CONFERENCE PROCEEDINGS 8

SEVENTH NATIONAL CONFERENCE ON LIGHT RAIL TRANSIT

VOLUME 2

WITH ASSOCIATED PAPERS ON ISSUES AND FUTURE OF RAIL TRANSIT

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Seventh National Conference on Light Rail Transit

Volume 2

With Associated Papers on Issues and Future of Rail Transit

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CONTENTS

VOLUME 1

Foreword vii

PART 1: POLICY AND PLANNING FOR LIGHT RAIL TRANSIT SYSTEMS

Operating System Status

Status of North American Light Rail Transit Systems: 1995 Update 3
John W. Shumann and Suzanne R. Tidrick

Sacramento Regional Transit's Light Rail: Approaching Middle Age 15
Cameron Beach

Updates on New Systems and Extensions

Light Rail Transit Implementation Perpsectives for the Future: Lessons Learned in Silicon Valley 23
Robert L. Bertini, Jan L. Botha, and K. Odila Nielsen

Light Rail—A Mile High: The Denver Experience 33
John D. Claflin

Beyond the Field of Dreams: Light Rail and Growth Management in Portland 42
G. B. Arrington

Edmonton Light Rail Transit Experience 52
Larry McLachlan

Light Rail in Switzerland: Case Study of Bern Suburban Area 66
Peter Scheidegger

Urban Design and Aesthetics

Public Art and Public Transportation 75
Craig Amundsen

Art Integration: An Essential Design Component and Vehicle for Community Commitment in Santa Clara County 87
William L. Barnes, Jack Mackie, and Robert L. Bertini

PART 2: LRT ADMINISTRATION AND GENERAL MANAGEMENT

How Do Others See Us?

Citizen Involvement in Planning Light Rail Systems in U.S. Cities 99
Harriet Parcells

Review of Recent American Light Rail Experiences 104
Robert T. Dunphy

Perspectives on Standardization

New Jersey Light Rail Transit Standardization Issues 117
John P. Aurelius

New Jersey Transit Light Rail Transit Initiatives 126
Jerome M. Lutin, Richard Hernon, Michael Magdziak, and James Schwarzwalder

Standardization: Historic Perspectives on Modern California Light Rail Transir Systems 135
Paul O'Brien

Standardization: The Los Angeles Experience in Divergent Technologies 140
Neil Peterson

Joint Use Corridors

Issues Associated with Light Rail Transit Use of Freight Railroad Right-of-Way 147
Richard D. Pilgrim, Lonnie D. Blaydes, and William D. Burgel

Joint Use of Track by Electric Railways and Railroads: Historic View 154
J. William Vigrass

Hudson-Bergen Light Rail Transit System Joint Occupancy—Joint Use 164
Richard F. Hernon

PART 3: TECHNICAL ISSUES

Light Rail Vehicles

Introduction of Low-Floor Light Rail Vehicles to North America: History and Status of the Portland Type 2 Vehicle 175
Dennis L. Porter

Applicability of Low-Floor Light Rail Vehicles in North America 184
James R. Zebarth

Compression Loads for Light Rail Vehicles in the United States 194
Joe Lewalski

Innovative Approach to Light Rail Vehicle Design 199
Thomas G. Holqvist

Transit Cooperative Research Program: Projects Under Way

Transit Cooperative Research Program Project A-8: Rail Transit Capacity 207
Tom Parkinson and Ian Fisher

Americans with Disabilities Act Issues

Mass Transit: The Blind Person's Car 221
Steven Hastalis

Making an Accessible Light Rail System More Accessible Under the Americans with Disabilities Act 226
Douglas J. Cross

Technology To Help Compliance with Americans with Disabilities Act in Public Transit 235
Elizabeth Eva Lewalski

Providing Platform/Vehicle Access To Satisfy the Americans with Disabilities Act: Santa Clara County Solution 240
Willard D. Weiss, Robert E. Murphy, and Paul S. McCauley

Passenger Security

Crime on Maryland Mass Transit Administration Light Rail Line: Myth or Reality? 253
Bernard Foster and Ronald Freeland

Security Assessment of San Diego Light Rail Transit Service 257
Jeffrey Martin

Transit Security: Keeping Perceptions in Perspective 263
William B. Rumford

PART 4: LRT OPERATIONS

Traffic Engineering and Safety

Transportation Management Plan for the Chicago Central Area Circulator 273
Richard J. Hocking and Mark P. Medema

Light Rail Preemption of Traffic Signals: A Question of Balance 285
Woodrow Hood III, Thomas Hicks, and Linda I. Singer

Integration of Light Rail Transit into City Streets 294
Hans W. Korve, José I. Farran, and Douglas M. Mansel

Operations and Maintenance Issues

Reorganizing for Tomorrow 307
Anthony J. Schill

Assessing Effectiveness of Light Rail Transit Systems: An Application of Malcolm Baldrige National Quality Award Criteria 315
Burton V. Dean and Taeho Park

Organizing for Efficiency: The Denver Teamwork Experience 327
John D. Claflin

VOLUME 2

Foreword ix

PART 1: LIGHT-RAIL TRANSIT CONFERENCE PAPERS

Light-Rail Transit Developments in Western Europe 3
Glen D. Bottoms

Lighr-Rail Transit in Calgary, 1981–1995: A Retrospective Review 15
John Hubbell, Dave Colquhoun, Dan Bolger, and John Morrall

North American Light-Rail Transit Ridership and Operating Costs: A Basis for Comparison 27
Duncan W. Allen and Timothy H. White

Light-Rail Developmenrs in Great Britain 36
Anthony P. Young

New Technologies for Improving Light-Rail Grade Crossing Safety 46
Linda J. Meadow and James P. Curry

Light-Rail Transit for Miami Beach 55
Mark C. Walker

Integration of Extended Vintage Trolley Operations into New Light-Rail System in Dallas, Texas 69
Rodney W. Kelly

The Denver Experience: Starting Small 83
Mark Imhoff

PART 2: LIGHT-RAIL TRANSIT ISSUES

Pedestrian Control Systems for Light-Rail Transit Operations in Metropolitan Environments 91
Hans W. Korve, José I. Farran, and Douglas M. Mansel

Overview of Light-Rail Train Control Technologies 103
Diana Ospina, Fang Zhao, and L. David Shen

Sensitivity of Hudson-Bergen Light-Rail Transit System Model Forecasts 114
Brenda Killen Johnson and Thomas Adler

Networkwide Approach to Optimal Signal Timing for Integrated Transit Vehicle and Traffic Operations 126
Matthew I. Koch, Daniel C. Chin, and Richard H. Smith

Application of Light-Rail Transit Flexibility: Dallas Area Rapid Transit Experience 132
Stephen L. Salin and Douglas A. Allen

Evaluating Efficiency of Transit Alternatives in Griffin Line Corridor, Hartford, Connecticut 142
Paul A. Ehrhardt, David J. Vozzolo, Elizabeth S. Riklin, and Peter McMahon

Application of Simulation and Animation To Analyze Light-Rail Transit Operations 153
U. Vandebona and S.C. Wirasinghe

PART 3: FUTURE OF RAIL TRANSIT

Progression or Regression: Case Study for Commuter Rail in San Francisco Bay Area 163
Peter Gertler and David Kutrosky

Analysis of Suburb-to-Suburb Commuter Rail Potential: Metrolink in Southern California 175
Lynne Marie Whately, Bradley E. Friel, and Gregory L. Thompson

Accounting for Multimodal System Performance in Benefit-Cost Analysis of Transit Investment 184
Daniel Brod

Operational Level-of-Service Index Model for Rail Rapid Transit 191
Fang Zhao, Liping Wang, Young-Kyun Lee, and L. David Shen

Foreword

The 1995 National Conference on Light Rail Transit (LRT) is the seventh such meeting. At the first conference, held in Philadelphia in June 1975, the technical session focused on introducing—or reintroducing—the concept of LRT in North America.

Now, 20 years later, there are 20 North American LRT systems in operation (including 11 urban areas that have initiated LRT systems since the first conference), eight areas with new starts or extensions under construction, and numerous others in various stages of planning and engineering.

The six prior national conferences have paralleled the development and reintroduction of LRT in North America. The technical information contained in the Proceedings of these conferences provides the planner, designer, decision maker, and operator with a rich bounty of experiences and ingredients necessary to a successful transit development project. The evolution of LRT experience is shown by the focus of the previous conferences:

- 1975—Reintroduction to LRT (Philadelphia, TRB *Special Report 161*),
- 1978—Planning and technology (Boston, TRB *Special Report 182*),
- 1982—Planning, design, and implementation (San Diego, TRB *Special Report 195*),
- 1985—System design for cost-effectiveness (Pittsburgh, TRB *State-of-the-Art Report 2*),
- 1988—New system successes at affordable prices (San Jose, TRB *Special Report 221*), and
- 1992—Planning, design, and operating experience (Calgary, *Transportation Research Record 1361*).

The seventh national conference emphasizes the lessons resulting from the maturing of North American LRT systems. Thus, the Conference Planning Committee decided that the conference title should be "Building on Success—Learning from Experience."

The conference also features the Transportation Research Board (TRB) and the American Public Transit Association (APTA) as cosponsors. This partnership is a formal recognition of the mutual and supportive respect for each other's aims and purposes in a cooperative conference venture.

Finally, there is the conference itself and the wealth of technical material offered in it. There are 18 sessions and several technical tours of Baltimore's LRT system. The Transit Cooperative Research Program, which was introduced by the Intermodal Surface Transportation Efficiency Act of 1991, is featured with two sessions. Other subjects cover the state of the art in light rail vehicles, intermodal connections, implications of the Americans with Disabilities Act, urban design considerations, safety and security planning, and operations and maintenance issues.

The objective of these conferences is to add to the growing body of knowledge and real-world experiences with modern LRT applications in order to continuously improve the systems being planned and those already in operation. Success can be fleeting, and we need to learn from past experience in order to do a better job of providing cost-effective public transportation services. The information, data, and research contained in these proceedings are meant to serve this need.

Thomas F. Larwin, Chairman, Conference Planning Committee
General Manager, San Diego Metropolitan Transit Development Board

Note: Volume 2 of these proceedings contains both papers from the Seventh National Conference on Light Rail Transit and associated papers presented at the 1996 Annual Meeting of the Transportation Research Board in Washington, D.C.

PART 1
LIGHT-RAIL TRANSIT CONFERENCE PAPERS

Light-Rail Transit Developments in Western Europe

Glen D. Bottoms, *Federal Transit Administration, U.S. Department of Transportation*

Events in Europe during the past 5 years have shown a number of important trends that favorably position the light-rail concept, in both existing and proposed systems, for continued positive development and intensified implementation. The building of new systems in western Europe has been a key element in enhancing the visibility of the concept. The widespread upgrading of existing systems has further accentuated the concept. Finally, the almost total market penetration and acceptable performance of low-floor light-rail vehicles have allowed light rail to serve diverse populations while retaining its inherent flexibility. In light of the above developments, the most significant events in light rail in western Europe will be described, first by touching on significant advances on a country-by-country basis but then largely concentrating on the phenomenal growth of new systems in France and the implementation of the regional or "Karlsruhe" concept of joint light-rail–railroad operations in Germany. This approach will point out the trends that have emerged in Europe and document the strong desire to employ affordable fixed-guideway solutions that support the overall objectives of heightened mobility, compatible urban growth, and improved quality of life.

The 1990s have witnessed the significant interest in cities across western European in revitalizing public transportation in general and fixed-guideway systems in particular. In every city that has retained light-rail and tram operations, serious efforts have been undertaken to renew or expand the existing systems. In a number of cities that had previously discontinued old tram services, new systems have been implemented or are currently in final planning (principally in France and Great Britain).

The following is a quick survey of these activities. Although the primary focus of this paper is the emergence of new systems in France, another key objective is to briefly chronicle, in some depth, activities in other countries as well. Therefore, the following narrative highlights events in eight key western European countries and supports the premise that the renewed interest in light rail is not confined to a single country or region.

Overview of Light Rail in Western Europe

France

France has clearly emerged as the European, if not the world, leader (followed closely by the United Kingdom) in the design and implementation of new light-rail systems. The success of new light-rail systems in Nantes (1984), Grenoble (1987), Paris-Saint Denis-Bobigny (1992), and Rouen and Strasbourg (1994) has provided momentum for other medium-sized conurbations with populations over 300,000 to seriously examine the advantages of the light-rail concept. A detailed look at light rail in France is provided later in this paper.

United Kingdom

The United Kingdom has recently seen the successful start-up of new systems in Manchester (April 1992) and Sheffield (South Yorkshire Supertram, May 1994), the approval of the Midlands Metro (Birmingham to Wolverhampton), and well-advanced planning in Leeds, Croydon (Greater London), and Nottingham. A completely grade-separated hybrid light-rail system was opened in Newcastle (Tyne and Wear Metro) in 1980 and in London (Docklands) in 1987. The Newcastle system is now 60 km long, and the Docklands Railway undertaking, an automated operation, has reached a length of 20 km. The Manchester system has achieved a length of 15 km and is carrying more than 50,000 passengers daily. Two proposed extensions have already been approved. The Sheffield undertaking is being expanded in phases. Of note is the fact that the Croydon proposal (Croydon Tramlink) may involve a significant investment from the private sector. Final approval of this project by the Department of Transport will hinge on confirmation of the private-sector participation (Parliament assented to the project in July 1994). The Leeds Supertram line received Parliamentary authority in 1993, and a funding application is expected to be approved in 1996. The Nottingham proposal would apply the Karlsruhe, Germany, regional approach utilizing British Rail rights-of-way to access diverse regional destinations.

Germany

In Germany, the acknowledged western European leader in light rail with 55 individual light-rail systems currently in operation, an innovative variation has been embraced called the Karlsruhe approach, in which light rail assumes a truly regional character through the shared use of existing main-line railroad alignments. The city in which this innovation was developed and proven feasible, Karlsruhe, is described in more detail in the third section of this paper. One city, Saarbreucken, has secured approval for a light-rail system (the first new system in Germany in over 60 years) that will create a regional network based on the Karlsruhe experience.

Although many other countries in the West (including France) moved to discontinue existing tram operations before and soon after World War II, German cities, once they recovered from the devastation of the war, began to upgrade street tramways incrementally to what would be characterized today as true light-rail standards. Among the major German cities, only Hamburg and West Berlin discontinued tram operations, in 1978 and 1967, respectively. In the case of Berlin, reunification has meant the resurgence of trams (tram service was retained in the eastern half of the city), which will now be selectively reextended into the western sectors of the city. In Hamburg, plans have been developed for reintroducing trams in the form of a four-route light-rail network. Foremost among German cities implementing the full range of light-rail oprions (subway, aerial, partially and fully reserved street alignment, fully segregated right-of-way, and high and low platform operation) are Bonn, Frankfurt, Hannover, Cologne, and Stuttgart (the last also effected a change from meter gauge to standard railroad gauge). All remaining German cities, including those in the former eastern part of the country, are in the midst of some type of modernization activity, including acquisition of low-floor light-rail vehicles (LRVs), increasing the percentage of segregated traffic, extending routes, and renewing infrastructure.

Italy

Italy has experienced a resurgence of emphasis on surface rail urban transit; Milan, Turin, Rome, and Naples, each in its own way, have increased reliance on an expanded light-rail infrastructure as an alternative to mounting traffic congestion, air pollution, and the high cost of full metro construction. A change in the city administration in Milan has led to increased emphasis on the tram network, including planning for new extensions. Turin, after flirting with plans for an automated metro, has returned to previous plans for incrementally upgrading the existing tram system to light-rail standards over the long term. Rome has developed firm plans for extensions to the existing system and has recently taken delivery of low-floor LRVs (which was interrupted, however, when the original builder went bankrupt). After abandoning a traditional tram network in 1966, Genoa recently opened a hybrid light-rail–metro system, connecting a new subway section to the old Certosa tram tunnel. Light-rail systems have also been proposed for Bologna and Florence.

Belgium

Belgium, with strong systems in Brussels, Antwerp, and Ghent and a unique coastal operation (Coastal Vicinal) serving Belgium's North Sea beaches, pioneered the "pre-metro" concept in Brussels. The pre-metro approach as practiced in Brussels consists of the phased upgrading of tram lines to full metro status (high platforms, grade-separated operation) over a period of years as increased ridership justifies such service. Antwerp is slowly constructing a series of tram subways in the downtown area as funding permits while fully segregating many on-street segments to enhance system speed and overall attractiveness for current and potential riders (the automobile is a serious competitor in Belgium, too). Ghent, a small town by most standards (200,000), has skillfully employed its meter-gauge tram system to avoid ridership losses to the ever-present automobile. The last remnant of the vast regional system that once blanketed Belgium remains in operation in and around the southern Belgian industrial city of Charleroi, Belgium's parallel to America's Rust Belt, which has sunk scarce capital into upgrading interurban lines linking the city with surrounding jurisdictions. Although these improvements have failed to arrest a downward trend in ridership, additional measures to enhance system attractiveness (reserved rights-of-way, traffic preemption, etc.) have been instituted.

The Netherlands

The Netherlands, ever progressive and deliberate, has aggressively pursued preservation and expansion of light rail in Amsterdam, The Hague, Rotterdam, and Utrecht (which has a relatively new system opened in 1983). A final decision on expansion of the Utrecht system remains under consideration. A long extension was recently opened in The Hague, with plans to implement short subways in areas of concentrated congestion. Rotterdam will reextend light rail across the Scheldt River to connect with previously isolated Route 3 in South Rotterdam. Additional extensions will also be implemented in a recently adopted program entitled "Tram Plus." Amsterdam, where the effectiveness of light-rail operations has earned them the label "street metro," adroitly employs every facet of light-rail technology, including a hybrid "sneltram" concept, first introduced in 1992. Sneltram utilizes third-rail and overhead power as well as high-platform operation and thus possesses the ability to operate over light-rail or metro tracks. Rotterdam also chose to employ this approach as a lower-cost extension of its metro system. Construction is well advanced on a circular sneltram line in Amsterdam utilizing space carved from existing railroad rights-of-way.

Spain

Valencia, which has recently upgraded largely grade-separated light-rail routes including the provision of a crosstown subway and new rolling stock patterned after the Utrecht LRV, in May 1994 opened a new 9.7-km light-rail line (Route 4). The line utilizes on-street alignments segregated from traffic except at intersections. The new service employs 21 German-designed (Siemens/Duewag), Spanish-assembled low-floor double-articulated LRVs. Zaragoza is currently in the planning stages for a light-rail system.

Switzerland

In Switzerland, where textbook light-rail systems operate in Zurich, Basel, Bern, and Neuchâtel, there has also been a revival of light rail in Geneva and the establishment of a new line in Lausanne. In Geneva, where by 1969 the system had been pared to a single route, new LRVs have been acquired, including Europe's first modern low-floor car, and a new route was opened in 1995. Plans are also firm to extend the system further in 1996. In Lausanne a new light-rail line (TSOL, or Metro Ouest) was opened in 1991 to connect the suburb of Renens with the center city at Flon. An immediate success, the mostly single-track line is equipped with 12 LRVs.

LRV Trends

Another trend, not linked to a specific area but to a change in technology, is the tidal wave of orders for low-floor LRVs, irrevocably changing the European transit vehicle market. In fact, all new systems now being implemented feature low-floor equipment, either the 60 to 70 percent or 100 percent variety. Since the successful advent of a low-floor vehicle in regular service in the modern era—the Vevey/Duewag low-floor car for Geneva, Switzerland, in 1984—the market has steadily gained momentum. In fact, the market is currently flooded with competing low-floor designs offered by some 12 builders.

Light-Rail Developments in France

When Paris consigned its last tram to posterity in 1937, the event was heralded as a profound change for public transport, not only in Ile de France, but also across France and Europe in general. Ultimately the impact proved to be minimal in Europe (only London and Madrid among major European cities followed suit, not counting Hamburg, which terminated tram operations in 1978), but it obviously set the trend for France. By the mid-1960s, almost all major French cities had discontinued tramway operations, even though some systems remained in use, possessing, for example, substantial reserved or private rights-of-way.

By 1970 only three small systems survived: (*a*) in Lille, an industrial conurbation in northern France near the Belgian border; (*b*) in Saint Etienne, an industrial town in southeast France; and (*c*) in Marseilles, a Mediterranean port city. As was the case in the United States, each system possessed some unique aspect that contributed to its longevity. In the case of Lille, two long lines (locally known collectively as Le Mongy after the city official who masterminded its planning and original construction) to the industrial suburbs of Tourcoing and Roubaix retained a healthy ridership with well-maintained but antique equipment, copious amounts of reserved trackage, and an efficient operation. But even in this case, the authority was simply fully depreciating the plant before supplanting these residual lines with Véhicule Automatique Léger (VAL), a successfully employed but rather expensive automated system. By 1965 the Marseilles system had been pared to one single line accessing the downtown area via a short subway, the line's one endearing quality. Saint Etienne chose to modernize, taking delivery of 30 Belgian-built (La Brugeoisie) PCC trams in 1958, with an additional 5 articulated PCCs ordered from the same builder in 1964. However, it was not until the pioneering Nantes system was successfully launched in 1984, with official government encouragement, demonstrating the workability of the concept of light rail (*métro léger* in French) that other French cities began to seriously consider the concept as legitimate. Light rail then began to make headway against other competing types of transit.

In the following sections, additional detail is provided on the development of light rail in individual urban settings in France. System features for nine new and existing operations are given in Table 1. It should be noted that the decision to proceed with the light-rail option was not a foregone conclusion in any of these cities. Although a consensus was obviously achieved in each instance, the road to that consensus was neither smooth nor uneventful. There was pressure from industry and some local politicians to adopt the rival VAL system. The success of the Lille installation had proved that the system was workable and could function reliably in the unforgiving urban environment on a daily basis. This emboldened VAL advocates to push for adoption of the automated system in other French cities. The VAL system was subsequently chosen over the light-rail option in Toulouse, Bordeaux, Rennes, and, initially, Strasbourg. The Toulouse system is now operating smoothly. In Bordeaux the initial decision for VAL is being reviewed. In Strasbourg the decision to install a VAL system was overturned. Other French cities, it should be noted, have opted for less capital-intensive options such as improved bus service or trolleybus operation. Just recently, Caen opted for a third form of fixed-guideway operations, a bus guided by a single rail embedded in the roadbed with power collection by overhead wire.

Nantes

Officials in the greater Nantes area sensed that upgraded public transport was the key to ensuring the growth and prosperity of this French city of over 450,000. After receiving encouragement from the French government in 1975 to investigate the possibility of introducing upgraded tram systems, Nantes decided to aggressively pursue the implementation of a fixed-guideway solution.

TABLE 1 Light-Rail Systems in France

Locality	Year System Opened	System Length	High/Low Platform	Type & No. of Vehicles	Vehicle Builder	Total Cost ($ millions)	Patronage/ Day	Future Plans
Paris (Ste. Denis-Bobigny)	1992	9.0 km	Low	Low Floor (20)	GEC Alsthom	121	63,000	Extensions proposed
Paris[1] (Val de Seine)	1997	14.1 km	Low	Low Floor (20)	GEC Alsthom	280	41,000 (Projected)	Extend along Petite Ceinture; other routes planned
Nantes	1984	27.0 km	Low	Modified Low Floor (20) Low Floor (26)	GEC Alsthom	100[4]	68,000	Additional extensions planned
Grenoble[2]	1987	18.4 km	Low	Low Floor (53)	GEC Alsthom	120	85,000	Additional extensions planned
Rouen	1994	11.2 km	Low	Low Floor (28)	GEC Alsthom	480	45,000	Additional extensions planned
Strasbourg[3]	1994	9.8 km	Low	Low Floor (26)	ABB	388	57,500	Additional extensions planned
Lille	1909	19 km	Low	Low Floor (24)	Breda	240	28,500	Modernization completed
Ste. Etienne	1901	9.3 km	Low	Low Floor (27)	Vevy/Duewag	NA	95,000	Modernization continues
Marseille	1911	3 km	Low	Conventional	La Brugeoisie	NA	35,000	Single line may form basis for expanded system

[1]Initial segment to run to Issy-Plaine

[2]Includes extensions to line A & B scheduled to open in 1995 & 1997 respectively

[3]Full service inaugurated in February 1995

[4]Cost for initial line segment only

Note: Total cost converted to USD @5FF=$1

Armed with the promise of 50 percent funding from the central government, Nantes was able to complete a financing package for the line through use of the famous *versement transport*. This national provision, adopted originally for the Paris region in 1971 and later extended to apply to all other localities with populations over 300,000, allowed the imposition of a payroll tax on companies with 10 or more employees (Nantes adopted a 1.5 percent rate). The terms of this provision required that proceeds from the tax be dedicated to transit improvements.

