a yardstick for establishing preliminary cost ranges, has been plotted on this same exhibit to indicate the effects of inflation.[81]

---

*The project at Edmonton in Canada is the only new LRT construction in North America in recent years (excluding, of course, improvements at San Francisco and elsewhere). At Edmonton, capital costs for the 4.5 mile line, exclusive of rolling stock, are projected at $56.2 million, averaging $12.5 million per mile. This figure includes the effects of inflation to 1978 when the project would be completed. This line includes a one mile segment underground which, as pointed out, tends to skew the costs toward the high end of the scale. The tunnel segment is estimated at $37 million and its two underground stations at $8.7 million. The remaining 3.5 miles of at-grade line average $3.5 million per mile. This is at the low end of the scale, because the line is being built on an existing railroad right-of-way.

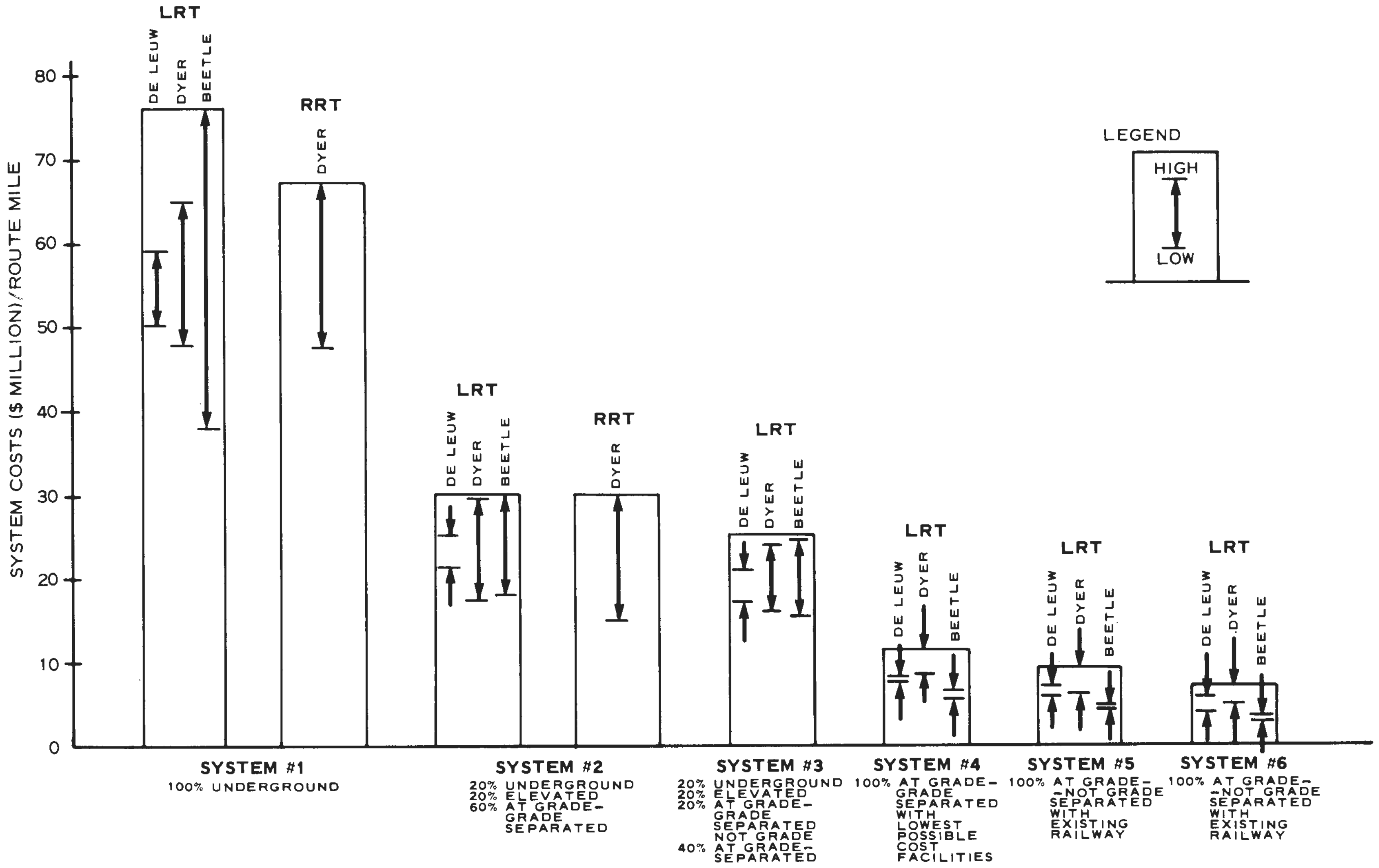


Figure 101. Impact of Operating and Right-of-Way Characteristics on Capital Costs

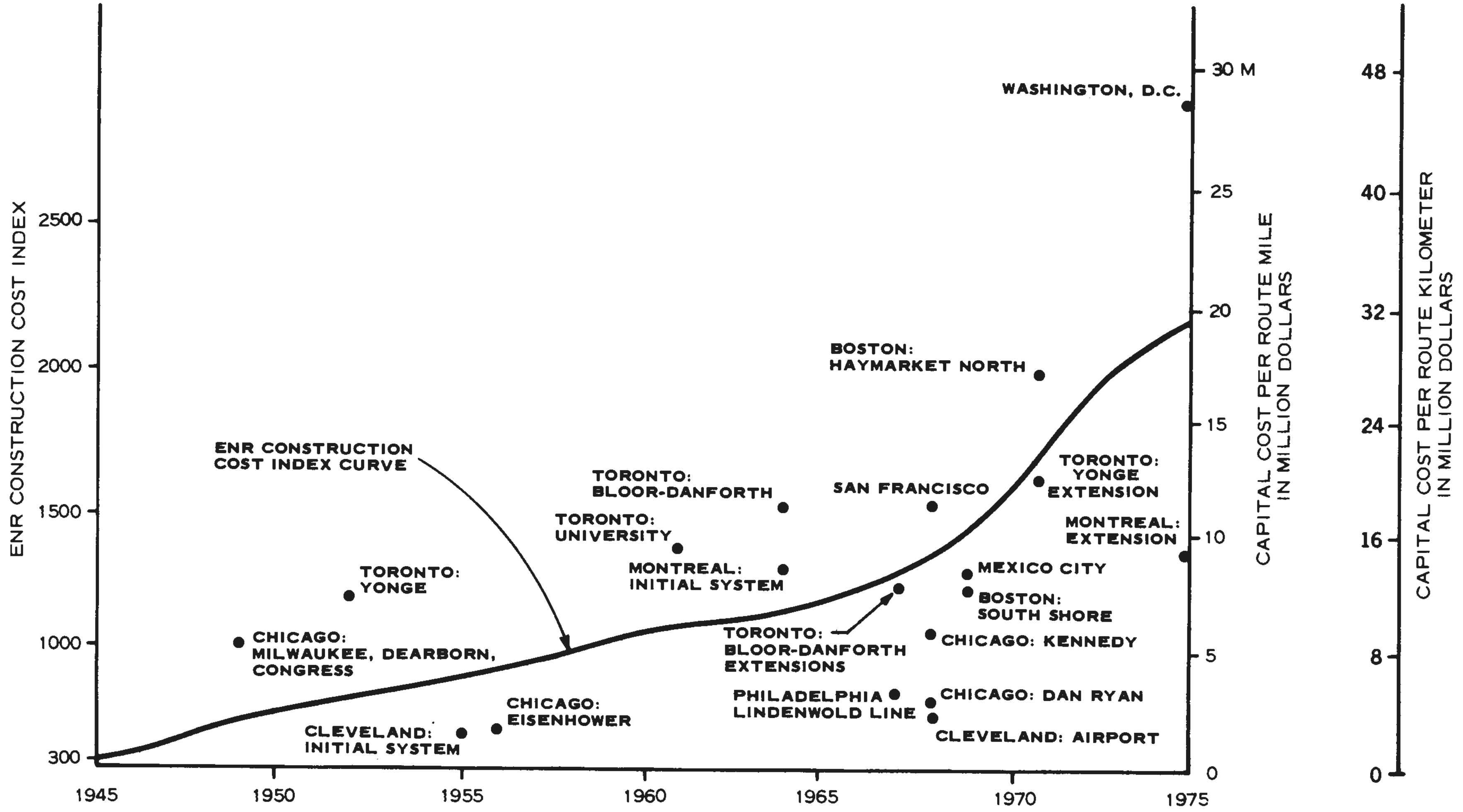


Figure 102. Historical Trends in Capital Costs for Rail Transit Projects

Several of the projects shown were implemented with the LRT philosophy of using railroad and freeway rights-of-way. The graph illustrates that these projects were generally completed at much lower costs per route mile than conventional rail rapid projects, because they involved minimal costs for right-of-way, earthworks, and crossroad structures. For instance, the initial sections of the Cleveland transit system were constructed in 1955 predominantly along a railroad right-of-way at a cost per mile significantly less than the Chicago and Toronto lines constructed some years earlier. The cost per mile in 1956 for the rail route in the median of the Eisenhower Expressway in Chicago was comparable to that for the initial Cleveland system.

The Lindenwold Line was constructed on an existing right-of-way in the late 1960s at a cost of less than $10 million per mile. This cost was less than half the cost per mile of the Bloor-Danforth extension in Toronto constructed during the same year principally as cut-and-cover tunnel under an existing street. The Cleveland Airport extension partially on a railroad right-of-way and the Kennedy Expressway extension in Chicago, both constructed in 1968, cost less than $10 million per mile. This cost was less than half the cost per mile of rapid transit projects constructed in Boston, Mexico City, Toronto and San Francisco during that same era.

By shifting the *Engineering News-Record* curve downward, the relationship over time between the Cleveland routes following railroad rights-of-way, the Chicago routes in the medians of expressways and the Lindenwold Line can be shown. Similarly, by shifting the curve upward, the relationship between the Dearborn routes in Chicago; the Yonge Street, University Avenue, and Bloor-Danforth routes in Toronto; the Washington Metro system and other conventional rail rapid projects with extensive tunnel can also be seen.

OPERATING AND MAINTENANCE COSTS

The significant elements of operating and maintenance costs (O&M) are usually expressed in units of dollars or cents per vehicle mile or vehicle hour. (Certain lesser O&M cost elements, such as administrative costs, are independent of the operational statistics and may be stated in a different form.)

The operational fleet statistics are, however, directly related to the characteristics of the network and certain associated operating policies of the transit system. Therefore, when using available LRT O&M data from U.S. or foreign sources, it is significant to recall that the statistics reflect indirectly the operations on widely different on-street at grade, off-street and grade separated rights-of-way of the particular networks. The mix of operations has a pronounced effect on fleet size, fleet hours and other critical parameters to the estimating of O&M costs. Unless the projected LRT installation will have a similar mix of network elements and operating policies, the direct, indiscriminate use of O&M cost statistics may be misleading. To overcome these difficulties, a combined analytical, empirical costing approach is required. Unit costs may be developed for light rail operation in categories which conform mainly to American transit accounting practices.*

---

*Due to the wide interest in German transit operating practices, an account of O&M costing methods used by West German light rail transit operators is given in Appendix I.

COST ELEMENTS

Maintenance of Way and Structures

The operating accounts from LRT systems in North America and Europe provide the basis for developing estimates of this element of the O&M costs. For this element, the best correlation is obtained when costs are related to vehicle miles of travel rather than the system's miles of line. This suggests that trackwork maintenance, which relates directly to vehicle usage, accounts for a higher proportion of the total cost than the maintenance of the remaining basic structure.

Maintenance costs for support facilities are generally related to their initial cost. Each element of these facilities should require a certain percentage of the initial capital cost for annual maintenance. The percentage used to derive the annual maintenance cost depends on the sensitivity of individual items to weather exposure, wear and tear, etc. As a rule of thumb, the percentage of construction cost applicable to annual maintenance costs is as follows:

• Buildings	5 percent
• Yard approach structures	2 percent
• Yard trackwork	5 percent
• Yard electrification	3 percent
• Yard train control	3 percent
• Yard equipment	10 percent

The estimated maintenance costs for support facilities can then be prorated to the fleet size and a maintenance cost per vehicle can be developed.

The procedure used to derive the unit cost for maintenance of fixed electrical facilities is similar to that used for guideway maintenance. These costs correlate closely with vehicle miles travelled.

Station O&M costs include maintenance of escalators plus elevators; heating, ventilation and air conditioning; fare collection equipment; and illumination and electrical systems. For an average station, these items can be estimated on the basis of an annual lump sum. Such maintenance would be handled by the equipment manufacturer in accordance with industry practice. The remainder of station maintenance costs can be estimated on the basis of the number of manhours per year required plus supplies.

Total average station maintenance cost for medium volume light rail stations could run as high as $30,000 per year per station. Maintenance costs for simple island or curbside shelters are, however, nominal. This ignores costs associated with restoring damage caused by vandalism which varies widely and must be assessed for individual locations. Maintenance for station parking lots is commonly approximately $30 per car space per year, a cost which provides for periodic resurfacing, striping, car stops and illumination.

Maintenance of Vehicles

Rail vehicle maintenance costs are based upon data for operating systems in North America and Europe. The unit of measure generally applied is cost per vehicle mile of travel.

Power

The cost of energy necessary to operate an LRT is based on system-wide estimates of the energy consumed and the prevailing energy unit costs. Energy consumption can be categorized according to vehicle, station, storage and maintenance requirements.

Vehicular energy consumption is determined most reliably by actual measurements on existing systems. For planned systems, energy requirements can be determined by mathematical simulation. The simulation models in use consider basic vehicle characteristics (e.g., weight, frontal area) and operational factors (e.g., speed, acceleration, distance between stops, grade) to determine the energy consumed on various route segments. Using the average energy consumption per vehicle mile and the projections of annual vehicle miles, an estimate of total vehicular energy consumption can be made. Energy unit costs for existing transit systems vary widely; therefore, local rates need to be used in estimating.

Requirements at stations are estimated by determining the energy consumption required for lighting, air conditioning, heating, elevators and escalators.

Requirements of maintenance facilities are based on estimates of floor space and type of maintenance equipment required. Similar estimates are needed for the storage areas. Using these estimates, the energy required to heat, ventilate and light these facilities can be calculated. The electrical requirements for heavy duty maintenance equipment can be computed on a per vehicle per year basis.

Transportation (Operating Labor)

Two methods of correlating this element of O&M costs were considered. The first assumes a linear relationship between vehicle hours and operator hours. This approach implies that any changes in fleet size or annual mileage are spread uniformly throughout the day. The second approach assumes a linear relationship between operators and fleet size. This approach implies that the number of operators is primarily set by peak hour requirements when nearly all vehicles are in operation. Heuristic calibration against data from typical CBD oriented rail systems indicates that the second approach is superior. Consequently, estimates are based on numbers of operators in proportion to fleet size. Aside from the fleet size, the other basic factors entering into the calculation are the assumed average training of cars, the proportion of the fleet in maintenance at a given time, and the number of operators per train.

Fare collection policies have an impact upon manpower requirements for stations and vehicles. The sensitivity of total maintenance and operating costs to these policies is discussed elsewhere in this chapter. Labor costs associated with money collection, counting, control and communication systems, and security must also be included in the total operating labor estimate.

General and Administrative

This item includes most of the indirect costs associated with the operation of a transit system such as advertising, scheduling, customer information, insurance and safety, legal and accounting, operating taxes, and operating rents where applicable. The cost for this category is generally not based on an item by item estimate. An allowance can be made based on the other direct operating and maintenance costs. Information from operating agencies is helpful in this area. Although accounting systems seem to vary widely, 15 percent of direct costs seems appropriate for line-haul systems.

OPERATING AND MAINTENANCE COST MODEL

To assess the magnitude of impact of the various elements of unit cost pertinent to operation and maintenance of a project light rail system, mathematical models can be used.[82] The model described in reference 82 utilizes a combination of empirical data and analytical techniques. Figure 103 shows a block diagram of the model approach. Coefficients are input to the program to compute way and structure maintenance costs and costs of transportation not associated with the operators' wages. These coefficients are based upon historical data and unit pricing of major cost elements as described above.

Separate models are used to determine the input values for vehicle maintenance costs, operator assignment and energy consumption. Cost categories identified by the program correspond as nearly as possible to American Public Transit Association accounting and classifications to assist in calibration against industry sources.

A vehicle maintenance module accounts for major cost items, including body repairs, automatic doors, vehicle washing and cleaning, wheel grinding, window and seat replacement, and power collection brush replacement. A way and structure module estimates non-vehicle maintenance costs, including guideway and shelter, yards and support facilities, electrical, and other major cost items discussed above. The costs of maintaining parking spaces, central controllers, and security personnel were not included because it was assumed that only simple shelters would be used and, consequently, station maintenance costs would be minimal.

By combining the various unit cost coefficients, a generalized cost equation may be developed of the form:

$$\text{COST} = g(a\text{VMT} + b\text{F} + c\text{TM} + d\text{S} + e) \qquad (1)$$

where:

COST = annual operating and maintenance cost

VMT = vehicle miles traveled

TM = track miles

F = fleet size in scheduled service during peak hour

S = number of shelters

g = multiplier for general and administrative expenses (G&A)

a,b,c,d,e = unit cost coefficients

Examination of the magnitude of these coefficients, based upon studies of O&M cost projections arrived at through the use of the cost model, indicates that the coefficients c, d and e have relatively low impact on the annual cost. The major determinants are vehicle miles traveled (VMT) and peak hour fleet size (F). System costs can then be fairly accurately modeled by the expression:

$$\text{COST} = a'\text{VMT} + b'\text{F} \qquad (2)$$

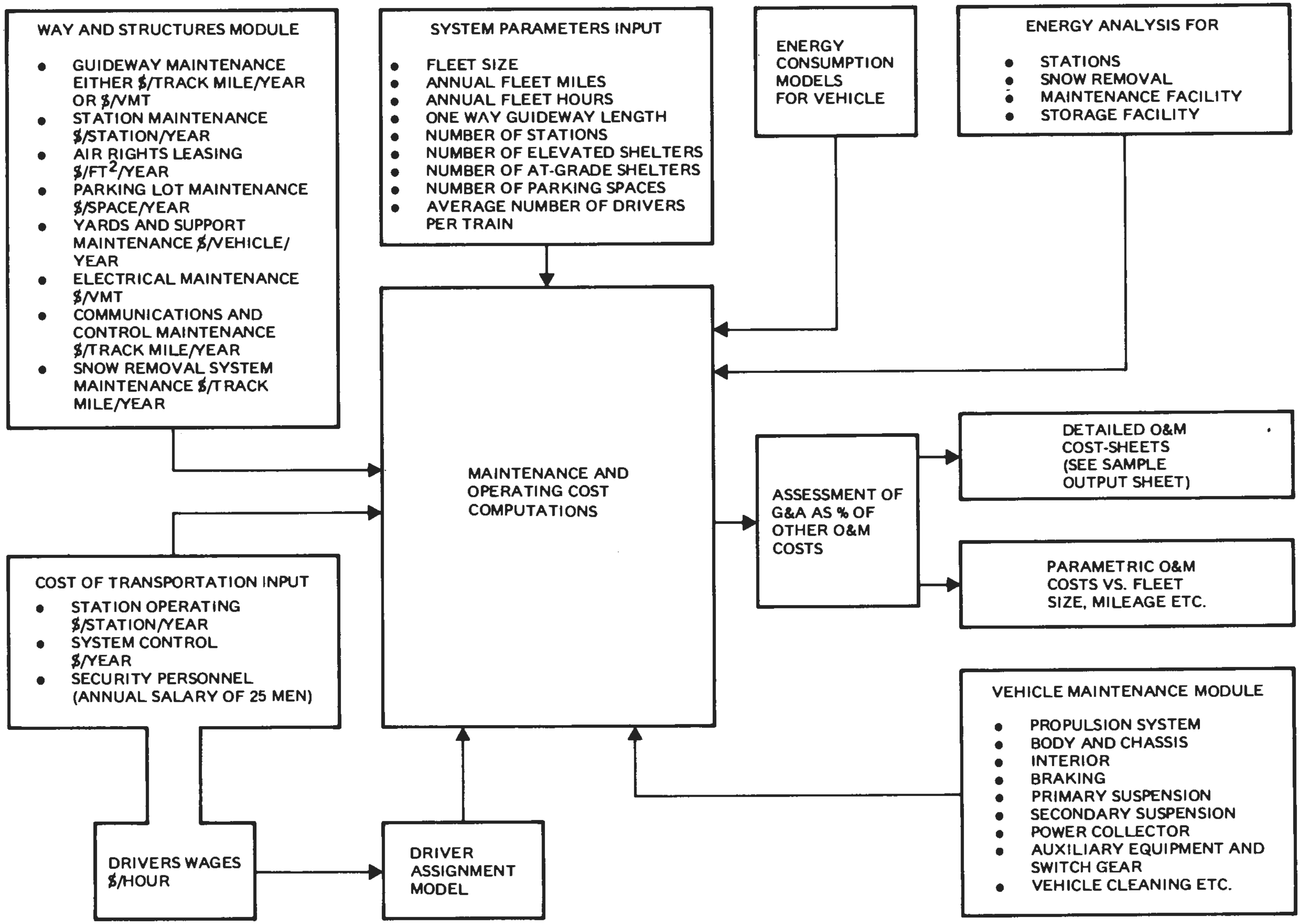


Figure 103. Block Diagram of Maintenance and Operating Cost Modeling Approach

where:

a' and b' = modified coefficients which incorporate the effects of G&A, track and station related costs. The following coefficients have been determined from an analysis of the data shown in Figure 104: a' = 1.073; b' = 31,584.

This expression implies that annual operating costs are proportional to the number of vehicle miles traveled augmented by a second term related to the peak hour fleet size. The latter accounts for the operating efficiency of the system. A system operating at high speeds will require fewer vehicles and fewer operators in peak hours to operate a given number of vehicle miles. Therefore, a reduction in the peak hour vehicle requirement implies a significant reduction in operating costs. The coefficient b' is thus heavily related to operators' wages. The operating cost per vehicle mile obtained from the above expression is given as:

$$\frac{\mathrm{COST}}{\mathrm{VMT}} = a' + \frac{b'F}{\mathrm{VMT}} \tag{3}$$

VMT/F represents the annual vehicle miles traveled divided by the maximum number of vehicles operated at one time (usually peak hours). It is an indicator of the fleet productivity, reflecting the impact of operating conditions along the routes, particularly the use of private rights-of-way. The higher speed which is possible due to better operating conditions on private rights-of-way results in a higher number of annual vehicle miles traveled per operated vehicle.