This initial new light-rail system in Nantes was an effective demonstration of the flexibility afforded by the light-rail concept. The alignment selected for Route 1 sought to link residential and employment centers and reemphasize the centrality of the downtown area. Stations (all with low platforms) embodied the simple, low-cost nature of the system. Alignments were blended into the surrounding environment using modern urban design concepts to ensure lasting compatibility. The initial line, running from Haluchère to Commerce, opened in January 1985. This was followed by extensions from Commerce to Bellevue in February 1985 and from Haluchère to Beaujoire in April 1989. The line was an immediate success, reaching a patronage level of over 45,000/day by mid-1986. Today that number has climbed to 68,000/day. This initial line cost approximately $100 million (U.S.) (5 francs = $1.00), or about $16 million per mile. With extensions, Line 1 now extends 12.6 km (7.9 mi) and has 24 stations.

The success of the initial line encouraged the city to begin planning for construction of another line to serve areas north and south of the city. Construction was initiated on Line 2 in 1990, and it opened in increments completed in 1994. Like Line 1, this new route has achieved considerable success and a strong ridership base. Line 2 exhibits the same design concepts employed on Line 1. In fact, many improvements to the surrounding areas were undertaken during construction of the new line. The Cours des 50 Otages, a former four-lane highway, was converted into a tree-lined boulevard sporting a two-track light-rail path, normal lanes, and a pleasant environment for pedestrian movement. Vehicles for the initial line were designed to serve as France's standard LRV. The first 20 LRVs came equipped with center articulation but contained no provision for handicapped access. These cars have since been modified and equipped with center low-floor sections, significantly improving their accessibility. Follow-on orders have incorporated this feature as a standard item. All LRVs have been constructed by GEC Alsthom at its La Rochelle plant. The system will now continue to expand, with plans well advanced for a third line running northwest to southeast. Construction will be initiated on Line 3 in 1996. Plans also call for extending the original two lines in the long term. Total length of the system has now reached 27 km with service by 46 LRVs.

Grenoble

Following the example set in Nantes, Grenoble, located in southeast France, opened a new light-rail line in September 1987. The city had discontinued its antiquated, mostly single-track meter-gauge tram system in 1952. The renaissance of public transport in Grenoble can be traced to the creation in 1973 of the Syndicat Mixte des Transports en Commun de l'Agglomération Grenobloise (SMTC). This organization, the counterpart of the U.S. metropolitan planning organization (MPO), made up of representatives from Grenoble and the surrounding area, was to guide transport investment in the Grenoble region and distribute financial support for capital improvements. These organizations are a common feature among French cities. They were key to the resurgence of mass rransit, certainly in the French cities described here. In addition, the Société d'Economique Mixte des Transports Publics de l'Agglomération Grenobloise (SEMI-TAG), a hybrid entity owned jointly by local authorities and private enterprise, was established in 1975 with mission of operating the public transport system.

Armed with a study prepared by SOFRETU—a consulting subsidiary of the Paris transport authority, Régie Autonome des Transports Parisiens (RAPT), recommending the construction of four surface tram routes—SMTC began searching for the necessary political and financial consensus to bring the proposal to reality. In the same year, the French government proposed that French cities consider modern tramways as a means for meeting future urban transport demand. This action had the effect of legitimizing the concept and encouraging localities to give the concept serious consideration. The possibility of central government financial support was also envisioned.

By January 1983 a plan had been approved by SMTC to pursue construction of the first line. At the behest of an incoming mayor, the plan was subject to a popular referendum held in June 1983. The project passed with a 53 percent majority, not overwhelming approval but enough to get the project moving. Again, use of the *versement transport* (payroll tax) was crucial to generating the necessary financing for the line. The central government pledged $78 million toward the project, with the *versement transport* furnishing the balance. Although the Nantes LRV was initially envisioned as the rolling stock for the line, its lack of handicapped access forced a reconsideration. A committee was formed to consider a more accessible vehicle. The result was an order for vehicles with a low-floor design. The initial 20 LRVs for Grenoble incorporated this design and also essentially became the standard French LRV for future systems (excepting that in Strasbourg). Construction of the line began in late 1984, and it was opened with great fanfare in September 1987. The line carried more than 65,000 passengers daily in the first year of operation, representing a 26 percent increase in ridership over bus routes displaced by light rail, and now handles about 85,000 daily.

As with the Nantes undertaking, significant improvements were made in conjunction with the construction of the light-rail line. These included creating pedestrian precincts, altering the street environment to heighten the livability of the immediate area, and instituting new traffic patterns favoring the exclusivity and priority of the new light-rail line and other public transport (Grenoble also has a fine trolleybus network). The highest quality of urban design prevailed in all aspects of the light-rail undertaking.

As a testament to the success realized with Line A, construction was quickly begun on a second route, Line B, branching from Line A to serve a large university. Extending 4.6 km, this new line was opened in November 1990.

Currently, a 3.4-km southward extension of Line A is under construction, with service scheduled to commence in 1996. Line B is to be extended 1.6 km in a northwesterly direction; service is projected to begin in the spring of 1997. Cost of these two extensions is estimated at $200 million, including rolling stock (an additional 12 LRVs will be required for the extensions).

It should be noted that a key component in reintroducing surface rail into Grenoble was the expected patronage increase and stabilization of the local transit operating subsidy. Recent figures indicate that the regional operating ratio (or fare recovery ratio) is now 63 percent contrasted with 45 percent before light rail. This increase in the operating ratio stems in part from the fact that general transit usage in Grenoble has increased 50 percent since 1987.

Paris

When the French Transport Minister suggested in 1975 that eight French towns should seriously consider the light-rail concept, he did not have Paris in mind. Nevertheless, Paris has pursued the light-rail concept with a vengeance. Beginning in 1992 with the inauguration of service on the 9-km Saint Denis–Bobigny light-rail line and the initiation of construction of the ambitious Val de Seine line, the Paris conurbation has developed extensive plans to install light-rail services around the periphery of the City of Light.

Connecting the working-class suburbs of Saint Denis and Bobigny in the northeast quadrant of the metropolitan region, the first light-rail line reflects the same exacting design standards found in Nantes, Grenoble, Rouen, and Strasbourg. Describing an arc, the line intersects with the suburban terminals of three Paris Métro lines radiating from central Paris at Saint Denis, La Courneuve, and Bobigny as well as with the Réseau Express Régional (RER), the suburban commuter rail system, providing the interconnectivity envisioned when the line was conceived. The line also interfaces with a large number of bus routes. The line is fully segregated from surrounding traffic except at intersections through the use of various low-cost but effective traffic channelization techniques. Stations are spartan but attractive and provide the necessary elements (ticket machines, benches, weather protection, etc.) for passenger comfort. The overhead is unobtrusive, incorporating the latest in design advancements, which minimize the number of poles, pull-offs, and feeder cable connections on the system (the feeder cable itself is buried along the route). The line utilizes the same low-floor design for LRVs as the Grenoble system and is therefore completely handicapped-accessible. Ten-minute headways are maintained throughout operating hours. The line has achieved a daily patronage of 63,000, almost tripling the volume carried by the former bus line.

Now under construction and expected to open an initial segment for service in 1997 is the Val de Seine light-rail line. The line was originally conceived to replace an old third-rail commuter route originating northwest of Paris and essentially paralleling and then crossing the Seine to access central Paris. The line has since received approval for progressive extensions to penetrate deeper into central Paris south of the Seine. Originating at La Défense, an edge-city development northwest of downtown Paris, the line was slated to terminate at Issy-Plaine along the Seine. Plans now call for extending the line to Porte de Versailles, an additional 2.7 km, for a total length of 14.1 km. With the extension to Porte de Versailles, the line is projected to carry 41,000 passengers/day. A total of 22 LRVs, currently being delivered by GEC Alstholm, will be required. A further extension of 7 km from Porte de Versailles to Porte d'Ivry is now also under consideration. The line would utilize an existing trackbed (La Petite Ceinture) and interface with the experimental Meteor automated metro now under construction. Cost of the line without the proposed extension to Porte de Versailles is an estimated $210 million (including rolling stock).

Rouen

Another medium-sized town encouraged by the French government in 1975 to consider modernized tram systems, Rouen followed the same design criteria so successfully applied in Nantes, Grenoble, and Paris and inaugurated 14.2 km of Metrobus in December 1994. The two-branch system represents the culmination of planning begun in 1986 when an assessment of the area's public transport revealed serious shortcomings. After an exhaustive study and evaluation, authorities (as in Grenoble), guided by the French equivalent of the MPO, opted for light rail, and ground was broken in November 1991. Although there was much debate over the amount of tunneling envisioned, the final system alignment features roughly a mile of subway in the downtown area and two grade separations at major intersections (including the line branches). This civil works project resulted in a higher price tag than that for the other new systems in France: $480 million, or approximately $56 million per mile.

A total of 28 LRVs were built in France to the GEC Alsthom standard for the Metrobus system. Although the Strasbourg design was considered, the proven performance of the GEC Alsthom LRV in Grenoble and Paris (its French-built aspect was also an attraction) tipped the scales. A variety of surface right-of-way configurations are employed throughout the system, although the majority entail side-of-the-road reservations. Many sections feature grass surfaces, lending an ambiance that is distinctly environmentally compatible.

Strasbourg

Construction of one of France's most handsome light-rail systems was not accomplished without difficulty. In fact, the decision to implement the rival VAL automated metro had actually been made but was overturned when the election for mayor of Strasbourg in 1990 resulted in defeat for the incumbent and victory for a "pro-tram" slate. Thus the capital city of Alsace, home to over 430,000 people, proceeded to design and build a textbook light-rail system (Figure 1).

First-hand experience with this magnificent example of light rail confirms that a fixed-rail facility, when designed in a meticulous and sensitive manner, can achieve multiple urban design objectives, including the significant enhancement of the basic livability of an area. The result is an urban transport facility that effortlessly blends into a full range of urban settings, enhancing their beauty and efficacy while furnishing the city with effective, efficient, and pleasant transit service. The eclectic, even eccentric, nature of French urban design is well known. One need only look at the recent addition to the Louvre, the many-colored edifice dedicated to former French President Georges Pompidou at Les Halles, the new National Opera, and the burgeoning city development at La Défense (all in Paris) to gain an appreciation for the French flair for unusual, surprising, even bizarre, but never dull, architecture. This flair is present throughout the Strasbourg system. Even the LRV for the line is reflective of this approach, being not the standard, French-built 60 percent low-floor vehicle but an Italian-designed (Socimi), British-built (ABB), 100 percent low-floor conveyance, representing an almost flamboyant dimensional design change.

The rights-of-way are finely crafted into the Strasbourg urban environment. The 9.8-km line employs a variety of right-of-way treatments, including grass, colored gravel, and cobblestone, achieving a smooth, unobtrusive integration with the surrounding area. To further beautify the route, over 1,000 trees were planted along the rights-of-way. These included cherry, lime, and chestnut varieties. Artwork was also commissioned and sited at key stations. Right-of-way placements for the outer portions of the line have been largely on the side of the road, whereas entire streets have been dedicated exclusively to the line and pedestrians in the central city. A 1.2-km tunnel takes the line under a railroad yard, a highway, the old city fortifications, and finally the city's railway station (Gare), where the only subway station is situated. The city took the opportunity to restrict the plaza fronting the Gare (Place de la Gare) to pedestrians in reconstructing the area after subway excavation. In fact, the inner-city route of the line was also completely restricted to pedestrians, with traffic channelization measures instituted to deflect automobile traffic along four loops outside the inner historic district. Convenient parking provisions were also made at critical locations. These measures were specifically designed to discourage automobile access and promote use of light rail (transit) to gain access to and traverse the city's historic section.

Service was implemented in three phases over three months to minimize start-up problems and promote familiarity with the system. Although service began on a limited basis in November 1994, full integration with the existing bus system (including discontinuance of parallel bus services) did not occur until February 1995. Authorities expected the system to attract over 55,000 passengers per day, and they were not disappointed (current patronage is over 57,000). Cost of the system totaled $388 million, or approximately $66 million/mile. As with the financing scheme for other new French systems, the *versement transport* played a large part in generating the funds necessary to construct the system. This tax provided 27 percent of the cost of the system, with the French government granting 17 percent and the remainder from the Strasbourg city council and other levels of government.

The southern portion of the line, which was to have been opened with the rest of the line, will be further extended in 1996 or 1997 past Baggersee. The city already has advanced planning for a second line on an east-west orientation. The success of the original line will likely

FIGURE 1 Strasbourg light-rail system (line will be extended past Baggersee in 1997) (courtesy of city of Strasbourg).

dictate the level of enthusiasm for undertaking this extension.

Saint Etienne

One of the original "gang of three" that survived the lean 1950s and 1960s, this working-class city continues to operate one modern 9.3-km meter-gauge light-rail line. Not electing to stand pat, and in the tradition of other recent undertakings in France, the local transport entity has aggressively sought to enhance the efficiency and effectiveness of its backbone light-rail service. The city modernized early, purchasing cars of the PCC design in 1958 followed by an order for five articulated PCC cars in 1964. Both orders were filled by La Brugeoisie of Brugges, Belgium. Intensified efforts were made in the 1970s to physically segregate the line from other traffic. The line was also extended by some 1.5 km in 1983 and further extended in 1993. The line now carries a total of 95,000 passengers/day and covers over 70 percent of operating costs from the farebox. Finally, new low-floor vehicles built by a combination of Vevey, Duewag, and GEC Alsthom were introduced in 1991–1992 and have gradually replaced refurbished PCCs, which had previously provided the bulk of service.

Marseilles

Route 68, the sole remaining tram line in Marseilles, managed to survive because of a strategically placed 900-m tunnel that gave the line excellent access to the downtown. Since the service could not be replicated with buses (the tunnel was too narrow to be converted to bus operations), it was decided to modernize the 3-km line over the near term. This modernization included acquiring 16 new trams, 2-m-wide PCCs, built as in St. Etienne by Belgium's La Brugeoisie in 1969. In 1984 the line's tunnel access was diverted to provide a direct transfer to the Marseilles rubber-tired metro Line 2 at the Noailles station. The PCC fleet has recently been refurbished, and the line boasts a healthy 35,000-passenger volume/day. Plans recently unveiled project an expansion of the light-rail network in Marseilles. Route 68 would serve as a centerpiece of this proposed system.

Lille

Lille, the fourth largest conurbation in France (after Paris, Lyon, and Marseilles), boasts a two-route, meter-gauge light-rail system serving the twin suburbs of Roubaix and Tourcoing. Known locally as Le Mongy after the town's public works director, the lines follow two wide boulevards to reach their destinations. Lille also inaugurated France's first automated system, VAL (Véhicule Automatique Léger), in 1983. In fact, plans called for a VAL expansion to supplant the light-rail lines before the year 2000. To implement this plan, 33 second-hand trams were acquired in 1983 from Germany and Switzerland to replace 1950-vintage equipment and enable the service to continue until the VAL extension had been built. After intense pressure from users of the system, this plan was shelved in 1989 and the decision made to modernize the system. This modernization included procurement of 24 new full low-floor vehicles (eventually built by Breda Costruzione of Pistoia, Italy), a new maintenance facility (replacing the original 1909 complex), two grade separations, and complete rehabilitation of track and right-of-way as well as electrical subsystems (upgraded to 750 V d.c.). Basic station designs are identical to those on the Saint Denis–Bobigny line. With a short subway in downtown Lille to gain entry to the main train station (La Gare), Le Mongy will provide cross-platform access to VAL and to train services, including the Très Grand Vitesse (TGV) high-speed rail line. The subway was originally provided in 1983 but subsequently relocated to provide better access to long-distance trains and the VAL terminal. An expansion of VAL (currently under construction) will put stations at both Tourcoing and Roubaix and will parallel the Roubaix service on its outer section. What effect this will have on the Roubaix patronage levels is subject to conjecture at this point. However, authorities believe that the high-level transit service in the corridor provided by VAL plus Le Mongy will encourage greater development and eventually foster high ridership for both services. The area was once the center of a strong textile industry, which has downsized in recent years.

Other Cities

At this juncture, a number of other French cities are thought to be close to decisions regarding the light-rail option. Montpellier has now chosen light rail and hopes to have an initial line in operation by the year 2000. Nice, Toulon, and Valenciennes all have advancing plans in which light rail could play a significant role. Moreover, Orléans is seriously considering a regional-type system based on the Karlsruhe approach, using shared rights-of-way with existing mainline railroad operations [those of the French National Railways (SNCF)] to reach distant suburbs. With intensive implementation over the past 10 years and a growing pipeline of potential projects, France can truly stake its claim as being the vanguard of new system development for the European continent.

Light-Rail Trends in Germany

With the few exceptions already mentioned (Hamburg and Berlin), major German cities elected to retain traditional tram systems and incrementally upgrade operations by increasing stretches of unencumbered rights-of-way, short tunnel segments to avoid areas of congestion, and well-conceived traffic measures to ensure priority for public transport in general and light rail specifically. Moreover, Germany took the lead in developing high-performance, high-capacity vehicles to fully capitalize on the concept. Now emerging is an operational variation that further exploits the flexibility of light rail. The following narrative examines the developments in Karlsruhe where innovative local government and transit officials cooperated to turn their local light-rail network into a genuine regional transit service.

Karlsruhe

A progressive town with a regional population exceeding 400,000 located on the northern edge of Black Forest region (Schwarzwald), Karlsruhe is bucking the trend in some German cities of stagnating transit patronage because of record automobile ownership. The reasons for transit's success in Karlsruhe are simple: the provision of high-quality, competitively priced transit that goes where people want to go.

Karlsruhe authorities, with the cooperation of surrounding jurisdictions and the German Federal Railways [Deutsche Bundesbahn (DB)], have forged an innovative and low-cost approach to creating a truly regional light-rail network. By pioneering the shared use of existing regional DB lines by LRVs, Karlsruhe has been able to institute high levels of service to multiple regional destinations in relatively short periods of time. The higher costs, long implementation times, and disruptions normally accompanying the construction of conventional light-rail extensions have been avoided as well.

The regional light-rail system that has emerged over the last 8 years was based on the original experience gained in operating a mixed passenger and freight operation since 1958 (known locally as the Albtalbahn line). Having acquired this dilapidated meter-gauge electric railway in 1958, Karlsruhe proceeded to modernize the line, changing to standard gauge (in order to institute through running with the existing city tram system and thus eliminate a time-consuming transfer) and retaining the capability to accommodate goods traffic. This latter provision required that the LRVs be equipped to accommodate mainline railroad design and safety standards (wheel profiles, ability to negotiate railroad switch pointwork, and provision of safety equipment). An additional extension in 1979 in the Neureut area again utilized portions of existing DB lines and provided further experience in joint operations as well as institutionalizing the necessary arrangements between the Karlsruhe transport undertaking and DB to ensure smooth operations.

Bolstered by this experience and a study that projected significant time savings for passengers destined for and departing from the center city (on the order of 12 to 13 min for a majority of passengers), the possibility of utilizing one or more of the seven electrified passenger routes operated by DB became a tempting option. A major obstacle to this possibility was the requirement for a vehicle capable of operating under the 750-V d. c. power of the city system and at 1500 kV a. c. on the National Railway lines. This impediment was resolved when trials undertaken in 1987 to test LRVs equipped for dual voltage confirmed that the operation was technically feasible. Moreover, it was also found that the necessary a.c./d.c. equipment could be accommodated within the existing LRV envelope.

The first line to receive this versatile service was the DB line to Bretten, of which 23.8 km of the 28.2-km length would actually be under DB 1500-kV power. Provision of the service was not without some capital expense (about $30 million) and some lengthy negotiations with DB. The need for capital expense sprang from the need to provide additional stops on the line, improve station access, and build the necessary connections between the two systems. Moreover, 10 dual-voltage LRVs were required and ordered for the line at a cost of $23.3 million. Although the construction work attracted 85 percent financing shared by the federal government and the Land (equivalent to a U.S. state), the cost of the new LRVs was a local responsibility, with the city of Karlsruhe paying the majority, or 60 percent, and the remainder being picked up by other benefiting towns along the line.

The second application slated to receive this treatment will be the Woerth line. Again, estimated construction costs are projected to be reasonable ($24 million). Environmental problems have forced a delay in the implementation of service on this line, although four dual-voltage LRVs have been unofficially assisting in providing service on the line.

The option to utilize existing infrastructure to access regional markets has provided Karlsruhe with a powerful tool to provide high-quality service at low cost. The success of this program has encouraged other areas in Europe to follow the "Karlsruhe approach." Orléans, in France, has made plans for a regional light-rail system based on the Karlsruhe approach. Nottingham, England, is pursuing a similar plan. And in Germany itself, Saarbruecken has received official approval to build a regional system based on shared use of DB lines. A description of this nascenr system is provided in the next section.

It is worth noting that the Karlsruhe system features a pedestrian mall 2.5 km long that serves as the spine of the regional system. As suburban services over DB lines are added, the rraffic channeled into this line will inevitably climb, posing the possibility of resulting congestion. Thus, in the long term, Karlsruhe planners are hoping to construct a tunnel for regional lines feeding into the downtown. City tram lines would continue to use the surface alignment.

Saarbruecken

This city of 200,000, located in the Saargebiet and hard on the French border, has recently received approval to construct a new light-rail system, the first in Germany in at least 50 years. Local authorities had compared the cost and applicability of an enhanced bus system, a VAL minimetro (similar to the VAL in Lille, France), and light rail (*Stadtbahn*). Authorities decided after extensive study that light rail was the most efficient mode for achieving a system serving both Saarbruecken and surrounding areas. This decision was influenced in part by the ability of light rail to utilize DB lines to provide the desired comprehensive regional service. During the planning phase, local authorities engaged planning teams from Karlsruhe and Cologne, thus tapping the experience gained by Karlsruhe in pioneering the shared-running concept and accessing Cologne's extensive light-rail design and operating knowledge.

As now planned, phase one of Stadtbahn Saar will consist of a 42-km route stretching from Jabach in the north through downtown Saarbruecken to Sarreguemines (actually located in France) in the south. The route alignment will partially utilize electrified mainline DB rights-of-way on both the north and south segments. The line will also be built in reserved space on downtown streets in Saarbruecken proper and in Reigelsberg on the northern segment. Partial service is slated to begin in May 1997. Phase one is projected to cost $360 million, with the German federal government contributing $142.7 million.

A total of 28 partial low-floor LRVs are initially envisioned for the system with the capability of operating both under 750 V d. c. on city sections and under 1500 kV a. c. on the DB mainline segments. The LRVs are being built by Bombardier Eurorail.

Additional extensions to the initial system are being actively planned, including service that would also employ DB rights-of-way and actually supplant existing DB local passenger rail service.

Conclusion: Accelerating Trends

The almost frenzied action in light rail in Europe since 1984, especially in the building of new light-rail systems and the application of low-floor car designs, reveals a heightened appreciation for the attributes of the system in a region of the world where the concept has already gained wide acceptance. The potential to insert a high-capacity mode in a mature urban setting has led the French to implement five new systems over the past 10 years and has given impetus for at least three additional systems likely to be approved in the near term. The British have built two new systems and have three systems on the drawing boards.

Also key in France has been the favorable institutional setting in which the existence of firm financing mechanisms and multimodal-oriented organizations with the power to nurture and guide urban transport investment has proved as effective as the attractiveness of the concept itself. The ability of transport officials to truly forge a balanced multimodal approach and largely avoid the modal biases that plague other areas deserves much credit for the success in implementing the new systems in France. This success is being duplicated in other European countries within the context of their own institutions and decision-making environments.

The attractiveness of the modern light-rail concept in France has also been enhanced by the high standards of design found in the new systems and the high degree of passenger acceptance and acclaim. Strasbourg, Rouen, and Nantes have demonstrated that public transit systems can be enhanced in such a manner as to not only markedly improve transit access and institute higher levels of service, but also dramatically alter urban settings to create pleasant, attractive places to live, work, and play.

The success of the Karlsruhe approach, with joint light-rail and railroad operations, has already spawned one new system in Germany (Saarbruecken) and fostered considerable interest for this approach in French light-rail decisions, especially in Orléans. The ability to expand light-rail services cheaply and relatively quickly has been key to the popularity of this approach.

The popularity of low-floor LRVs throughout Europe will likely lead to this design's becoming an inextricable component in decisions to build new light-rail systems as well as to upgrade existing ones. The ability to accommodate the disabled without expensive station facilities as well as the anticipated decreases in dwell times (leading to reduced car requirements) are compelling elements. The veritable explosion of contending low-floor designs offered by 12 builders is resulting in some consolidation of car builders in Europe, which could lead to needed efficiencies. Price economics achieved through standardization and consolidated orders will probably become an absolute necessity if the boom in light rail is to be sustained.

With proposals appearing for new systems throughout Europe, the next 10 years are likely to be as active as the last 10, if not more so. The next National Conference on Light-Rail Transit may indeed chronicle these advances but will most likely also include an abundance of positive developments in many other locations throughout the world. In fact, on the basis of what has already been achieved in Tunis, Guadalahara, Monterrey, Manila, and Tuen Muen, to name just a few, it seems more than likely.

Light-Rail Transit in Calgary, 1981–1995: A Retrospective Review

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In the past 14 years, the city of Calgary has invested approximately $543 million (Canadian) in developing a three-leg radial light-rail transit (LRT) system. Currently the LRT system consists of 30 km (18.6 mi) of double track, 31 stations, and 85 light-rail vehicles and carries approximately 100,000 passengers each weekday. Approximately 87 percent of the system is composed of surface operation in the right-of-way of city streets and an existing rail corridor. The present transportation and land use policies for downtown Calgary reinforce the importance of public transit for downtown work travel. Access-mode planning at the LRT stations also provides for a comprehensive range of access modes and effective coordination of feeder bus and LRT transfers to optimize the development of the transit market. Strategies have also been developed to integrate surface LRT operations within a shared right-of-way with private automobile, pedestrian, and bicycle traffic while giving priority to LRT operations through traffic signal preemption. These factors have enhanced the attractiveness of the LRT system for travel to downtown and suburban employment and educational and retail centers. The impact of LRT on travel behavior in Calgary and the planning and design lessons that can be learned from the first 14 years of LRT operation are examined. The lessons learned encompass systems planning and design, access-mode planning, personal security, and fare collection, in addition to overall experience gained with LRT operations.

With more than 14 years of light-rail transit (LRT) construction and operating experience, Calgary Transit has a substantial knowledge base regarding planning, design, and operation of LRT systems. The experience gained from construction and operation of successive stages of the LRT system has been used to adapt LRT operations to a variety of surface operating environments. Experiences with station design, access-mode planning, fare collection, and safety and security have also been used to improve operations.

Background

Calgary is a city of approximately 738,000 situated at the base of the Rocky Mountain foothills in southern Alberta. The city's economy has been built on an economic base of agriculture, energy, and tourism. Since the 1960s, Calgary's history has been one of overall steady growth from 400,000 in 1971 to almost twice that amount. The city has developed around a concentrated commercial core with a crescent of residential development radiating away from the downtown to the north, west, and south and an industrial district to the east. Approximately one-third of the present employment is located in the downtown and inner city, one-third along the east industrial area, and one-third throughout the city.

Calgary is a "unicity" in the sense that it is an urbanized area surrounded by agricultural or country residential areas. This situation allows the Calgary City Council to exercise almost complete control over its urban environment, including the transportation system. This combination of strong, continuous growth and unicity jurisdiction contributed to the advent of a successful LRT system in Calgary.

System Development

Discussion

In 1967, Calgary City Council adopted a balanced plan of freeways and heavy-rail transit, that was to be implemented over the subsequent 20 years (*1*). Projected expenditures showed an expected emphasis on freeways, with estimates of $450 million and $80 million for roads and transit, respectively. The freeway network plan adopted in principle met quick opposition with respect to plans for individual sections, and the momentum for a revised approach to urban mobility began in 1971 when a section of a major north-south freeway was relocated.

In 1972, the Calgary City Council took advantage of its unicity status and established a Transportation Department, which brought together a number of transportation functions previously administered by separate city departments. Traffic operations, public transit, and transportation planning (both transit and roads) were included in this department. The Transportation Department was placed under the jurisdiction of a Commissioner of Planning and Transportation, who has similar management responsibility over the City Planning Department. Coordination of the activities of transportation and land use planning under a unified administrative structure facilitated the integration of transportation modes (e.g., transit, roadways, parking, pedestrians) and development of mutually supportive land use and transportation policies.

Also in 1972, the province of Alberta initiated a new funding program for transportation in urban areas. Labeled as "responsive" to the right needs, the program provided financial assistance to municipalities for planning and construction of public transit and arterial roads. Receipt of funds was conditional on a municipality's passing a Transportation Bylaw based on a comprehensive study and on provincial approval of funded projects.

Initially, after abandoning much of the freeways proposed for the inner city but retaining some peripheral and suburban radial routes, Calgary concentrated on rehabilitating the public transit bus system. New equipment was purchased and a new express bus service was developed, forming a prototype system for the eventual rail system proposed. The express bus system promoted the development of transit corridors and included park-and-ride facilities and supporting feeder bus routes.

In 1976 the Transportation Department initiated several studies on the feasibility of LRT for Calgary. Light rail versus bus was compared for the south corridor, and transit versus roadway expansion was analyzed (*2*). While maintaining a substantial suburban roadway expansion program, Calgary City Council adopted the concept of LRT. After further review, implementation of LRT began in 1977, and in May 1981 the 10.0-km (6.6-mi) south line opened for revenue service.

With the downturn in the economy in the early 1980s, the city's perceived need for rapid implementation of LRT and its ability to finance the system were altered. A new staging schedule was adopted, and in 1984 the province announced a restructured assistance program providing continued financial support for the city's objectives.

Implementation of a northwest extension was delayed by controversy over its alignment. Although this line had been advocated by a Transit Commission in 1964, no action had been taken on right-of-way acquisition through the inner city. While extensive community consultation on this issue was being undertaken, implementation priority was switched to a northeast line whose right-of-way had been protected in the median of roadways planned for the area. The 9.8-km (6.1-mi) northeast line opened in 1985, sharing a downtown section with the south line.

The impending 1988 Winter Olympics gave impetus to resolving community opposition to the northwest line, which served important venues at the University and McMahon Stadium for the games. The 5.8-km (3.6-mi) line was opened in 1987 and connected to the south line. A further 0.8-km (0.6-mi) extension of the northwest line was opened in 1990, providing improved terminal connections to bus routes and park-and-ride facilities.

The existing LRT system (Figure 1) is operated as two lines—Anderson to Brentwood (south to northwest) and Whitehorn to downtown (northeast). On weekdays, LRT carries approximately 100,000 passengers (378 boarding passengers per operating hour), including 20,000 passengers within the downtown free-fare zone on 7th Avenue S. W. Average weekday bus ridership is approximately 161,800 (45 boarding passengers per operating hour).

To accommodate future system expansion, right-of-way has been protected for extension of the LRT system to the northwest, south, and northeast. Route location studies have also been undertaken to protect the right-

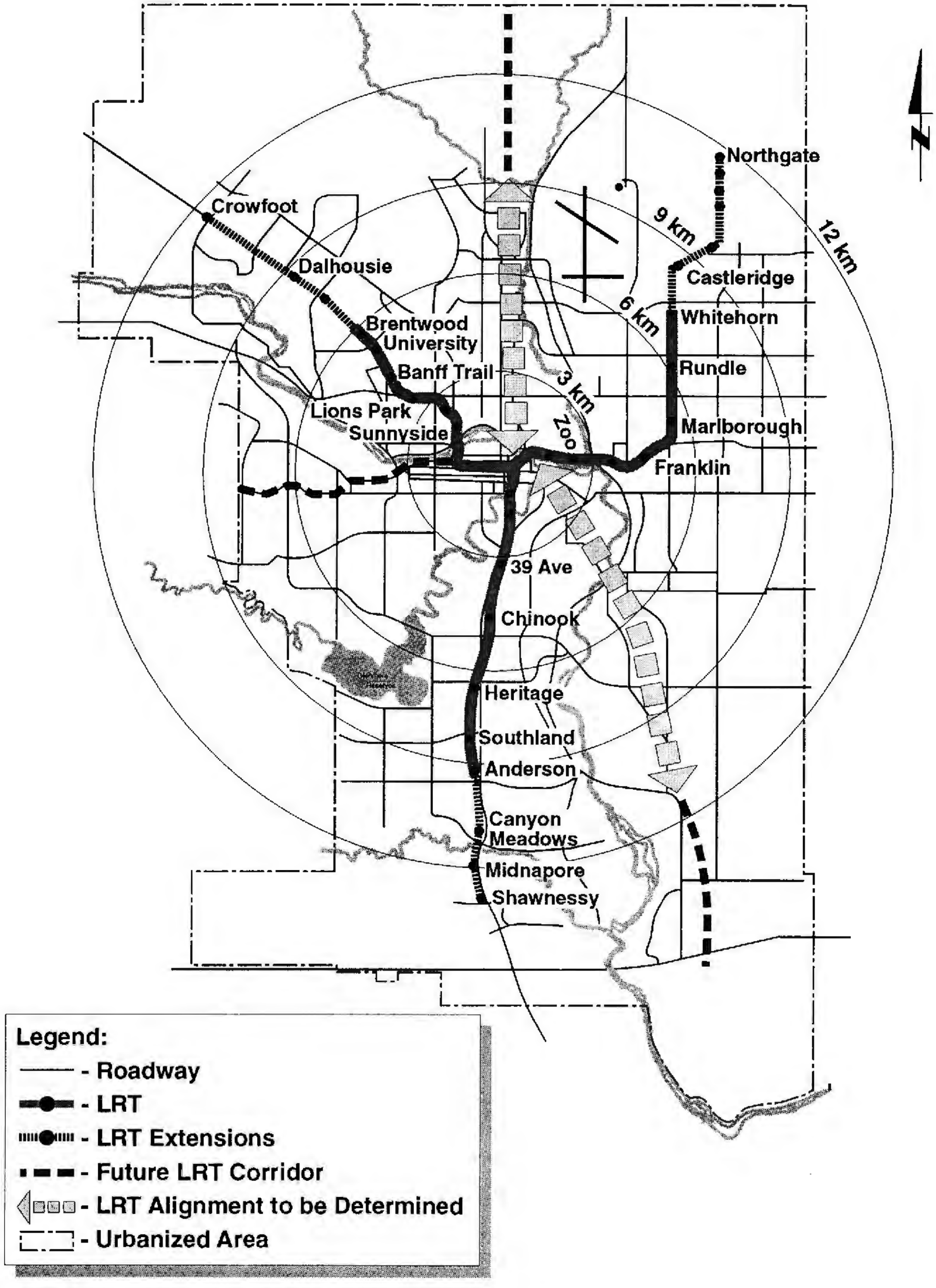

FIGURE 1 Calgary roadway and LRT networks.

of-way for future LRT lines to the southeast, west, and north.

Lessons Learned

1. Long-range plans should be developed to protect LRT right-of-way, including station areas and adequate land for park-and-ride and feeder bus facilities. Because the land is required well in advance of actual use, it is advisable to consider potential interim land uses to lower the overall capital investment. In addition, at this stage it is worthwhile to assess the potential of adjacent properties for compatible shared parking.
2. An LRT system prototype with express bus service and park-and-ride facilities should be developed to promote ridership in future rail corridors.
3. Transit planning should be integrated with transportation (roads, parking, pedestrian) and land use planning by creating multidisciplinary project teams under the control of a single administrative entity.
4. If possible, LRT expansion should be implemented in successive stages to continue momentum and develop expertise among the project management team and construction contractors.

Performance and Downtown Transportation Policies

Although Calgary may be characterized as being typical of western North American cities with high automobile ownership and low-density suburban neighborhoods, it differs from many similar-sized cities in that it has a well-defined, intensively developed downtown. With 86,700 employees, 10,000 residents, and 8.94 million m^2 (31 million ft^2) of office space plus hotels and retail space concentrated in only 3.6 km^2 (approximately 1.4 mi^2), downtown Calgary has one of the more concentrated central business districts (CBDs) in North America.

Calgary's present transportation policies are designed to alter the modal split in favor of public transit, particularly for work travel to downtown. The cornerstone of the policies for downtown transportation is the gradual reduction in availability of long-term parking relative to downtown growth. Current Land Use Bylaw requirements for office buildings in the CBD specify one parking stall per 140 m^2 (1,500 ft^2) of net floor area. For the downtown core area, which has restricted vehicular access because of the exclusive LRT-bus corridor on 7th Avenue and a pedestrian mall along 8th Avenue, the city has a cash-in-lieu program of on-site parking. The Calgary Parking Authority utilizes funds collected through this program to construct parking structures in designated corridors on the periphery of the downtown core. These structures have been connected to the office and retail core by an extensive, elevated walkway system known locally as the Plus 15 network.

To complement the downtown parking policies, the city has made a major investment in improving transit service by developing a radial system of LRT lines and mainline bus routes leading to the downtown. Complementary policies such as suburban park-and-ride, traffic management, roadway capacity restrictions, improved pedestrian environments, and downtown residential development complete the strategy.

Figure 2 summarizes the changes in parking supply, employment, and modal split to the CBD between 1964 and 1992. The period of greatest growth in the modal split occurred between 1971 and 1981, when parking supply lagged behind employment growth. Since 1981, transit usage has declined as parking supply has increased in proportion to downtown employment. The contributing factors to this situation are high office vacancy rates and the existence of a large supply of parking in office buildings and on temporary surface parking lots awaiting development. Of the approximately 45,000 downtown parking stalls, approximately 63 percent of the total supply is included in the category of bylawed parking (required under the Land Use Bylaw) and the remainder, non-bylaw parking is composed of on-street parking (5 percent) and surface parking lots (32 percent).

LRT has generally had a positive effect on transit usage, particularly for travel to downtown. Since the inception of the south LRT service, the line has carried between 38,000 and 40,000 passengers on weekdays, with the most notable impact being the attraction of nearly 20 percent of this ridership from previous automobile users (*3*). Between 1981 and 1985, the peak-hour modal split to transit for trips to the downtown increased from 37 to 47 percent but has since declined to approximately 42 percent.

Since its initial year of operation in 1985, the northeast LRT ridership has increased from 23,000 to 28,000 weekday passengers. Again, approximately 20 percent of these riders were previous automobile users (*4*). The peak-hour modal split for downtown work travel increased from 42 to 52 percent from 1985 to 1988 in the northeast corridor.

Because of funding constraints, the northwest line has been constructed in stages and does not extend into the center of the catchment area. This factor has limited ridership development. Currently, daily ridership is approximately 24,000 weekday passengers, and the modal split has remained at approximately 35 percent since the line opened in 1987 (*5*).

In general, public reaction to the introduction of LRT has been very favorable in each of the LRT corridors. Customer surveys indicate that 90 percent of LRT riders

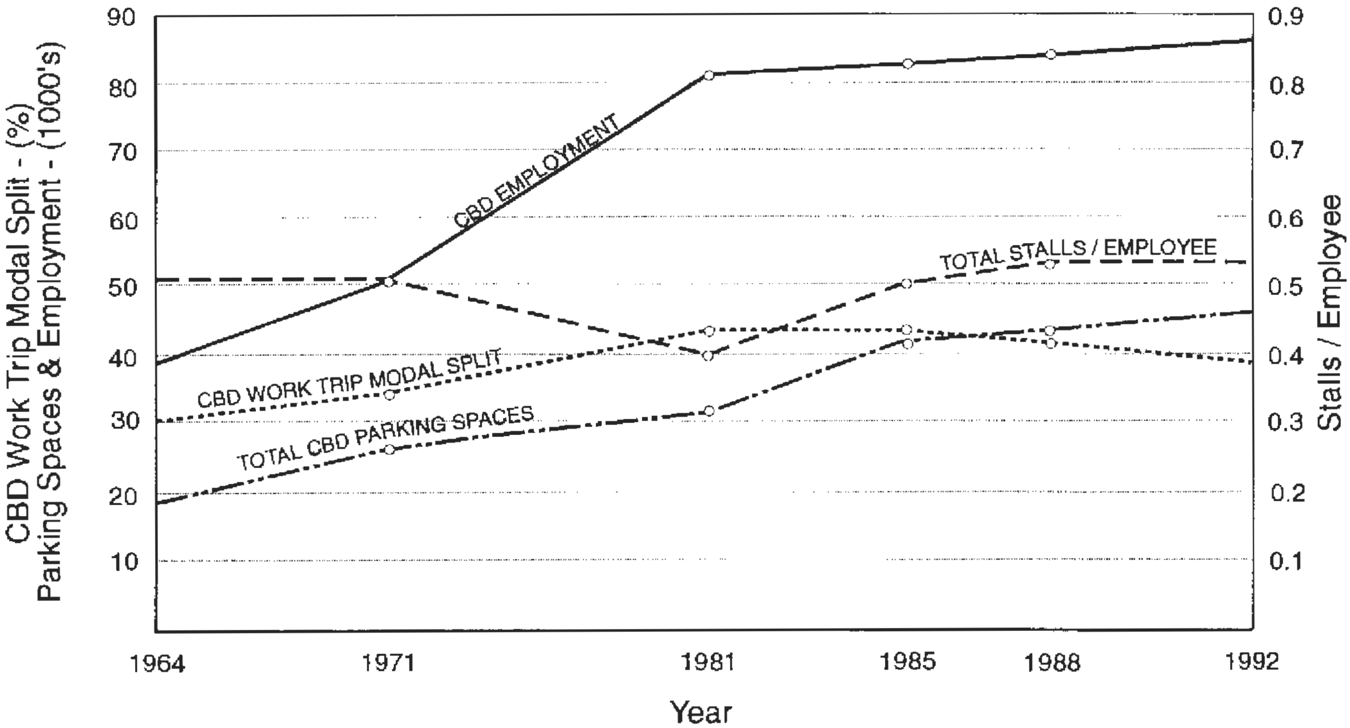

FIGURE 2 CBD work trip modal split.

are satisfied with the service. The qualities most often mentioned by transit customers who have switched from their private automobile to LRT relate to convenience and reliability of LRT travel, travel time savings compared with automobile travel, and the reduction of out-of-pocket costs for travel to downtown. Market research surveys also indicate strong support among transit users and nonusers for further extensions of the LRT system.

Future Situation

A recent study (6) has confirmed that there is a strong statistical relationship between the supply of long-term downtown parking and the amount of transit usage. In general, the more stalls per employee, the lower the propensity to use transit.

To manage future downtown growth, recommendations have been developed to match the supply of long-term parking to a desired modal split for transit travel to downtown. The matching policy for long-term parking is based on increasing the peak-hour work trip modal split from 40 to 50 percent within a 30-year period and higher beyond that time frame. An important part of the strategy to match parking supply to the modal split goal is to encourage further residential development within the downtown. Taken together, these initiatives and additional investment in public transit improvements (i.e., LRT and bus) will contribute to the achievement of the city's goals to provide a balanced transportation system and maintain a strong, viable downtown.

Lesson Learned

1. LRT has had a positive effect on increasing the modal split for downtown work travel when supportive parking policies are working to restrain long-term downtown parking.

System Design and Operations

Calgary's LRT system now consists of approximately 30 km (18.6 mi) of double track, of which 87 percent is for surface operation, 5 percent is on grade-separated bridges, and 8 percent is underground. Surface LRT operations have been adapted to operate in city streets (e.g., downtown Calgary), within an existing railway corridor (e.g., the south corridor), in the median of an expressway and major arterial roadway (e.g., the northeast corridor), and within existing communities and educational institutions on an exclusive right-of-way or parallel to existing local streets (e.g., the northwest corridor). In total, there are 43 grade-level roadway crossings on the LRT system.

Outside the downtown, train movements are controlled by an automatic block signal (ABS) system that allows only one train to occupy each section, or block, of track. At grade-level crossings outside of the downtown, trains preempt the normal operation of traffic signals to allow uninterrupted movement between stations. Grade-level roadway crossings are protected by LRT gates, bells, and flashing lights. Currently the gate warning time is about 22 sec, with an additional 10 to 15 sec for the gates to ascend and the warning lights and bells to turn off. In the northeast corridor, the operation of the traffic signals at the 10 grade-level intersection crossings along 36th Street N.E. is designed so that preempted traffic movements (e.g., north and south left turns) are reserviced if a preset green time has not been met once the train clears the intersection.

Within the downtown, the LRT operates along the 7th Avenue transit mall under line-of-sight operation with buses and emergency vehicles. Cross-street traffic and train and bus movements are controlled by conventional traffic signals. Although LRT trains are not given special priority at downtown traffic signals, a signal progression has been designed along 7th Avenue to minimize delays as the trains travel between stations.

Since the opening of the LRT system in 1981, there have been an average of 4.9 vehicle and pedestrian collision accidents per 1 million km. This compares with 17.3 collisions per 1 million km for the bus system. From a passenger safety perspective, there has been 0.56 passenger injury per million passengers on the LRT system compared with 3.5 passenger injuries per million passengers on the bus system. In comparison, a recent study of European and North American LRT systems revealed that LRT accident rates are similar to those for buses per vehicle kilometer and that on a passenger-kilometer basis, LRT is generally safer than bus, which, in turn, is safer than car (7).

Operating Experience Within Downtown

In examining temporal trends in collision accidents involving private vehicles and pedestrians, there is clear evidence of a learning curve with respect to LRT operations in the downtown. In the initial years of LRT operation, the system experienced over 22 vehicular accidents per year in comparison with the more recent average of 10 per year. However, no similar trend has been noted with respect to pedestrian accidents as the system continues to experience an average of six incidents per year (i.e., contact of any type).

The majority of accidents involving other motor vehicles in the downtown have occurred as a result of failure by private vehicles to obey traffic control devices at the streets intersecting 7th Avenue and 9th Street. Most pedestrian-LRT accidents are a direct result of persons jaywalking or disobeying signals at intersections.

New features and signage have been developed to increase the level of safety along the 7th Avenue transit mall. To summarize,

- LRT trains are restricted to a maximum speed of 40 km/hr along 7th Avenue, 15 km/hr through the turn at 7th Avenue and 9th Street S. W., and 25 km/hr on 9th Street S.W.;
- Pedestrian gates, signals, and railway crossing bells have been installed at the intersection of 7th Avenue and 3rd Street S. E. where the south and northeast legs merge; pedestrian bedstead barriers have also been installed at specific intersections to channelize pedestrian flow;
- Posts and chains have been erected along a one-block area on 7th Avenue where there are a number of taverns and at other locations where jaywalking has presented a problem;
- No Jaywalking signs have been installed along the 7th Avenue corridor, and support has been solicited from the local police to enforce the jaywalking bylaws; and
- A public awareness campaign has been established to develop a greater level of safety consciousness regarding the LRT system.

With the implementation of these improvements, there has been a gradual reduction in the number of accidents along 7th Avenue and 9th Street.

Operating Experience Outside of Downtown

A review of vehicle and pedestrian collisions for the outer sections of the LRT system indicates that the accident rate is substantially less than that for in-street operation within the downtown, which has experienced an average accident rate of 13 collisions per 1 million vehicle-km. In general, the northeast corridor, which incorporates median running in a major arterial roadway, has a slightly higher vehicle accident rate (0.33 collision per 1 million vehicle-km) than the south or northwest corridors (0.16 and 0.08 collision per 1 million vehicle-km, respectively). This difference is attributable to the concentration of commercial land uses and the heavy volume of cross-street and left-turn movements at the 10 grade-level intersections along 36th Street N.E.

Lessons Learned

1. Surface LRT operations can be safely integrated into city streets and other environments by using existing traffic signals, railway crossing equipment, and other pedestrian and traffic control techniques.

2. Use of LRT signal preemption provides travel time savings for transit travel and can be accommodated in major arterial roadways without compromising safety.

3. On the basis of Calgary Transit's experience, LRT accident rates are lower than those for the bus system, per vehicle kilometer. On a passenger-kilometer basis, LRT is also generally safer than bus.

Station Design

Discussion

The experience gained from construction and operation of each of the LRT lines has resulted in changes in the scale and design of Calgary's LRT stations.

The initial south LRT line includes six center-load stations fed by enclosed stairways and a single set of escalators at the north end of the platform. No provision was made for elevators or ramp facilities to accommodate persons with disabilities; however, equivalent funds were committed by City Council to upgrade the specialized door-to-door Handi-Bus service. In the downtown, short stairways and access ramps were constructed at the 11 side-load stations on 7th Avenue.

The design of the second leg of the LRT system to the northeast incorporated the LRT alignment in the median of an expressway and major arterial roadway. The seven center-load stations on this line are fed by stairways and ramps spanning the roadways. Within the station, an elevator and two sets of escalators were provided to accommodate access between the fare process area and the platform. Access to the platforms incorporates alternate end loading at successive stations. This revision emanated from a review of loading patterns on the south LRT stations, which showed that customers tend to cluster near the end of the platform closest to the only access point (*8*). Placement of the access points at opposite ends of the platform at adjacent stations has improved the evenness of passenger loads in the three-car train sets, resulting in better equipment utilization and passenger comfort compared with the same end-loading pattern on the south LRT.

Unlike the first two LRT lines, where limited community interface problems were encountered, the northwest LRT line presented a major challenge in integrating the stations and track alignment within established neighborhoods. To facilitate this process, Calgary City Council allocated $4.1 million to the $107 million capital budget specifically for aesthetic upgrade purposes and appointed an urban design consultant to work with community representatives and project management staff on the integration of the line within each affected community (*9*). Although the vertical and horizontal alignments were held as "givens" for this process, the scope of the review allowed the communities to influence decisions affecting pedestrian access and circulation, buffering for noise and vibration, landscaping of the right-of-way, and appearance of the stations, bridges, tunnel portals, and ancilliary structures.