OPERATING AND MAINTENANCE COST DATA FOR EXISTING SYSTEMS

Operating cost data were obtained from a variety of streetcar and light rail systems in North America and Europe.[83] Costs were converted from foreign currencies to U.S. dollars, using the average of the rate of exchange for the four quarters of the operating year for which the data were obtained.[84] Costs were then inflated to December, 1974 levels using the rate of inflation for transit operating costs as determined from APTA trend data.[85] The operating and maintenance cost data in 1974 dollars obtained from the various systems are summarized in Table 34.

Despite the economic vagaries of different currencies and varying inflation rates, the correlation between European and American operating costs is reasonably good. Major variations in cost occur in energy and wage labor rates. Energy costs per vehicle mile are generally higher in Europe than in the U.S. Energy costs for the various systems for which data was obtained are summarized separately in Table 35.[86] Costs vary significantly from system to system both within the United States and Europe. This critical element of total maintenance costs for light rail systems must be dealt with on an individual basis using realistic local rates per kilowatt hour. The section that follows dealing with the sensitivity analyses of maintenance and operating costs discusses the impact of varying energy costs upon local operating costs per mile.

Transportation costs, that is the wages and fringe benefits of trainmen, station attendants and other operating personnel, also vary by locale. Table 36 summarizes operator wages for the several European systems for which such data was available, as well as for systems in the United States and Toronto, Canada.[87] Hourly wages for transit personnel in West Germany do not vary much between transit agencies or cities. All transit agencies are public, and one national union (OTV) negotiates wages. The sensitivity analyses that follow will also deal with the impact of varying wages upon total light rail operating costs.

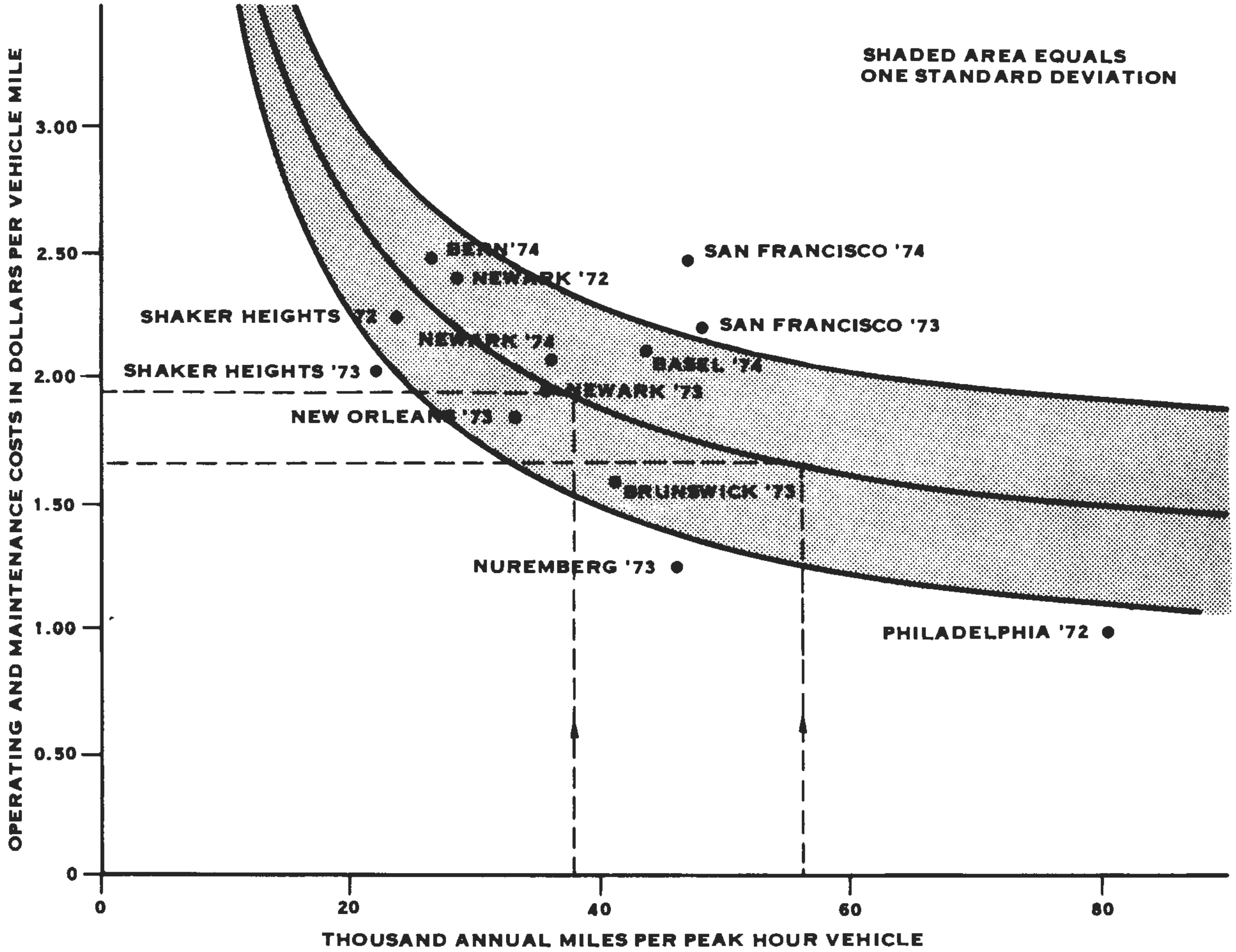


Figure 104. Relationship Between Vehicle Usage and Operating and Maintenance Costs*

---

*ALL COSTS ARE ADJUSTED TO 1974

Table 34. Comparison of Operating and Maintenance Costs

	Shaker Heights (1973)	SEPTA (1972)	New Orleans (1973)	Newark (1972)	San Francisco (1974)	Basel (1974)	Bern (1974)	Nuremberg (1973)	Brunswick (1973)	Gothenburg	Munich (1974)	Stuttgart
Miles of Single Track (GM)	27	120	14.6	9	N/A	58.6	17.3	86.8	19.5	N/A	149	154
Light Rail Vehicles Owned	55	424	35	27	115	375	84	351	53	358	630	467
Light Rail Vehicles Peak Hour (FS)	53	283	35	16	N/A	235	70	192	36	304	N/A	182
Light Rail Vehicle Miles (VM-000s)	1,042	22,812	827	462	3,304	10,320	1,850	8,910	1,400	9,560	11,750	15,535
Kwh Consumed (000s)	4,500	138,183	3,406	2,618	N/A	N/A	N/A	N/A	5,860	N/A	N/A	N/A
Kwh per Car Mile	4.3	6.06	4.1	5.7	N/A	N/A	N/A	N/A	4.10	N/A	N/A	
Way and Structures ($000s)	267	3,211	560.9	93	354.8	3,803	452	N/A	496	N/A		
¢/VM	25.6	14.0	67.8	20.2	10.45	36.9	24.4	30	35.4	62.5		
$/GM	9,889	26,761	38,417	10,369	N/A	64,983	26,127	N/A	25,421	N/A		
Vehicle Maintenance ($000s)	207	3,554	183.2	72	909.3	4,024	(2)	N/A	563	N/A		
¢/VM	19.8	15.6	22.1	15.6	27.5	39.0	(2)	26	40.2	81.8		
$/GM	7,667	29,613	12,549	8,011	N/A	68,669	(2)	N/A	28,855	N/A		
Power Maintenance ($000s)	3.8	165	N/A	N/A	N/A	(2)	(2)	N/A	181	N/A		
¢/VM	0.3	0.2	N/A			(2)	(2)	(2)	12.9			
$/GM	222	1,371	N/A			(2)	(2)	N/A	9,277			
Power Purchased and Generated ($000s)	N/A	1,872	37.8	74	181.3	712	248	N/A	167	N/A		
¢/VM	N/A	8.2	4.6	16.1	5.61	6.9	13.4	13	11.9	17.65		
$/Kwh	N/A	1.1	0.01	2.4	N/A	N/A	N/A	N/A	2.3	N/A		
Conducting Transportation (¢/VM)	1.03(1)	43.9	N/A	96.7	112.33	109.7	192.5	52	41.2	N/A		
Trainmen Wages (total)	657(1)	6,534	N/A	262	N/A	6,610	N/A	N/A	N/A	N/A		
¢/VM	60(1)	30.4		56.7		64.0						
$/FS	14,292(1)	24,501		16,352		28,128						
Other	475(1)	3,089		185		4,712						
General & Administrative ($000s)	51.2	3,302		414	2,079	1,683	314	0	0	N/A		
¢/VM	4.9	14.5		89.6	62.9	16.3	17.0	0	0	24		
$/FS	966	11,563		25,854	N/A	7,161	4,486	0	0	N/A		
Total Operating Expenses ($000s)	2,125	22,126	1,512	1,100	8,036	21,550	4,576	20,500(3)	2,176	50,500(3)		40,700(3)
¢/VM	203.8	97.0	182.8	238.3	243.2	208.8	247.4	121	155.4	260	175	131.4
$/GM	78,704	184,386	103,561	122,254	N/A	367,747	263,899	124,185	111,424	N/A	N/A	190,242

(1) 1972 data; 1973 data not available
(2) Included in Ways & Structures
(3) Based on 2.4 DM/$

Table 35. Energy Costs

	Kwh/VMT	¢/Kwh	¢/VMT
Bern	–	–	13.4
Stuttgart*	4.23	6.2	26.2
Hamburg*	3.29	7.0	23.0
Bremen*	3.33	4.7	15.7
Bochum*	4.64	5.2	24.2
SEPTA	7.45	1.1	8.2
New Orleans	4.1	1.1	4.6
Newark	4.7 - 5.7	2.2 - 2.4	12.7 - 16.1
Shaker Heights	4.1 - 4.3	3.2	15.7

*Based on 2.4 DM/$

Source: Reference 16 and communications with Dr. F. Lehner

Table 36. Operator Wage Rates

Hannover*	$5.75
Cologne*	$6.04
Stuttgart*	$6.00
United States	$5.99/hr – benefits approx. $2.00/hr
Toronto**	$6.50/hr
Newcastle**	$5.20/hr

*Average current rates containing certain overtime additions but not including social security benefits (usually an additional 25%). Conversion to U.S. currency based on 2.4 DM/$.

**Converted to U.S. dollars and inflated to 1974 level at applicable exchange and inflation rates.

Source: Dr. F. Lehner

A statistical analysis of cost data obtained from operating systems in the U.S. and overseas was used to obtain best fit values for the coefficients of equation (3). Figure 104 relates the operating and maintenance costs data for the various systems summarized herein to the best fit curve. To present data in a more usable form, the data is related to the reciprocal of the quantity F/VMT of equation (3). The graph, therefore, illustrates the average cost per vehicle mile related to average annual vehicle miles of travel for one, two or three car units, all with only one operator. The various systems for which operating cost data were obtained are plotted on the curve to illustrate the correlation between the European and the United States data and the best fit curves.

Mathematical models are often used to estimate the O&M costs of projected LRT facilities. Table 37 lists the unit cost parameters employed by one model of this type. The parameters have been calibrated against the data shown in Figure 104. It must be emphasized that these are only representative unit costs. Energy, wages, operating policy, security policy, number of stations and shelters, total system length, and many other factors can significantly affect these costs. The unit costs described herein are adequate for illustrative purposes and for defining average O&M costs for shelters, yards, support facilities, electrical systems, vehicle maintenance, and administration. There is no substitute for input of actual cost information for energy, wages and the several other critical units when assessing an actual situation.

COST-SPEED RELATIONSHIP

For the most part, the European systems for which cost data were obtained operate at average speeds of less than 12 miles per hour and an average vehicle usage of less than 50,000 miles per vehicle per year. High performance light rail systems should be capable of schedule speeds of greater than 15 miles per hour, resulting in higher annual vehicle usage and lower average operating costs per vehicle mile.

Table 37. O&M Unit Costs

Element	Unit Cost Bases (per year)
Track maintenance	34¢ per VMT
Shelter maintenance	$500 per shelter
Yards and support maintenance	$1000 per peak hour vehicle
Electrical maintenance	4¢ per VMT
Communications and control maintenance	$2500 per track mile
Vehicle maintenance	24¢ per VMT
Vehicle energy consumption	14¢ per VMT
Maintenance facility energy consumption	$50 per peak hour vehicle
Vehicle storage energy consumption	$400 per peak hour vehicle
Operator's wages	$12,000 per year + $4000 benefits, 1.5 drivers per peak hour vehicle
Other transportation	17¢ per VMT
General and administrative	15% of other costs

The relationship between the annual mileage (VMT/F) and the vehicle schedule speed is of the form:

$$\frac{VMT}{F} = Ku \quad 1 + .5\frac{Mp}{M} \tag{4}$$

where:

Mp/M = ratio of peak to non-peak hour load factors

u = vehicle schedule speed, miles per hour

K = the number of peak hours per vehicle in a year (typically 1250)

.5 = ratio of non-peak trips to peak trips

This expression is plotted in Figure 105, assuming the non-peak load factor to be one-fourth of the peak period factor and assuming two-thirds of the passengers to be carried during the peak periods. Data for a variety of light rail and rail rapid transit systems are plotted on the curve to illustrate the extent of agreement with this relationship.[88] It was necessary to include some rapid transit systems to develop points at the higher end of the curve.

The graph illustrates that on the average, vehicle utilization at schedule speeds of ten miles per hour results in annual utilization of less than 40,000 vehicle miles per peak hour vehicle. At a speed of 15 miles per hour, annual utilization increases to an average of 56,000 vehicle miles per peak hour vehicle. Applying these values to the curve in Figure 00, the expected operating and maintenance costs can be estimated as follows: for systems operating at an average speed of 15 miles per hour, the O&M costs average approximately $1.63 per vehicle mile; for systems using extensive on-street operation with schedule speeds closer to 10 miles per hour, the corresponding O&M cost is approximately $1.91 per vehicle mile. This figure illustrates the savings in operating costs per vehicle mile that can be obtained from higher speed operations which make better utilization of vehicle and operators.

SENSITIVITY ANALYSES

With the unit cost model properly calibrated against empirical data, and using the parameters of Table 37, the sensitivity of O&M costs can be determined with respect to:

- Increased energy costs
- Varying fare collection policies
- Multiple unit operation.

Figure 106 illustrates the sensitivity of O&M costs to the cost of energy. Since energy consumption depends on vehicle speed, vehicle weight, efficiency of traction motors and their controls, number of accelerations and decelerations per mile (or station and intersection crossing stops), the graph is somewhat complex. It has been constructed for the projected energy consumption of the Boeing LRV. The graph can be used to estimate the effect of changes in the cost of energy for a range of vehicle speeds on level track (when grades are traversed, the energy consumption will increase beyond the values shown on the right side of the graph) and for a range of station spacings. As an illustration, for operation at 30 mph on a line with six stops per mile, the consumption is some 10.5 kwh/vehicle mile. Changing the cost of energy

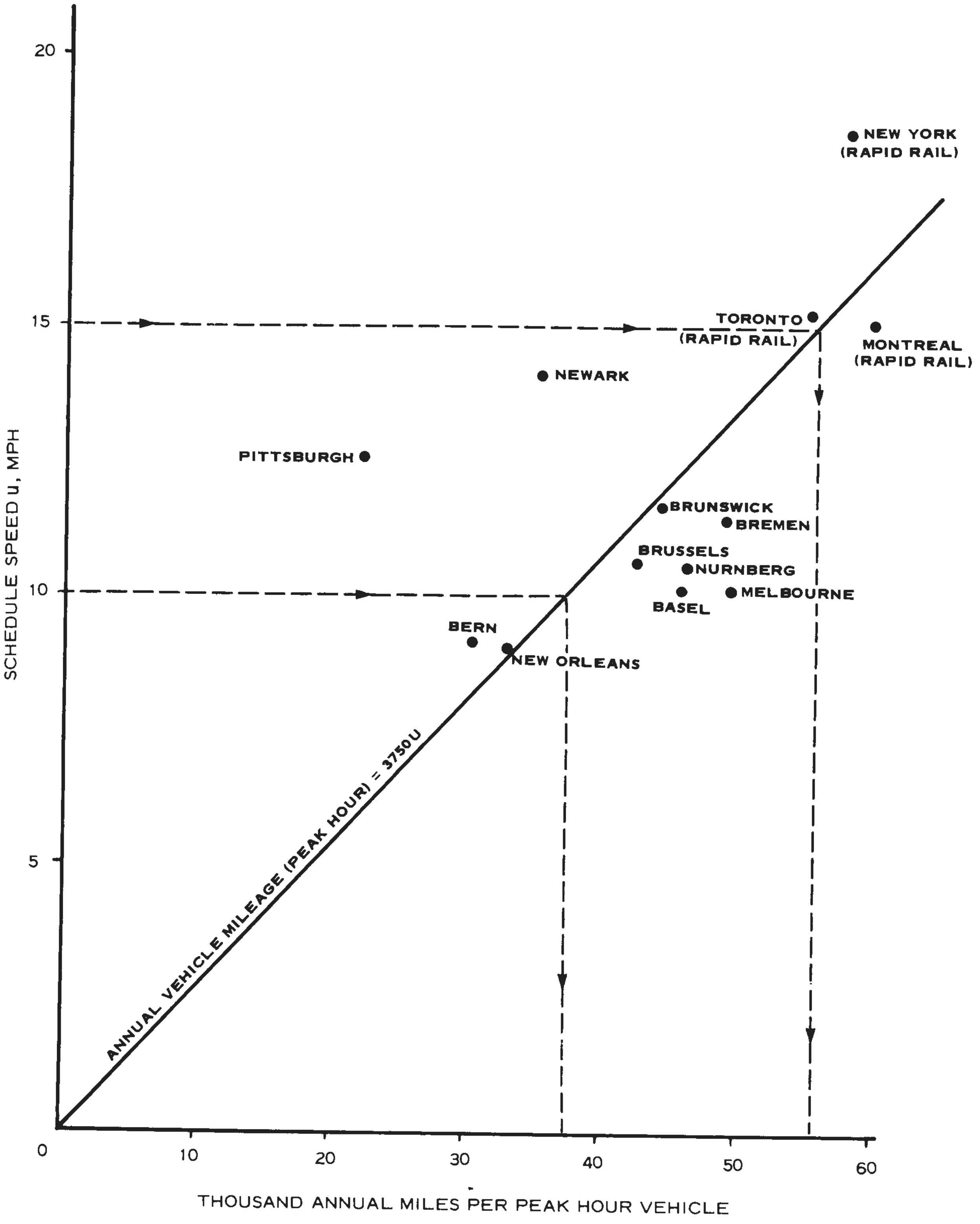
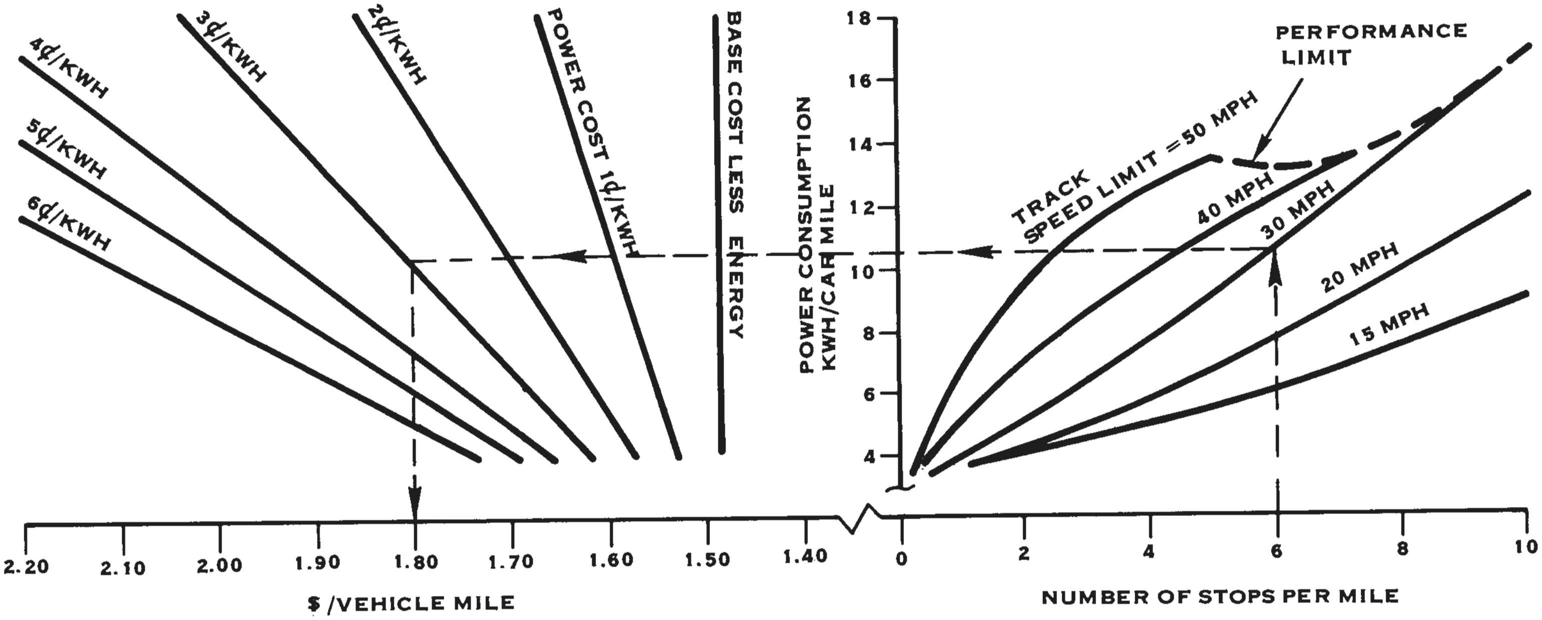


Figure 105. Speed Versus Fleet Mileage Relationship



NOTES:

1. 35 KW AUXILIARY LOAD
2. 100 PASSENGER LOAD
3. 15 SECOND STATION STOPS

SOURCE: BOEING VERTOL COMPANY FOR BOEING LRV DATA.