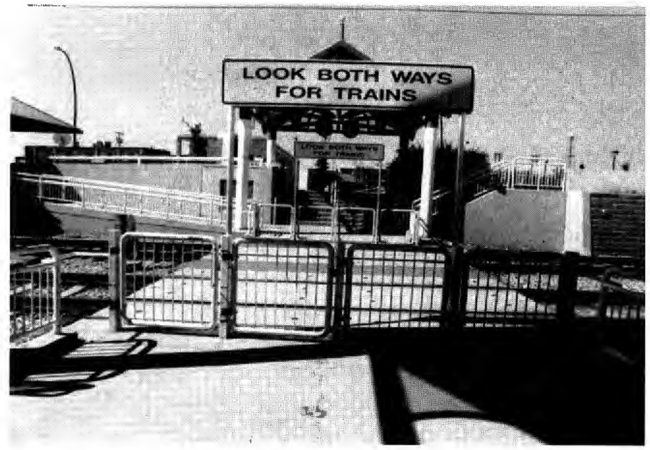

FIGURE 3 LRT station grade-level pedestrian crossing with gates, railway lights, bells, and large warning signs.

The alignment of the northwest LRT readily accommodated grade-level pedestrian access to the meter-high, side-loading platforms and presented an opportunity to design low-scale "local stations." Because the station design represented a major community concern from both aesthetic and functional perspectives, the philosophy adopted was that the stations should reflect the local urban character of the community both in design and materials and need not have a profile greater than a single-family house. To accommodate customer access, railway signals, pedestrian gates, and staggered bedstead railings are used to provide crossing protection at designated access points (see Figure 3). These grade-level crossings enhance customer access and also have been linked with the community pathway and bicycle network, which connect the northwest communities. Standard railway crossing signals, bedstead barriers, and pedestrian gates have been effective in providing protection for the volume of pedestrian and bicycle traffic crossing the tracks.

On the basis of the experience with grade-level access to the northwest LRT stations, new grade-level pedestrian connections are being constructed to accommodate handicapped access to the south LRT stations. The new connections incorporate a new set of stairs and a ramp and concrete apron linking the open end of the station platform with the park-and-ride lots. There is a single grade-level crossing of the southbound LRT track, which is controlled by a system of railway signals and staggered bedstead railings.

Lessons Learned

1. Station access walking time should be minimized by keeping the station design simple, and, if possible, direct grade-level access to the platforms should be provided.
2. Where appropriate, "local station" concepts should be considered to integrate LRT within established residential areas. The scale of the station should be minimized and urban design elements that complement adjacent land uses should be incorporated. Efforts should be made to integrate station access with the local pedestrian-bicycle pathway system. As a general rule, major park-and-ride lots should not be located at local stations except possibly on a shared-use arrangement with a land use such as a community center.
3. Barrier-free access should be incorporated in station design to accommodate persons with disabilities and other transit customers (e.g., persons with parcels, baby strollers, or small children).
4. Alternate end loading should be incorporated at successive center-load stations to balance passenger loads between cars in the train consist and achieve more efficient use of available capacity.

Access-Mode Planning

Access-mode planning for Calgary's LRT system accommodates a comprehensive range of access modes (*10*). In suburban areas, access is by feeder bus, park and ride, automobile drop-off, walking, and cycle. The predominant access mode to LRT stations for the inner city, University of Calgary, Southern Alberta Institute of Technology, and the Zoo is pedestrian (Figure 4).

Suburban Stations

The access-mode guidelines for suburban stations are as follows:

Access Mode	*Modal Share (%)*
Bus	60–65
Park and ride	15–20
Kiss and ride	15
Walk	5

The policy target is to accommodate two-thirds of total a. m. LRT boardings by feeder bus. This strategy recognizes that feeder buses are best able to supply the required capacity for customer access to the LRT system and addresses community concerns regarding the traffic and environmental impact of developing large parking facilities adjacent to residential areas.

To ensure the provision of a high-quality feeder bus service, public transit requirements are reviewed and incorporated at each stage in the development process as a condition for development approval. Through this process, the collector road system is molded to maximize transit coverage and enhance directness of travel. In developing feeder bus networks, every effort is made to provide direct bus service to and from the LRT to accommodate trips leaving the catchment area, serve a range of community-oriented trips (e.g., school, shopping), and, where possible, increase the potential for crosstown and intercommunity trips. Together, the LRT system and connecting feeder bus network form a citywide network of transit services.

To provide for private automobile access to the LRT system, park-and-ride and automobile passenger drop-off facilities have also been developed at suburban LRT stations. Currently there are more than 7,000 stalls at 11 stations and an additional 5,900 stalls are planned in extensions of the system. Accommodating 15 to 20 percent of peak-hour demand by automobile access represents a strategy to strike a balance between satisfying the demand for park and ride and maintaining a viable feeder bus service.

Inner-City Stations and Educational Institutions

The main access mode to inner-city stations and large institutions is pedestrian and, to a much lesser extent, the bicycle. Planning guidelines for these stations emphasize the pedestrian mode.

Lessons Learned

1. The feeder route network and LRT are mutually dependent for their success. Integration of LRT and feeder bus services substantially enhances the attractiveness of transit for travel to downtown and also utilizes opportunities that LRT presents for meeting non-CBD-oriented transit trips.
2. Public participation is required for access-mode planning at suburban stations to allay the fears of local residents with respect to increased automobile and bus traffic and spill over parking. The Calgary experience is that there is no substitute for detailed planning and public participation to gain public acceptance of feeder bus routes and park-and-ride facilities in close proximity to residential areas.
3. It is essential that an appropriate balance be maintained between park and ride and other access modes to sustain a viable feeder bus system and minimize traffic impacts in adjacent residential areas. Experience has demonstrated that parking expansion programs may

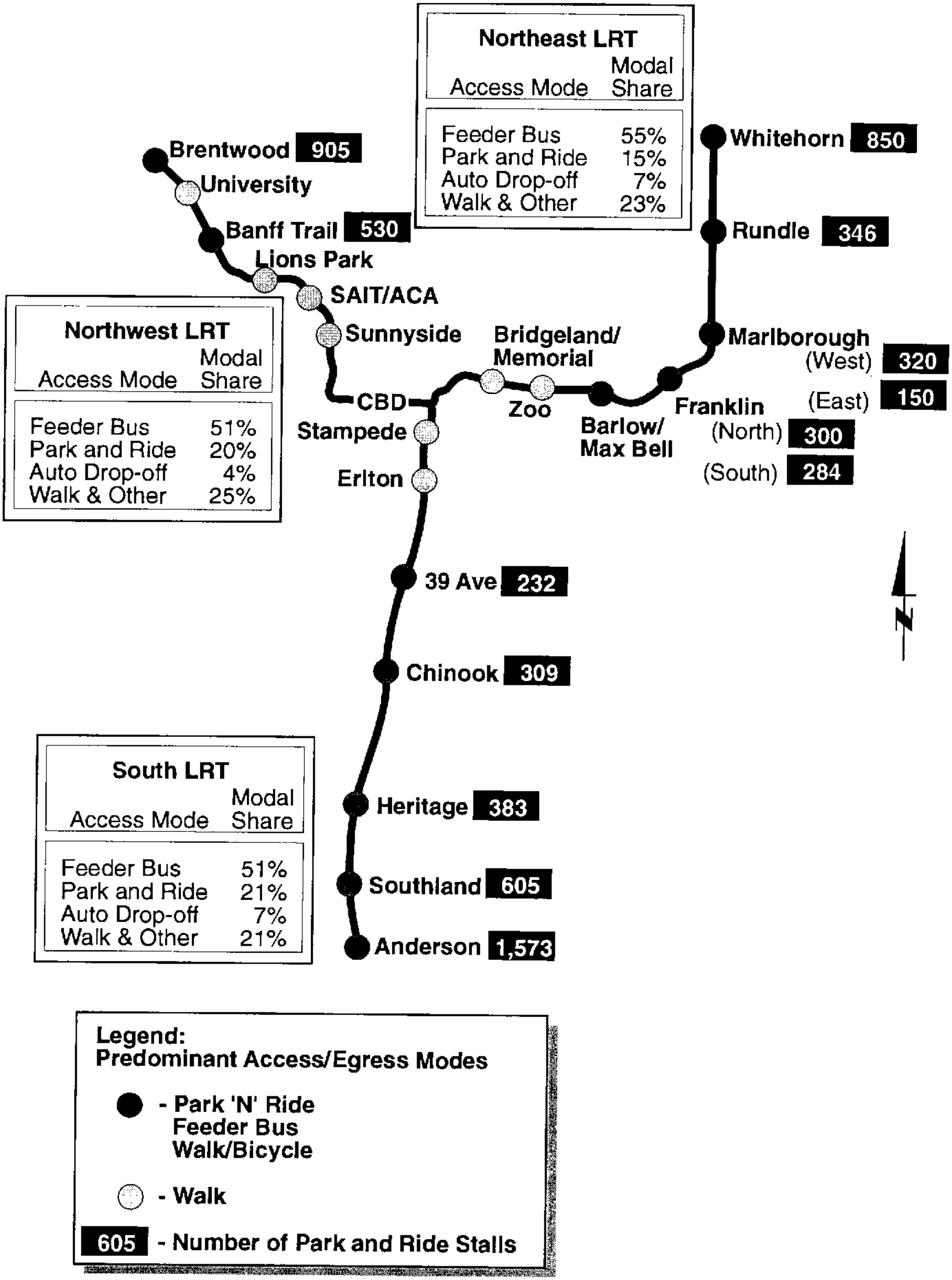

FIGURE 4 LRT access modes (a.m. peak period).

trigger some shift from other access modes such as feeder buses to park and ride rather than generating entirely new ridership (*11*). Oversupply of park-and-ride stalls not only is economically undesirable but also could result in unacceptable environmental and community impacts. Undersupply of park and ride can also result in unacceptable impacts such as spillover parking on adjacent streets and discourage public transit patronage by commuters now driving to work downtown. Part of the lesson learned is that the commutershed concept (*12*) is very useful for estimating the demand for park and ride as well as the trip generation to and from park-and-ride facilities (*13*).

Personal Security

The number of criminal acts against persons on transit property is low in relation to the number of customers who regularly use the system and the total crimes against persons reported citywide. In 1992 there were 112 crimes against persons involving C-Train passengers among approximately 70,000 Calgarians who use the C-Train regularly. This represents less than 2 percent of the total crimes against persons in Calgary.

Although 90 percent of transit customers report that they feel safe when using the LRT system (*14*), Calgary Transit is concerned that any perception that the LRT system is not safe from a personal security perspective may cause customers to use the system less frequently or not at all. To enhance public security and customer confidence in the LRT system, the following initiatives have been undertaken.

Equipment Enhancements

In 1992, Calgary Transit implemented HELP telephones on all LRT platforms and an intercom system in all light-rail vehicles. This system allows customers to communicate directly with Calgary Transit personnel in the event of an emergency or threat to their personal security. A multi-year replacement program has also been initiated to upgrade the 40 television monitors in the LRT control center and the 190 cameras located at LRT stations.

Crime Prevention Initiatives

Calgary Transit and the Calgary Police Service jointly endorse the concepts of Crime Prevention Through Environmental Design (CPTED) and have conducted facility audits to determine where CPTED principles could be applied to deter criminal activity and encourage greater confidence in the security of the LRT system. CPTED concepts include the design of buildings and surrounding areas to provide natural surveillance and natural access control. Integrating natural crime prevention approaches into the design of public buildings and property encourages greater use of facilities and reduces the need for intervention by traditional enforcement personnel.

Staffing Initiatives

To provide greater visibility of uniformed personnel patrolling the LRT system, additional uniformed employees have been assigned to assist existing Calgary Transit Protective Services officers in enforcing the Transit Bylaw. The Protective Services unit also continues to assign plainclothes officers to deter criminal activity and threats to personal security. As well, Calgary Transit deploys staff from the Transit Operator Spare Board to increase surveillance of park-and-ride lots.

Lighting Standards

The LRT system has been developed in phases over a 12-year period with no uniform standards for lighting at the stations and park-and-ride lots.

Calgary Transit has recently developed design guidelines for lighting levels at LRT stations (see Table 1) and has taken steps to address deficiencies in the downtown and the older south line stations. Lighting levels at downtown stations have been increased from 54 to 215 lux (5 to 20 footcandles). Work has also begun to correct lighting deficiencies at suburban stations and park-and-ride lots, particularly on the south LRT line.

TABLE 1 Design Guidelines for Lighting Levels at LRT Stations

Area To Be Lighted	Minimum Levels	
	Footcandles	Lux
1.1 Outlying platform	10 avg	108
1.2 Downtown platforms	15–20 avg	161–215
1.3 Interior stairs	8–10 avg	86–108
1.4 Lobby	8–10 avg	86–108
1.5 Ticket area	20 min	215
1.6 Parking lots	0.9 min	10
1.7 Above-ground building	8 avg	86
1.8 Sidewalks, bridges	4 avg	43
1.9 Ramps, exterior stairs	4 avg	43
1.10 Bus waiting areas	4 avg	43
1.11 Sidewalks in parking lots	2 avg	22

NOTE: 1 footcandle = 10.76391 lux. Lux is defined as the illuminance produced by a flux of 1 lumen uniformly distributed over 1 m^2.

Liaison with Calgary Police Service

Calgary Transit has increased liaison with the Calgary Police Service and other security units of organizations that operate in close proximity to the LRT line (e.g., educational institutions, shopping centers) to share information and coordinate public security efforts.

Customer Information

A communications program has been initiated to promote public awareness and confidence regarding the personal security features on the LRT system.

Lessons Learned

1. A visible, uniformed security presence and good customer information regarding personal security features are essential to maintain public confidence in the safety of LRT systems.
2. A variety of approaches may be employed to deter criminal activity and reinforce public confidence in transit travel, including environmental design to preventing crime, effective training and use of staff resources, up-to-date security equipment and lighting standards, ongoing liaison with police and other security agencies, and regular monitoring of crime trends and customer perceptions.

Fare Collection

Discussion

Calgary's LRT system uses a barrier-free, self-serve fare system that has been widely adopted by Canadian and American LRT systems. This system was chosen because it offers the highest potential savings in labor and equipment costs, provides the greatest flexibility in station design, and controls the level of fraud by regular fare evasion checks and issuance of fines to customers who do not pay.

In May 1993, Calgary Transit conducted a survey of fare evasion on the LRT system and found that 7.4 percent of riders failed to produce proof of fare payment when requested to do so. This level of fare evasion represented a loss of $2.3 million in annual revenue. Surveys before this time indicated a substantially lower fare evasion rate.

On a time-period basis, higher levels of evasion were reported during off-peak hours and on weekends than during peak periods. The highest levels of evasion were associated with stations closest to the downtown. High levels of fare evasion were reported on both inbound (to the downtown) and outbound directions of travel.

To reduce the incidence of fare evasion, several actions were initiated:

- The specified fine for fare evasion was increased from $35 to $150. This decision reflected the belief that the penalty for failing to produce a valid fare should be no less than three times the cost of a monthly adult transit pass (i.e., $46 per month).
- Additional staff resources were assigned to enforce the payment of fares, and regular "fare blitzes" have been conducted.

Subsequent fare evasion surveys have revealed that fare evasion levels have been reduced from 7.4 to 1.5 percent, which is considered a very satisfactory industry standard.

Lessons Learned

1. Calgary Transit continues to believe that the self-serve honor system is the most efficient and economical for LRT systems.
2. Fines for fare evasion must be set at a level that serves as an effective deterrent to avoid paying a transit fare. Calgary's philosophy is that the fine for fare evasion should be no less than three times the cost of a monthly adult transit pass.
3. Regular surveys must be conducted to monitor the rate of fare evasion and assign staff resources to address locations where fare evasion problems persist.

Conclusion

On the basis of more than a decade of operating experience, Calgary Transit has demonstrated that an LRT system can be successfully integrated within the right-of-way of city streets. Adoption of traffic signal preemption for LRT operations at grade-level crossings; a comprehensive, balanced range of access modes; and an integrated package of policies for managing downtown growth (e.g., emphasis on public transit, long-term parking restraints, deemphasis of the road system, enhanced pedestrian environment) have contributed to a greater than 40 percent modal split for downtown work travel and created an environment that supports further development of the transit market. Other lessons relating to station design, personal security, and fare collection have also improved the safety and operation of the LRT system.

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North American Light-Rail Transit Ridership and Operating Costs: A Basis for Comparison

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Comparisons of light-rail transit (LRT) performance on the basis of per mile or per kilometer cost or ridership ratios may be misleading, particularly if the systems are of different length or are located in urban areas with different populations and forms. A method for adjusting for these factors is presented, and the 1992 performance of North American LRT in terms of new indexes reflecting the additional factors is evaluated. Observations are made regarding relative performance of North America's LRT systems, and conclusions are reached as to additional factors that influence their relative positions. Also compared is the ranking of LRT systems according to the new indexes with a ranking derived from per-kilometer measures.

Planners and designers of new light-rail transit (LRT) systems or extensions to existing systems benefit from information on, and comparison among, systems already in service. Regularly published statistics by the Federal Transit Administration (FTA) can provide considerable insight into many aspects of comparison, as demonstrated at the Sixth National Conference on Light Rail Transit in 1992 (*1,2*).

Comparisons of ridership and operating costs among North America's LRT systems are complicated, however, by significant differences among both the characteristics of the systems and the metropolitan areas in which they operate. Principal among these differences are size of the metropolitan area, urban form, physical extent of the system, operating speed, level of service provided, and crewing arrangements for multiple-unit trains, where applicable. Significant ridership differences also appear to exist between Canadian and U.S. transit systems in cities of comparable size. Although numerous other factors also contribute, these begin to require knowledge of local geographic features, the extent of highway congestion, and other information not readily available from published sources.

This paper is intended to compare the performance of existing LRT systems by adjusting for the above-mentioned differences. It attempts to level the field to some extent by comparing each system's reported operating results for 1992 against an objective estimate that incorporates the principal system characteristics just listed. Each system's performance relative to these estimates may be considered as an index of performance distinct from traditional "per kilometer" ratio measures. Per kilometer ratios do not account satisfactorily for either differences in operating speed or trip end density related to urban size. On the indexed basis, a small system may be indicated as a good performer while still exhibiting higher costs per passenger-kilometer (PK) or lower ridership per route-kilometer (RK) than a larger system. Similarly, a system in a larger, denser, East Coast city may have higher ridership than a system in a less dense area, but a lower ridership index. This way of viewing relative performance may point to some existing systems that should receive more attention from planners looking for examples of good practice.

Approach and Limitations

For most of the U.S. systems covered by FTA in 1992, and to the extent possible for Calgary and Edmonton, both ridership and operating costs were estimated from system characteristics with a mathematical model; these models are described in the following sections. Two major LRT systems are notable by their absence: those in Toronto and Philadelphia. These systems are predominantly streetcar operations with a complex network of radial and crosstown routes; proper application of the ridership model would have required much more information than is readily available in published sources. Other, simpler, predominantly radial streetcar systems (e.g., those in San Francisco and New Orleans) were evaluated.

The ridership and operating cost relationships used here were derived by both linear and nonlinear regression techniques from both time-series and cross-sectional data. Although much of the underlying data came from two published sources (3,4), much information on individual LRT lines and stations was collected by the principal author from transit operators over a period of approximately 20 years.

The ridership index used here was formed by dividing the reported ridership by the model estimate; values greater than 1.0 indicate higher-than-estimated ridership. The operating cost index was formed by dividing the estimated cost by the reported value, so values greater than 1.0 indicate lower-than-estimated costs. Higher values of both indexes therefore represent better performance relative to the model estimates.

Because the information used in computing these indexes was derived from secondary sources, index values may not in some instances fairly represent the actual situation, for example, in cases of under-, over-, or misreporting of costs or ridership. Observations on some special situations that may have contributed to outlying values of the indexes are made in the Observations section of this paper.

Although the techniques discussed here could be nsed to estimate ridership or costs for a system in the planning stages, their accuracy is relatively low; estimates prepared using knowledge of local conditions, especially the distribution of land use and the nature of the transit labor contracts in a specific urban area, will almost always be more accurate.

Ridership Model

Formulation

The basic ridership forecasting technique applied was developed by the principal author in 1989 to identify a likely ridership range for a transit line given various urban and line characteristics and is documented elsewhere (5). The original technique yielded a ridership range expressed in terms of a central (most likely) weekday inbound ridership value and a cumulative frequency distribution of the ratio of ridership to the central value. The technique has since heen upgraded by the principal author to adjust for two of its major shortcomings: the inability to reflect major differences in urban age and form and the absence of an adjustment for operating speed. Given R_{peer}, the central value peer group baseline daily inbound ridership predicted by the original method as documented, the original adjustment factor of 1.5 for Canadian cities is replaced by a form factor, F_{form}. This factor is in turn expressed in terms of a variable called the urban form criterion (UFC) and is computed according to

$$F_{\text{form}}^{\text{USA}} = 0.35 + 0.98e^{-.31\text{UFC}}$$

for U.S. metropolitan areas and

$$F_{\text{form}}^{\text{Canada}} = 0.06 + 1.95e^{-.17\text{UFC}}$$

for Canadian metropolitan areas. The separate Canadian formula accounts for both a higher tendency for downtown concentration and a higher acceptance of transit for daily commuting by automobile owners.

The UFC used in this technique represents the ratio of the 1970 (1971 in Canada) census population of the central city of the metropolitan area to the 1920 (1921 in Canada) population. These years were selected to represent the transition between a primarily streetcar-centered development pattern and one predominantly centered on the automobile.

Typical values of UFC for states and provinces appear in Table 1 and may be used as working values if population data are not available. A range of likely values is also shown in Table 1; values derived from actual population data that lie outside these ranges should he checked carefully.

In the upgraded technique, the central ridership value is also multiplied by a speed factor, F_{speed}, determined by

$$F_{\text{speed}} = 0.45\,(V - 5.0)^{0.366}$$

where V is the average LRT operating speed in revenue service in miles per hour. For most cases this speed was obtained from the FTA operating statistics.

The upgraded technique yields the basis for the ridership index in this paper:

$$R_{\text{basis}} = 2DF_{\text{form}}F_{\text{speed}}R_{\text{peer}}\,(1 - F_{\text{linked}})$$

TABLE 1 Typical Values of UFC

State or *Province* (Postal Abbreviation)	Urban Form Criterion (UFC) Typical Value	Check Range
New England (CT,MA,ME,NH,RI,VT)	0.9	0.7 - 1.5
Northwest (northern CA,OR,WA,*BC*)	1.6	1.2 - 2.5
South (AL,AR,GA,KY,MS, NC,SC,TN,VA)	2.5	1.5 - 5.0
Plains (CO,ID,IA,KS,MO,MT,ND,NE, SD,UT,WY,*AB,MB,SK*)	2.0	1.2 - 4.0
Sun Belt (southern CA,FL,LA,NM,NV,OK,TX)	6.5	3.5 - 15.0
All others	1.4	1.0 - 4.5

where D is the effective weekdays per year (i.e., the total annual ridership divided by average weekday ridership), and F_{linked} is the assumed fraction of linked trips (e.g., transfers between branches). The factor 2 expands the ridership to include both directions.

Example of Ridership Estimation

The LRT system in St. Louis, Missouri, began operation in 1993, and therefore had no results published in the 1992 FTA reports. The base ridership for the index used in this paper would be prepared as follows:

1. Application of the 1989 basic peer forecasting technique to the St. Louis system would yield a central ridership value (R_{peer}) of 14,340 [for 2 million metropolitan population, 27 km (17 mi) of route with the center of the central business district (CBD) 4 km (2.5 mi) from one end, and 19 stations]; space limitations prevent showing these calculations here.
2. The ratio of the city of St. Louis' population in 1970 to the 1920 population is 0.806; however, this value is below the Table 1 check range for Missouri. Examination of historical population data for greater St. Louis indicates that municipal boundaries are continuing to change with the incorporation of new suburbs in the metropolitan area, so the value 1.2 (minimum check value from Table 1) should probably be used instead; the true value could be even higher. Application of the U.S. equation for F_{form} would return a value of $0.35 + 0.98e^{(-.31 \times 1.2)}$, or about 1.026.
3. The average operating speed of the St. Louis LRT is about 35 km/hr. Assuming a corresponding value of 22 mph, the equation for F_{speed} yields approximately 1.269.
4. St. Louis' motor bus system exhibits annual ridership equivalent to 278 weekdays, and because the LRT system has only one line with no branches, all trips should be unlinked trips. The basis for the ridership index would therefore be as follows: 2 directions $\times$ 14,340 $\times$ 1.026 $\times$ 1.269 $\times$ 278, or about 10.4 million unlinked passenger trips per year. This value corresponds to approximately 37,300 riders per weekday.

According to a recent account (6), ridership on this line has reached 35,000 per weekday. This value suggests that the ridership index ratio for St. Louis has reached 0.94 in less than 2 years of operation. If the UFC is actually closer to a typical "plains state" value of 2.0, the actual ridership index ratio could be as high as 1.10.

Ridership Estimates

Table 2 shows the values used for population, UFC, form factor, speed factor, and the central value ridership for the LRT systems examined. The results of the R_{basis} computations are shown in the column titled "Estimated Unlinked Passenger Trips." The reported values for unlinked passenger trips were taken from the 1992 FTA Section 15 annual report (4), except where noted in Table 2. The estimating technique explains 67.76 percent of the variation among the properties reported in Table 2; that is, the R^2 value is 0.6776.

Operating and Maintenance Cost Model

The operating and maintenance cost model was the result of a simple linear regression against the 1992 FTA reported operating cost results:

TABLE 2 Comparative System Statistics and Ridership, 1992: FTA Section 15 Reports Versus Ridership Model Estimates

Urban Area	System	Estimated Metro. Population (Millions)	UFC	Central Ridership Value (Rpeer)	Form Factor (Fform)	Speed Factor (Fspeed)	Assumed Fraction Linked Trips (Flinked)	Effective Weekdays per Year (D)	Estimated Unlinked Passenger Trips (000s)	Reported Unlinked Passenger Trips (000s)	Ratio of Reported to Estimated
Baltimore[a]	MD DOT	1.89	1.23	644	1.019	1.04	0.00	289	393	208	0.53
Boston[b]	MBTA	2.68	0.86	52,951	1.101	1.05	0.02	323	38,887	58,500	1.51
Buffalo	NFTA	0.95	0.91	5,308	1.089	0.94	0.00	288	3,123	8,570	2.74
Calgary[c]	C-Train	0.78	6.30	15,235	0.728	1.21	0.05	300	7,665	24,300	3.17
Cleveland	GCRTA	1.75	0.94	17,746	1.082	1.13	0.02	285	12,119	5,044	0.42
Edmonton[d]	ETS	0.85	7.10	7,216	0.643	1.18	0.00	300	3,291	10,300	3.13
Los Angeles	SCRTD	8.00	7.80	70,162	0.437	1.16	0.00	356	25,241	11,307	0.45
New Orleans	RTA	1.08	1.53	14,355	0.960	0.70	0.00	312	6,036	6,912	1.15
Newark (New York)	NJT	15.59	1.40	6,706	0.985	1.01	0.00	288	3,854	3,057	0.79
Pittsburgh[e]	PAT	1.81	0.88	24,257	1.096	1.05	0.02	290	15,807	9,968	0.63
Portland	Tri-Met	1.17	2.20	10,187	0.845	1.05	0.00	330	5,962	7,703	1.29
Sacramento	RT	1.10	3.60	16,712	0.671	1.21	0.05	285	7,356	6,781	0.92
San Diego	SD Trolley	2.35	9.40	39,636	0.403	1.23	0.02	342	13,130	17,163	1.31
San Francisco	Muni	3.63	1.41	87,861	0.983	0.85	0.02	298	51,319	39,034	0.76
San Jose	SCCTD	1.44	6.60	23,919	0.477	1.08	0.05	311	7,291	6,135	0.84
Seattle	Metro	1.39	1.69	376	0.930	0.45	0.00	292	92	186	2.02

[a]System opened in 1992; only a few weeks of system operation were reported. Central ridership value was adjusted to compensate.
[b]Ridership from 1991 ridership study by Calgary Transit.
[c]Ridership from Planning Unit, Edmonton Transit
[d]Reported trips adjusted to remove subway portion reported as rapid transit
[e]Prior Year (1991) datum used because of work stoppage in 1992.

$$OC_{LRT} = 0.68 * AM_{LRT} + 112.70 * TH_{LRT}$$

where

OC = operating cost per year (including labor cost), in 1992 dollars;
TH = train-hours of operations per year; and
AM = axle-miles of light-rail vehicle (LRV) operations per year.

Axle-miles, the product of vehicle-miles and axles per vehicle, was used to adjust for the difference between four-axle and six-axle LRVs on various systems. Train-hours represents the number of hours operated by LRV consists, regardless of length. For agencies operating multiple-unit trains, train-hours were estimated from published revenue operator hours, vehicle-miles, and known operating practices.

The costs reported for 1992 in the FTA Section 15 reports are compared with the results of the estimate in Table 3. The index ratio of estimated to reported values is used to preserve the "higher is better" convention. The estimating technique explains 77.21 percent of the variation among the agencies reported in Table 2; that is, the R^2 value is 0.7721.

INDEXED RESULTS

Tables 2 and 3 contain the index ratios for ridership and operating costs, respectively. Figure 1 presents the index results with the ridership index on the horizontal axis and the cost index on the vertical axis. The points corresponding to each system are labeled. In keeping with the "higher is better" convention for both indexes, the farther from the origin (lower left corner) a point is, the better its overall performance relative to the estimates. Three quadrants in Figure 1 have been labeled to indicate both the relative ridership and cost performance in the portions of the "index space" formed by the graph.

Factors not included in the estimating equations, and largely associated with local or site-specific conditions, should provide some clues as to the systems' positions within the index space of Figure 1. Chief among these factors are likely to be

- Location of the LRT route and stations in the urban context, that is, with respect to specific population and employment concentrations and major activity centers;
- Relative cost and complexity of LRT infrastructure, such as the extent of subway operation;
- Ability of the system to operate multiple-unit trains with a single crewperson; and
- Presence or absence of major trip generators on the routes.

TABLE 3 Comparative System Operating Costs

Urban Area	System	Estimated Operating Cost (Millions)	1992 Reported Operating Cost	Ratio of Estimated to Reported
Baltimore	MD DOT	$2.81	$1.24	0.441
Boston	MBTA	$25.30	$15.64	0.658
Buffalo	NFTA	$12.20	$6.59	0.540
Calgary[a]	C-Train	$17.10	$29.34	1.716
Cleveland	GCRTA	$10.91	$10.48	0.961
Edmonton[a]	ETS	$9.10	$9.26	1.018
Los Angeles	SCRTD	$41.19	$23.26	0.565
New Orleans	RTA	$5.30	$11.63	2.193
Newark	NJT	$4.30	$6.89	1.604
Philadelphia	SEPTA	$56.96	$65.63	1.152
Pittsburgh	PAT	$23.49	$22.59	0.962
Portland	Tri-Met	$11.44	$10.78	0.942
Sacramento	RT	$11.35	$12.76	1.124
San Diego	SD Trolley	$18.93	$31.06	1.642
San Francisco	Muni	$62.26	$44.24	0.711
San Jose	SCCTD	$19.23	$19.81	1.030
Seattle	Metro	$1.27	$1.45	1.141

[a]Canadian dollars discounted 15 percent

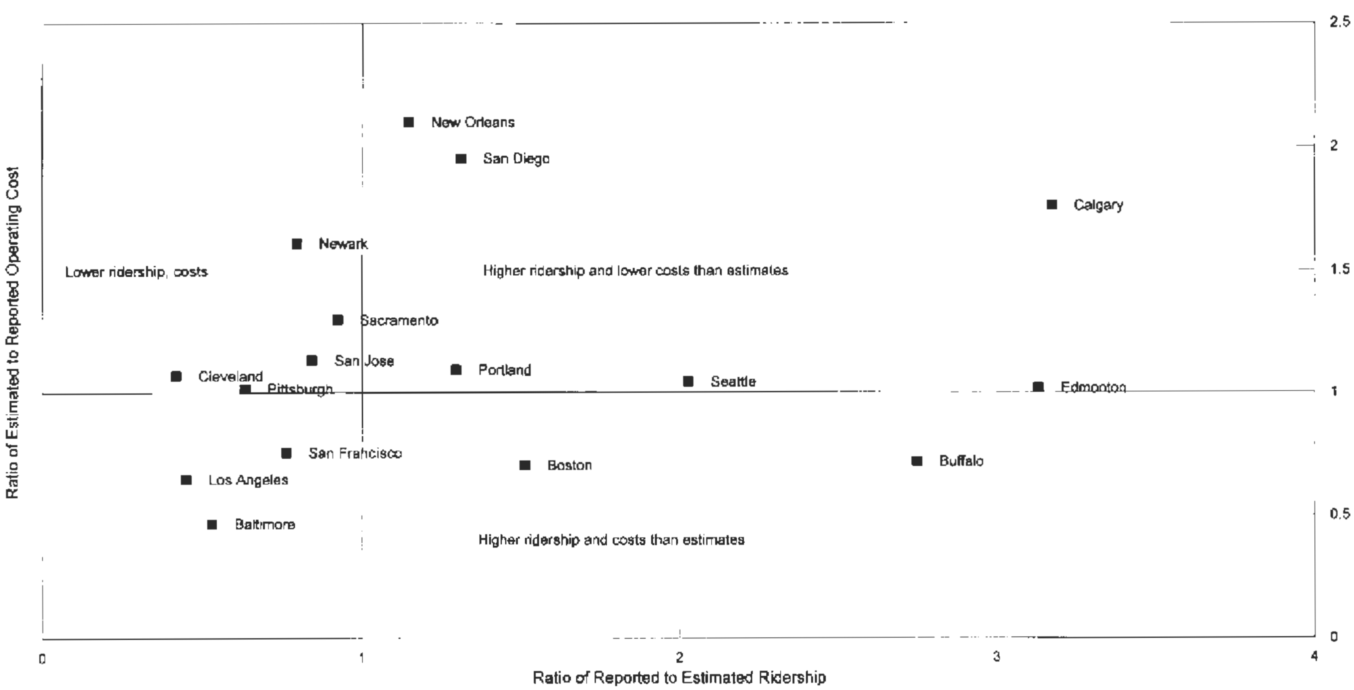

FIGURE 1 Comparison of ridership and cost ratios.

Some of these factors are discussed in the following section. Once again, relatively minor differences in index values should not be considered significant.

Observations

The following observations may be readily drawn from Figure 1:

1. Calgary appears to have the best all-around performance, with significantly higher ridership and lower costs than the estimating equations would suggest (i.e., in terms of indexed values).
2. Buffalo and Edmonton, and to a lesser extent Seattle, have very high ridership in indexed terms.
3. San Diego and New Orleans exhibit relatively low operating costs, that is, high index values.
4. Boston, Portland, and San Diego have relatively strong ridership indexes.
5. Cleveland, Pittsburgh, Los Angeles, and Baltimore have relatively weak ridership indexes.
6. Los Angeles, Baltimore, San Francisco, Boston, and Buffalo exhibit relatively high costs, that is, low index values.

Likely contributing factors can be advanced for many of these observations; other differences may prompt the study of individual systems. Factors relating to cost and ridership are considered separately in the following sections.

Operating and Maintenance Cost

First and foremost, it is not surprising that San Diego and Calgary have a very similar, positive cost experience. These systems both went into operation in the same year (1981); are almost entirely at-grade, operating on street in downtown areas; use the same rolling stock; have extensive stretches of high-speed (80 km/hr) running; and carefully tailor their single-operator consists to demand. Edmonton also shares the age, equipment, and operating practice similarity, but has an extensive underground infrastructure, including several subway stations, to operate and maintain.

From a cost perspective, the systems with an index near 1.0 (Cleveland, Pittsburgh, San Jose, and Portland) can be considered the mainstream of modern North American LRT.

The cost experiences of San Francisco, Boston, and Buffalo are probably similar because all these systems have extensive underground operation, with correspondingly higher maintenance costs for infrastructure, and predominantly single-unit operation or an operator in each car of the train.

New Orleans' high cost index (i.e., relatively low costs) may in part be due to lower wages than the national average, an entirely at-grade system without extensive signaling, lower track maintenance associated with lower operating speeds, and the recent extensive refurbishment of the fleet. It should be remembered that the index takes into consideration and adjusts for the effect of additional operator hours for low-speed operation.

Los Angeles' high cost may be attributable to its security efforts, which have been suggested to be as much as 40 percent of the total operating cost. An adjustment for this expense would place the system close to the mainstream systems of modern LRT. Edmonton also spends close to 30 percent of its costs on fare collection and security.

Baltimore's high cost result probably reflects the start-up nature of the operation, which operated only during a small fraction of the year.

None of the foregoing factors offers a convenient explanation for Newark's apparently low relative costs. The system is largely underground, has a complex infrastructure, and operates single-unit vehicles. The agency's reporting practices for costs may be a contributing factor, but they could not be explored as part of this paper.

Ridership

Alberta's two large cities, Edmonton and Calgary, have very high ridership indexes. In effect, they violate the built-in premises of the ridership model in two important respects. First, both cities grew very rapidly during the 1970s, with planning controls such that tremendous concentrations of downtown employment were established; in other words, their UFCs are effectively much lower than their population data for 1921 and 1971 would suggest. Second, for moderately large cities (on the order of 800,000 population), they are unusual in not having radial freeway systems converging on, and connecting into, the downtown; in both cases, LRT was implemented as an alternative to freeways before the fact rather than as a remedy for existing central area freeway congestion. Both systems also connect large urban university campuses to the downtown. The construction of major sports facilities directly on the LRT routes in both cities has also been advanced as a significant contribution to their ridership (7). In considering all these factors, it should be remembered that the index takes into account and adjusts for generally higher ridership in Canada.

Seattle's high ridership is probably related to its atypical market; it draws roughly twice as many riders as a commuter route would a similar distance from the CBD, including substantial tourist trips.

Boston's solid ridership performance is probably linked to the branching surface routes serving several universities, hospitals, and other major generators as well as major employment centers in the Back Bay.

A university anchoring the outer end of the line probably contributes to Buffalo's high relative ridership, but other factors are almost certainly active. One possibility is its direct location under a major urban arterial, which is more characteristic of heavy-rail rapid transit than LRT.

Adverse economic developments of the past several decades may have contributed to the relatively low ridership indexes of Cleveland and Pittsburgh. The major universities on Cleveland's east side are either not well served by LRT or are better served by "heavy" rapid transit in the corridor, whereas none of Pittsburgh's major urban universities outside the CBD are in the South Hills LRT corridor.

The economic conditions prevailing in many of the neighborhoods surrounding the Los Angeles Blue Line may account in part for its lower ridership index. Recent accounts suggest, however, that the Blue Line's ridership index has increased to at least 0.50, indicating that its relatively recent start-up may have also been a factor in 1992.

Baltimore's lower ridership is likely to relate to its start-up status, though later experience suggests that its index remains less than 1. 0. A contributing factor may be the poor position of the line relative to outlying population concentrations, including several that have good competing bus service. There are no universities on the line outside the CBD. Adverse general economic conditions may also have contributed.

Index Performance Versus Per Kilometer Comparisons

When the systems are ranked according to the indexes used in this paper rather than the more traditional bases of per RK (for ridership) or per PK (for costs), some interesting differences emerge. The comparative results for ridership are shown in Table 4. The two leading systems on a per RK basis (Boston and San Francisco) fall several places in ranking when compared on the index basis. In effect, because these are larger and denser cities than many others, their ridership per RK should be higher. In the indexed-ridership sense, some of the newer systems in California rate higher than San Francisco because they are relatively more successful in attracting ridership in their respective contexts. Age of the systems also clearly appears to be a factor; the indexed value rankings for

TABLE 4 Ridership Ranking Comparison: Per RK Versus Index

Urban Area	System	Rank by Riders per Route-km	Rank by Ridership Index	"Survivor" System?	Difference in Ranking
Baltimore	MD DOT	14	14	No	0
Boston	MBTA	1	5	Yes	(4)
Buffalo	NFTA	4	2	No	2
Calgary	C-Train	3	1	No	2
Cleveland	GCRTA	13	16	Yes	(3)
Edmonton	ETS	5	3	No	2
Los Angeles	SCRTD	9	15	No	6
New Orleans	RTA	6	8	Yes	(2)
Newark	NJT	7	11	Yes	(4)
Pittsburgh	PAT	11	13	Yes	(2)
Portland	Tri-Met	10	7	No	3
Sacramento	RT	12	9	No	3
San Diego	SD Trolley	8	6	No	2
San Francisco	Muni	2	12	Yes	(10)
San Jose	SCCTD	15	10	No	5
Seattle	Metro	16	4	No	12

Boston and San Francisco, and in fact for all "survivor" LRT systems that have been operating for decades, are all lower than their per RK rankings. This is not unexpected for systems that were planned around more recent developments than the survivor systems.

The comparative results for operating cost are shown in Table 5. There is generally little difference between the systems, with the exception of Los Angeles and Edmonton, which are ranked seven places lower on the indexed basis, and three systems that rated significantly higher: San Jose, New Orleans, and Newark. There is no immediately apparent reason for these exceptions. Los Angeles and Edmonton have significant security and infrastructure maintenance costs in common, but without further research they cannot be presumed to be unique in this respect. The three systems that are higher-ranked are very disparate, suggesting that further research would also be appropriate.

Conclusions

A number of conclusions may be drawn:

1. At least two-thirds of the variance in ridership and operating costs among North American LRT systems can be attributed to large-scale aggregate characteristics of the systems and the metropolitan areas they serve.

2. Single-person operation of multiple-unit trains is a key source of operating cost efficiencies on the continent's newer LRT systems.

3. Underground operation, particularly of subway stations, drives LRT operating costs up significantly.

4. The strongest relative ridership performances in North America are achieved by systems that either (*a*) concentrated an employment growth boom downtown without building freeways into the CBD (Calgary and Edmonton) or (*b*) invested heavily in an underground alignment along a major arterial (Buffalo).

5. Systems that are building on readily available right-of-way not located through population concentrations may be trading off relatively low ridership for construction cost savings.

6. All LRT systems with ridership indexes near 1.0 or higher, including the new St. Louis system, connect the CBD to at least one major university campus outside the CBD.

Acknowledgments

The authors wish to express their appreciation to the individuals who supplied information on the two Cana-

TABLE 5 Operating Cost Ranking Comparison: Per PK Versus Index

Urban Area	System	Rank by Cost per Passenger-km	Rank by Operating Cost Index	Difference in Ranking
Baltimore	MD DOT	16	16	0
Boston	MBTA	15	14	1
Buffalo	NFTA	14	13	1
Calgary	C-Train	2	3	(1)
Cleveland	GCRTA	6	8	(2)
Edmonton	ETS	3	10	(7)
Los Angeles	SCRTD	8	15	(7)
New Orleans	RTA	7	1	6
Newark	NJT	10	4	6
Pittsburgh	PAT	12	11	1
Portland	Tri-Met	4	7	(3)
Sacramento	RT	5	5	0
San Diego	SD Trolley	1	2	(1)
San Francisco	Muni	13	12	1
San Jose	SCCTD	11	6	5
Seattle	Metro	9	9	0

dian LRT systems included in the analysis: David Padgett of the Planning Unit of the Edmonton Transit System and Oliver Bowen, Director of Transportation for the City of Calgary.

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Light-Rail Developments in Great Britain

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Nearly all street railways in Britain had disappeared by the 1950s, but their resurgence as light rail is now well established. Tyne and Wear Metro brought light-rail technology to the United Kingdom in 1980. Manchester opened the first light-rail system with street running in 1992, and Sheffield followed in 1994. Outlined in this paper are light-rail schemes at various stages of planning and implementation in Great Britain. The efforts to secure private-sector funding to meet government objectives and the environmental concerns about congestion and pollution are described. A summary of the characteristics of schemes built, under construction, and planned is given, and the costs of construction for each system and proposed extension are compared. The characteristics of light-rail vehicles are summarized together with the benefits obtained from light rail.

Street railways, known as tramways in Britain, all but disappeared in the 1950s. Buses took over, as in many North American cities, in the belief that railed vehicles in the streets were a prime cause of congestion. Now the severe congestion in most large cities as a result of too many automobiles is causing a major reappraisal of transport policies.

Transit in the form of bus lines has been in decline in Britain for more than three decades as buses are delayed by congestion and become increasingly unreliable and unattractive. Efforts to provide protection through bus priority measures, including transit lanes, have met with limited success.

It has become clear that a step change is needed in the quality of urban transit and that this is extremely difficult to achieve with bus-based systems. The first new street running light-rail system in Britain, opened in Manchester in 1992, has demonstrated the ability of light rail to attract car users in substantial numbers.

The resurgence of the modern tramway is now gaining momentum in Britain, albeit with a struggle against central government reluctance to provide capital funding. A new government approach to funding, combining highway and transit expenditure in a single package, is encouraging local authorities to review their policies. It allows them to give high priority to light-rail schemes where costs and benefits meet specified criteria.

It has finally been accepted by the government's Department of Transport that new highway construction does generate additional traffic. It has also been recognized that there is no way that future growth in traffic can be accommodated by constructing more new or expanded highways. These fundamental changes have yet to be reflected in major changes to government policies for roads and railways or in spending priorities, but such changes are slowly emerging.

The emphasis is moving toward managing demand for travel, not trying to meet the demand. This is already having an effect on planning policies, which have recently moved away from support for out-of-town shopping centers and business parks toward more centralized developments closer to existing town and city centers.

Private-Sector Funding

The government is, however, adhering rigidly to the belief that the role of the private sector is paramount and that private finance and private-sector operation are essential to the success of any scheme. Government policy is to maximize the involvement of the private sector, not just in funding but in transferring risks from the public to the private sector and in harnessing private-sector skills and enterprise. This policy is being encouraged through the Private Finance Initiative and is being applied to all forms of transport investment.

Although private-sector contributions must be sought by the promoter of any light-rail scheme, efforts to meet these demands for private-sector funding have so far had only limited success. Schemes like the Docklands Light Railway or Manchester Metrolink are often quoted as good examples of private-sector participation, but the proportion of capital investment from private sources is in fact very small.

New forms of procurement have been developed in an attempt to entice private-sector capital and to transfer risk from the public sector. Manchester was the first light-rail scheme to be built using a Design, Build, Operate, and Maintain (DBOM) form of contract. This enabled the bidding consortia to place a value on the 15-year operating concession, which could then be reflected as a capital contribution to the design and construction of the scheme. The mechanism devised was for a new company to be created that is owned by the companies forming the group that won the contract. The new company then subcontracted with its constituent companies for the design and construction of the light-rail system, including supply of rolling stock. The company itself became the operator of the system.

It should be noted that this approach works only if the operation of the system is predicted to be profitable. Profitability is a prerequisite for any proposed light-rail scheme in Britain. If its direct operating costs are not predicted to be profitable, it will not even be considered for any form of funding by the central government. No other source of capital funds exists, because there is no provincial or state government, and local government finances are strictly controlled by central government.

Other light-rail schemes in Britain are following the DBOM approach, including those in Birmingham and Leeds, but other variations are being developed. In every case a key objective is to maximize the private-sector role and financial contribution.

Environmental Concerns

Increasing congestion and atmospheric pollution from road vehicles has heightened public concern over their effects on health. There is a growing awareness that major policy changes are needed, and this is reflected in an increasing readiness to accept restrictions on private automobile use in cities. More people now want investment in transit rather than in expanded highways.

The Royal Commission on Environmental Pollution published its report in October 1994 (*1*). Over 100 recommendations were made, many of which affect urban transit systems. A key objective in the recommendations was to ensure that an effective transport policy at all levels of government is integrated with land use policy and that priority is given to increasing the proportion of trips made by less environmentally damaging modes, including walk, cycle, and light rail. Further, the Royal Commission recommended that the government make more resources available for light-rail systems so that they can be built within a reasonable time, provided they form an integral part of an overall transport strategy for the conurbation.

A string of recommendations related to improving air-quality standards, including government encouragement of the development of electric power for transit systems operating with frequent stops in urban areas. The Royal Commission's strong support for electric traction in general, and light rail in particular, has been welcomed, but it has yet to find expression in government policy on funding for light-rail schemes.

Environmental benefits are an important part of the evaluation of any light-rail scheme and an environmental impact assessment is now required for major projects under European regulations.

Existing Light-Rail Systems

Currently there are four operational "new generation" light-rail systems in Britain, the most recent of which, Manchester and Sheffield, include street running. There is also the Blackpool Tramway, which was the country's first electrified tramway system in 1885 and was the only one to survive the abandonment policies of the 1940s and 1950s. The Isle of Man also has its historic Manx Electric Railway and Snaefell Railway, which may be classed as light rail.

The principal characteristics and performance of the four new systems are given in Table 1, together with those for the next two systems to be built, Midland Metro and Croydon Tramlink. A brief outline is given for each system.

TABLE 1 Line Lengths, Car Fleets, and Productivity

System/City	Year open	Route length kms (mls)	No. cars	Annual rides (M)	Cars/km (cars/ml)	Rides/km (M) (rides/ml) (M)	Rides per car (M)
Tyne and Wear Metro Newcastle upon Tyne	1980	59 (36.9)	90	41	1.6 (2.4)	0.69 (1.11)	0.45
Docklands Light Railway London	1987	21.5 (13.4)	80	17	3.7 (6.0)	0.79 (1.27)	0.21
Metrolink Manchester	1992	30.9 (19.3)	26	13	0.8 (1.3)	0.42 (0.67)	0.50
South Yorkshire Supertram Sheffield	1994	29.0 (18.1)	25	17*	0.9 (1.4)	0.59 (0.93)	0.68
Midlands Metro Birmingham	1998*	20.4 (12.8)	15	14*	0.7 (1.2)	0.68 (1.09)	0.93
Croydon Tramlink London	1998*	28.0 (17.5)	22-30	22*	0.8-1.1 (1.3-1.7)	0.78 (1.26)	1.00-1.36

* estimated

Tyne and Wear Metro

Tyne and Wear Metro introduced light-rail technology to the United Kingdom in 1980. The Metro is fully segregated and has no street running and was the first "new generation" light-rail system in Britain. It was also the first, and so far it is the only, example of an integrated bus-and-rail network in the United Kingdom. The system was an immediate success and reversed the downward trend in ridership, which elsewhere in the country was still in decline.