Figure 106. Sensitivity of LRT Operating and Maintenance Costs to Energy Cost

from 2 to 3 ¢/kwh would increase the O&M cost estimated with the aid of a mathematical model from $1.68 to $1.80/vehicle mile or some 12¢/vehicle mile. This is less than 10 percent of the O&M cost estimate at 2¢/kwh.

Figure 107 illustrates the sensitivity of light rail operating costs to changes in operator wages and average systems speeds. The graph shows that even with wages at $11.00 per hour, operating costs could be kept to $1.92 per vehicle mile of travel, if 15 mile per hour schedule speeds are attainable.

It was assumed that a single operator per train will be used with multiple unit operation. Curves in Figure 108 illustrate the effects of multiple unit operation with a single operator calculated with the basic empirical cost equation. At 15 miles per hour average schedule speed, for example, with 56,000 vehicle miles of travel annually per peak hour vehicle, costs savings of approximately 29 cents per vehicle mile are possible with three unit consists.

The cost curves presented in Figure 108 assumed application of the self-service fare system. By eliminating the need for conductors or station attendants to collect fares and substituting a lesser number of roving inspectors, a savings in labor costs can be realized. It is essential, however, that these costs be assessed against potential losses in fares and vandalism to unattended equipment. If a conductor is required onboard multiple unit trains, the savings are reduced, as shown in Figure 109. At 15 mph (56,000 vehicle miles of travel annually), the cost savings from using four unit trains with an operator and conductor is 22 cents per vehicle mile.

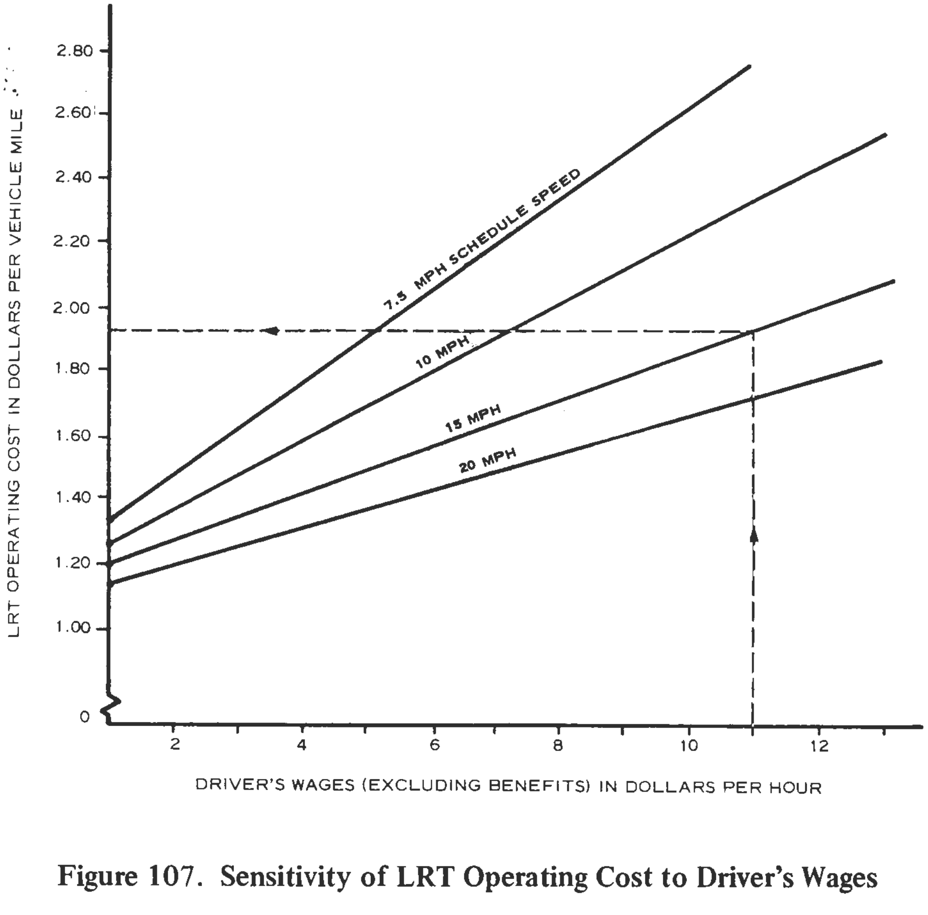


Figure 107. Sensitivity of LRT Operating Cost to Driver's Wages

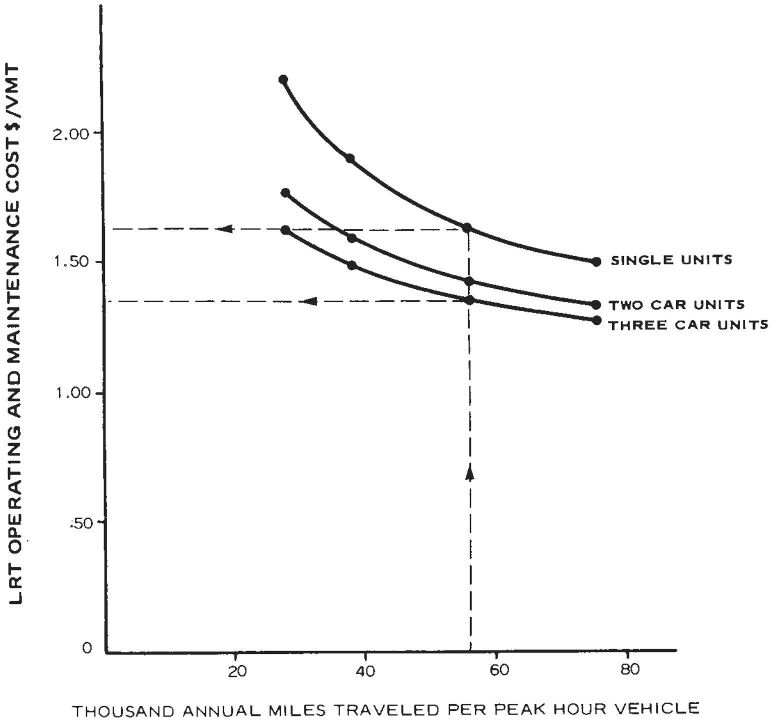


Figure 108. Potential Savings from Multiple Unit Operation With a Single Driver

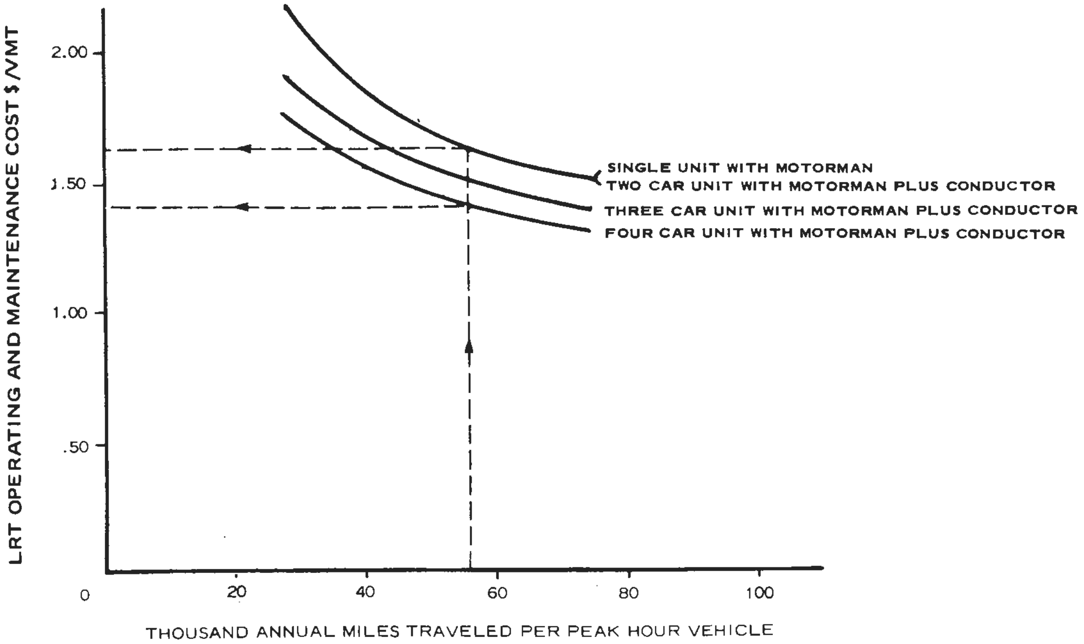


Figure 109. Potential Savings From Multiple Unit Operation With a Conductor

CONCLUSION

Light rail right-of-way costs vary widely, depending on the right-of-way type used. Fully controlled right-of-way types, such as tunnels, elevated or at grade, are not very much different from those which rapid transit requires. However, the ability of LRT to use different right-of-way types for the same route leads to major capital cost savings.

As shown, the order of magnitude capital costs per route mile can vary from less than five million dollars to over 50 million dollars, depending upon operating and right-of-way policies.

Average light rail operating and maintenance costs show significant reductions compared with conventional streetcar operations as a result of improved operating efficiency. O&M costs for a single car operation can vary from approximately $1.60 per vehicle mile at speeds of more than 15 mph and for system-wide equipment utilization of approximately 50,000 vehicle miles per year to $2.20 per vehicle mile at speeds averaging 7.5 mph and with system-wide equipment utilization approximating 30,000 vehicle miles per year. These costs are order of magnitude and illustrative. They are not intended to serve as a surrogate for detailed cost analyses of individual projects.

CHAPTER 9

GENERAL PLANNING CONSIDERATIONS FOR LRT APPLICATIONS

Light rail transit is a broadly defined generic transit mode. Because of historical trends in transit and the wide range of variations of LRT applications, services and operations, planners in the U.S. have not readily perceived this mode's role in modern transit. Light rail's capabilities as a modern transit technology are often debated. Planners and non-professionals are usually challenged when dealing with LRT as one of several candidate transit modes. The number of significant deployments of LRT in Western Europe and North America reviewed in this report should provide a basis for improved perception of this mode's range of potential applications. As a step toward generalization and increasing the utility of this information, certain basic LRT planning considerations are drawn together here. Boundaries are sketched for viable applications of LRT, and particular LRT planning problems are discussed. Finally, a range of typical applications for LRT are reviewed.

ELEMENTS OF LIGHT RAIL TRANSIT PLANNING

Urban transportation planning has traditionally estimated the future demand for transit trips by considering various future land use alternatives. These alternatives are used to estimate trip generation and attraction, and to produce a total trip matrix (or spider network) from which transit trips are estimated. The fraction of all travel carried by transit is estimated by modal choice analysis. Certain parameters are used in this analysis including income levels, car ownership and a cost function. But the principal parameter is always travel time expressed in terms of automobile and transit travel time. The transit part of travel time generally includes access, egress, waiting and transfer times, often weighed by various penalty factors. Travel time estimates are based on the various transport networks under study, and the projected number of trips is assigned to specific existing and proposed facilities. To obtain favorable transit travel times, high speeds are needed with short access and egress. On major corridors to employment areas, rail rapid transit fills this role. Rail rapid transit lines operate or are planned in many urban corridors in North America where the high cost of such rail rapid transit installations can be justified by actual or projected levels of passenger trips.

When the transportation planning process described above was introduced some 15 to 18 years ago, coincident with the availability of large digital computers, the principal transit modes considered by planners were rail rapid and bus. Streetcars had been written off as outmoded, and commuter rail was assigned a very limited role. Even the bus was regarded with little enthusiasm and planners showed little interest in innovative uses of this mode. The net results of these early studies were often recommendations for an urban expressway network and/or some rail rapid transit. Often, transit corridors were identified for an "intermediate" mode with the attributes of rail rapid transit but with lower capacity and lower cost.

The search for this intermediate mode challenged urban transit technology for well over a decade. As described elsewhere in this report, LRT applications in Western Europe during the last decade show that, given conditions suitable for its deployment, the fairly conventional technology of light rail provided a pragmatic answer to the search for the intermediate mode.

In recent years, simplified urban transportation planning methods began to be used. These methods placed less emphasis on the very detailed analysis of street, highway and transit networks, but stressed environmental issues. This change was brought about by increased opposition to further intrusion of urban expressways or aerial transit structures into neighborhoods, concerns for environmental protection and for energy conservation. In one approach for corridors already served by buses, transit ridership is projected in direct proportion to the population changes brought about by future land use alternatives. Adjustments are then made for proposed transit improvements. Other planning procedures have simplified the conventional process by reducing substantially the number of analysis zones, and therefore the analytical effort. For example, the Metropolitan Toronto Transportation Plan Review of 1975 data was compiled for 35 zones compared with almost 300 in the previous conventional model.[89] The amount of data required for transit planning thus is massively reduced. Therefore, a number of modal alternatives can be examined in different network configurations without incurring exorbitant costs. Still another approach to simplified transit planning is the use of sketch planning models to quickly evaluate transit corridors and networks.

Simplified analysis procedures produce travel estimates which are assigned to major corridors rather than individual facilities. Travel estimates derived in this manner imply that the precise alignment of the LRT or other fixed guideway systems will not affect the planning results significantly. This conclusion is not difficult to support except where walk-in patronage is important, such as in the CBD. Imperfect as transportation planning must always be, the simplified procedures permit more attention to be paid to issues of urban structure, land use planning, environmental and social impacts, economic feasibility, operating cost comparisons, and public information and participation.

Whatever the transportation planning procedure used, total transit travel time remained the most important factor in determining patronage, but at the same time, an improved perception emerged of its relevance to decision making for capital intensive projects. This is significant in LRT system planning. In a recent study,[90] the systemwide value of time saved through improved transit operations was calculated in normalized fashion, i.e., in terms of the effects of one minute reduction in travel time. The reductions in operating cost, the increases in revenue, and the value of passengers' time saved for a range of transit line passenger volumes were calculated. Of course, in actual planning, the numbers would have to be prorated to correspond to the actual project savings in time (i.e., numbers of minutes). The results are shown in Tables 38, 39 and 40. These estimates are for a hypothetical route; actual estimates should be made for each individual application.[91] The magnitude of the savings from travel time reductions suggests that major capital investment will, in general, be difficult to justify at low to moderate volumes.

With regard to LRT potential applications, the results suggest that system design should attempt to keep facilities simple and the alignment on the surface. These conclusions reinforce a major advantage in the application of LRT: capital costs can be tailored to the patronage estimates. The system can be incrementally upgraded and extended as patronage (and hence benefits) increase in future years. Upgrading can include additional grade separations, including the elimination of selected grade crossings and on street running (if any). Downtown sections which can also be built in stages using temporary ramps with the provision of more elaborate stations. LRT's flexibility in these respects is unique among fixed guideway transit systems.

For LRT insofar as travel time is concerned, this will be affected primarily by the degree of grade separation (Figure 93) and by several additional factors. Speed restrictions may be imposed for institutional, safety or curvature reasons. The performance specifications of different LRT vehicles, as shown in Table 23, are fairly uniform and not likely to cause additional travel time impacts. Station spacing, however, is a major factor in determining average schedule speed. As shown in Figure 93, the Boeing LRV operating on a median strip with 50 percent signal preemption will experience a schedule speed increase from 15 mph at 3 stops per mile to 30 mph with station spacing over one mile. This represents a line-haul travel time difference of 12 minutes on a typical 6 mile trip. A lot of speed restrictions and non-preempted traffic signals are required to impose a 12 minute delay.

Table 38. Reduction in Direct Operating Cost for a One Minute Savings in Running Time (in 1975 dollars)

Line Volume pphd*	Annual Saving in Direct Operating Cost		Capitalized Value (1975 dollars)
	One Operator per Car	One Operator per Train	
2,000	$ 26,000	$ 26,000	$ 260,000
5,000	65,000	50,400	504,000
8,000	104,000	87,000	870,000
12,000	156,000	131,000	1,310,000

Table 39. Net Revenue Increase for a One Minute Reduction in Running Time (based on time elasticity of +0.35)

Line Volume pphd*	Annual Increase in Net Revenue (1975 dollars) at 6¢ per passenger mile	Capitalized Value (1975 dollars)
2,000	$ 8,000	$ 80,000
5,000	20,000	200,000
8,000	32,000	320,000
12,000	48,000	480,000

Table 40. Assigned Value of Passenger Time Saving for a One Minute Reduction in Running Time ($1975)

Line Volume pphd*	Annual Savings Assigning an Average of $4.00/hour to Passenger's Time	Capitalized Value (million)
2,000	$ 320,000	$ 3.2
5,000	800,000	8.0
8,000	1,280,000	12.8
12,000	1,920,000	19.2

Source: Reference 90

Note: Assumptions include operator cost at $6.50 per hour with 20 percent fringe benefits; the use of multiple unit operation at times with off-vehicle or self-service fare collection; and specific levels of service throughout a 20 hour day. See reference for details. Savings are valid only for "peak point" on the line. If the time saving is at the outer end of the line, fewer passengers will benefit and the monetary saving must be factored accordingly. Capitalized value is taken at a conservative 10 times the annual saving estimate.

*Passengers per peak hour direction.

The planner must, therefore, attempt to maximize station spacing while giving due attention to land use plans and the closely related factor of access and egress time. The flexibility of LRT permits the addition of stations in the future as land use changes and demand grows. It also permits, under certain circumstances, LRVs to make station stops only on demand, as buses do. Schedule speed can thus increase at off-peak times as some of the stations are "skipped". Careful system design is required to determine the effect of skip-stop operation and the resulting impact on patronage and/or added costs for duplicate lines to serve skipped stations where travel demand is high enough to justify this design approach. Demand stopping improves transit's competitiveness at times when the highway network is more likely to be free flowing. This operational flexibility is a feature of the Norristown LRT line in Philadelphia. Scheduled skip-stops used on some rail operations are only possible when headways are tailored to permit the free flow of vehicles on line.

Access and egress times, rather than line-haul schedule speeds, are often the critical factor which determines whether a trip is assigned to the automobile rather than to transit. Access and egress times plus waiting (transfer) time are often given penalty weightings based on the perceived inconvenience to the public. These inconveniences must be minimized by innovative planning of not just the LRT line but of the entire transit network, including feeder services. Often the planner must also go beyond the bounds of conventional transit planning to obtain the most favorable environment for the application of LRT.[92]

BASIC PLANNING CONSIDERATIONS FOR LRT

The pragmatism that has brought LRT, as a lower cost option, into widespread consideration recently in Western Europe and in North America, has received considerable acceptance from recent economic realities. However, prudent planning cannot assure that the implementation of an LRT route or network will be a panacea for all of a region's transit problems. LRT may, at certain times and in certain locations, be competitive with the automobile, but it is important to regard LRT as one of a family of transit modes that collectively form an alternative to the automobile. LRT has, as do other transit systems, the capability to handle rush hour trips to the CBD when the road system is saturated and difficult to expand. The planning of transit, including LRT, could well aim beyond this limited market and strive to provide a multiplicity of destinations and reasonable service outside the peak periods. This would improve revenue and would, in the long run, promote increased acceptance of transit service.

Improving transit is only one part of a total transportation program. As communities strive to maximize their transportation benefits, other steps might be weighed as well, including traffic and parking restraints and reserving parts of the CBD for pedestrians only. Such steps might also be effective in energy conservation and in reduction of air pollution in conformance with the guidelines of the Environmental Protection Agency. Most of these aspects are outside the scope of this report.

One item that impinges directly on LRT planning is the treatment of pedestrians. Most LRT riders are also pedestrians at least at one end of each trip. If the pedestrian systems are deficient in sidewalks, crosswalks, shelters or transit information at the suburban end and consist of unsympathetic pedestrian treatment at the CBD end, then the trip will be perceived much less favorably by passengers. Patronage will suffer as a result.

In most multi-modal transit planning studies, defining the conditions which are favorable to LRT deployment is an important first step. Most of these conditions are site specific and difficult to generalize. However, some guidance concerning the viability of LRT can be derived from broad observations regarding the projected passenger volumes and the size of the network.

PASSENGER VOLUMES

The upper limit of passenger volumes for LRT is somewhat controversial. Limits are quoted of 15,000 passengers per peak hour and more. Theoretically, short headways can be combined with long trains to yield line capacities as high as 30,000 passengers per hour, but vehicular traffic on streets traversed by LRT, transit service quality and speeds may be seriously impaired. For a maximum LRT train and station platform length of 300 feet (e.g., 4 Boeing LRVs is a multiple unit operation filled to capacity with up to 600 passengers) under signal control operation and a minimum headway of 90 seconds, the upper limit becomes 24,000 passengers per hour. But here too, the vehicular traffic at at-grade intersections may be severely impaired. Consequently, to handle these large passenger volumes, large proportions of rights-of-way must be of Category A (fully grade separated).

Where long-term patronage estimates are above the upper range of LRT capacities, consideration may be given to adopting pre-metro design standards to enable the line to be ultimately upgraded to rail rapid transit. However, pre-metro configuration involves increases in cost and is difficult to justify unless passenger volumes much too high for LRT are projected.

Provided that eventual passenger volumes do not exceed the upper limit of LRT capacities, light rail may have an important advantage in being able to be built and upgraded incrementally so that its facilities at any point in time match passenger demand closely and economically.

It is much more difficult to determine the lower level of patronage, at which an LRT line becomes viable. This is a system specific determination that requires economic analysis in which alternative modes can be examined and compared on an equal footing.

NETWORK DIMENSIONS

There are no unequivocal guidelines to limit the viable size of a region's LRT network. The capacity limit of a CBD tunnel may determine how many routes can be fed into it. However, it may be possible to use the subway at close to capacity in early years by feeding several routes into it, and then construct an additional subway to accommodate growth. Alternately, platforms at subway stations can be designed to be extended beyond LRT length, so that in the future, trains from two or more routes can be coupled together for subway operation. San Francisco is using this principle in its Market Street LRT subway, but with stations built to their full length from the start.

To obtain political/institutional acceptance of a capital intensive transit facility, extensive networks serving all sections of the involved jurisdictions are sometimes proposed. The extensive systems, however, will be built in phases; the later phases may be delayed or not built. This is also true for LRT, but is somewhat mitigated since more miles of LRT can be built for a given cost. The lower volume network branches are likely to be more economically viable with LRT than with other rail transit installations.

How small a network or how short a line may be before negative economies of scale become apparent is an institutional question. If the LRT is to be built and operated by a separate agency, then there are distinct size limitations which are best determined by specific studies. Examples of small operations that run with considerable economy exist at Newark and Shaker Heights, but may not be particularly relevant to planning of new systems.