The Metro replaced outworn suburban diesel multiple units on the north and south Tyne branch lines and linked them through new tunnels under the twin centers of Newcastle upon Tyne and Gateshead. Because the River Tyne is in a deep gorge at this point, the tracks emerge from the tunnels to cross the river on a high-level bridge, as in Edmonton.

The Metro was also the first transit system in Britain to provide level boarding from platform to car floor and hence offer mobility to those with pushchairs or in wheelchairs. All stations have either ramps or lifts. Initially the Metro was operated as a closed system with automatic barriers at each station entrance, but these were later removed and it is now an open system with increased levels of ticket inspection.

An extension to serve Newcastle Airport opened in 1991, and a second extension is planned to Sunderland that will entail joint running over the tracks used by Railtrack (the successor to British Rail as owner of the existing railway). Details of proposed extensions are included in Table 2.

Docklands Light Railway

The Docklands Light Railway (DLR) in London opened in 1987. It was conceived and developed by London Transport in close liaison with the London Docklands Development Corporation (LDDC), a public-sector entity set up to encourage new investment in the Docklands area. The system is now owned by LDDC and is to be privatized. It is fully automatic with no drivers, although each train carries a train captain, who inspects tickets, deals with any passenger concerns, and drives the train in emergencies. It is powered from a protected third rail pickup.

The initial system ran from Tower Gateway close to Fenchurch Street Station in the city of London to Stratford in London's East End and The Isle of Dogs, which was formerly the focus of London's docks. It was built primarily to encourage new development rather than because of any existing demand. In this respect it was almost embarrassingly successful, needing a major upgrade and reconstruction only a few years after opening.

TABLE 2 Capital Costs for Existing and Proposed Light-Rail Lines

System/Line or Extension	Year Open	Route length km (mls)	Capital Cost(a) £M	Capital Cost(a) $M	Capital Cost(a) £M/km	Capital Cost(a) £M/ml	Capital Cost(a) $M/ml
Tyne and Wear Metro							
Initial System	1980	55 (34.4)	284	446	5.2	8.3	13.0
Airport extension	1991	3.5 (2.2)	12	19	3.4	5.5	8.6
Sunderland extension	1999*	19.2 (12.0)	56(b)	88	2.9	4.6	7.3
Docklands Light Railway							
Initial System	1987	12 (7.5)	77	121	6.4	10.3	16.1
Bank Extension	1991	1.5 (0.9)	276	433	184	306.7	481.1
Beckton Extension	1994	8 (5.0)	280	440	35.0	56.0	88.0
Lewisham Extension	1999*	4.5 (2.8)	140	220	31.1	50.0	78.6
Greater Manchester Metrolink							
Initial System	1992	30.9 (19.3)	145	228	4.7	7.5	11.8
Salford Quays/Eccles Ext.	1999*	7.5 (4.7)	85	133	11.3	18.1	28.3
Oldham/Rochdale Ext.	2001*	24 (15.0)	115	181	4.8	7.7	12.1
Airport/Wythenshawe Ext.	2003*	21 (13.1)	145	228	6.9	11.1	17.4
East Didsbury Extension	2003*	10 (6.3)	80	126	8.0	12.7	20.0
Trafford Park Extension	2001*	7 (4.4)	55	86	7.9	12.5	19.5
East Manchester/Ashton Ext.	2003*	10 (6.3)	100	157	10.0	15.9	24.9
South Yorkshire Supertram							
Initial System	1994/5	29.0 (18.1)	260	408	9.0	14.4	22.5
Midland Metro							
Birmingham-Wolverhampton	1998*	20.4 (12.8)	145	228	7.1	11.3	17.8
Birmingham-Airport	2001*	27.5 (17.2)	343	539	12.5	19.9	31.3
Wolverhampton-Dudley	2001*	31.4 (19.6)	228	358	7.3	11.6	18.3
Croydon Tramlink							
Initial System	1997/8*	28.0 (17.5)	154	242	5.5	8.8	13.8

[(a) price bases not consistent; (b) excluding rolling stock; * estimate;]

Two extensions have since been opened, to Bank in the heart of the city and to Becton via the Royal Docks. The former is in tunnel and at a cost of over $480,000,000 per mile may be the most expensive section of light-rail alignment anywhere in the world. The latter is also expensive by light-rail standards because of the need for total segregation, which is essential for a fully automated railway.

A third extension, under the River Thames to Greenwich and Lewisham, is in the advanced planning stages; construction is expected to start in 1996. An initial 7-year franchise is expected to lead to full privatization.

Greater Manchester Metrolink

Manchester became the first city to bring back trams (streetcars) running on the streets in 1992. The concept is very similar to Tyne and Wear Metro in that two former suburban railways have been converted to light rail and linked through the city center. The key difference is that although Tyne and Wear Metro runs in tunnels, Manchester's Metrolink runs through the streets. An earlier plan to build a tunnel for suburban rail services, similar to Philadelphia's city center regional rail link, had to be abandoned because of the high cost.

The light-rail plans were formulated by the Passenger Transport Executive (PTE) in the early 1980s, although some light-rail proposals had been made in the early 1970s. Parliamentary powers and approval for funding were obtained in 1988, and construction began at the end of 1989. The first section opened in March 1992 with the whole first phase system complete by July.

Peak traffic grew more slowly than expected, but off-peak traffic grew much faster. The private-sector operating company, Greater Manchester Metro Limited, decided to double the off-peak frequency between the peaks on purely commercial grounds. Peak capacity has now been reached without the addition of more rolling stock. One car has been modified experimentally with a lower number of seats and more standing space to increase total capacity. This has also been done on Tyne and Wear Metro and the DLR.

One more existing rail line is proposed for conversion to light rail and a number of further extensions are planned to serve other parts of Greater Manchester that are not served by the commuter rail network. Parliamentary powers have already been obtained for four lines, including one for Salford Quays, which is the old Manchester Docks and similar in character to parts of London's Docklands. Powers are currently being sought under the new Transport and Works Act procedures for two more lines to serve the airport to the south and Ashton to the east.

South Yorkshire Supertram

Sheffield is the largest city in South Yorkshire and was the last city in Britain to operate streetcars in 1960. The first section of a three-line light-rail network opened in 1994, and the last section was completed in October 1995. Most of the system is street running, with extensive sections of side and central reservation.

Sheffield's hills demanded a vehicle specification that could cope with 10 percent gradients in the snow. The Siemens Duewag eight-axle double articulated cars have all axles motored and are probably some of the most powerful light-rail vehicles built, having a power-to-weight ratio of 24 kW/t. They proved their worth in snowstorms early in 1996 when all other traffic in the city stopped.

Although Manchester introduced street running, Sheffield claims to have the first new street tramway system, given its very different character. One line, to the out-of-town shopping mall at Meadowhall, is entirely on reserved track and uses some former freight rail alignments. Sheffield is also the first British system to adopt low-floor cars, and like the other three systems is fully accessible.

A condition of the government grant was that the system be privatized when fully operational. However, the revenues have been well below predicted levels, and the operation currently falls far short of profitability. The future structure for the company is still under debate.

Light-Rail System Under Construction

The next system to be built will run on a former rail alignment between the center of Birmingham in the West Midlands and the town of Wolverhampton. The first 4.5 km (2.8 mi) from Birmingham is shared right-of-way with a recently reopened suburban rail line, but with no shared track, and the last 1.8 km (1.1 mi) into Wolverhampton is street running.

The project was developed by the West Midlands PTE and is being funded by the Passenger Transport Authority (PTA), a government grant, European grants, and the private sector. A contracting consortium was selected for the DBOM contract in 1993, but funding from the government was not finally secured until July 1995. The private contribution is in return for a 23-year concession, 3 years to design and build the line and 20 to operate it. It is still hoped to open this first phase in 1998.

Two more phases are planned and with Parliamentary powers will take the network to Walsall, Dudley, and Birmingham Airport, giving a total network of 80 km (50 mi). An eventual network of 200 km (125 mi) is envisaged.

Proposed Light-Rail Systems

Croydon Tramlink

The other system that is close to realization is Croydon Tramlink in south London, developed jointly between London Transport and the London borough of Croydon. It is similar in concept to Manchester: Croydon also has two railway stations on opposite edges of its town center. Tramlink will take over two lines from Railtrack, serving Wimbledon, Beckenham Junction, and Elmer's End, and link them through the center with a street-running loop. A third line is entirely on new light-rail alignment to serve the large suburb of New Addington, which has been the subject of new rapid transit proposals for more than 25 years.

Low-floor cars will operate over the 28-km (17.5-mi) network at speeds up to 80 km/hr (50 mph) with a very high proportion of segregated running. The operation is expected to generate substantially more revenue than the operating costs.

An unusual method of procurement was adopted that involved setting up a project development group (PDG) after a brief contest between a number of consortium bidders. The PDG developed the design to what in effect is tender stage and then becomes one of the tenderers. Thus the PDG, which has been paid for its design development, had to bid in competition with other consortia.

Government approval was obtained in December 1994 subject to a satisfactory private-sector contribution. A short-list of tenderers was published and final bids for the 99-year DBOM franchise were due in January 1996. The preferred bidder, Tramtrack Croydon, was announced by London Transport in April 1996 and is a consortium including Bombardier Eurorail, civil engineering contractors Amey and Robert McAlpine, London bus company CentreWest, and the Royal Bank of Scotland. It is hoped that construction will start in 1996, with completion by 1998.

Leeds Supertram

Plans are well advanced in Leeds for the first phase of a light-rail line to the south of the city serving a major housing area at Middleton and a large park-and-ride lot at Stourton at the northern end of the M1 motorway from London. Part of the route incorporates a tramway alignment that was originally built in 1948 only to be abandoned in 1958. It should reopen by 1999.

Parliamentary powers were obtained and approval in principle has been given by the government. A DBOM form of contract is proposed and a short-list of bidders has been prepared. The promoter, West Yorkshire PTE, is hopeful that it may he possible to start construction in 1996. A further two lines are planned, serving Headingley in the northwest and Seacroft in the northeast, both with major park-and-ride lots.

Nottingham

A 14-km (9-mi) line has been authorized from Nottingham city center to Hucknall in the north. It may be the first in Britain to involve shared track between heavy-rail trains and street-running light-rail vehicles. Work undertaken by British Rail Research at Derby has investigated in detail the technical options for solving a number of issues on shared track (2). There are a number of potential applications in British cities that could considerably expand the future role of light rail.

The project is being promoted hy Greater Nottingham Light Rapid Transit Limited, a company owned jointly by the City Council, the County Council, and the private-sector Nottingham Development Enterprise. As with most schemes, funding will be the major hurdle, but construction could possibly start in 1997.

South Hampshire

The unique geography of the Portsmouth Harbour area would benefit from a planned light-rail scheme linking Fareham with Gosport and then running by tunnel under the harbor into Portsmouth city center. At present there is no road link and the quickest route for many commuters is by cycle using the ferry. The light-rail vehicles will have to be adapted to carry large numbers of cyclists.

The project is out for public consultation, and a draft order under the new Transport and Works Act procedures will be sought in 1996. Planned extensions would serve Portsmouth to the north and Southampton to the west, the latter requiring shared track with the existing electrified railway.

Glasgow

Britain's last city to have a tramway should see it return in the form of light rail early next century. Powers are being sought under the Scottish legal system to construct and operate a light-rail line from Maryhill in the northwest through the city center to Easterhouse in the east.

The first line is 24 km (15 mi) long and will cost £180,000,000 ($270,000,000). Further extensions are being planned to create a 40-km (25-mi) network, which will complement the extensive suburban electrified railway network.

Bristol

The proposed light-rail network for the city of Bristol, promoted by Avon County Council, has been called Westway and will run from north of the city through the principal shopping area to a loop around the southern suburbs. The 32-km (20-mi) first phase will cost over £400,000,000 ($600,000,000) and a number of extensions are planned.

A wholly private-sector scheme was proposed some 10 years ago but was abandoned. The current scheme has been well received at public consultation. Avon is to be reorganized, and the County Council will be replaced by a number of single-tier authorities, including Bristol City Council. It is hoped that this reorganization will not delay the light-rail scheme.

Cardiff

The Welsh capital city may see light rail on its streets. A project is well advanced to operate a line from the city center to the former docks area, sponsored by Cardiff Bay Development Corporation and supported by local authorities. Later phases would see the initial line extended northward up the valleys over existing railways, another example where track sharing could result in an extensive network. The line will be street running through the city center but on reserved track elsewhere.

Medway Towns

The Kentish towns in the Medway Valley include Maidstone, Strood, Rochester, Chatham, and Gillingham. An existing suburban railway line does not serve the town centers. Plans are progressing to convert the line to light rail but retain some heavy-rail use, at least for freight. The line would be extended at each end to run on street into the town centers. It would also serve major park-and-ride lots on the M2 and M20 motorways. Public consultation on this scheme is currently in progress.

Liverpool

The most recent city to announce that it is planning light rail is Liverpool, which once had one of the most extensive streetcar systems in Britain, with many miles of reservations. At a launch last week it was indicated that the first line would run from the newly rebuilt dockside area through the main pedestrianized city center shopping streets to suburbs to the north at Page Moss. A former central reservation will be used for about half the route.

Another proposal for a light-rail line has already been announced by a private-sector group to link the city center with Liverpool Airport.

Small-Scale and Heritage Tramways

Interest is growing in the possible role of heritage tramways in smaller towns and cities. An established narrow-gauge line has operated in Seaton, Devon, for many years, and a new line opened this year in Birkenhead, using new trams built in Hong Kong. In addition to providing tourist facilities, some could play important park-and-ride roles. A proposal for a seafront line has been made by a private company in Margate, Kent.

Low-cost, small-scale tramways could also benefit a number of smaller towns that could not afford conventional light rail but that need more attractive transit than the bus. Historic cities like Chester and Bath have been studying the potential for light rail to tackle local traffic problems by linking fringe park-and-ride lots with the center city. The key is to create a segregated right-of-way that can ensure reliable, speedy operation.

A flywheel-powered minitram known as the Parry Peoplemover is being developed by a small private company and has been demonstrated in a number of towns, including Brighton and Swansea.

Costs of Light-Rail Systems

One of the advantages of light rail over metro or underground systems is light rail's much lower capital costs. However, substantial investment is still needed for even the more modest schemes, and most of this has to come from the public sector. It is therefore crucial to the progress of any scheme to ensure that its capital costs be kept to a minimum.

Capital costs of the light-rail lines already built or under construction, including extensions where planned, are set out in Table 2. The initial systems or first phases are in the range of $11 million/mile to $22.5 million/mile. The lowest costs are for those lines that utilize former railway rights-of-way, such as Manchester and Croydon ($11.8 and $13.8 million/mile, respectively). The higher cost of the Sheffield system reflects the much greater proportion of street running and the fact that it is a new system throughout, with no reuse of track. It also reflects a higher vehicle specification, which costs nearly twice that for the Manchester cars.

The most notable differences can be seen in the costs for the DLR. Although the initial system was within the same range and made use of some existing railway infrastructure, subsequent extensions have proved extremely expensive. The Bank extension may be regarded as a special case, involving some of the most difficult tunneling and underground station construction to be found anywhere, but the Becton and Lewisham extensions are also very costly. Lewisham does include a tunnel under the River Thames, but Becton could have been constructed at much lower cost if it were not an automated system. Grade separation of all intersections has resulted in long sections of elevated track where at-grade running would have been feasible with manual operation. This is an added cost, which is not always considered when the benefits of automation are evaluated.

The low costs for Tyne and Wear extensions again show the benefits of being able to use existing rail alignments and track. Manchester's Oldham/Rochdale extension is a conversion of an existing railway with a similar cost to the initial system, but other extensions that generally involve new construction are up to twice this cost. The Salford Quays line includes bridges over the

Bridgewater Canal and the River Irwell and a higher proportion of civil engineering works.

One concern is the high cost of diverting public utilities plant and equipment, averaging between $2 million/mile and $5 million/mile, with some city center streets costing even more. This high cost has prompted the proposal of a new form of track construction that would not require excavation for a trackbed. It would use the strength of the highway structure to spread the rail loadings. Laboratory tests have been carried out, and field trials are planned.

Another concern is the high cost of light-rail vehicles—at least 10 times the cost of a bus. Another project is developing a lightweight low-cost vehicle using a high proportion of standardized components from the automobile industry. Both projects are being carried out by Lewis Lesley at John Moores University in Liverpool.

A number of smaller towns and cities are considering lower-cost, fixed-track systems such as busways or guided busways. A guided busway operated in Birmingham in the 1980s, and the first section of a new guided busway has recently opened in Leeds.

The strong financial discipline demanded by the Department of Transport in the evaluation and justification of light-rail schemes has encouraged promoters to seek cost-effective solutions. The British light-rail schemes built so far demonstrate how effective projects can be achieved within a reasonable budget.

Benefits of Light-Rail Systems

When Britain's first light-rail system opened in Tyne and Wear, some were skeptical of its value in a car-dominated era. Although demand for transit was decreasing everywhere else in the country, in Tyne and Wear it grew despite population loss, unemployment, declining economic activity, and growth in car ownership. After only 5 years of operation, Metro was carrying 61 million passengers per year, half from car-owning households and one-third with driver's licenses. The current patronage of only 41 million is the result in part of the deregulation of bus services and in part the dismantling of the integrated bus-rail network.

A key benefit of light rail is the ability of travelers to go into and through busy congested cities without delay or disruption, whether during peak or off-peak times. Manchester's Metrolink achieves excellent levels of reliability and is the only transit system to practice timed transfer. Metrolink has also shown the power of light rail to attract car users. About half of the 13 million passengers per year have a car available for the journey but have chosen to use Metrolink. Up to 15 percent of passengers formerly made the journey by car. There is also some evidence that car ownership levels have been influenced: car ownership continued to increase in Greater Manchester as a whole but has stabilized or even decreased in the Bury and Altrincham corridors (3).

Both Tyne and Wear Metro and Metrolink have proved particularly attractive for shopping and leisure trips and have strengthened shopping centers along their routes. There was less evidence of significant changes to land use patterns although in the longer term there is a trend for new development to locate near the Metro.

The movement was not all inward to the regional center of Newcastle. Businesses in towns at the outer ends of the line, South Shields and Whitley Bay, also benefited. Two-way flows also occur in Manchester; Altrincham and Bury, at the extremities of Metrolink, have seen increased shopping activity. Traders believe this to be a direct result of light rail.

The ability of the DLR to act as a catalyst for new development was greater than any expectations. When construction started on the Isle of Dogs, there were acres of derelict land and abandoned dock areas and industrial sites. Today it is a new city with massive investment in offices and leisure activities. The DLR threads through the new development, forming a spine route. This pattern has not been repeated along the Becton extension, where the property market has been depressed and little investment has followed construction of light rail. This difference illustrates how difficult it is to predict real estate movements: light rail is no guarantee.

One of the greatest benefits of British light-rail systems is their accessibility. They all offer level boarding without the need for platform lifts or on-vehicle lifts. Where stations are not at grade, elevators or ramps are provided to allow access between platforms and street level. Although level boarding is invaluable for wheelchair users, it benefits a large proportion of the population, including those with pushchairs or luggage and those who have difficulty climbing steps.

Environmental benefits continue to advance in importance and have been the subject of a European Communities study (4). The low noise and pollution levels of light rail contrast starkly with those of the deregulated bus services. This benefit has influenced both Manchester and Sheffield city councils to seek to reduce the number of bus movements through the main shopping streets. Constructing light rail creates opportunities for improvements by extending pedestrian zones, building more hard and soft landscaping, and enhancing the urban environment. Examples can be found in Newcastle, Manchester, and Sheffield, although much more could be achieved with the level of funding that French cities have enjoyed.

The benefits from the investment made in building light rail can be greatly enhanced if a comprehensive approach is adopted. Light rail is much more effective as part of a package, which may include traffic manage-

TABLE 3 Characteristics of Light-Rail Vehicles on British Light-Rail Systems

System	Newcastle	Docklands	Manchester	Sheffield	Birmingham	Strasbourg
Builder	Metro Cammell	Bombardier	Firema	Siemens	Firem	ABB (York)
Length	27.8m	28.8m	29.0m	35.0m	24.0m	33.1m
Width	2.65m	2.65m	2.65m	2.65m	2.65m	2.40m
Articulations	1	1	1	2	2	6
Axles	6	6	6	8	6	8
Floor height	960mm	1025mm	915mm	420/880mm	350/850mm	350mm
Seats	84	66	86	90	58	66
Standing(4p/m²)	125	145	120	160	102	144
Total capacity	209	211	206	250	160	210
Max. speed	80km/h	80km/h	80km/h	80km/h	75km/h	70km/h
Acceleration		1.1m/sec²	1.3m/sec²	1.3m/sec²	1.4m/sec²	-
Braking	1.0m/sec²	1.3m/sec²	1.3m/sec²	1.3m/sec²	1.4m/sec²	-
Emergency Braking	1.6m/sec²	-	3.0m/sec²	1.3m/sec²	4.0m/sec²	-
Max. gradient	4%	6.5%	6.5%	10%	-	-
Min. radius	70m	38m	25m	25m	18m	-
Line voltage	1500Vdc	750Vdc	750Vdc	750Vdc	750Vdc	750Vdc
Weight (empty)	39.0t	36.0t	48.0t	46.5t	-	40.5t

ment, bus priority measures, some highway construction, pedestrian streets, and parking controls. In the future it may include road pricing.

Technical Comparisons

The principal technical characteristics of the light-rail vehicles for the first five British light-rail schemes are shown in Table 3. Comparable data for Strasbourg are included as an example of a new European system and the only one to have British-built vehicles.

The only common features are the gauge—all are 1435-mm (4-ft 8½-in.)—and the width. The levels of performance are generally similar. Discussions between promoting authorities and representatives of manufacturers on standardization have not produced any form of standardization that could potentially reduce costs. The essential competitive-bid procedures and the move toward all-embracing DBOM forms of contract make any attempt at commonality very difficult.

It is likely that any future systems will adopt low-floor cars, and a preference is emerging for the narrower gauge width of 2.4 m (7 ft 10 in.) in place of 2.65 m (8 ft 8 in.) where narrow streets have to be negotiated such as in Croydon and Portsmouth.

The specification for vehicles and for the track, power supply, and signaling have to meet all safety requirements or recommendations of Her Majesty's Railway Inspectorate. A completely revised set of documentation incorporating a new section dealing with street running has just completed the consultation stage and will be published in 1996 (5).

Prospects for Light Rail

A substantial number of light-rail schemes are in various stages of planning and may eventually be added to the four operational schemes and the one under construction. There is great concern over the rise of traffic congestion and environmental pollution, and light rail is seen by many as one way to attract car users onto transit.

However, the relatively high capital costs do not make it a popular choice for government. The Minister of Transport indicated recently that only the systems in Leeds and Nottingham and the extension of Manchester's Metrolink to Salford Quays had any chance of funding in the foreseeable future. Any other authorities considering light rail would be better advised to examine cheaper alternatives such as guided buses. This situation does not bode well for light rail in Britain, but the implied policy may not last too long. It is not discouraging a number of authorities from progressing with their light-rail projects. They realize that most attempts to make buses attractive to car users have not had great success. A step change in quality is needed, and this is difficult to achieve with any type of bus-based system. However, hard factual data on the effects of light rail are not always readily available. More effort is needed to monitor and document the changes in travel patterns when light rail is introduced so that justification of new schemes can be related more closely to actual experience.

One positive effect of the government's pessimism is to further encourage development of lower-cost, light-rail vehicles and systems, exemplified by the work of Lesley at John Moores University. Major vehicle manufacturers are responding to the need to drive down the capital costs although not many examples are in production as yet. But the future of light-rail systems will depend more on the funding mechanisms devised for their implementation than on the technical development of their specifications.