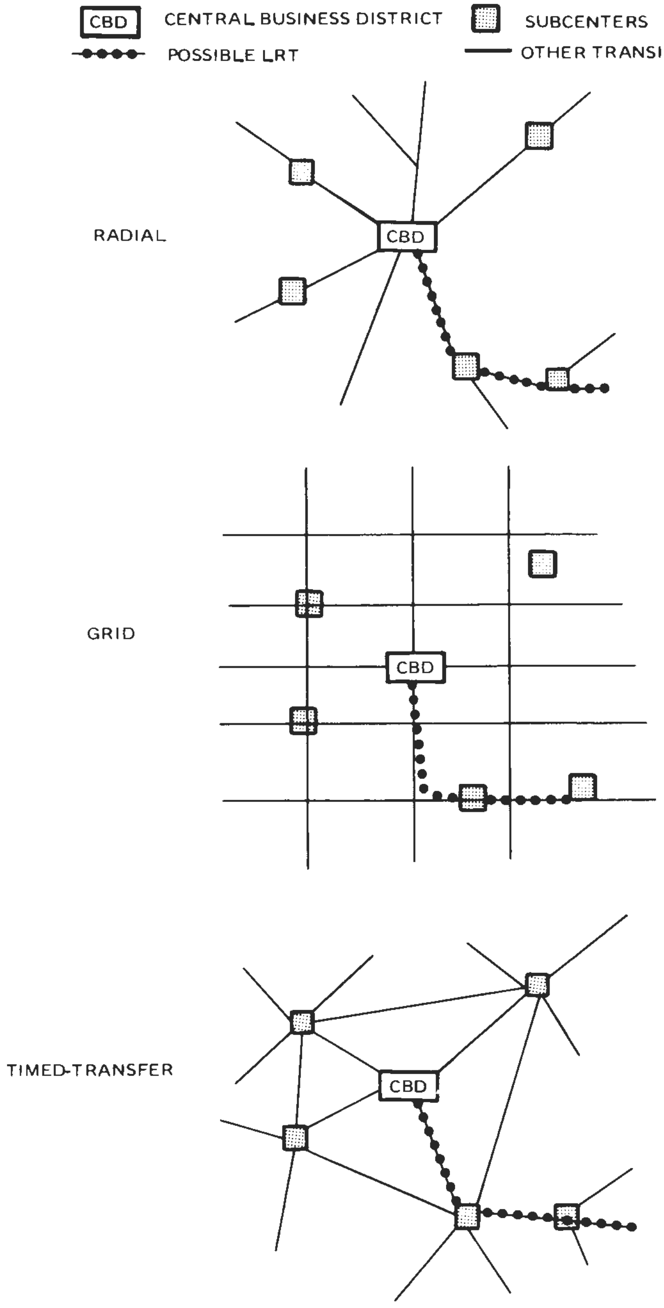
The importance of travel time as a means to meet the needs of potential passengers in planning LRT routes or networks has been discussed, but other factors must be examined as well. Recent work has compared consumer response to transit characteristics in an attempt to determine the most important variables that affected patronage.[93] Analysis showed that the single most important variable in influencing annual ridership was the degree to which the system was not oriented entirely to central city. This characteristic can be referred to as "connectivity" or the availability of a multiplicity of convenient destinations, reflecting the dispersion of trips in North American cities. Other variables with high ranking were frequency of service and route coverage.

Notwithstanding this analysis, the planner must still largely orient transit services to the largest market, which in many cities involves work trips to the CBD. CBD oriented travel requires, typically, a series of unrelated radial routes, each oriented to a single corridor (Figure 110). An alternative to the radial or single route philosophy views each transit service as an element in an interacting network. Each route has its specific patronage but each, to some extent, feeds traffic to others that the latter would otherwise not receive.

In the largest North American cities, good connectivity was achieved with a grid system of bus routes (Figure 110). However, where frequency of service is poor, such as outside the peak periods on non-CBD routes, transferring on street corners is inconvenient and often must be done with no weather protection. The grid system does establish, however, clearly defined transit corridors with established patronage for which implementation of an LRT alternative may be considered. Indeed, this has been the pattern for construction of many of the older rail transit lines. When a fixed guideway mode is introduced, good transfer facilities should be provided, and service on the cross-grid feeder should be restructured for best integration with the new transit line. Historically, grid systems have been applied in cities with suitable road networks and high transit demand. Since the grid links are concentrated closer to the CBD, *cross-radial* movements are favored only in the central area and in the close-in suburbs.

One answer to improving area-wide mobility while still serving the dominant CBD demand is to combine elements of the radial and grid system into a "cobweb". This cobweb has a limited number of nodes, at which several of the routes serving that portion of the urban area meet (Figure 110). By careful control of the route length and by limiting the number of connecting points on any one route, it is possible to coordinate the arrival of the various transit modes at these transfer points.[94] This design approach results in a number of major transfer points, more than with a radial system but less than with a grid system. Significantly, transfer times at these transfer points can be minimized. Specific facilities such as shelters or small bus stations can be provided at these nodes which are often referred to as "timed transfer focal points". Community centers and shopping centers may sometimes provide land for these focal points, including space for park-and-ride, kiss-and-ride and taxi services.

The above general transit planning concepts have particular relevance to LRT. Basically, the transit network is conceptualized as an array of local or feeder routes complementing an array of line-haul routes interconnecting the focal points and the CBD. The distinction between transit service on the two networks is not absolute. Some routes may encompass both types of service or change from one type to another along the route. On the line-haul routes, local collection and distribution functions are diminished, and fast service, through limited-stop, semi-express or express operations is possible. Line-haul routes may, at times, utilize freeway and/or arterial rights-of-way on which previous transit service was limited and can avoid residential streets. Passengers are offered, through transfers, fast service and a greater choice of convenient regional or local destinations. In the long run this system could replace a number of routes with *separate* local, feeder and line-haul service.



SOURCE: REFERENCE 94

Figure 110. Radial, Grid and Timed-Transfer Approaches in a Hypothetical Metropolitan Area

Regions unable to locate corridors with sufficient potential demand for LRT may still approach the development of such transit networks. The timed transfer focal point network can be established while LRT is in the planning stage, thereby orienting passengers to links that will later be converted to LRT or indeed to any improved mode, including freeway bus service and commuter rail. Transfer facilities can be built to become or to be integrated into LRT stations at a later date. Line-haul routes without LRT potential or with potential at a much later date can use many concepts to expedite and improve the regularity of service, including busways, reserved bus lanes, signal preemption and so on.

The timed transfer focal point (TTFP) concept is used in several European cities (Cologne, Munich), often with line-haul LRT links. Four Canadian cities (Edmonton, Victoria, Vancouver, Peterborough) have implemented the TTFP concept. Edmonton, Alberta (pop. 580,000) started on a small scale in 1964, and by 1973 had built annual transit patronage up from 26 million to 44 million.[95] During the same period, the similar sized city of Calgary, Alberta, using traditional routing structure, including CBD express bus services, increased annual patronage from 26 million to 28 million. The striking difference may be explained when it is considered that Edmonton has a much more dispersed work force than Calgary. As described in Chapter 3, Edmonton is constructing a single LRT line scheduled to open in 1978. This line will provide transit service on a route currently served by a TTFP line-haul bus route. Edmonton has plans to convert four more links on which patronage has already been established.

INTERMODAL TRANSFER FACILITIES

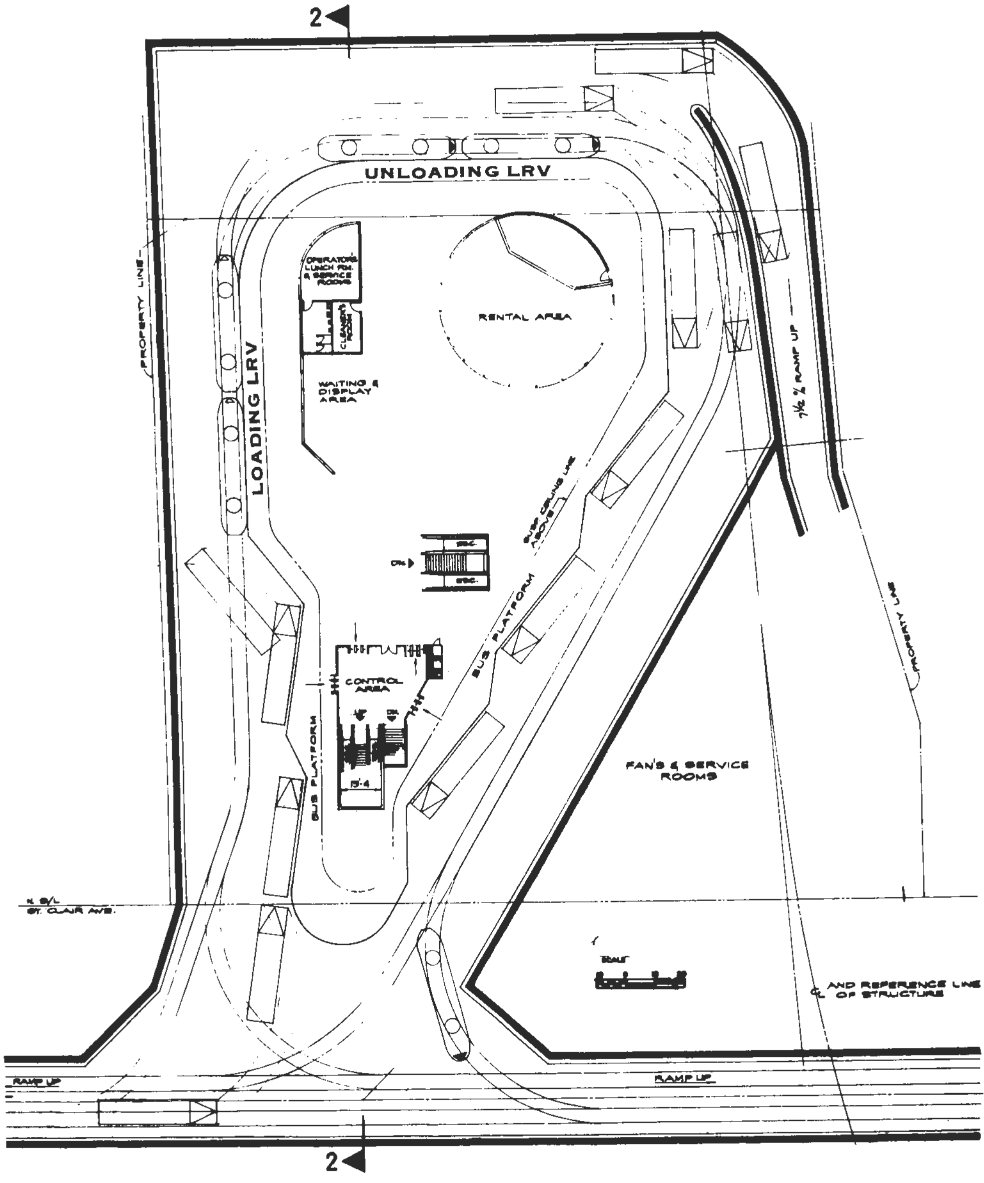
Transfers are often regarded by the public as impediments to travel. Since they are essential features in most transit networks, it is desirable to make transfers as convenient as possible. Transfer facilities should provide protection from inclement weather. Where economically possible, free transfer between modes will enhance the quality of service and consequently, the attraction to transit. Scheduling should minimize transfer times. To add to the convenience aspects of the transfer, stop-and-shop and other commercial activities may be offered.

Figure 111 shows Toronto's St. Clair West interchange station among surface LRT, buses and rail rapid transit, where the LRT operation is in the median. Simple LRT stations can be accommodated in the median, but where major interchanges are required, ramping of the LRT down in the center of the road, and bringing it into an off-street loop could be used, as shown in Figure 111. Pedestrians enter via escalators into an unpaid area and pass through turnstiles into the large fare control area with retail rental space and loading for six bus routes and two LRT routes. Track areas are paved and shared with buses, including the central street ramps. However, an extra ramp is provided for buses to exit into traffic. The off-street interchange area is fully covered, but only the passenger area need be covered if it is necessary to reduce costs. The subway platforms below this area are not shown. Light rail vehicles and buses can turn from either direction, providing operational flexibility.

Another intermodal transfer station design is shown in Figure 112 for Toronto's proposed Kennedy station, the terminal point of the Bloor-Danforth subway extension. This four level interchange has many features designed to make transit operation and passenger transfers convenient:

- The LRT route is at the upper level with escalators to the main interchange area at ground level.
- Buses are brought into this level by ramps and an overpass to minimize traffic conflicts. Bays are provided for 10 metropolitan bus routes.
- An auxiliary bus platform is provided with grade separated passenger walkways for regional and intercity buses.
- The walkway to the auxiliary bus platform extends to a kiss-and-ride carousel and then to extensive parking which shares the kiss-and-ride drop-off entrances.
- A below-grade walkway provides access to both sides of an existing commuter rail line where a new station is possible.

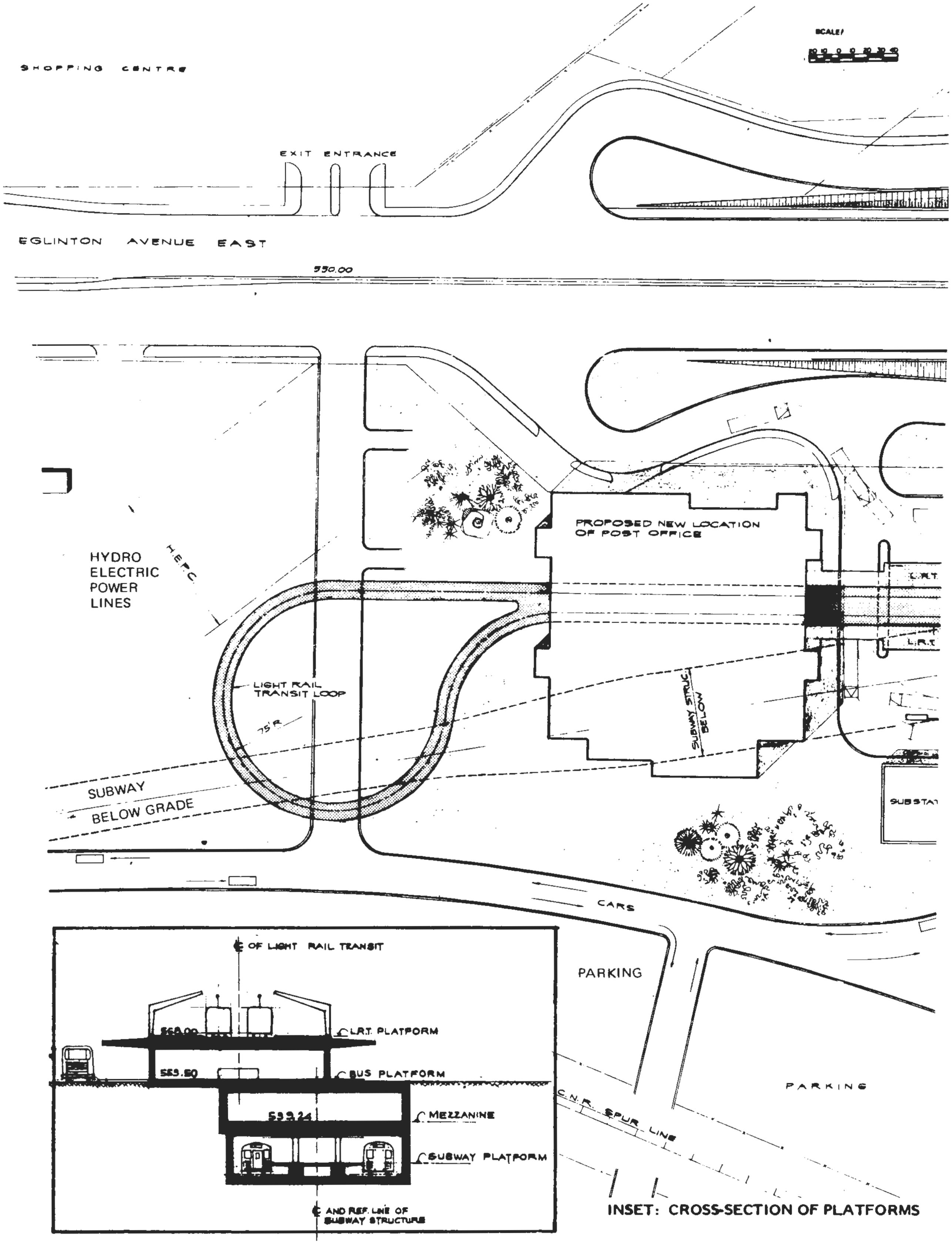
- Automobile, commuter rail and auxiliary bus passengers pass into an automatic or manned fare collection area at the east end of the mezzanine and bus levels. The remainder of the interchange is fare free with no paper transfer requirements.
- Facilities for operating staff are provided on the bus, mezzanine and subway levels.
- A substation is incorporated into the structure to provide power for the subway and LRT.
- The station is the terminal of the LRT line which has an elevated loop reached by passing through the second story of a proposed new post office building.



BUS AND LRT PLATFORM LEVEL PLAN

SOURCE: TORONTO TRANSIT COMMISSION

Figure 111. St. Clair West Station, Spadira Subway at Toronto (Under Construction)



INSET: CROSS-SECTION OF PLATFORMS

SOURCE: TORONTO TRANSIT COMMISSION

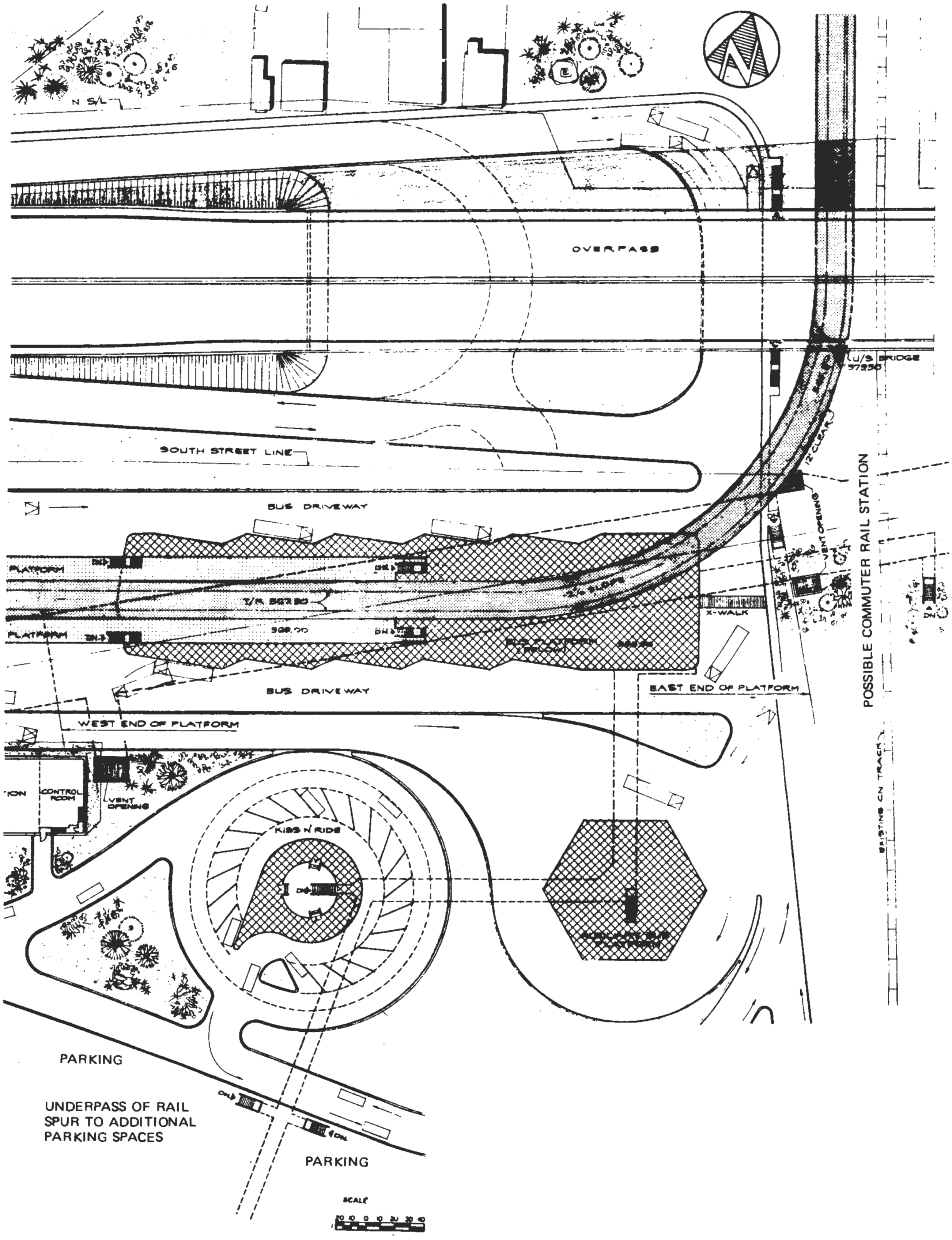


Figure 112. Proposed Kennedy Station

These interchange stations obviously would be considerably more costly than the simple street-level platform station. Although only a few interchange stations of this type would be required on any network, the cost would be significant in proportion to the other elements of the system.

While many LRT lines will have certain major stations, most stations will only require simple facilities which can be provided at low cost (see Chapter 4).

LRT APPLICATIONS

Light rail transit can and does fulfill many facets of transit operation. A single LRT route may combine several of the functions listed below.

- Basic transit mode
- Urban line-haul routes to and through the CBD
- Urban line-haul cross town routes
- Activity center and CBD distribution
- Suburban and regional line-haul routes
- Special applications.

The starting point for the planner interested in the potential application of LRT is to identify the potential passenger volumes. That information can be combined with existing right-of-way opportunities in network configurations that 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 size cities, such as The Hague, Zurich, Cologne, Rotterdam and Gothenburg. Physical dimensions and population densities in these cities are not very much different from those in the older U.S. cities of similar size. However, there are considerable differences in other urban characteristics of these cities and the younger U.S. cities, such as those in the southwestern part of the country. Thus, in Europe and the eastern United States, the population of cities in this category is generally in the range between 300,000 and two million. The population of younger U.S. cities with comparable requirements for transit is probably in the range between 500,000 and four million.

The requirements for transit service in the medium size cities which make the LRT mode a viable candidate for these applications are:

- Higher speed and reliability of service than ordinary surface transit (i.e., bus) can provide;
- Greater seating and riding comfort, which are featured in large LRT vehicles and could attract longer, regional trips from the automobile;
- Higher capacity on major routes than could be provided efficiently by buses.

Most typical LRT networks in medium size cities consist of diametrical routes, often with two or more branches in outlying areas. The central area network consists of routes on most major streets. If these sections are placed in tunnel, the central network is usually somewhat reduced. This decrease in area coverage may, in some cases, partly offset the gains obtained through higher speed and reliability or service.

In medium size cities with complete LRT networks, buses have a limited role in the central city; they operate on a few lightly traveled routes. However, their use in suburban areas, often as feeders to LRT, is extensive. In cities with partial use of LRT or streetcars, these modes share the role of the basic carrier with buses. A good example is Toronto, where the two modes and rapid transit represent an integrated transit network.

In some larger cities which abandoned streetcars as they expanded their rail rapid transit networks, LRT was retained and upgraded to provide complementary or feeder service to rapid transit.

The list of large cities which feature both rail modes includes Moscow, Philadelphia, and San Francisco; somewhat smaller cities which operate rapid transit and LRT are Boston, Cleveland, Rotterdam, Oslo, Prague and Budapest; Milan and Toronto retain streetcars as complements to rapid transit. LRT can have three different roles in cities with rail rapid transit:

- Main carrier in corridors not served by rapid transit (Boston)
- High performance feeder to rail rapid transit lines (Philadelphia Red Arrow rail lines);
- Surface carrier on lighter traveled routes (Toronto, Milan).

LRT SHARING BASIC ROLE WITH BUSES (MEDIUM AND SMALL CITIES)

In low density, medium size and in small cities, LRT can be used along certain heavily traveled corridors. In those cases, most of the transit network may be served by bus routes while LRT could serve several, or only one, heavily traveled route(s).

An example of this type of application in medium size cities is at Geneva, where one rail line carries some 30 percent of the city's transit passengers. Small cities served by "core" LRT networks are Bern, Bielefeld and Linz (Austria). The recently proposed LRT lines in Dayton and Rochester are examples of single rail lines (at least in the first stage of the transit system development) which would be complementary to the much larger bus networks.

CBD ACCESS

LRT may operate on radial or diametrical routes. Radial routes terminate in the city center and thus provide a connection between one outlying area and the center. Diametrical routes also known as traverse or through routes, consist of two radial sections connected through the central area. They can provide a better distribution in the CBD than radial routes, and avoid the problem of stub-end terminal operations in high density centers. The trend has been toward use of diametrical routes, although many radial ones operate successfully in a number of cities.

Examples of radial alignments are the five LRT routes in San Francisco, Figure 113, the Shaker Heights line in Cleveland, the Pittsburgh system and subway/surface lines in Philadelphia. Diametrical lines include the north-south streetcar routes in Philadelphia; the east-west routes in Toronto; and a great majority of LRT routes in European cities, such as Rotterdam, Dusseldorf and Stuttgart.

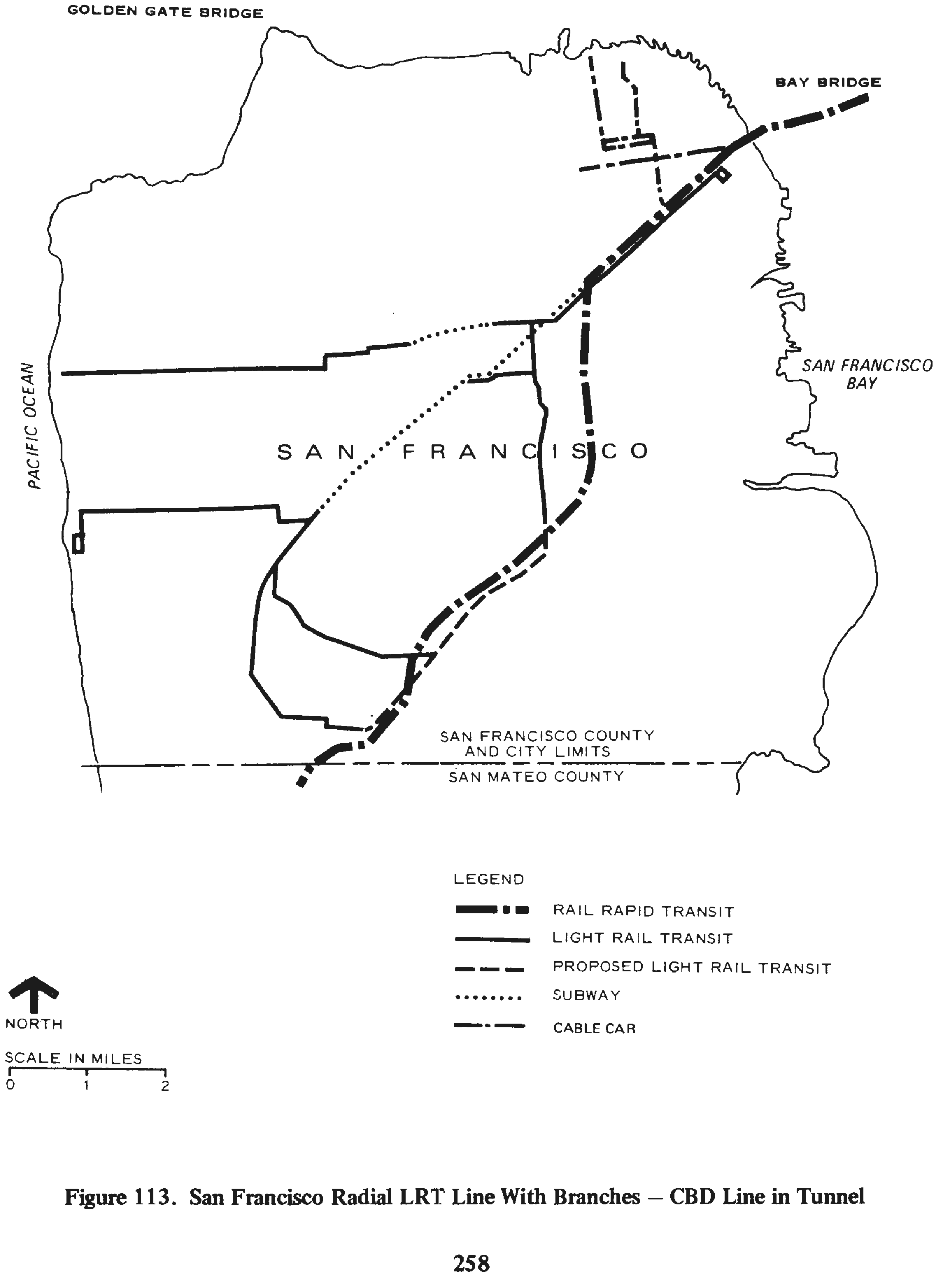


Figure 113. San Francisco Radial LRT Line With Branches – CBD Line in Tunnel

Both radial and diametrical routes may be applicable to U.S. cities. While the diametrical option may be more advantageous from the service and operations points of view, the radial option may often be built as the first stage due to funding limitations, environmental concerns or difficulties in finding adequate and extensive right-of-way through the whole CBD.

The typical LRT application is on main corridors to the CBD, where radial right-of-way opportunities are usually available. Some of these rights-of-way may be in corridors of potential demand, but rarely will then enter into or go through downtown. The lowest cost solution is to obtain a surface alignment, even if this involves on-street running.

CBD CIRCULATION

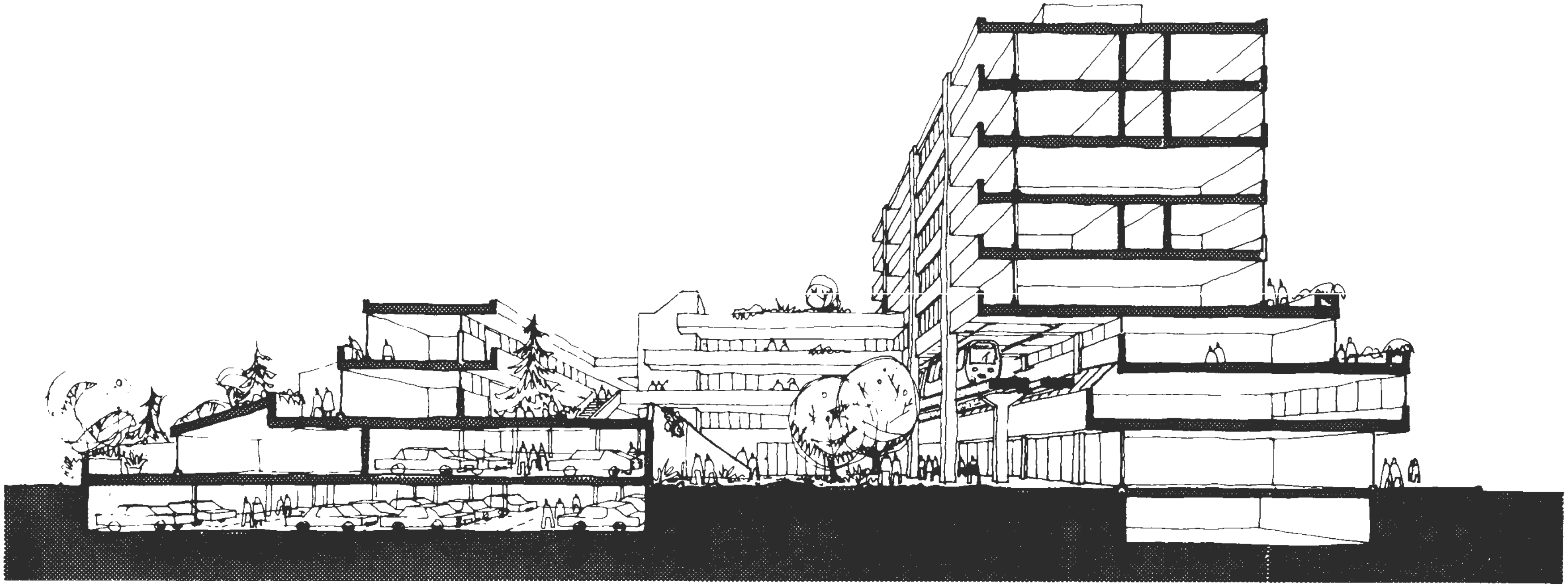
LRT can be operated in the CBD surface streets with mixed traffic, but such service is unsatisfactory in many ways. It is slow and frequently unreliable. Rail cars are delayed and often travel in platoons (a frequent phenomenon on Market Street in San Francisco prior to street reconstruction). Considerable additional congestion is created on the streets when diametrical routes are used. Delays created in central areas by surface running seriously affect regularity of service on the outbound sections of routes. Therefore, most cities are making efforts to upgrade operations of LRT in central areas. Two major procedures used for upgrading service are preferential treatment and grade separation.

- Preferential treatment on surface streets, as discussed in Chapters 4 and 7.
- Grade separation of LRT by operation in tunnels (Boston, San Francisco, Hannover, Cologne, and many other cities). Elevated alignment will rarely be acceptable although it may be possible to combine an aerial alignment with major redevelopment as illustrated in Figure 114.

Both preferential treatment and grade separation have been used extensively, particularly since the mid-1960s. Which solution is better depends largely on local conditions. Preferential treatment, when effectively implemented, provides easier access and greater convenience for passengers to board and alight, and to use the system for short distances. It is also a solution which requires only moderate investment. The problem is that opportunities for preferential treatment are limited in some cities. Also, the opportunities for high speed operation are limited, so that the service quality deteriorates as vehicles arrive from line-haul sections into the CBD (similar to modern busways terminating on congested CBD streets).

Grade separation requires a substantial investment and causes major economic and traffic disruptions, creates environmental and/or social problems, and involves more difficult access to vehicles.

However, grade separation secures high speed operation and thus assures high performance of the whole network. In addition, this solution permanently eliminates conflicts between automotive and pedestrian traffic and transit vehicles, to the benefit of all. Finally, further upgrading of LRT into rapid transit is possible, particularly if it is planned from the beginning (e.g., Brussels).



SOURCE: METROPOLITAN TORONTO TRANSPORTATION PLAN REVIEW, REPORT 63-15

Figure 114. A Hypothetical Example of an Elevated LRT Alignment Incorporated Into a New Development

If subway is the only option available, there are four approaches to minimize the cost.

- Minimize the extent of the subway. Short subways can be self-ventilating, and with the correct grade, self-draining. Use LRTs incremental capability to stage construction of the subway in sections. Combine with redevelopment when possible. Avoid or minimize underground stations. Avoid the application of rail rapid transit standards when unnecessary.
- Utilize an existing rail rapid subway to enter downtown. While such possibilities are very limited, Shaker Heights (Figure 115) is an excellent example of joint rail use by different transit systems, utilizing very different vehicle standards. Where a new subway is planned for rail rapid, vehicles compatible with rail rapid and LRT can be acquired with compatible onboard equipment, performance, signal control, floor height and width. To some extent, LRT then loses its identity and becomes a lower cost surface extension of the rail rapid service.
- Combine several LRT routes to maximize use of the expensive CBD section. Boston is an excellent example with five routes converging into the subway, and one route extending through to the other side of the city.
- Design the subway as close to the street surface as possible without mezzanine levels.

FEEDER APPLICATIONS

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. Boston's Green Line network is a good example. While maintaining high standards of performance is less critical at the outer ends of transit lines, i.e., where LRT could provide feeder services, scheduling of train arrivals at branch points may become a problem. Various operational strategies may be devised, such as coupling branch trains together (which can be done while underway between stations, as on Route 7 at Gothenburg), but the even spacing of trains on the common part of the route becomes difficult.

In most cases, other modes provide feeder services to LRT lines, but this involves transfers, principally from autos or bus transit. At stations where auto is the primary form of access, parking facilities and drop-off facilities should be designed to minimize walking distances. Where required by the climate, covered walkways would be desirable.

There are a number of examples of LRT applications providing feeder routes to rapid transit and regional rail. In Philadelphia (Figure 116), three Red Arrow Division lines (one of which is fully grade separated, the other two mostly with reserved right-of-way) terminates at the 69th Street Terminal of the Market-Frankford rapid transit line. In Rotterdam, an upgraded LRT route with reserved right-of-way and some grade separation crosses the rapid transit line south of the River Maas and serves as its feeder from two directions. In Toronto, in addition to several connections between LRT and rapid transit lines, a new high speed, grade separated LRT line is planned as a connection between the eastern terminal of the Bloor-Danforth rapid transit line and the town of Scarborough.

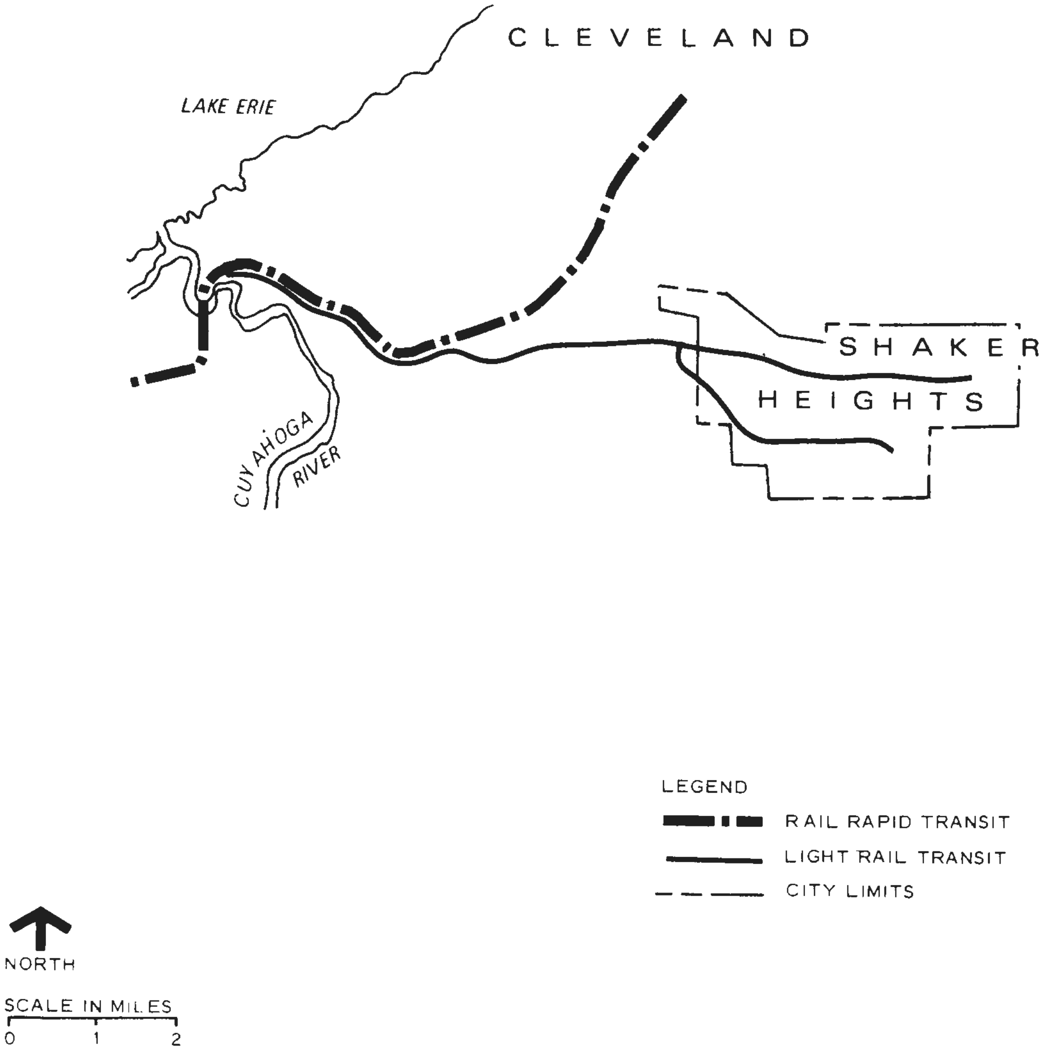


Figure 115. Cleveland-Shaker Heights Joint LRT-Rail Rapid Transit Operation

LRT can be most efficiently applied to provide feeder service to rapid transit and regional rail lines when one or more of the following conditions exist:

- A reasonably heavily travelled access corridor approaches a rapid transit station;
- A reserved right-of-way either in a street/highway median, a railroad line or other type of available public easement, can be obtained;
- The feeder line(s) would be at least two to three miles in length (otherwise the small scale operation of a single mode is extremely uneconomic);
- High speed, high quality feeder service is needed so that the investment in the rail line can be justified by greater patronage attraction compared to buses.

Most of these conditions are more typical for American than for European cities.

Figure 116. Philadelphia LRT Lines Complementing Rail Rapid Transit

SPECIAL LRT APPLICATIONS

Loops and shuttles serving as collector/distributors of major transit lines or parking lots in CBD, airports, and similar locations, can be served by light rail, as exemplified by the shuttle service between the parking area and a department store at Fort Worth. However, these applications often cannot be designated as light rail transit, although the technology may be similar.

Tourist attractions, historical concerns or special environmental requirements may also justify use of rail vehicles; again, some of these services cannot be designated as LRT systems in a strict sense since the only feature they have in common with LRT is the basic technology. Blackpool in England has retained a rail line as a tourist attraction; tourism and historical features have influenced retention of very old streetcar vehicles in New Orleans. Many European cities (Mannheim, Kassel, Zurich) have introduced LRT lines in pedestrian malls, because the operation of these vehicles is quiet and pollution-free.

Some of these design concepts may have potential use in U.S. cities, but they are less significant than the application on major radial urban transit problems.

CHAPTER 10

COMPARISON OF LRT WITH OTHER MODES

Certain fundamental considerations largely dictate the scope and direction of analyses devoted to the comparative evaluation of transit modes. These include the physical characteristics of the area under study: terrain, topography, development patterns, and especially the transportation system infrastructure. The current status of transit service also influences the analysis process. Different analytical approaches are needed, depending on whether an existing system is to be upgraded or an entirely new system is to be introduced. Finally, the characteristics of the demand which transit might serve are additional parameters of importance.

The evaluation of transit alternatives has been identified as one of the processes which will guide future Federal decisions in determining an area's eligibility for Federal assistance for major fixed guideway investments. In its statement of "Policy on Major Urban Mass Transportation Investment" dated March 1976, UMTA indicated that ...

> *Any metropolitan area which intends to apply for Federal assistance for a major mass transportation investment must undertake an analysis of alternatives with regard to any corridors in which fixed guideway facilities have been proposed for implementation.*
>
> *This analysis should estimate each alternative's capital and operating costs; ridership attraction; capital and operating efficiency and productivity; effects on modal choice, level of automobile use, air quality, and energy consumption; impact on land use and development patterns; extent of neighborhood disruption and displacement; job creation impact; and such other factors as are considered important by the local community.*
>
> *The analysis should also compare the relative cost-effectiveness of each alternative, where effectiveness is measured by the degree to which the alternative meets the locality's transportation requirements and attains its social, economic, environmental and urban preservation goals ...*[96]

While it is generally accepted that transit influences urban development, few transit planners have the opportunity to take full advantage of the distinctive attributes of a particular mode in shaping the urban environment. In general, the transit mode is fitted to a relatively inflexible urban setting. Achieving this fit typically implies selection of a transit mode which satisfies various evaluation criteria in the most effective manner, but operates at less than theoretically optimum levels. The ability of LRT to operate effectively under a wide variety of conditions may be the needed instrument to effect a better match among transit technology capabilities, travel demand patterns, and land use goals or constraints.

COMPARISON OF PROPOSED LRT SYSTEMS

Recent studies have evaluated light rail systems in different cities throughout the United States. Comparisons of these analyses will highlight some significant characteristics of LRT systems as seen in the context of contemporary transit planning. These comparisons are not intended to show whether LRT should be implemented in the cities examined, but rather to emphasize some of the main characteristics of this mode. Differences in intended service level, local topographical, operational and economic factors make it difficult to make direct comparisons between cities.

While a number of metropolitan areas in the U.S. have recently considered LRT options, the findings of the following five evaluations only are reviewed here.