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New Technologies for Improving Light-Rail Grade Crossing Safety

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Light-rail transit (LRT) systems have become popular throughout the world because of their ability to operate both on and off city streets, with large capacity for transporting passengers and frequent stops in urban areas. However, operation of LRT systems in shared right-of-way presents an opportunity for collisions. Many safety problems are the result of failure of motorists and pedestrians to obey or accurately understand warning devices and traffic controls. New technologies, such as those of intelligent transportation systems (ITS), are being applied to improve safety at railroad grade crossings in Los Angeles County on the Metro Blue Line (MBL), a 22-mi (35-km) light-rail line. The Los Angeles County Metropolitan Transportation Authority (MTA) has demonstrated that photographic enforcement can assist in reducing the number of traffic accidents. For MBL grade crossings, camera equipment is activated by vehicles running under or around crossing gates or making left turns against red-turn arrows. On a 7-month demonstration project in the city of Compton, the number of violations recorded by the equipment dropped off dramatically from one violation per hour to one violation every 12 hr. In downtown Los Angeles, where motorists make left turns on red-arrow signals in front of the train, a demonstration project using photographic enforcement has resulted in a 34 percent reduction in violations. Another ITS technology being used on the MBL is the AUTOSCOPE video detection system. This system is being used to detect vehicles making illegal left turns across the MBL tracks, which triggers the photographic enforcement camera to take pictures of violators. New technologies are being incorporated for two other safety improvement projects. A four-quadrant or full-closure crossing gate system will be installed at one MBL grade crossing. A wayside horn system was tested that allows an approaching train to sound a horn at the grade crossing for motorists and pedestrians using the crossing. The horn equipment is activated by the train operator. The MTA successfully sponsored the Rail Transit Safety Act, a California-wide bill that imposes additional fines and points on persons who violate rail grade crossing safety laws. The legislation also allows a judge to order a grade crossing violator to attend traffic school and view a film on rail transit safety. In addition, it requires the Department of Motor Vehicles (DMV) to include more information on rail transit safety in its handbooks and other publications. The MTA supported the Rail Transit Safety Enforcement Act, another California-wide bill, which clarifies the use of photographic enforcement for grade crossing violations and places a DMV hold on violators who do not pay grade crossing citation fines.

Light-rail transit (LRT) systems are being developed in urban areas throughout North America, operating on newly constructed rights-of-way or on upgraded existing trackage. The introduction of LRT into medium-sized to large urban areas often results in the creation of new highway-rail grade crossings. Although some LRT systems operate partially below or above ground (such as portions of the LRT systems in Boston, Buffalo, Cleveland, Edmonton, Los Angeles, Newark, Philadelphia, Pittsburgh, St. Louis, and San Francisco), most cities adapt the lower-cost approach of placing most or all of the system on city streets, in medians, or in separate at-grade rights-of-way.

Operation of LRT in urban shared right-of-way can be attractive, but it introduces the potential for collisions between motorists, pedestrians, or bicyclists and the train. The Institute of Transportation Engineers (ITE) recently conducted a survey of 17 LRT operating systems concerning their operating practices at grade crossings. Survey responses indicared a wide range of safety-related concerns and problem areas. The most critical areas of concern identified by the survey respondents included the following:

- Motorists' disobedience of traffic laws, specifically motorists running around closed crossing gates or making illegal turns in front of the light rail vehicle (LRV) at intersections;
- Motorist confusion over traffic signals, LRT signals, and signage at intersections; and
- Pedestrian inattention or confusion at station areas and street LRT crossings.

The Transit Cooperative Research Program (TCRP) Project A–5, Integration of Light Rail into City Streets, has confirmed these problem areas and has provided additional insights into specific safety problem areas for LRT street running operations under 35 mph (56 km/hr). An additional TCRP study (Project A–13) will focus on LRT operations over 35 mph.

Each of these problems has been experienced by the Los Angeles County Metropolitan Transportation Authority (MTA) at crossings on its 22-mi (35-km) Metro Blue Line (MBL) (Figure 1). There were over 250 train-vehicle and train-pedestrian collisions in the first 4 years of MBL revenue operations, from July 1990 through April 1995. The collisions resulted in 28 fatalities and numerous injuries.

The MBL is an LRT line that runs in a subway in downtown Los Angeles for about 1 mi (1.6 km), along the middle or side of city streets for about 6 mi (9.6 km) of its length in downtown Los Angeles and downtown Long Beach, and on its own semiexclusive right-of-way for 15 mi where it operates adjacent to the Southern Pacific lines. The MTA is applying a variety of solutions in the areas of enforcement, engineering, education, and legislation to address public safety problems at MBL grade crossings. Although certain technological strategies can successfully reduce collisions, such as the use of medians to prevent cars from running around crossing gates, the MTA has embraced new technologies identified in the U.S. Department of Transportation's intelligent transportation systems (ITS) program. The MTA is an active participant in the development of LRT guidelines and standards for signage, signals, and roadway markings. The Light Rail Safety Committee of the California Traffic Control Devices Committee produced the Light Rail Safety Manual, which will be referenced as part of the Caltrans Traffic Manual for use by California light-rail properties. The MTA is also working with the

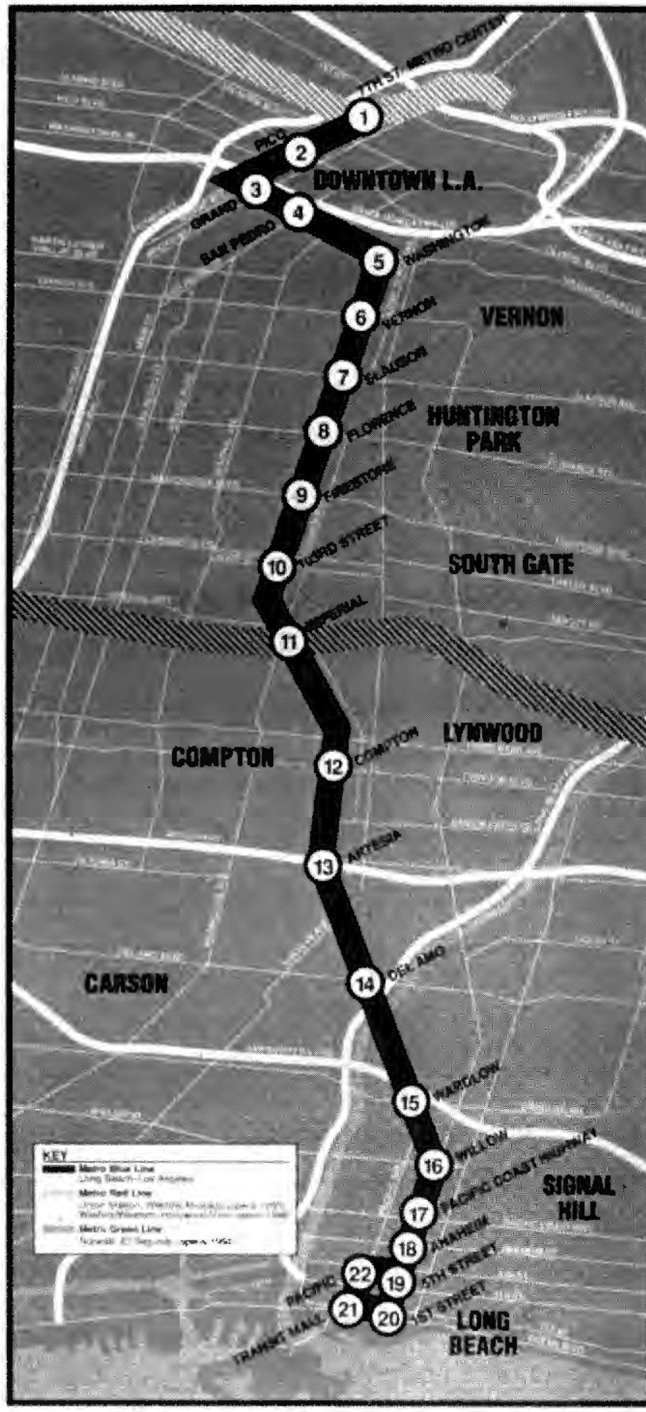

FIGURE 1 Metro Blue Line map.

National Committee on Uniform Traffic Control Devices to produce a section on LRT to be included in the 1997 revision of the *Manual on Uniform Traffic Control Devices* (MUTCD).

The Los Angeles MBL Grade Crossing Safety Program was initiated in March 1993 to evaluate various means to discourage or prevent illegal movements by vehicles at grade crossings that cause train-vehicle collisions. Although the program is focused primarily on evaluating measures to decrease train-vehicle collisions, the safety program is also concerned with improvements that will reduce train-pedestrian collisions. The MTA is seeking to apply innovative equipment and methods developed for street and highway traffic applications. These engineering improvements will address unique characteristics of MBL grade crossings and improve public safety.

The safety program includes four elements:

- Enforcement of traffic regulations at grade crossings using police officers and automated photographic enforcement systems;
- Engineering improvements, including the use of ITS technologies, warning devices, and street and traffic signal improvements;
- Legislation to establish higher fines and statewide rail safety educational programs; and
- Bilingual public information and safety education.

Vehicular and Pedestrian Hazard Analysis for Light-Rail Grade Crossings

As part of the MBL Grade Crossing Safety Improvement Program, the MTA performed a hazard analysis for various types of light-rail grade crossings. The analysis consisted of two parts:

- Identification of factors or conditions contributing to train-vehicle and train-pedestrian accidents, and
- Mitigating traffic control devices and systems.

After the grade crossing hazard analysis results had been developed, MBL grade crossings were analyzed to determine which traffic control devices and systems could be applied to mitigate the factors and conditions contributing to accidents at each of the crossings. Then a plan was prepared to implement the selected solutions.

Public Perception of Grade Crossing Problem Areas

An important component of the design of a safety improvement program is to determine community attitudes concerning safety problems and possible areas for improvement along the rail line. The MTA performed a bilingual (English and Spanish) survey of 400 persons who live near the MBL and use MBL grade crossings at least once a week. Residents were asked to describe problem areas that affect safety at grade crossings; the following problems were identified:

- Lack of understanding by drivers and pedestrians that MBL trains reach the intersection quickly after the warning lights start flashing (80 percent),
- Attempts by drivers to beat the train by driving around lowered crossing gates (76 percent),
- Length and slowness of Southern Pacific's freight trains (70 percent),
- Lack of understanding by drivers and pedestrians that two, and sometimes three, trains can go through an intersection at the same time (70 percent), and
- Lack of enough barriers to keep pedestrians and children off the tracks (68 percent).

New Technologies for Grade Crossing Safety

New technologies that can be applied to solve safety problems at highway-rail grade crossings were identified as a part of the ITS program by the Texas Transportation Institute (TTI). Additional information may be provided to the train operator, central dispatching facility, motorists, and pedestrians so informed decisions can be made to avoid an accident. New technologies may be applied for safety-related problems in the areas of intrusion detection, collision avoidance, dynamic displays, vehicle proximity alerting, automated wayside horns, and warning signs.

The MTA is applying ITS technologies to implement elements of the Grade Crossing Safety Improvement Program, including projects for the installation and operation of photographic enforcement systems, the trial installation of a four-quadrant crossing gate system, the use of dynamic displays, and automated wayside horns. Three of these projects are described in the following sections of this paper.

In addition, the MBL Grade Crossing Safety Improvement Program includes the following projects:

- Installation of swing gates at pedestrian-only crossings at the Artesia and Imperial stations;
- Installation of a railroad-style pedestrian gate at the Florence Avenue, Gage Avenue, and Vernon Avenue crossings;
- Construction of center line medians at six crossings (generally, it is not possible to construct medians at MBL crossings because of streets running parallel to the tracks);

- Testing of active No Left Turn and Train signs in conjunction with the relocation of the train T-signals;
- Testing of programmed visibility signal heads for the through and left-turn signals at selected intersections on Long Beach Boulevard where left turns are made across the MBL tracks;
- Left-turn lanes and separate left-turn phases at five signalized intersections where left turns are made across the MBL tracks;
- Evaluation of Second Train warning signs, including the investigation of alternative methods for activating signs that provide directional, arrival time, or second-train warnings; and
- Investigation of in-vehicle alerting systems for vehicles hauling hazardous materials and school transportation vehicles.

Photographic Enforcement

One major thrust of the improvement program has been expanded grade crossing enforcement efforts, which have included the use of both Sheriff's deputies and photographic enforcement systems. In particular, the MTA's use of photographic enforcement equipment at MBL crossings has generated an impressive reduction in the number of crossing violations. With the efforts being made to reduce the number of violations at crossings, it is expected that the number of collisions will also be reduced.

The MTA has completed five demonstration projects of photographic enforcement equipment at grade crossings. On the basis of the demonstration project results, the MTA is currently proceeding with the installation of photographic enforcement equipment at 17 crossings on the cab signal route segment. The selection of U.S. Public Technologies for the installation and operation of the equipment was approved by the MTA Board of Directors on February 22, 1995. It is expected that the equipment will be in place and operational at 3 crossings by July 1995 and at 10 crossings by early 1996.

System Description

Photographic enforcement systems use high-resolution cameras to photograph motorists driving under or around railroad crossing gates. Bilingual signs informing motorists that photographic citations are being issued at the crossing are installed on all street approaches to the crossing (Figure 2*a*). The camera equipment is mounted in a 2-ft (3.7-m) high bullet-resistant cabinet (Figure 2*b*). The camera is triggered when vehicles cross inductive loop detectors in the ground after the gates have started down or are already lowered. Two photographs of the vehicle, its license plate, and the driver's face are taken as the basis for issuing a citation as required by the California Vehicle Code. Superimposed on each photograph is the date and time of the violation, the speed of the violating vehicle, and the number of elapsed seconds since the red flashing lights were activated at the crossing (Figure 2*c*).

Photographic enforcement systems have been used worldwide, including in several cities in the United States and Canada, to capture speed and red-light violations. Photoradar equipment has been widely used for the enforcement of speed violations. In addition to freeing police officers from traffic enforcement work, the use of photographic enforcement for speed and red-light violations has significantly reduced collisions wherever it has been used.

Demonstration Project Results

Two demonstration projects were carried out at gated crossings. A 7-month demonstration project at Compton Boulevard was completed in September 1993. The project resulted in a 92 percent reduction in the number of violations occurring at the crossing, reaching one violation every 12 hr.

A 3-month demonstration project was completed at Alondra Boulevard in September 1993. Signs and the camera pole and cabinet were installed for about 6 months at this location before citations were issued. Grade crossing violations dropped by 78 percent from 0.50 violation per hour in December 1992 to 0.11 violation per hour in September 1993 when the demonstration project was completed. A total of 265 citations were issued for violations recorded by the camera equipment at these crossings.

Photographic enforcement equipment was operational at the intersection of Washington Boulevard and Los Angeles Street for about 7 months from September 1993 through the middle of April 1994. The equipment was installed to record left turns made across the MBL tracks against a red left-turn arrow (toward downtown Los Angeles). For about 6 weeks from February 15 through March 31, 510 citations were issued to violators recorded at the intersection.

The rate of left-turn violations on weekdays declined by approximately 34 percent over the duration of the demonstration project, dropping from 2.02 per hour on the average during September and October to approximately 1.34 per hour for the month of March. This is a much lower percentage reduction than experienced for crossing violations at Compton and Alondra boulevards.

The other two demonstration projects have involved testing alternative camera system and vehicle detection technologies. The first project, completed in April 1994, used a low-resolution digital camera system to record left-turn violations. Images of the recorded violations

(a) (b) (c)

FIGURE 2 Photographic enforcement (*a*) sign, (*b*) pole, and (*c*) citation photograph.

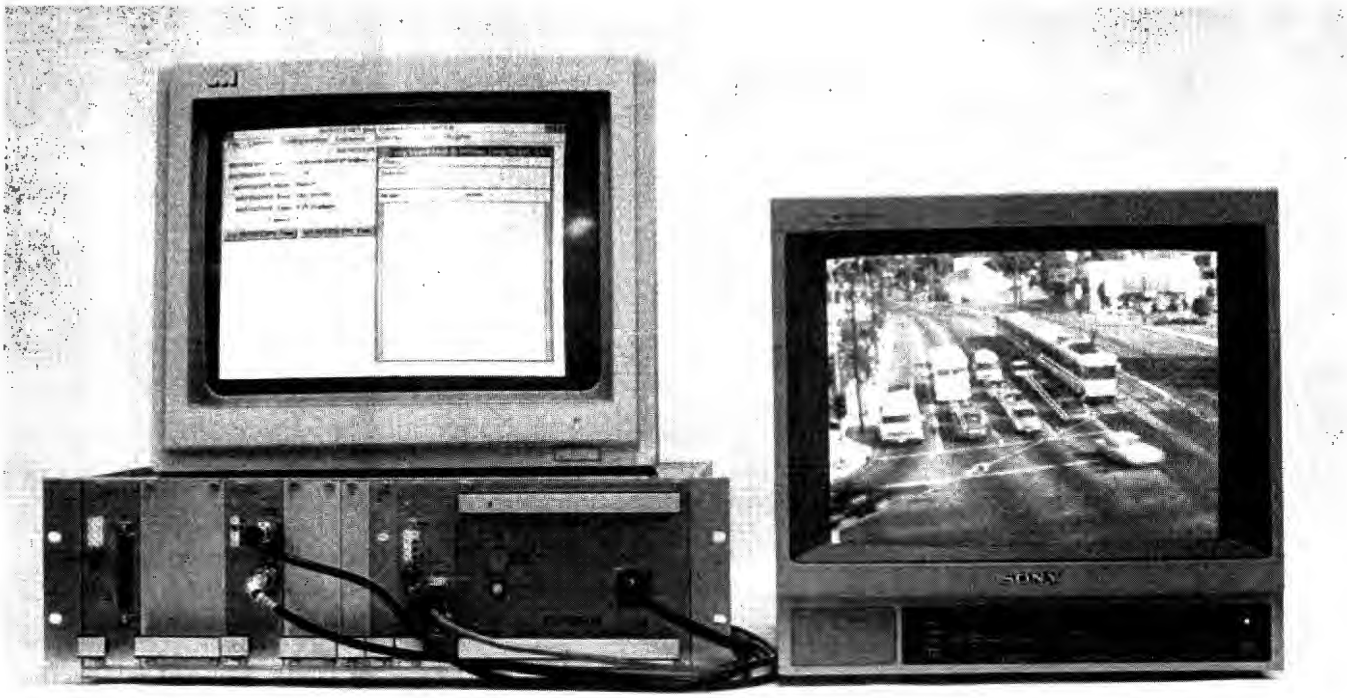

FIGURE 3 AUTOSCOPE screen showing intersection at Long Beach Boulevard and Willow Street.

were stored and transmitted by a cellular telephone link at night, eliminating the need to change and develop film.

The second project under way in the city of Long Beach involves video loops using the AUTOSCOPE system to detect motorists making illegal left turns across the MBL tracks. The AUTOSCOPE system can detect traffic at numerous locations within the field of view of the camera. The user specifies the locations using a mouse and interactive software. Detection zones can be placed along the tracks or on the street. When a vehicle or train passes through a detection zone, a detection signal is generated, the same type of signal that would he generated by an inductive loop or other vehicle detection device installed in the street. A view of the equipment showing the intersection in Long Beach where the AUTOSCOPE image and vehicle detectors are operational is shown in Figure 3.

Setting up the detection loops at this location has involved eliminating false camera triggers caused by the following conditions:

- Shadows of the train (into the left-turn lane);
- Eastbound pedestrian and high vehicle traffic on Willow Street;
- Southbound high vehicle traffic in the lane next to the left lane on Long Beach Boulevard; and
- Differences in the system response time for dark and light vehicles.

Recent Accident Experience

Recent accident statistics suggest that the MTA's enforcement efforts are having the desired results. On the cab signal route segment where trains operate at high speeds, there were two train-vehicle accidents at a gated crossing in 11 months. For each of the prior 3 years of MBL operation, there were seven train-vehicle accidents at gated crossings.

Systemwide Installation

The installation and operation of photographic enforcement equipment during the five demonstration projects have indicated some areas in which special attention was required during the demonstration projects and further attention will be necessary in order to make the system operational at 17 MBL crossings:

- Placement of the camera equipment at crossings, taking into account the width of the crossing area, ambient lighting conditions, and the location of traffic signals and crossing protection equipment;
- Placement of the detector loops, especially for left

turns and at crossings where loops are already in place for traffic signals;

- Working out citation processing details with the participating courts, Department of Motor Vehicles, and City or District Attorney's office;
- Development of a working relationship with the law enforcement agency that has jurisdiction for the crossings;
- Defining a crossing violation consistent with applicable sections of the California Vehicle Code for grade crossing and left-turn violations;
- Obtaining clarification concerning the use of photographic enforcement equipment at grade crossings through discussions with court officials and legislative initiatives, such as the Rail Transit Safety Enforcement Act and Senate Bill 1802, currently California law.

As already noted, it is expected that the photographic enforcement equipment will be in place and operational at 3 crossings by July 1995 and at 10 crossings by early 1996.

The U.S. Department of Transportation is funding the preparation of a report concerning the effectiveness of photographic enforcement and the lessons learned from its implementation at MBL grade crossings. Funding participants include the Federal Railroad Administration, the Federal Highway Administration, and the Federal Transit Administration. It is expected that this report will be available by as early as mid-1996.

Public Perception of Enforcement

Community survey results indicated that 83 percent of those living near the MBL who use MBL crossings at least once a week support the use of automated photographic enforcement equipment for the enforcement of traffic laws at grade crossings. Seventy-one percent of the survey respondents believed that use of the photographic enforcement equipment would reduce the number of accidents.

Four-Quadrant Crossing Gate System

A highway-rail grade crossing may be considered to have four quadrants formed by the rail tracks running from left to right and the street or highway crossing the tracks running from top to bottom. With a four-quadrant gate system, gates at both entrances to and exits from the crossing completely closed off the crossing when trains approach (the typical crossing gate configuration).

The use of this type of crossing gate system offers an approach for eliminating or minimizing grade crossing accidents without the high costs and impacts of grade separation. For the MBL, it offers the potential for eliminating collisions involving motorists making left turns from streets running parallel to the tracks. This system can also potentially decrease the number of collisions involving motorists driving around closed crossing gates from the crossing street who are hit by a second train as it passes through the crossing.

A number of design-related factors typical of many MBL grade crossings make it appropriate to consider the use of four-quadrant gates at these crossings. In addition, the cost of installing and maintaining four-quadrant crossing gate systems is substantially less than the costs of grade separation.

The first design-related factor is that grade crossings from 24th to 103rd streets and at Manville Street on the cab signal route segment require vehicles to cross four tracks. Crossings at 20th Street and from 108th Street to Greenleaf Boulevard on the cab signal segment require vehicles to cross three tracks. The width of these crossings makes it easier for vehicles to drive around lowered gates, using an S-shaped path.

Second, vehicles are able to make left turns from streets running parallel to the tracks at many MBL grade crossings. These turns can be made easily around lowered crossing gates when drivers try to avoid being delayed by a train.

Third, many of the accidents on the cab signal route segment have involved a vehicle driving around lowered gates to avoid waiting for a slow-moving SP freight train or after a train passes through the crossing. The vehicle is then hit by another train that was not seen by the driver. Typically in this situation, the crossing gates are down for a longer time than usual (or the driver, seeing a slow freight train approaching, anticipates that the gates will be down for a longer time).

The MTA is installing a four-quadrant crossing gate system at the 124th Street crossing in the Willowbrook area. At this crossing, one SP track runs parallel to the MBL tracks and streets also run parallel to the tracks on both sides.

Trial Installation Project Objectives

The objectives of the demonstration project are as follows:

- Design and install a four-quadrant gate system that eliminates the risk that motorists will be trapped between closed entrance and exit crossing gates;
- Investigate the use of ITS technologies, which are becoming more widely used for a variety of street and highway traffic improvement applications, to improve highway-railroad grade crossing safety;
- Evaluate the effectiveness of a four-quadrant gate system in preventing accidents caused by drivers going

around closed crossing gates in an urban LRT operating environment; and

- Determine the additional costs of constructing and maintaining a four-quadrant gate system.

Existing North American Four-Quadrant Gate Installations

Four-quadrant gate systems are currently operational in the United States and Canada at three locations:

- Broad Street in Red Bank, New Jersey, as part of New Jersey Transit;
- 24th Street in Cheyenne, Wyoming, as part of the Burlington Northern; and
- 20th Avenue in Calgary, Alberta, as part of Calgary Transit.

Planned installations include

- Gilette, Wyoming, on the Burlington Northern;
- Charlotte, North Carolina, on the Norfolk Southern;
- Mystic, Connecticut, on the Northeast Corridor high-speed rail line; and
- Proposed high-speed rail corridors that are authorized by ISTEA (Section 1010), for example, 7 out of 73 crossings on the 67-mi (107-km) Miami–West Palm Beach corridor identified by the Florida Department of Transportation.

Design Approach and Assumptions

Four safety features, involving different approaches for preventing vehicles from being trapped between the lowered entrance and exit gates, have been considered as elements of the design for the four-quadrant crossing gate system.

Delayed Lowering of Exit Gates The exit gates will be lowered a number of seconds after the entrance gates are down (or have started down). The exit gates at the Broad Street, New Jersey, crossing where four-quadrant gates are used are delayed by 8 to 10 sec after the entrance gates are lowered. At the 24th Street crossing in Cheyenne, Wyoming, the exit gates are delayed 2 to 4 sec after the entrance gates are lowered. In proposed guidelines issued in November 1992, the Federal Railroad Administration has suggested that exit gates should start to descend from 1 to 3 sec after the entrance gates, providing only a short delay time in the lowering of the exit gates.