- Pittsburgh, Pennsylvania: South Hills Corridor[97]
- Dayton, Ohio: Southeast Corridor[98]
- Buffalo, New York: Buffalo-Amherst Corridor[99]
- Los Angeles, California: San Fernando Valley to Long Beach Line[100]
- Denver, Colorado: Regional transportation[101]

General system characteristics, such as length of route, number of stations and their spacing, and fleet requirements, as well as various operational statistics of the various LRT proposed systems are summarized in Table 41. This tabulation shows that the proposed systems are considerably different in many important characteristics. For example, total line-haul route miles range from 79.1 for Denver to 10.7 for Buffalo. Denver has a high proportion of its guideway proposed as an aerial structure. Buffalo has extensive alignment in tunnel, while Dayton proposed almost total use of at-grade operations on existing rights-of-way.

Table 42 compares the service characteristics of the five systems. Data shown are generally for the year 1995 or 2000. The summary illustrates that the Pittsburgh and Denver systems are projected to carry volumes of 3300 and 2600 trips per route mile respectively. Buffalo shows a projected volume of 12,200 trips per route mile. This difference can be attributed to the greater average density and closer station spacing within the Buffalo corridor. Los Angeles shows projected patronage of 5700 trips per route mile, approximately twice the number for Pittsburgh or Denver. This again can be attributed to greater population densities through the light rail corridors.

Table 41. Comparison of System Characteristics of Light Rail System Alternatives

	Pittsburgh	Dayton	Denver	Buffalo	Los Angeles
Total line-haul route miles	22.4	12.2	79.1	10.7	41
• Aerial (miles)	1.2	–	28.5	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 42. Comparison of Service Characteristics of Light Rail System Alternatives

	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 miles 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

Table 42 illustrates that daily vehicle miles per route mile on the Pittsburgh, Dayton and Denver alternatives range from 600 to 670. Vehicle miles per route for Buffalo are projected at 1224, while the same number for Los Angeles is projected at 1512. The above relationships lead to a marked difference in the average daily passengers per vehicle mile. They range from 3.8 for Los Angeles and 5.0 for Pittsburgh to 10.0 for Buffalo, which generates a significantly higher number of trips than the other systems on a per route mile basis.

Table 43 summarizes total capital costs including the line-haul light rail, as well as feeder bus vehicles. A more meaningful comparison of capital costs is presented in Table 44 which summarizes the major cost items on a per route mile and per station basis. The table also summarizes the total capital costs per route mile excluding the vehicles. These costs range from $1.56 million per mile for Dayton which makes extensive use of at-grade operations on existing rail rights-of-way, to $30.26 million per mile for Buffalo with extensive tunnel sections.

COMPARISON WITH OTHER MODES

Comparisons of some generalized modal characteristics can be made between LRT systems and other transit modes. Where evaluation of comparable modes can be made for a specific corridor, the process is more straightforward and the results are more meaningful. The comparisons allow determination of the least cost alternative for basically similar operational systems instead of systems in which findings may be distorted by differences in area coverage, route patterns, and other factors.

Table 43. Comparison of Capital Costs of Light Rail System Alternatives (in millions of dollars)

	Pittsburgh (1975)	Dayton (1973)	Denver (1974)	Buffalo (1975)	Los Angeles (1975)
CAPITAL COSTS					
Property acquisition	23.3	1.8	68.2	211.3	29.0
Line-haul route cost	97.7	11.6	745.3		399.0
Line-haul station cost	28.3	1.0	148.5		132.0
Line-haul vehicle cost	77.3	14.4	80.7	36.8	108.0
Feeder vehicle cost	34.2	0.3	37.7	10.1	N/A
Other fixed facilities	77.1	4.6	119.5	43.2	30.0
Other system costs	82.1	0.1	369.9	69.3	273.0
Total Capital Costs	420.0	19.1	1,569.8	370.7	971.0

Table 44. Comparison of Unit Costs of Light Rail Systems Alternatives (in millions of dollars per route mile)

Item	Pittsburgh	Dayton	Denver	Buffalo	Los Angeles
Property acquisition	1.04	0.15	0.86		0.71
Line-haul route	4.36	0.95	9.42	19.75	9.73
Stations	0.49	0.08	2.28		3.30
Other fixed facilities	3.44	0.38	1.51	4.04	0.73
Other system costs	3.67	0.01	11.68	6.48	6.66
Total capital cost excluding vehicles	13.77	1.56	18.34	30.26	21.05

To help present as clear a picture as possible of LRT comparative parameters, *most* of the data cited below have been derived from a study of alternative transit modes for the South Hills Corridor in Pittsburgh.[102] In this fairly narrow corridor, the routing and other operational differences between the four transit modes were held to a minimum. Some cited parameters, however, are less corridor specific so that generalized conclusions may be drawn without identification of the deployment site.

In the study reviewed herein, the modes covered nearly identical alignments, and the population served varied little between alternatives. Patronage differences could be ascribed to basic operating differences between modes, such as travel times, station spacing and accessibility to stations. Differences in capital costs reflected the degree to which the various modes required exclusive facilities or could make use of available rights-of-way opportunities.

While all of the results of these comparisons cannot be directly used in other localities, the data are useful in a general planning context. They display the relative characteristics of LRT vis-a-vis the other modes in circumstances which neutralize the often confusing effects of site or routing specificity usually associated with most other transit alternatives data.

VEHICLE SYSTEMS

The systems which were considered in this comparison are:

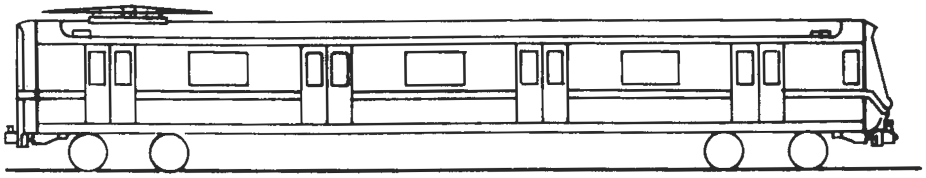
- Light rail transit (LRT) – the light rail vehicle developed by the Boeing Vertol Company.
- Rail rapid transit (RRT) – the standard four-axle rail rapid transit UMTA developed state-of-the-art car (SOAC) (Figure 117).
- Bus – the West Germany based Maschinenfabrik Augsburg Nuerbrerg (M.A.N.) articulated bus (Figure 118).
- Automated guideway transit (AGT) – the rubber-tired vehicle adapted specifically for use in Pittsburgh based upon the Westinghouse skybus vehicle (Figure 119).

Feeder service to each of the four fixed guideway alternatives was provided by conventional 40 foot buses (Figure 120). These buses also provided a part of the fixed guideway service for the busway alternative.

GUIDEWAY SYSTEMS

Because each of the alternatives in Pittsburgh involved different lengths of fixed guideway, facilities, and differing feeder bus requirements, a meaningful comparison of costs between alternatives could not be made on a system basis. A specific section of alignment common to all four alternatives was isolated for comparison of costs. This section extended from South Hills Junction south of the Monongahela River in the city of Pittsburgh to South Hills Village shopping center in the southern part of Allegheny County, about 7.5 airline miles from the downtown Pittsburgh Golden Triangle area. A summary of the guideway parameters for this example are shown in Table 45. All alternatives use guideways of essentially the same length, but some minor differences remained. The mileage differences connecting two common points result from differences in radius and curvature requirements, cross-sectional requirements, and route deviations from one alternative or another to avoid areas incompatible with that particular type of operation.

For the rail rapid transit and AGT options, differences in the cost of guideway and other facilities reflect the different geometrics of the hardware and different maintenance requirements; cost for stations and other facility elements are essentially the same. For the LRT and bus options, costs of guideways and stations are not too different, but are significantly lower for the other two modes. Based only on the cost of fixed facilities, the unit capital costs range from $19 million per mile for AGT to $7.4 million per mile for the bus option. Total projected facilities costs are, however, much higher if engineering, administration, contingencies and vehicles are included. There are also significant differences in the proportion of total costs devoted to vehicles. On a per mile basis, the percentage of costs devoted to line-haul vehicles ranges from about 20 percent for rail rapid transit and 24 percent for AGT to 29 percent for LRT and 41 percent for bus. But the inclusion of feeder vehicle costs tends to level the cost differentials: total vehicle costs range, as a percentage of total facilities cost expressed on a per mile basis, from 32 percent for rail rapid transit and 35 percent for AGT to 43 percent for LRT and 41 percent for bus.

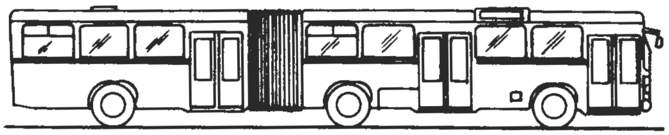


The SOAC is a standard four axle rail rapid transit car available as a self-sufficient car, or in married pairs. The self-sufficient car considered for the South Hills system is trainable, with an operator console at each car end. One operator only is required per train. The vehicle is designed for fast loading and disembarking, permitting high volume-high frequency operation. Power pickup is available via third rail or overhead pantograph, and the vehicle is designed to operate on exclusive right-of-way, with high platform loading. Descriptive data follow:

Overall length	75.0 feet	Total passenger carrying capacity* per car	150
Overall width	9.75 feet	Empty weight	90,000 pounds
Floor to ceiling height	7.36 feet	Nominal weight	112,500 pounds
Number of doors per side	4	Interior noise level	63 dBA
Door opening width	4.17 feet	Exterior noise level 50 feet from vehicle	73 dBA
Door opening height	6.30 feet		
Number of seats per car	62		

*PennDOT Standards

Figure 117. Rail Rapid Transit

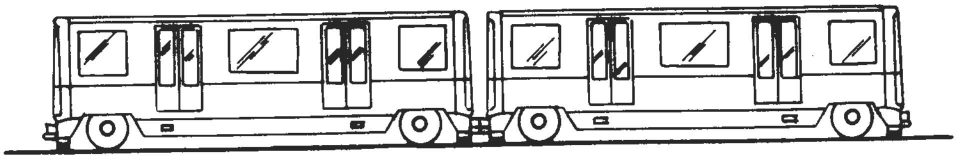


The West-German-based Maschinenfabrik Augsburg Nuerbrerg (M.A.N.) has developed the articulated bus M.A.N. Model SG 192. For the purpose of marketing in the U.S. the American M.A.N. Corp. was established, and AM-General Corporation was licensed to build the U.S. version (M.A.N./AMC). A description of the basic high-capacity bus follows:

Overall length*	54.1 feet	Number of seats per bus	52
Overall width	8.2 feet	Total passenger carrying capacity* per bus	87
Floor to ceiling height	6.56 feet	Empty weight	26,450 pounds
Number of doors (right side only)	3	Nominal weight	39,500 pounds
Door opening width (all doors)	4.1 feet		

* 59.0-foot version also available
** PennDOT Standards

Figure 118. M.A.N. Articulated Bus

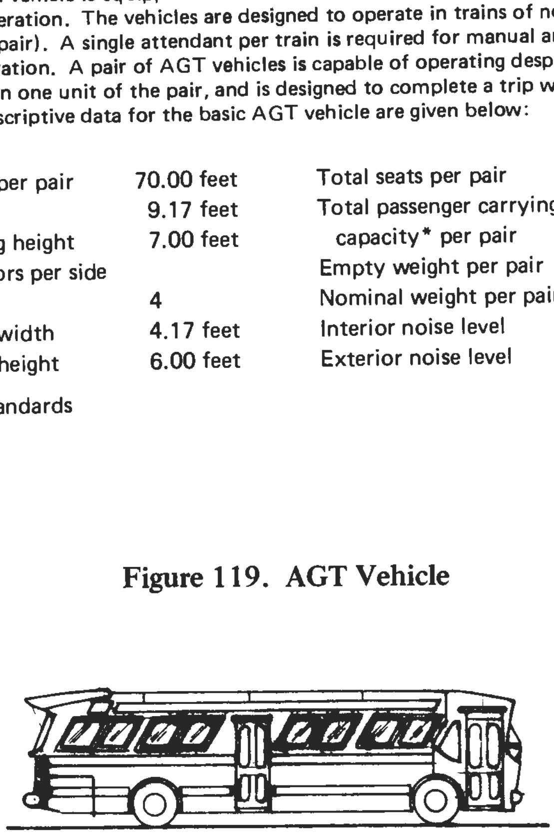


The rubber-tired AGT vehicle is positively guided by an I beam in the center of the guideway. Each vehicle is equipped with a control console at one end, and is capable of reversible operation. The vehicles are designed to operate in trains of no less than two vehicles (a pair). A single attendant per train is required for manual and semi-automated operation. A pair of AGT vehicles is capable of operating despite propulsion failure in one unit of the pair, and is designed to complete a trip with one tire failure. Descriptive data for the basic AGT vehicle are given below:

Overall length per pair	70.00 feet	Total seats per pair	52
Overall width	9.17 feet	Total passenger carrying capacity* per pair	112
Floor to ceiling height	7.00 feet	Empty weight per pair	50,000 pounds
Number of doors per side per pair	4	Nominal weight per pair	66,800 pounds
Door opening width	4.17 feet	Interior noise level	65 dBA
Door opening height	6.00 feet	Exterior noise level	75 dBA

*PennDOT Standards

Figure 119. AGT Vehicle



The conventional 40-foot urban bus is currently utilized by most operating properties in urban transit. The major manufacturers in the United States are: Flxible Company, AM-General Corporation and General Motors Corporation. The following data are for the General Motors Model TGH-5307N:

Overall length	40.0 feet	Number of passenger seats	53
Overall width	8.5 feet	Total passenger carrying capacity* per bus	67
Floor to ceiling height	6.5 feet	Empty weight	20,050 pounds
Number of doors per bus (right side only)	2	Nominal weight	30,100 pounds
Door opening width (entrance/exit)	2.5/2.2 feet	Interior noise level at bus speed of 35 mph on level grade	80 dBA
Door opening height (entrance/exit)	6.6/6.4 feet	Exterior noise level, at grade 50 feet from vehicle	84 dBA

*PennDOT Standards

Figure 120. Conventional Urban Bus

Table 45. Guideway Parameters

	AGT	LRT	RRT	BUS
Guideway (route miles)				
Aerial	4.99	0.52	4.97	0.11
At grade	1.29	6.04	1.29	6.27
Subsurface	2.27	1.28	2.28	1.28
Total	8.55	7.84	8.54	7.66
Percent Grade Separated				
Aerial	58.4	6.6	58.2	1.4
Subsurface	26.5	16.3	26.7	16.7
Total Grade Separated	84.9	22.9	84.9	18.1
At grade	15.1	77.1	15.1	81.9
Total	100.0	100.0	100.0	100.0
Number of Stations				
At grade platforms	–	26	–	26
Two level, controlled access	9	–	9	–

CAPITAL COSTS

Capital costs for the four alternatives are summarized in Table 46. The bus alternative emerges as the lowest cost in large part due to partial at-grade operation of that system. The LRT system is also low cost in relation to rail rapid transit and AGT. Again, this is primarily a function of operations at grade.

It is important to note that the alignment used in this example is part of longer routes serving a CBD area. Due to the similar traffic on each of the alternatives derived in the study, the vehicle fleet size and costs were not modified, even though only a part of the total system is being utilized in the cost comparison example.

OPERATING AND MAINTENANCE COSTS

System operating and maintenance costs include the total cost for both line-haul and collector/distributor service and all local bus service in the corridor. In comparative terms, the most significant feature is the line-haul cost per vehicle mile and per passenger mile.

Table 47 summarizes the average 1985 costs per vehicle mile for each of the four alternatives. Differences between vehicle maintenance, right-of-way maintenance, energy, transportation, and general and administrative costs can be noted. As might be expected, the vehicle maintenance costs for AGT, the most technologically sophisticated option, are higher by about 50 percent as compared with LRT, but AGT conducting transportation costs are lowest. Maintenance of the right-of-way for rail rapid transit is highest, and contributes to

Table 46. Capital Costs Comparison
(in millions constant 1975 dollars)

COST ELEMENTS	AGT (8.55 Route-miles)		RRT (8.54 Route-miles)		LRT (7.84 Route-miles)		BUS (7.66 Route-miles)	
	Total	$/Route Mile	Total	$/Route Mile	Total	$/Route Mile	Total	$/Route Mile
Guideway	70.0	8.19	59.5	6.97	22.5	2.87	26.1	3.41
Trackwork	1.8	0.21	7.5	0.88	7.5	0.96	–	–
Landscaping (guideway only)	0.3	0.04	0.3	0.04	0.0	0.0	–	–
Stations and parking lots	22.4	2.62	21.2	2.48	6.9	0.88	3.9	0.51
Rights-of-way costs	13.8	1.61	13.8	1.62	5.6	0.71	5.6	0.73
Ice and snow control	0.7	0.08	0.04	0.0	0.1	0.01	–	–
Yards and shops	15.1	1.77	9.6	1.12	7.6	0.97	7.0	0.91
Power collection and distribution	15.8	1.85	14.2	1.66	5.9	0.75	–	–
Control and crossing protection	9.8	1.15	9.0	1.05	2.0	0.26	0.7	0.09
Feeders busway facilities	13.3	1.56	13.3	1.56	13.3	1.70	13.3	1.74
Subtotal	163.0	19.06	148.4	17.38	71.4	9.11	56.6	7.39
Engineering and Administration (15%)	24.5	2.97	22.3	2.61	10.7	1.36	8.5	1.11
Contingencies (25%)	40.8	4.77	37.1	4.34	17.9	2.28	14.2	1.85
Guideway vehicles	83.7	9.79	60.3	7.06	50.4	6.43	–	–
Feeder vehicles	37.3	4.36	37.3	4.37	24.2	3.09	55.0	7.18
Total Capital Costs	349.3	40.85	305.4	35.76	174.6	22.27	134.3	17.53

Table 47. **Average Operating and Maintenance Costs Per Vehicle-Mile**

	LRT	RRT	AGT	Bus
Line-Haul System				
Vehicle Maintenance	$0.216	$0.200	$0.325	$0.258
Maintenance of Right-of-Way	0.191	0.345	0.160	0.037
Energy Cost	0.209	0.291	0.327	0.101
Conducting Transportation	0.650	0.651	0.496	0.852
General and Administration	0.532	0.532	0.450	0.628
Line-Haul Subtotal	$1.798	$2.019	$1.758	$1.876
Line-Haul and Feeder System Total	$1.658	$1.677	$1.644	$1.655

Source: Reference 97

its highest cost on a per vehicle mile basis. To illustrate the effect of the feeder bus requirements on each of the alternatives, the total system cost per vehicle mile including the feeder bus service is also shown in the table. In this example, feeder bus operations were costed at $1.58 per vehicle mile. The resulting total costs on a per vehicle mile basis are almost identical, thus illustrating the significance of feeder costs to the comparative evaluation of transit modes which might otherwise show significant differences between alternatives.

Table 48 summarizes the differences among the four Pittsburgh alternatives for costs per passenger mile in 1985. In this example, rail rapid transit operations result in the lowest cost per passenger mile, and bus operations result in the highest costs with the bus operations being significantly affected by the cost of conducting transportation per passenger mile. Comparisons between operating costs should not be based upon a single year of operation. Unit costs will change significantly over time as patronage increases and vehicle requirements change.

Table 48. **Average Operating and Maintenance Cost Per Passenger-Mile**

	LRT	RRT	AGT	Bus
Line-haul system				
Vehicle maintenance	$0.008	$0.004	$0.014	$0.015
Maintenance of right-of-way	0.007	0.008	0.007	0.002
Energy cost	0.007	0.007	0.014	0.006
Conducting transportation	0.023	0.015	0.021	0.048
General and administration	0.019	0.012	0.019	0.035
Line-haul subtotal	$0.064	$0.046	$0.075	$0.106
Line-haul and feeder system total	$0.094	$0.088	$0.101	$0.101

Source: Reference 97

LINE-HAUL CAPACITY

As discussed in earlier chapters, capacity on the line-haul portions of a transit network is determined by the combined influences of vehicle size, headways, and train lengths. Vehicle capacity should be based upon comfortable capacity and not crush load conditions. Table 49 summarizes line-haul capacities for existing conventional bus, articulated bus, light rail, and rail rapid transit alternatives. Assuming that capacity is based upon five square feet of vehicle area per passenger (a more generous allowance than used for capacity data shown elsewhere in this report), representative maximum train lengths, and minimum headways, a wide range of capacities can be projected. Capacities for AGT vary widely with the size of the particular vehicle, and are not shown in Table 49 for that reason.

Table 49. Line-Haul Capacities

	Conventional Bus	Articulated Bus	LRT	RRT
Vehicle capacity	67	87	115	130
Maximum train consist	1 bus	1 bus	3 car	8 car
Minimum headway (seconds)	30	30	90	90
Passengers per hour	8000	10,400	14,000	40,000

SCHEDULE SPEEDS

As pointed out elsewhere in this report, schedule speeds depend upon vehicle acceleration and braking rates, cruise speeds, station spacing, and station dwell times. Operating policies and different equipment designs may cause these factors to vary widely even within the same mode. Table 50 summarizes the range of speeds for *existing* transit operations. Speeds beyond these ranges are possible, e.g., by changing operating parameters, such as station spacing. Average speed on the Lindenwold Line, for example, is significantly greater than the 28 miles per hour shown below because of greater station spacing. European LRT schedule speed statistics derived from various sources and discussed in Chapter 7 are comparable with those presented in the table.

Table 50. Range of Transit Operating Speeds (mph

Mode	
Bus in mixed traffic	5 to 12
Express bus with stops	6 to 22
Streetcar	8 to 14
Light rail	16 to 25
Rail rapid transit	18 to 28

SYSTEM ATTRACTION

System attraction may be measured in relative terms that permit intermodal comparisons. Such relative productivity measures as annual riders per route-kilometer and per vehicle-kilometer are shown in Table 51 for bus and LRT operation in eight European cities, and for nine European and four U.S. rail rapid transit systems.

Passengers per route-kilometer is a surrogate for network coverage; on certain networks, a higher number of passengers per system-kilometer might be indicative of the coarseness of the network. Passengers per vehicle-kilometer reflects the relative productivity of the system. Note that all bus systems considered operate in conjunction with an LRT system and provide supporting service.

Based on the data shown in Table 51, the productivity of the LRT systems compares favorably with that of the other two modes tabulated. As a future comparison, the Buffalo-Amherst Corridor discussed earlier will generate an estimated 12,100 passengers per mile daily or 3,660,000 passengers per route mile annually (2.269 x 10^6 per route-kilometer). The Pittsburgh South Hills routes will generate an estimated 3300 passengers per day or 990,000 passengers per route mile annually (0.618 x 10^6 per route-kilometer).

TRAVEL TIME AND ACCESSIBILITY

Total trip time includes the time required to travel from origin to destination including all ride time, waiting time, access time, transfer time, and the time lost when the vehicle is stopped. For each of the transit modes evaluated, these time components vary greatly and affect the number and character of trips that will be attracted to each alternative. The differences in travel time for each alternative and their general impact upon accessibility, as perceived in the South Hills Corridor at Pittsburgh, are summarized as follows:

AGT and rail rapid transit involve the fastest travel time on the fixed guideway portion of the trip. However, average feeder bus trips are involved of a longer distance with a greater number of transfers between transit modes.

Table 51. System Performance Comparison

Mode	Passengers/Route-Km (Range) (Mean x 10^6)	Passengers/Veh-Km (Range) (Mean x 10^6)
Bus (8 European cities)	0.064 - 0.383 0.183	1.923 - 6.667 3.356
LRT (8 European cities)	0.632 - 2.169 1.015	4.054 - 9.800 6.514
Rail Rapid (9 European cities)	1.321 - 11.461 3.949	1.912 - 10.345 6.034
Rail Rapid (4 U.S. cities)	0.402 - 0.912 0.693	0.288 - 2.382 1.168

Source: Reference 103

LRT involves greater travel time on the fixed guideway facility, lesser and shorter feeder bus trips, and a higher percentage of access trips by walking. It also involves a lesser percentage of transfers than the AGT and rail rapid transit systems.

Express bus generally involves the greatest total travel time. However, a high percentage of this travel time is on a single transit vehicle, since a high percentage of the buses will pick up trips in neighborhoods before entering the fixed guideway system. This also results in very low percentages of required transfers.

At Pittsburgh, these factors combined to project relatively similar patronage for all modes, but with significantly different patterns of transit trips. On AGT and rail rapid transit, the higher line-haul speed would balance the longer access travel time and induce a higher percentage of long distance trips. On LRT, the close spacing of stations and easy walk-in access balanced the lower speed and was projected to induce a higher percentage of short distance trips within the corridor.

PASSENGER COMFORT AND CONVENIENCE

The ability of a system to provide a clean, quiet and comfortable environment for the rider will significantly affect its usage. Pertinent measures of ride quality describing passenger comfort and convenience are summarized in Table 52.

The bus alternative can carry, generally, the highest percentage of capacity seated and has the lowest acceleration rate. However, it is the least convenient vehicle to board.

LRT has, generally, a lower percentage of seated capacity. Under crush load conditions a higher percentage of passengers can be accommodated standing. The acceleration is higher but still within passenger comfort limits, and there is improved boarding convenience compared with the bus.

AGT (as specified for the Pittsburgh study) and rail rapid transit have the lowest percentage of passengers seated but have high levels of boarding convenience.

Another very important measure of passenger comfort and convenience is the attractiveness of the stations and the amenities they provide. Elements of station facilities for each of the four alternatives considered in Pittsburgh are summarized in Table 53.

TRANSFERS

Comfort and convenience must also be considered from the standpoint of the necessity to transfer between transit modes. In the Pittsburgh comparisons, bus transit generally requires the lowest percentage of transfers and brings transit service directly into the neighborhoods providing a direct trip on the fixed guideway facility into downtown. LRT results in the

Table 52. Measures of Ride Quality

	LRT	RRT	AGT	Bus
Ratio of Seated to Standing Passengers	50	45	46	61
Service Acceleration Rate (feet per second^2)	4.5 - 5.1	3.9 - 4.8	4.5 - 6.4	0.3 - 3.2
Door Opening Width per Car (one side in feet)	13.5	16.7	16.7	12.3

Table 53. Outlying Station Amenities

	LRT	RRT	AGT	Bus
Air Conditioning	No	Yes	Yes	No
Heating	Yes	Yes	Yes	Yes
Elevators	N/A	Yes	Yes	N/A
Escalators	N/A	Yes	Yes	N/A
Lavatories	No	Yes	Yes	No
Capacity for Concessions	No	Yes	Yes	No
Lighting	Yes	Yes	Yes	Yes
Rain Shelter	Yes	Yes	Yes	Yes
Attendant on Duty	No	Yes	Yes	No

second lowest percentage of transfers, principally because a higher percentage of the total riders walk to the stations. (Conceivably, this could be an offsetting disadvantage during inclement weather.) AGT and rail rapid transit require the highest percentage of transfers, with almost 20 percent of the passengers making two transfers or more.

Table 54 summarizes the transfer requirements for each alternative system scheduled in Pittsburgh.

Table 54. Percent of Trips Requiring Transfer
Average Weekday – Year 2000

	LRT	RRT	AGT	Bus
No Transfer	33	27	27	41
One Transfer	51	54	54	53
Two or More Transfers	16	19	19	6

Source: Reference 97

ABILITY TO SERVE TRANSIT DEPENDENT GROUPS

The ability of the system to serve transit dependent groups, particularly the aged and handicapped, can be evaluated a number of ways: first, from the standpoint of walk-in coverage; second, from the standpoint of ease in boarding the vehicle from street platform level; and third, from the standpoint of station design.

Because of the generally greater station spacing on rail rapid transit systems, there is a significant reduction of walk-in coverage, which could adversely affect transit dependent groups over 65 years of age and households with no car. From the standpoint of direct access to stations without utilization of an automobile or a supplementary transit mode, the comparison is as follows.

Buses provide the highest level of service to transit dependent groups, because they can provide direct service into the neighborhoods. Due to their flexibility, buses can provide direct service to institutional buildings.

LRT provides the second highest level of service, because this concept provides a greater number of stations per mile from which access to the system can be obtained. AGT and rail rapid transit provide the lowest level of direct access to transit dependent groups because of limitations in corridor coverage and greater distances between stations.

At Pittsburgh, from the standpoint of ease of boarding the vehicle, AGT and rail rapid transit represented the highest level of service, because they could be boarded by ambulatory persons directly from station platforms. Because of the spaciousness of the vehicles, they could most readily accommodate wheelchairs or persons on crutches. LRT and bus alternatives could be provided with special boarding facilities for aged and infirmed passengers. However, these special modifications would be at an added cost per vehicle, and each vehicle would have to be so equipped to make the system totally effective.

From the standpoint of the station facilities proposed at Pittsburgh, the AGT and rail rapid transit alternatives would be provided with escalators and elevators in all stations providing direct access from the street to platform levels where persons can conveniently board the vehicles. These stations would also provide comfort and heating to accommodate passengers in inclement weather. The LRT and bus alternatives would have station platforms at street level and generally would be protected by shelters in only one direction of travel. These station facilities would less comfortably accommodate aged and infirmed persons.

No attempt is made to arrive at an overall rating of the four alternatives from the standpoint of their ability to serve transit dependent passengers. However, from the standpoint of those who are ambulatory, LRT and bus transit offer advantages, because they are more accessible to direct walk-in patronage. From the standpoint of those persons who are not ambulatory and who will most likely be driven to the transit facilities, the automated guideway and rail rapid transit alternatives offer advantages, because they have protected station facilities, escalators and elevators, and direct access from platform level.

PASSENGER SECURITY

The following subjective assessment of passenger security is based upon the assumptions that risk is greater when there are a greater number of stations, when stations are unattended, when access and waiting times are longer, and when train lengths are longer and cars are unattended.

Rail rapid transit generally offers the best degree of in-station security, because a lesser number of line-haul stations are involved. On new systems, stations are generally well lighted and attended at all times.

LRT and bus transit could offer the best passenger security from the standpoint of access and waiting times, given a frequency of service comparable to that of rail rapid transit, because they involve shorter access times to the stations and a lower percentage of transfers. LRT and bus offer the best on-board security where operating policies and vehicle characteristics dictate there be an operator in each vehicle at all times.

Studies in Chicago and other cities have shown that the probability of risk from assault on a station platform is far greater than on-board the vehicle. On an overall basis, therefore, rail rapid transit would have to be rated the highest from the standpoint of passenger security.

PASSENGER SAFETY

At Pittsburgh, the level of safety of each alternative system was assessed in relation to the reported safety performance on conventional bus and rail rapid transit systems. A qualitative comparison of hazards is shown in Table 55.

AGT and rail rapid transit, because of their exclusive guideways, represent safe systems. Potential accidents in most categories would be minimal and the possibility of fixed object collisions would be small, because of the completely grade separated, limited access facilities.

LRT at-grade operations increase the risk of vehicle-vehicle and vehicle-fixed object collisions, but the effects may be mitigated by LRT's lower speeds. The *risk exposure* needs to be considered also. Vehicle-vehicle or vehicle-fixed object collisions of LRT would involve, on the average, fewer passengers than on rail rapid transit but more than on AGT or bus options. The probability of injury or fatality may, therefore, not be significantly different than on other modes, and in most cases, actually may be lower than on rail rapid transit. Compared with a bus, the massive structure of the light rail vehicle offers more protection to passengers in the event of low to moderate vehicle-vehicle collisions.

POTENTIAL FOR SYSTEM EXPANSION

LRT and bus transit possess the highest expansion capabilities. Bus transit provides the greatest potential for expansion of service within its service area. With changes in or additions to bus routings, service can be altered to meet changes in demand. With other systems, changes of demand in the service area would be served by changes in the feeder system.

LRT has the greatest potential beyond its immediate service area. It, along with the bus, would be less obtrusive than automated guideway or rail rapid transit systems, and could be extended along existing rights-of-way. The AGT and rail rapid transit systems would encounter the most difficulty in extension, because of fewer right-of-way opportunities and restriction of at-grade operation.

Table 55. Qualitative Assessment of Hazards

	LRT	RRT	AGT	Bus
Accidents in Stations	Low	Low	Low	Low
Accidents at Vehicle-Station Interface	Low	Low	Low	Low
On-board Accidents	Minimum	Minimum	Minimum	Moderate
Vehicle-Vehicle Collisions	Moderate	Low	Low	Minimum
Vehicle-Fixed Object Collisions	Moderate	Nil	Nil	Minimum
Vehicle-Non-User Conflicts	Moderate	Minimum	Minimum	Moderate

SCHEDULE RELIABILITY

The comparisons summarized in Table 56 represent estimates of reliability measured in terms of mean time between failures (MTBF) for individual units (vehicles or trains, as appropriate). The vehicle MTBF shown in the table is for individual vehicles; systems operating in trains have a higher MTBF.

Reliability is best compared in terms of schedule reliability (number of trips completed per 100 trips originated). All alternatives shown will meet an initial goal established for Pittsburgh of 97.5 trips completed on time per 100 trips at eight minute headway.

Table 56. System Reliability

	LRT	RRT	Bus
Single Vehicle MTBF (hours)	426	424	421
Single Switch MTBF (hours)	3,600	3,600	–
System Power and Wayside Equipment (hours)	10,000	10,000	10,000
Schedule Reliability (trips completed on schedule per 100 trips)	99.5	99.7	99.6

Source: Pittsburgh Study

REFERENCES

1. Colin Buchanan, *Traffic in Towns* (London: Her Majesty's Stationery Office), 1963.

2. R.J. Henderson, "Transport in Towns: The Development of Public Policy," Working Paper No. 2 (Coventry: University of Warwick Urban Transport Research Group), 1972.

3. "U.S.A.," *Verkehr und Technik* Sonderheft 1960.

4. Hollatz and Tamms, *Die Kommunalen Verkehrsprobleme in der Bundesrepublik Deutschland* (Essen, West Germany: Vulkan Verlad), 1965.

5. *Statistiche Ubersichten 1974* (Cologne, West Germany: Verband Offentlicher Verkehrsbetriebe), 1975.

6. M. Bigey, "Le Transport Public, Instrument d'une Politique Urbaine," *Transports Urbains* January-March, 1975. pp. 11-12.

7. Friedrich Lehner, "Light Rail and Rapid Transit," *Light Rail Transit: Special Report 161* (Washington, D.C.: Transportation Research Board), 1975.

8. Verband Offentlicher Verkehrsbetriebe.

9. Vukan R. Vuchic, *Light Rail Transit Systems: A Definition and Evaluation* prepared for the U.S. Department of Transportation, Transportation Systems Center, Report DOT-TSC-310-1, October, 1972.

10. Interplan Corporation, *Integration of Transit Systems* Vols. I and II, prepared for the U.S. Department of Transportation, Urban Mass Transportation Administration, 1973.

11. *Lea Transit Compendium: Light Rail Transit* Vol. 1, No. 5 (Huntsville, AL: N.D. Lea Transportation Research Corporation), 1975; *Annual Statistics of the U.I.T.P.* (Brussels: Union of International Public Transport); *Transports Urbains* Vol. 30, No. 5, 1975; various issues of *Modern Tramway and Rapid Transit Review.*

12. *Tyne & Wear Rapid Transit Analysis* (London: Alan M. Voorhees & Associates), June 1972; Tyne & Wear Public Transport Executive, *A Plan for the People* (Newcastle-upon-Tyne: Tyneside Passenger Transport Authority), September, 1973.

13. John J. Fruin, *Pedestrian Planning and Design* (New York: Metropolitan Association of Urban Designers and Environmental Planners, Inc.), 1971.

14. C. F. Hirschfield, "The Electric Railway Presidents' Conference Committee Streetcar Research and Development Program: Five Technical Bulletins 1931-1933," Report UMTA-RDD-31-75-1.

15. Joseph S. Silien and Jeffrey G. Mora, "North American Light Rail Vehicles," *Light Rail Transit: Special Report 161* (Washington, D.C.: Transportation Research Board), 1975.

16. Joachim Von Rohr, "Foreign Light Rail Vehicle Development," *Light Rail Transit: Special Report 161* (Washington, D.C.: Transportation Research Board), 1975.

17. Manuel Padron and Richard Stanger, *The MARTA Study of No-Barrier Fare Collection Review and Discussion: Preliminary Draft Report* August, 1975.

18. H. Wenz, "Automatic Fare Collection in Surface Transport," presented at the 40th International Congress of the International Commission on Economic Policies in Europe (Brussels: International Union of Public Transport), 1973; Dr. R. Gutknecht, "Alternative Approaches to Public Transport Fares with their Revenue Implications," presented at the 40th International Congress of the International Commission on Economic Policies in Europe (Brussels: International Union of Public Transport), 1973.

19. Padron and Stanger.

20. Gerald D. Fox, *Light Rail Transit Systems, 1975: A European Trip Report* prepared for De Leuw, Cather & Company, August, 1975.

21. Ibid.

22. G. F. Swetnam, *Rationale for Exterior and Interior Noise Criteria for Dual-Mode and Personal Rapid Transit Systems* (McLean, VA: Mitre Corporation), Report MTR-381, March, 1973.

23. Ibid.

24. 1973 APTA data.

25. G. D. Fox

26. *Manual on Uniform Traffic Control Devices* prepared for the U.S. Department of Transportation, Federal Highway Administration, 1971.

27. John B. Hopkins, *Grade Crossing Protection in High-Speed High-Density Passenger Service Rail Corridors: Final Report* prepared for the U.S. Department of Transportation, Transportation Systems Center, Report FRA-ORD-D-74-14, September, 1973.

28. *Medium Capacity Transit System Study: Traffic Analysis* (Los Angeles: De Leuw, Cather & Company), prepared for the Southern California Rapid Transit District, October, 1975.

29. Ibid.

30. V. R. Vuchic, *LRT: A Definition.*

31. Frits Van Dam, "Tram (Bus) Priority at Intersections," Translation from Dutch to be published in *Modern Tramway.*

32. "Points and Traffic Lights Under Common Control Using Vetag," *Railway Gazette International* May, 1975. pp. 193-194.

33. N. D. Lea, *Light Rail Transit.*

34. De Leuw, Cather, *Medium Capacity.*

35. "Surface Transportation Systems," (Philadelphia: Boeing Vertol Company), June, 1975.

36. John Baerwald, *Traffic Engineering Handbook* 3rd ed. (Washington, D.C.: Institute of Traffic Engineers), 1965.

37. N. D. Lea, *Light Rail Transit.*

38. A. Bockemuhl and F. Bandi, "Horizontal and Vertical Separation of Public and Private Transport to Improve the Fluidity of Urban Traffic," XXXVth International Congress of the U.I.T.P., Vienna, 1963, (Brussels: International Union of Public Transport).

39. V. R. Vuchic, *LRT: A Definition.*

40. P. Reynaert, "A Consideration of Underground Urban Transport Systems: Metropolitan Railway, Underground Tramway or Motorbus Tunnels?," XXXVIIIth International Congress of the U.I.T.P., Barcelona, 1967, (Brussels: International Union of Public Transport).

41. "Promotion of Urban Public Transport," European Conference of Ministers of Transport, December, 1973.

42. *Light Rail Alternatives for San Diego Region* County of San Diego Public Works Agency, Department of Transportation, December 19, 1974.

43. D. B. Sanders and T. A. Reynen, *Characteristics of Urban Transportation Systems: A Handbook for Transportation Planners* prepared for the U.S. Department of Transportation, Urban Mass Transportation Administration, Report UMTA-IT-06-0049-74-1, PB 233 580, May, 1974.

44. N. D. Lea, *Light Rail Transit.*

45. *Lea Transit Compendium: Bus Transit* Vol. 1, No. 7, (Huntsville, AL: N.D. Lea Transportation Research Corporation), 1974.

46. V. R. Vuchic, *LRT: A Definition.*

47. *Recapitulation by Type: Traffic and Passenger Accidents* (New Orleans: New Orleans Public Service), 1974.

48. *Comparison Claims: Experience Report* (San Francisco: San Francisco Municipal Railway Claims Department), 1970-71, 1971-72, 1972-73.

49. G. D. Fox.

50. Hoy A. Richards and G. Sadler Bridges, "Traffic Control and Roadway Elements: Their Relationship to Highway Safety," *Railroad Grade Crossings* revised (Automotive Safety Foundation), 1968.

51. Donald E. Bray, "Noise Environments in Public Transportation," Joint ASCE-ASME Transportation Engineering Meeting, Seattle, Washington, July 26-July 30, 1971. Preprint 1469.

52. G. F. Swetman and F. L. Willingham, *Evaluation of Urban Transit Bus Modification Kits to Reduce Engine Smoke, Odor, Noxious Emissions and Noise* (McLean, VA: Mitre Corporation), Report UMTA-06-0022-73-1, May, 1973.

53. "Noise Levels Measures in Three European Tramcars," *Railway Gazette International* December, 1974. p. 482.

54. H. C. Meacham and W. D. Kaiser, *A Survey of Vehicle Design and Analysis Related to an Advanced Light Rail Transit System* (Columbus, OH: Battelle), October 31, 1974.

55. Boeing light rail vehicle data on noise, energy and ride quality received from John Cord, Boeing Vertol Company, Philadelphia, PA.

56. W. S. Murray, *Exterior and Interior Noise Levels of Shirley Express Buses* (McLean, VA: Mitre Corporation), Report WP 8698, March 24, 1974.

57. George P. Wilson, "Rapid Transit Noise and Vibrations," prepared for the American Transit Association Rail Transit Conference, April 1971; Robert H. Spencer, "Noise Control of New Rapid Transit Cars," (Philadelphia: Boeing Vertol Company), prepared for Inter-Noise '74, Washington, D.C., September 30-October 2, 1974; Donald E. Bray, "Noise Environments"; "Noise Levels Measures in Three European Tramcars," *Railway Gazette International.*

58. E. C. Richley, R. Yursin, G. Byron, *Noise Level Measurements on the UMTA Mark I Diagnostic Car (R42 Model)* prepared for the U.S. Department of Transportation, Transportation Systems Center, Report DOT-TSC-UMTA-72-3, October, 1971.

59. Meacham and Kaiser.

60. John J. Mede, "The Acousta-Flex Wheel and its Contributions to Sound Suppression," presented at the American Transit Association Conference, April 15, 1971.

61. Ibid.

62. J. J. Enright, *An Investigation of Steel Wheel Rail Noise and Techniques for its Suppression* (Columbus, OH: Battelle), PB 178-256, October, 1967.

63. G. D. Fox.

64. Ibid.

65. Boeing test data from John Cord.

66. Ibid.

67. J. G. Lieb, *A Comparative Analysis of the Energy Consumption for Several Urban Passenger Ground Transportation Systems* (McLean, VA: Mitre Corporation), Report MTR-6606, February 6, 1974.

68. C. E. Hanson and L. E. Wittig, "The Prediction of Wayside Railroad Noise," presented at the Transportation Research Board Annual Meeting, Washington, D.C., January 14, 1975.

69. Paul J. Remington et al., *Wheel/Rail Noise and Vibration Control* prepared for the U.S. Department of Transportation, Urban Mass Transportation Administration, Report UMTA-MA-06-0025-73-15, May, 1974.

70. G. F. Swetnam and W. S. Murray, *Feasibility Study of Noise Control Modifications for an Urban Tansit Bus* (McLean, VA: Mitre Corporation), Report MTR-380, March, 1973.

71. N. D. Lea, *Light Rail Transit.*

72. Ibid.

73. Discussion with Lorne Main, Vice President, Urban Transportation Development Corporation.

74. G. D. Fox.

75. N. D. Lea, *Light Rail Transit.*

76. H. P. Kaper, ed., "De Sneltram," committee report in Dutch, (Utrecht), 1975.

77. *Cost Estimates and Basis of Estimates for The Alternatives Analysis* (Denver: De Leuw, Cather & Company), prepared for the Regional Transportation District, Denver, Colorado, April 28, 1975.

78. George R. Beetle, "Light Rail Construction Costs," *Light Rail Transit: Special Report 161* (Washington, D.C.: Transportation Research Board), 1975.

79. Thomas K. Dyer, Inc., *Rail Transit System Cost Study: Final Report* prepared for the U. S. Department of Transportation, Transportation Systems Center, Report DOT-TSC-808, July, 1975.

80. J. H. Boyd, N. J. Asher and E. S. Wetzler, *Evaluation of Rail Rapid Transit and Express Bus Service in the Urban Commuter Market* prepared for the Institute of Defense Analysis, October, 1973.

81. *Engineering News-Record* March, 1975, pp. 62-63.

82. De Leuw, Cather, *Cost Estimates.*

83. American Transit Association, *1972 Transit Operating Report*, American Transit Association, *1973 Transit Operating Report*; "Summary of Financial Data and Operating Statistics on Streetcar System for the Ten Year Period of 1964 through 1973-74," (San Francisco: San Francisco Municipal Railway); "Trams and Light Rail Transit in the United Kingdom," (Coventry: University of Warwick Urban Transport Research Group), Working Paper No. 24; P. J. Walker, *Trip Report* prepared for De Leuw, Cather & Company; Correspondence with W. E. Henry, Transport of New Jersey, September 29, 1975; G. D. Fox.

84. International Monetary Fund, *International Financial Statistics* Vol. XXVIII, No. 9, September, 1975, and *Supplement*, 1973.

85. American Transit Association,*'73-'74 Transit Fact Book.*

86. American Transit Association, *1972 Transit Operating Report*; P. J. Walker, *Trip Report.*

87. *Statistical Abstract of the United States, 1973* p. 555; P. J. Walker, *Trip Report.*

88. D. B. Sanders and T. A. Reynen; N. D. Lea, *Light Rail Transit.*

89. *Development of Land Use and Transportation Alternatives* Report 62, (Toronto: Metropolitan Toronto Transportation Plan Review), 1974.

90. Tom E. Parkinson, "Light Rail Transit System Evaluation," *Light Rail Transit: Special Report 161* (Washington, D.C.: Transportation Research Board), 1975.

91. Ibid.

92. C. Kenneth Orski, ed., *The Urban Transportation Planning Process and Future Directions for Research in Urban Transportation* (Paris: O.E.C.D.)

93. Gregory L. Thompson, *Public Transport and the Metropolis: an Examination of Public Policy Focusing on the Bay Area* M.A. thesis, University of California, Berkeley, 1970; Gregory L. Thompson, "A Macro Analysis of the Factors Influencing Transit Usage," (Vancouver: British Columbia Bureau of Transit Services), 1973.

94. Brian E. Sullivan, "The Timed Transfer Focal Point: a Refinement in Public Transport Service Design," (Vancouver: British Columbia Bureau of Transit Services), February, 1975.

95. J. J. Baekker and T. O. Clement, "Transit Trends in Edmonton," Roads and Transport Association of Canada, 1974 Annual Meeting.

96. *Policy on Major Urban Transportation Investment: Draft* (Washington, D.C.: Urban Mass Transportation Administration), March, 1976.

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

98. *Dayton Light Rail Transit System Implementation Application: Southeast Corridor* (Dayton: Montgomery-Greene County Transportation and Development Planning Program), prepared for the Miami Valley Regional Transit Authority, Dayton, Ohio, July 14, 1975.

99. *Evaluation of Transit Alternatives Buffalo-Amherst-Tonowanda Corridor: Staff Conclusions and Recommendations* (Buffalo: Niagara Frontier Transportation Authority, Metro Construction Division), February, 1976.

100. De Leuw, Cather, *Medium Capacity.*

101. *Transit Concept Comparison: Long Range Transit Development Analysis* (Denver: System Management Contractor), prepared for the Regional Transportation District, Denver, Colorado, April, 1975.

102. De Leuw, Cather, *Comparative Analysis, South Hills.*

103. International Union of Public Transport, *Annual Statistics of the U.I.T.P.; Lea Transit Compendium: Heavy Rail Transit* Vol. II, No. 6, (Huntsville, AL: N. D. Lea Transportation Research Corporation), 1975.

APPENDIX I

OPERATING AND MAINTENANCE COSTS*
(WEST GERMAN PRACTICE)

Because West German operators often combine the management of LRT with that of other transit operations, specific light rail O&M cost data is not always readily available. Often, the LRT O&M costs can be only estimated as a share of the total cost reported. It is somewhat difficult to obtain basic O&M cost information, because transit agencies, for understandable reasons, are sometimes reluctant to release it. Data from a number of unidentified LRT operating agencies and one rail rapid transit agency are included in this review. Costs are sometimes related to vehicle-kilometers and sometimes to passenger space-kilometers, requiring that the appropriate conversion be made to establish some equivalence of the data.

West German transit operators include two categories in O&M costs: "pure operating costs" and "capital service costs".

PURE OPERATING COSTS

TRANSPORTATION COSTS

These costs are personnel costs, including drivers, supervisors, personnel in yards and stations, etc. In West Germany, neither light rail nor rail rapid transit employ conductors or other train crew. Most of the new transit systems, e.g., the U-Bahns in Munich and Hamburg, do not have personnel on station platforms either. Personnel costs include the costs of materials for uniforms, tickets, automatic ticketing machines, etc.

VEHICLE MAINTENANCE COSTS

These costs are the personnel and material expenditures necessary for the care, maintenance and cleaning of the operating vehicle fleet. This cost category includes cleaning of the cars, tests, and repairs of the equipment as specified by operating instructions. The instructions are based on the legal requirements spelled out in the *Betriebsordnung Strassenbahn* (BOStrab) [operating regulations for streetcars], dated 31 August 1965.** According to paragraph 9 of the BOStrab the operating safety of facilities and vehicles must be controlled by regular observations, functional checks and controlled measurements. Particular attention must be given to the effectiveness of the brakes and the electric equipment in the motor control. Vehicles built after January 1, 1950, must be overhauled at least every 500,000 kilometers or at least every eight years, as well as after heavy accidents.

TRACK MAINTENANCE COSTS

These costs include expenses for personnel and material required to clean and maintain the tracks. According to paragraph 9 of BOStrab, the operating safety of all fixed facilities must be checked by qualified personnel at least once every three years.

---

*The material in this appendix was furnished by Dr. Friedrich Lehner.

**While the original BOStrab was drafted for streetcars only, it is also used in light rail and rail rapid transit operations. A revision of BOStrab is underway at this time.

WAYSIDE FACILITIES MAINTENANCE COSTS

These costs include expenditures for personnel and material required to maintain the power supply (catenary or third rail), as well as the signal and block control equipment. According to paragraph 9 of BOStrab, all overhead wires must be examined every three years, the signal block control equipment and escalators at least every two years.

ENERGY COSTS

This category includes the cost of AC power purchased by the transit agency and the cost of the transformers. According to the BOStrab, the power supply facilities must be checked at least every 5 years.

OTHER COSTS

Additional cost elements classified as pure operating costs are the costs for maintaining buildings and grounds, and the general and administrative costs.

CAPITAL SERVICE COSTS

These costs include allowances for the depreciation of the equipment and vehicles, as well as the interest. The following depreciation rates (linear) are used by West German transit agencies:

Vehicles	4% of the purchase price
Tracks	3% of the purchase price
Wayside equipment	3% of the purchase price
Tunnel facilities	1 to 1.5% of the purchase price
Buildings	2% of the purchase price

The interest on capital is commonly calculated at the rate of 6.5 percent based on half of the invested capital. Depreciation and interest on tunnel structures are considered separate items in West German practice. Since tunnels are considered to be "underground streets", the cities provide the tunnels for the transit agencies and also financing and maintenance.

COST DETAILS

TRANSPORTATION COSTS

Vehicle Operators

In 1975, annual costs for drivers averaged \$14,600[*] including benefits which amount to some 25 percent of the total wages. Average hourly wages were \$5.40. In estimating the

---

[*] Cost data have been converted from DM to American dollars at the most recent 1976 rate of 2.4 DM/\$.

transportation costs for future installation, it is customary, in West German practice, to consider personnel efficiency, defined as the ratio of productive hours to paid hours. The efficiency is estimated by multiplying four separate coefficients which are defined as follows:

- Schedule efficiency is defined as the ratio of average speed to operating speed. Because of legal requirements for crew rest time, this coefficient can amount, at most, to 0.857. In practice, it lies between 0.75 and 0.85, with an average of 0.8.
- Working efficiency is used to indicate the loss of productive hours due to vacation, illness and suspension from service. This coefficient varies between 0.8 and 0.85.
- Roster efficiency accounts for unproductive hours in the schedule, including time spent in preparing for and ending work, lunch breaks, etc. Common values of this factor range between 0.75 and 0.85 with an average of 0.8. This efficiency factor, which was 0.85 to 0.92 in 1953, has decreased considerably with the improvement of working conditions.
- Service fluctuation efficiency accounts for work losses due to weekly fluctuations of operations. It can be as high as 1.0. Fluctuations are compensated by convenient rostering.

Multiplication of the four efficiency factors gives the overall personnel efficiency coefficient. For West German light rail operations, this lies between 0.5 and 0.6, with a good average of value considered to be 0.5. This factor indicates that drivers are productive for only 50 percent of the paid hours.

In West German transit operations, there are significant variations in driver costs estimates based on costs per passenger space-kilometer* for different modes and types of operations. Typical driver productivities per year on various systems is as follows:

- Hannover streetcar – for 4- and 6-axle vehicles, 5.15 million passenger space-kilometers per driver.
- Hannover bus – 2.10 million passenger space-kilometers per driver.
- Hannover light rail – for 8-axle articulated cars (2 per train in peak hours), 8.5 million passenger space-kilometers per driver.
- Hamburg rapid transit – 24.39 million passenger space-kilometers per driver for an average train length of 5.4 cars per train.
- Hamburg bus – 1.72 million passenger space-kilometers per driver.
- Munich rapid transit – 20.5 million passenger space-kilometers per driver (1973), for an average train length of 4.6 cars per train.

---

*A designation for unit capacity of a transit vehicle per kilometer, e.g., an LRV with a capacity of 100 passengers seated and standing will yield a *passenger space-kilometer* of 1,000 when traversing a 10 kilometer line.

- Munich rapid transit – 28.0 million passenger space-kilometers per driver (1974), for an average train length of 4.6 cars per train.
- Munich light rail – 4.9 million passenger space-kilometers per driver.

Other Transportation Costs

Other personnel employed in transit operations include employees working on scheduling, rostering, driver education, supervision, ticket sales, collection of fares, management of yards, etc. The number of personnel depends on the scale of the operation, as well as on the organizational structure of the transit agency. These differences cause wide fluctuations in the number of employees. Based on a survey of nine transit agencies, the number of other employees amounts to 70 per billion space-kilometers with a variation of ±30 percent. This estimate is valid for operations of one man crews on all modes. The ratio of drivers to total operating personnel varies with driver productivity, and can be graphed against annual passenger space-kilometers per driver (Figure I-1). This differs among modes. The ratio of drivers to total operating personnel is highest for streetcars and lowest for rail rapid transit: streetcars fall in the left upper portion of the shaded band in Figure I-1; LRT is lower, and rail rapid transit is the lowest. For the Munich rapid transit system, the point lies 3 percent below the

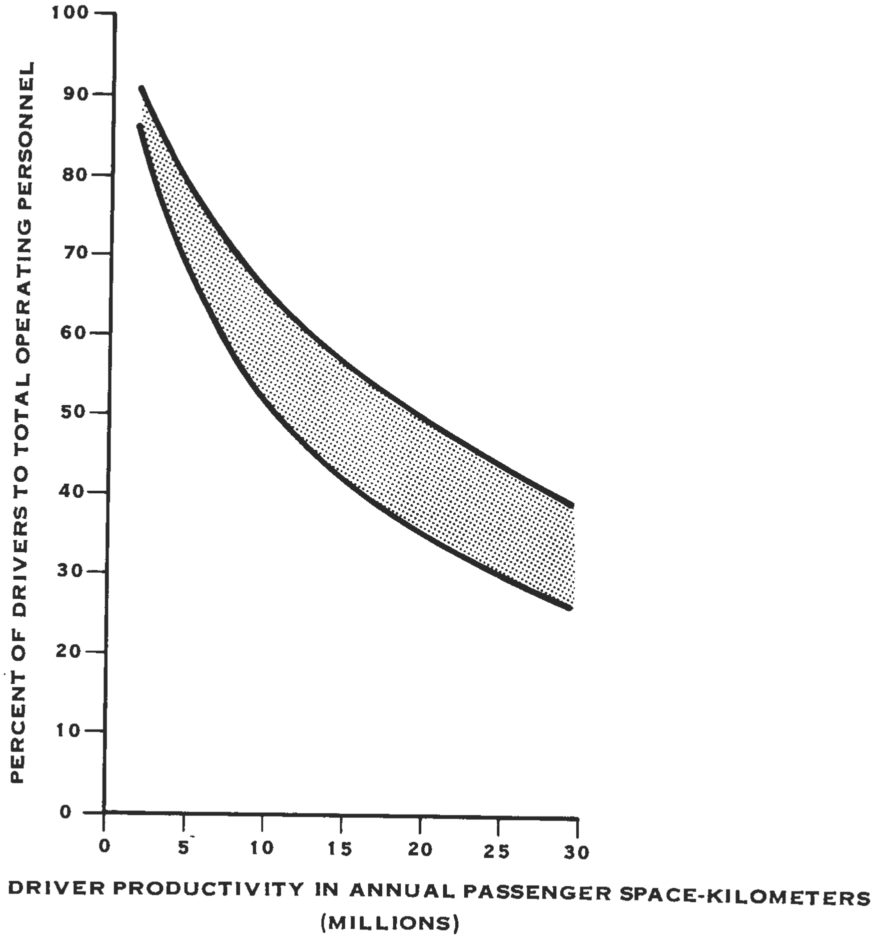


Figure I-1. Driver Productivity for LRT

lower curve in Figure I-1. This data checks for some of the operating experience in the United States. For instance, at Lindenwold, where the driver productivity is approximately 23 million annual passenger space-kilometers per driver, drivers constitute 39 percent of all transportation personnel and only 16.5 percent of all operating personnel.

Cost of Materials

Cost of materials for operation (tickets, uniforms, office stationery) are small. They amount to 1 to 3 percent of the personnel wages.

Total Transportation Costs

The average value of these costs for the nine agencies surveyed amounts to 33¢ ±15 percent per 100 passenger space-kilometers

VEHICLE MAINTENANCE

For nine surveyed transit agencies which have different mixes of light rail vehicles, including 6- and 8-axle vehicles, the average maintenance cost per vehicle per year was $22,500 ± 30 percent. For a 6-axle vehicle, approximately 2,200 hours of work are required for general overhaul; for an 8-axle vehicle, approximately 2,400 hours.

Maintenance costs vary greatly due to differences in fleet composition, average age, annual vehicle-kilometers and frequency of accidents. Vehicles with an annual operation of 63,500 kilometers must be overhauled every 8 years; those with an annual operation of 75,000 kilometers, every 6.7 years according to the legal requirements. On the average, vehicle maintenance costs amount to 20¢ ±20 percent per 100 passenger space-kilometers. The cost of material averages 18 percent of yearly maintenance cost. These maintenance costs also include contracted work for vehicle repairs after collision, which may amount to nine percent of the yearly costs.

The upkeep of vehicles, including the cleaning in yards, requires approximately 0.2 to 0.4 persons per vehicle.

Typical yearly vehicle maintenance costs per vehicle experienced by two transit agencies is shown below.

AGENCY A		AGENCY B	
49 4-axle cars	$15,900	84 4-axle	$15,800
73 6-axle cars	21,500	8 6-axle	26,350
12 8-axle cars	23,700	230 8-axle	31,000

MAINTENANCE COSTS OF RIGHTS-OF-WAY INCLUDING TRACKS AND FACILITIES

On the basis of data from seven agencies, which have 40 to 70 percent of their lines on separated rights-of-way, the maintenance costs per kilometer of track amount to an average $12,100 ±25 percent. For larger structures on the rights-of-way, such as bridges and viaducts, the maintenance cost per track kilometer will increase significantly. One rapid transit system with elevated routes recorded as much as $35,000 per kilometer.

Stated in terms of cost per 100 passenger space-kilometers, the maintenance of rights-of-way, including track and facilities amounts to 12¢ ±20 percent including the cost for maintaining stations.

WAYSIDE FACILITIES MAINTENANCE COSTS

These costs are estimated at $4,200 per year per kilometer of track with a great variation because of the different types of equipment, such as the type of catenary, type and complexity of the control system, etc. For two of the transit systems surveyed, the costs of maintaining wayside facilities, including signals, amounted to $8,300 per kilometer of track. Stated in costs per 100 passenger seat-kilometers, the cost for maintaining wayside facilities amounts to 3¢, but a substantial variation can be found among the surveyed agencies.

BUILDINGS AND GROUNDS MAINTENANCE COSTS

On the average, these costs amount to 5 cents per 100 passenger space-kilometers.

ENERGY COSTS

For nine surveyed agencies, the energy costs are on the average 8 cents ±20 percent for 100 passenger space-kilometers

GENERAL AND ADMINISTRATIVE COSTS

These costs are estimated to average 10 cents ±25 percent per 100 passenger space-kilometers.

COSTS FOR LEGALLY REQUIRED EMPLOYEE BENEFITS

These costs are estimated at 8 cents ±25 percent per 100 passenger space-kilometers. On the average, these costs amount to $1,500 per year per employee.

OTHER COSTS

Included in this miscellaneous category is an allowance of 1 cent per 100 passenger space-kilometers.

SUMMARY OF OPERATING AND MAINTENANCE COSTS

Table I-1 summarizes the O&M costs for nine LRT transit agencies, as well as one rapid transit system. Costs are given on a per 100 passenger space-kilometer basis. The variations of operating and maintenance costs for the nine LRT agencies amount to ±18 percent.

Table I-2 shows statistics of operators productivity obtained from the LRT and rail rapid transit agencies providing the cost data shown in Table I-1.

From the available data obtained by a survey of the various transit agencies, a correlation has been established between O&M costs and operating characteristics of conventional streetcar, light rail and rail rapid transit systems. This is shown in Figure I-2. There is a variability of ±18 percent from the curve shown in that figure among the values reported by the different transit agencies.

Table I-1. Summary of O&M Costs

	Light Rail Transit*		Rail Rapid Transit**	
Transportation	$0.33	33.0%	$0.18	34.7%
Maintenance				
Vehicles	0.20	19.8	0.06	13.2
Rights-of-Way, Tracks	0.12	11.5	0.09	17.4
Wayside Facilities	0.03	3.3	0.02	4.1
Buildings and Grounds	0.05	4.5	0.01	1.7
Energy Costs	0.08	8.2	0.05	9.1
Administrative	0.10	10.7	0.05	10.7
Legally Required Employee Benefits	0.08	8.2	0.04	7.4
Other	0.01	0.8	0.01	1.7
TOTAL O&M COSTS	$1.00	100.0%	$0.51	100.0%

*Average of nine light rail transit agencies.
**One rail rapid transit agency.

Table I-2. West German Operations Statistics

	Light Rail Transit*	Rail Rapid Transit**
Driver productivity (train-kilometer per driver per year)	21,000 (average)	35,000
Driver productivity (passenger space-kilometer per driver per year)	5,400,000 (average)	24,000,000
Train capacities (passenger spaces per train)	260	690
Train consist (cars per train)	1.66	5.4
Vehicle capacities (passenger spaces per vehicle)	157	128
Density of offered service (annual passenger space-kilometer per kilometer of line)	29,000,000	79,000,000
Intensity of operations (vehicle kilometer per kilometer of line)	185,000	620,000
Intensity of operations (train kilometer per kilometer of line)	115,000	114,000

*Average of nine light rail transit agencies.
**One rail rapid transit agency.

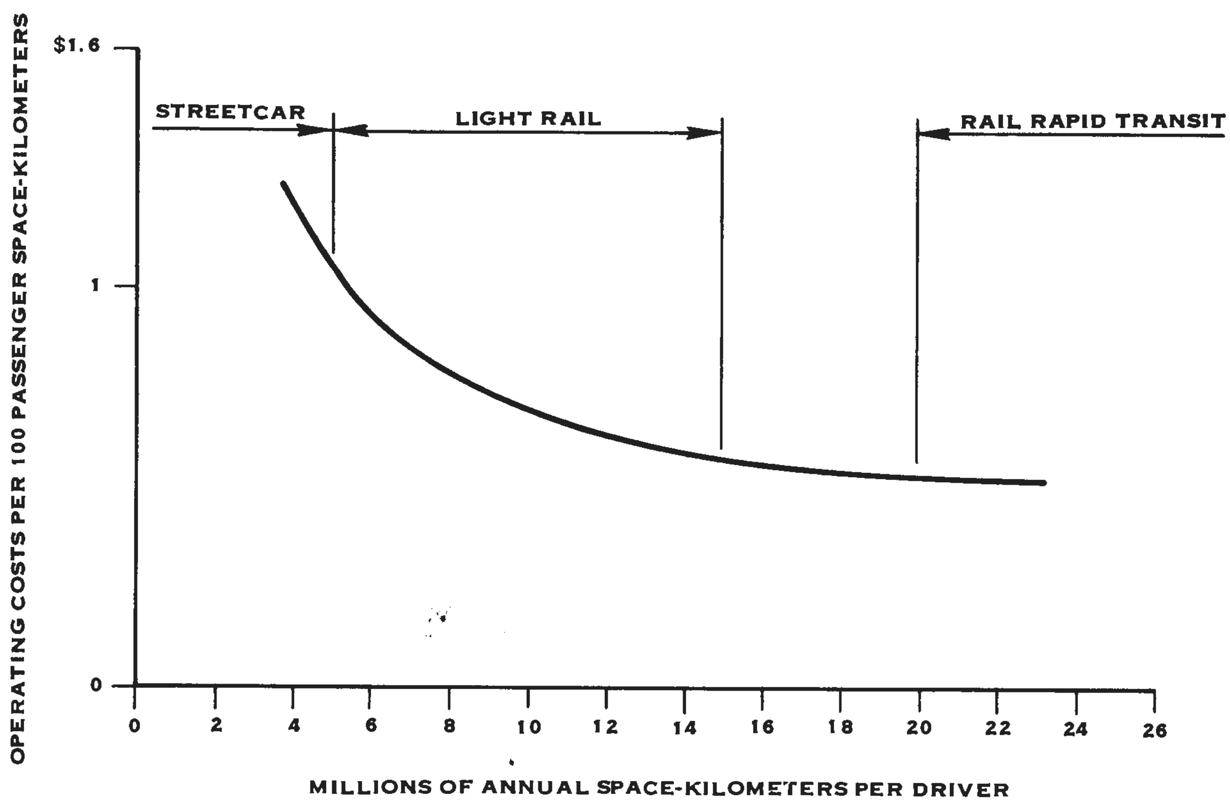


Figure I-2. Approximate Ranges of Driver Productivity for Different Transit Modes

☆ U.S. GOVERNMENT PRINTING OFFICE : 1976 O—215-865