Vehicle Detection System A vehicle detection system using inductive loops will be interfaced with the exit gate control circuits so that the exit gates are not lowered when a vehicle is detected in the track area.

Fail-Safe System for Exit Gates The exit gates will be counterbalanced so that they fail safe in the up position. The gates will need to be driven down and then held down.

Video Surveillance FTA is providing funding for the installation of video surveillance equipment at the 124th Street crossing. AUTOSCOPE will be used to provide video surveillance and backup loop detection.

Wayside Horn System

MBL train operators are required to sound the train horn when approaching grade crossings. For grade crossings on the cab signal route segment, the horns are sounded 6 to 8 sec before trains enter the crossings.

In accordance with California Public Utilities Commission General Order 143-A, train horns are required to provide an audible warning of at least 85 dBA for a distance of 18 ft (30.48 m) from the train. Although intended to warn motorists and pedestrians at grade crossings, the train horns can be loud and disruptive for persons living and working adjacent to the MBL tracks. For the MBL as well as other rail projects in Southern California, wayside horns may provide an effective means of mitigating certain noise impacts resulting from train operations.

An MBL wayside horn demonstration project was conducted. The train horn was mounted on a pole at a crossing on the MBL and at two crossings on the Pasadena extension to the MBL (under final design). The train operator actuated the horn by hitting a button mechanism attached to the horn. At the MBL crossing of Stockwell Street and Willowbrook Avenue, a focus group of 25 people was recruited from households and businesses within 1 mi of the grade crossing.

Four focus groups were set up around the intersection: two at opposite sides of the crossing, the third approximately 55 ft (90 m) down the parallel street, and the fourth approximately 55 ft down the cross street. The focus groups were asked to evaluate the horn on the train and the wayside horn at several different decibel levels.

The survey was designed to determine the focus group's opinions on the effectiveness of the wayside horn versus the train horn for warning motorists and pedestrians. Over 50 percent of the focus group respondents believed that the wayside horn was more effective than the train horn.

The use of radar detection is being explored for wayside horn annunciation. Using this approach, train speed will be determined by radar. Then the wayside horn will be activated automatically without operator involvement. The way to alert the train operator that the horn has sounded needs to be investigated as part of this demonstration project.

Legislation

In the last 2 years, the MTA has successfully sponsored and supported the Rail Transit Safety Act and the Rail Transit Safety Enforcement Act. The Rail Transit Safety Act, which became law in California on January 1, 1995, seeks to decrease the number of rail-related accidents by imposing additional fines and points on those who violate rail grade crossing safety laws. The legislation provides county transportation authorities, local governments, and law enforcement agencies with the tools needed to implement expanded enforcement and public education efforts targeted at rail grade crossing safety.

Specifically, the Rail Transit Safety Act provides for the following:

1. An additional fine for grade crossing violations: Currently, depending upon the jurisdiction, the fine for not stopping at a grade crossing when the warning signals are flashing or for driving around a closed gate is $104, whereas the fine for a high-occupancy-vehicle (HOV) lane violation, where the violation does not threaten the life of the driver or of others, is $271. The Rail Transit Safety Act authorizes the court to levy an additional $100 fine for a first violation of a rail grade crossing safety law. If a person is convicted of a second or subsequent offense, the court may order an additional fine of $200.
2. Traffic school for grade crossing violations: A person convicted of a grade crossing violation may be ordered to attend traffic school and view a film on rail transit safety.
3. Required section in Department of Motor Vehicles (DMV) driver handbooks: DMV driver handbooks are required to include a section on rail transit grade crossing safety.

The Rail Transit Safety Enforcement Act clarifies the use of photographic enforcement at highway-railroad grade crossings. It also allows the court to place a hold on violators who try to reregister their vehicle or renew their license without paying the fine for violation of grade crossing laws.

Further legislation is needed to allow transit agencies to recover portions of the fine revenues from grade crossing violations. Thus funding will be available for safety measures to be continued, such as photographic enforcement.

Conclusion

LRT safety issues can be addressed by using new technologies. Methods being evaluated include enforcement, engineering improvements, and legislation. Many of the techniques are proving to be successful in achieving safety objectives.

The MTA has successfully shown that photographic enforcement, which uses 35-mm complex camera units combined with inductive loops and custom software, reduces light-rail crossing violations and accidents. In addition, the MTA is conducting demonstrations of four-quadrant gates and wayside horns. The use of four-quadrant crossing gates offers an approach for eliminating or minimizing grade crossing collisions without the high costs and impacts of grade separation. Specifically for the MBL, it offers the potential for eliminating collisions involving motorists making left turns from streets running parallel to the tracks.

The MTA successfully sponsored the Rail Transit Safety Act and the Rail Transit Safety Enforcement Act, both of which are California-wide bills. The former imposes additional fines and points on those who violate rail grade crossing safety laws, allows a judge to order a grade crossing violator to attend traffic school and view a film on rail transit safety, and requires the DMV to include more information on rail transit safety in its handbooks and other publications. The latter clarifies the use of photographic enforcement at highway-railroad grade crossings. It also allows the court to place a hold on violators who try to reregister their vehicle or renew their license without paying the fine for violation of grade crossing laws.

Enforcement, engineering improvements, and legislation have proven to be a successful combination in reducing collisions on light-rail lines.

Light-Rail Transit for Miami Beach

Mark C. Walker, *Parsons, Brinckerhoff, Quade & Douglas, Inc.*

Issues related to the development of a light-rail line in Miami Beach, Florida, as part of a multimodal transportation system for metropolitan Dade County are presented. The Florida Department of Transportation is conducting a study of multimodal transportation improvements in an east-west corridor through Dade County extending to Miami Beach. Service from West Dade to the corridor's terminus in Miami Beach was originally envisioned as a through service using a single transit technology, possibly a hybrid technology combining elements of both heavy-rail and light-rail systems. However, conditions in Miami Beach differ significantly from those in the rest of the corridor. From West Dade to the seaport, a high-speed, exclusive right-of-way, high-capacity service is anticipated, whereas in Miami Beach an at-grade, on-street, slower-speed operation is envisioned. Because of issues related to operations, vehicle floor height, train length, and alignment impacts, the option of using heavy rail in West Dade and light rail between downtown Miami and Miami Beach is gaining momentum. A related issue, the location and features of the transfer between light-rail transit and heavy-rail lines, directly affects the convenience and quality of service provided. The second issue is the integration of the light-rail system within existing street rights-of-way in a dense urban setting. The choice of a route within Miami Beach and the design of trackways and stations are interactive issues. Three basic alignment options are considered along with detailed arrangement of tracks and station platforms within the existing street rights-of-way.

The Florida Department of Transportation (FDOT) is conducting a study of multimodal transportation improvements in an east-west corridor through Dade County. The East-West Multimodal Corridor Study, being conducted by a project team lead by Parsons, Brinckerhoff, Quade & Douglas, is evaluating highway improvements along SR 836 in western Dade County (West Dade) and priority transit improvements from West Dade to the Miami Beach Convention Center via Miami International Airport, downtown Miami, and the Port of Miami (Figure 1). A separate but related FDOT study is examining options for a multimodal facility, the Miami Intermodal Center (MIC), to be located east of the airport terminal area. A special feature of the East-West Multimodal Corridor Study is a proposed direct rail connection for cruise ship passengers between the airport and MIC and the seaport.

Prior transportation planning in Dade County considered the possibility of an elevated transit line in Miami Beach. However, this notion was resoundingly rejected by the residents of Miami Beach for aesthetic reasons. In 1988 a feasibility study for a light-rail transit (LRT) line from the Omni area in downtown Miami to 63rd Street in Miami Beach was conducted for the city of Miami Beach (*1*). This study introduced the idea of an at-grade LRT system in Miami Beach and suggested that its only link to other priority transit in the county would be by transfer to the downtown Metromover

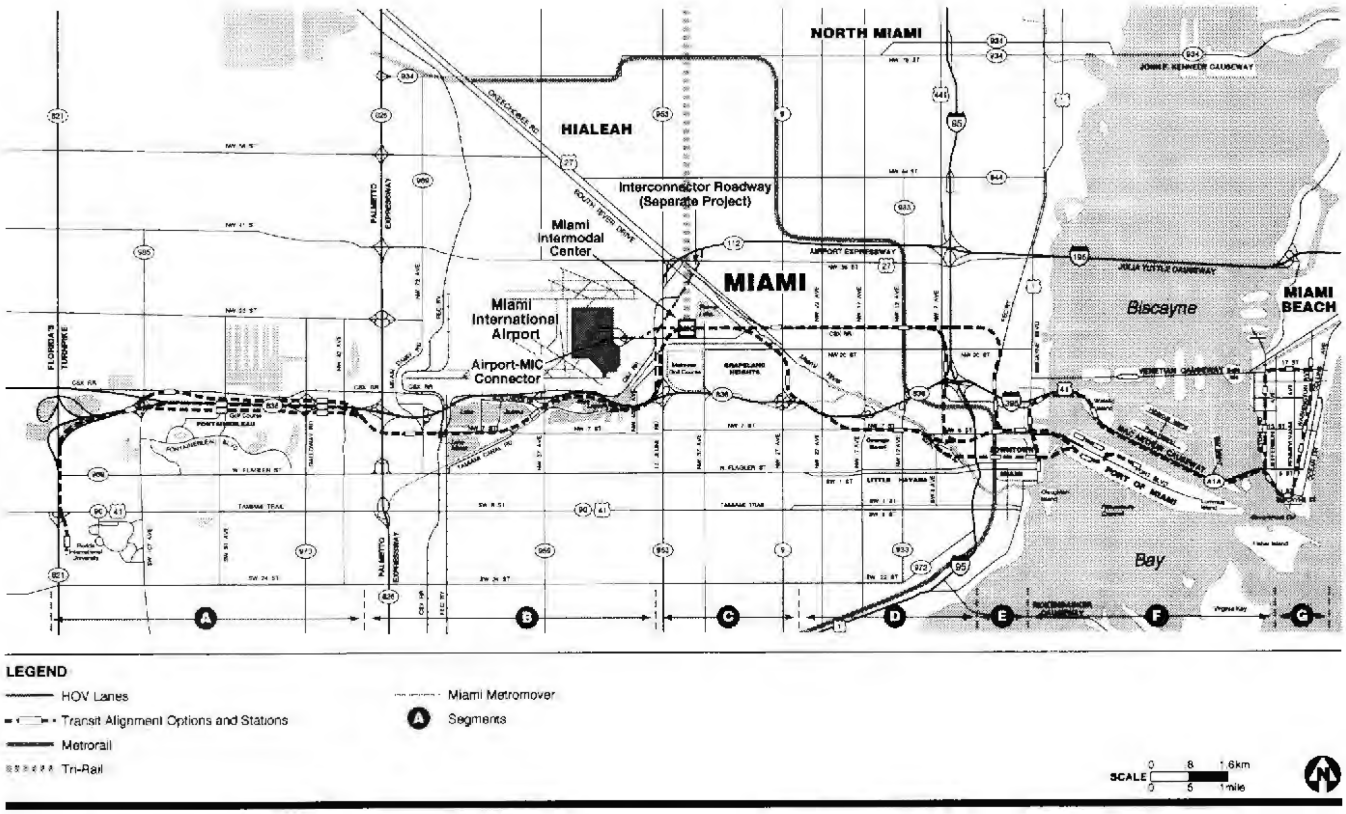

FIGURE 1 East-west multimodal corridor, Miami, Florida.

people-mover system. In 1993, the Transit Corridors Transitional Analysis, conducted for the metropolitan planning organization, continued to develop and evaluate the concept of a separate light-rail line but introduced the idea of a continuous transit line from West Dade to Miami Beach (2). The line would either be light rail or a hybrid, allowing it to operate in a heavy-rail configuration outside of Miami Beach and a light-rail configuration within Miami Beach. The notion of hybrid vehicles was introduced in that study in connection with other corridors that would be extensions of the existing Metrorail heavy-rail system to offer a one-seat ride to the central business district (CBD) without extending the heavy-rail structure.

At the beginning of the East-West Multimodal Corridor Study, service from West Dade to the corridor's terminus in Miami Beach was envisioned as a through service using a single transit technology. However, the physical and service conditions in Miami Beach differ significantly from those in the rest of the corridor. From West Dade to the seaport, a high-speed, exclusive right-of-way, high-capacity service is anticipated, whereas within Miami Beach, an at-grade, on-street, high-frequency operation is envisioned. This difference raised a number of key issues, including whether a through service would best serve the needs of the community, what characteristics a hybrid vehicle should have if chosen, and how to integrate the Miami Beach line into the rest of the transit system if it is separate from the east-west line.

A key aspect of the overall study is to provide an integrated means of travel between Miami Beach and points elsewhere in Dade County. Some of the travel markets that would be served by a connection include

- West Dade and other points on the mainland to Miami Beach destinations for recreation and entertainment,
- Miami Beach hotels and residences to Miami International Airport (including travelers and airport employees),
- Miami Beach residences to downtown and West Dade employment centers, and
- The seaport to Miami Beach hotels and entertainment.

Miami Beach: A Unique Community

Miami Beach is unique in South Florida. It presents a dense urban setting with mixed commercial, residential,

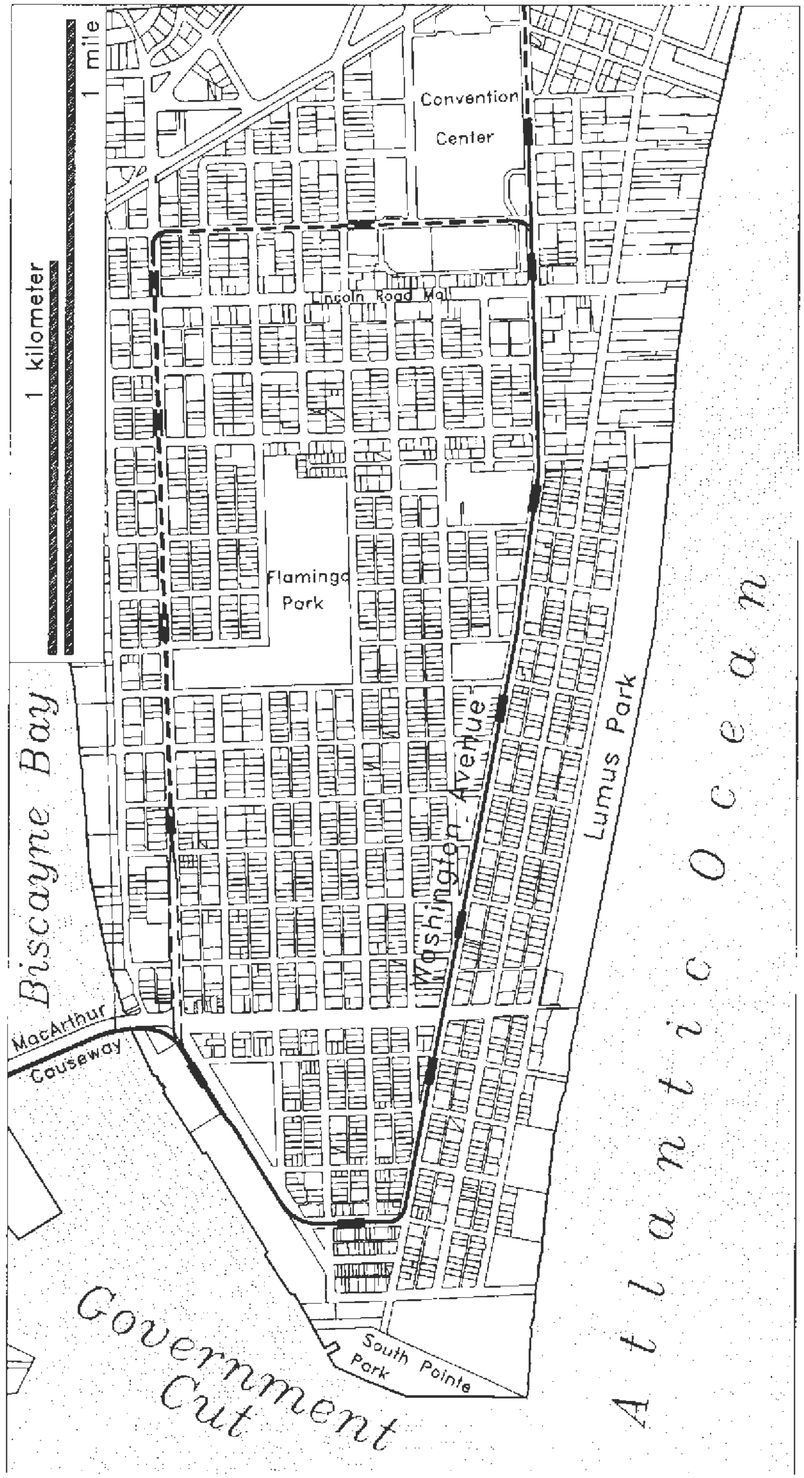

FIGURE 2 **Miami Beach: South Pointe to 22nd Street.**

hotel, and entertainment uses connected by lively pedestrian activity. Moreover, much of the South Beach area (SoBe) south of 20th Street is designated as the Art Deco Historic District, containing the most concentrated collection of art deco buildings in the world (Figure 2). In the Art Deco Historic District buildings are generally two to five stories tall, although taller apartments and hotels are found elsewhere in Miami Beach. Everywhere, buildings are built right up to the property lines, requiring new transit to both fit within the existing rights-of-way and coexist with the closely spaced buildings.

FIGURE 3 Streetcar on Washington Avenue in Miami Beach, 1930s (courtesy Historical Association of Southern Florida).

Miami Beach was built on a streetcar network (3). Streetcars were introduced in 1920 by Carl Fisher, the major developer of Miami Beach, and operated there until 1939 (Figure 3). Much of the development of Miami Beach occurred during this period and was heavily influenced by access to the streetcars. The first line ran across the County Causeway (now MacArthur Causeway) from Miami to Miami Beach where a single-track loop with passing sidings ran on Washington Avenue, Dade Boulevard, and Alton Road. Two lines later extended the system north to 45th and 50th streets. During the 1920s and 1930s, the streetcars had little automobile traffic to contend with. Indeed, few of the older art deco buildings have on-site parking, and many later buildings were built with parking that is inadequate today.

In recent years Miami Beach has seen a rebirth as an eating, entertainment, and tourist destination. Art deco buildings that have been vacant or underutilized for years are being remodeled for apartments and commercial and entertainment uses. New residential and commercial buildings are being constructed on vacant sites or sites previously used for parking, particularly in the South Pointe area below 5th Street. Ocean Drive and Washington Avenue now form one of the greatest concentrations of restaurants, bars, and nightclubs in the state. At the same time, the residential population is increasing, also shifting from an emphasis on retirees to a younger population, more of whom commute to jobs in other parts of the county. The renewed development has contributed to significant parking and traffic problems in Miami Beach, particularly in South Beach. Moreover, these problems will become even more acute as development continues.

These factors suggest a transportation mode that fits into this unique setting and provides attractive service for short trips as well as a connection to the metropolitan transit network.

Through Service or Separate Transit Lines?

Determining whether through service can or should be provided between West Dade and Miami Beach has consequences for the entire east-west transit service and is a critical element in determining the overall service provided.

The key reason to provide through service is the potential to travel between points in West Dade, particularly Miami International Airport, and points in Miami Beach without transferring. Through service also has some additional benefits. First, it would ensure a direct transfer to the existing Stage I Metrorail line, which passes by the west side of downtown Miami. Second, if all Miami Beach vehicles are compatible with the line to West Dade, through service would allow all maintenance and most vehicle storage to be provided at a site in West Dade. Locating a separate LRT storage and maintenance facility for the Miami Beach line has proved difficult because of the density and increasing viability for development of sites in Miami Beach.

Despite the strong desire to provide a one-seat ride where possible and other benefits of through service, many factors weigh against this option. Aesthetic, operational, and technical considerations suggest different solutions for the east-west line and service in Miami Beach. The key reasons for using separate systems are based on the distinct physical and operating characteristics of Miami Beach service versus the service from West Dade and the airport to the CBD and the seaport. Table 1 highlights those distinctions.

Because of the dense urban pattern and architectural character of Miami Beach, residents demand a transit system that fits into the character of the community. In particular, it cannot be elevated and therefore must be at-grade in existing street rights-of-way. Tunneling anywhere in south Florida is expensive because of the high water table. In addition, the pedestrian character and dense development of Miami Beach suggest on-street stations at relatively close spacings to be easily accessible to pedestrians. In contrast, West Dade offers a number of relatively open rights-of-way and potential for elevating the transit alignment, providing an alignment that is completely free of street crossings. Although stations can be located with joint development potential in mind, the spread-out character of Miami suggests more widely spaced stations with good car and bus access. In addition, the potential for very high volumes in the segment between the airport and the seaport suggests an alignment free of street crossings to avoid transit-traffic conflicts and to allow the possibility of automatic train control.

Since Miami Beach requires at-grade operation with electric power, power pickup must be by overhead catenary. In West Dade, although catenary could be used, the exclusive right-of-way allows the use of third rail. Third rail is less costly to install and maintain than catenary and does not present an unsightly appearance, particularly on elevated transit structures where catenary is even more visible.

Transit operating characteristics also differ significantly between West Dade and Miami Beach. In Miami Beach vehicles will never operate faster than the posted speed limits of about 35 mph (55 km/hr) and will usually operate even slower. On the MacArthur Causeway, a higher speed should be attained, but 55 mph (90 km/hr) is sufficient. In West Dade trains need to attain 55 mph on a regular basis to offer service that competes with car travel and could often attain 70 mph (110 km/hr) given the wide station spacings. Transit vehicles in Miami Beach must be able to turn within street rights-of-way, requiring a turning radius of approximately 90 ft (28 m) and short or articulated vehicles. In West Dade a minimum mainline turning radius of 1,000 ft (305 m) is provided, allowing longer, unarticulated vehicles, which are less costly per passenger to purchase and maintain. In Miami Beach train length is dictated by the length of the street blocks. The maximum length for a train in Miami Beach is 220 ft (67 m) or two 90-ft (28-m) vehicles. Train lengths are not limited by right-of-way characteristics in West Dade, and trains of four to six cars or 360 to 540 ft (110 to 165 m) are desirable for general revenue service and trains of six to eight cars or 540 to 720 ft (165 to 220 m) are desirable for airport-seaport service. Finally, operation in Miami Beach must be manual because of the on-street operation and heavy pedestrian movement. In West Dade manual or automatic operation is possible, with potential operating cost savings from an automated system, especially when close headways are offered between the airport and the seaport.

The height of vehicle floors and station platforms has also played a surprisingly important role in consideration of technology. Either low floors and platforms or high floors and platforms could be used in either area, but operational demands and aesthetic concerns suggest different solutions in Miami Beach and West Dade. High miniplatforms, or high-blocks, which give persons with disabilities access to only one door per train were rejected for Miami Beach because they do not fully comply with the Americans with Disabilities Act (ADA) and would obstruct needed circulation areas.

In Miami Beach, where station platforms will be an integral part of the streets and minimal visual intrusion is desirable, low platforms are suggested. As discussed later, stations on the sides or in the center of streets have been considered. High platforms would be unacceptable along the side of a street in Miami Beach because of visual obstruction and relatively poor access. Either high or low platforms could be used in the center of a street, but low platforms are less visually obtrusive and allow pedestrians to cross tracks and roadway when safe and feasible. A low-platform configuration is also suitable for the downtown Miami end of the Miami Beach line where stations would be in the median of Biscayne Boulevard.

TABLE 1 Key Distinctions Between West Dade and Miami Beach Transit Service

ISSUE	WEST DADE TO CBD / SEAPORT	MIAMI BEACH
Right-of-Way	All Grade-Separated, Primarily Elevated	At-grade, on-street operation
Power Pickup	Third Rail or Catenary (Third rail preferred for aesthetics and cost.)	Catenary only
Maximum Vehicle Speed	90 to 110 kph	40 to 55 kph in MB 90 kph on Causeway
Min. Turning Radius	305 m recommended	20 m required
Train Length	4 to 6 cars (110 to 165 m)	1 to 2 articulated cars (28 to 56 m) (absolute maximum is 67 m due to block lengths)
Operation	Automated or manual	Manual only
Station Platforms	High platforms recommended due to aesthetics and function	Low platforms recommended due to aesthetics and function
Vehicle Floor Height	High floor recommended	Low floor recommended
Peak Travel Times	AM & PM peaks, Airport-Seaport: 4-day morning and afternoon	AM and PM peaks, Weekends & all night
Potential Fare Policy (+/-)	$1.25 flat fare (medium to long trips)	$0.25-$0.50 (short trips) $1.25 (to CBD / beyond)
Fare Collection	Control area with turnstiles	Proof-of-payment system, no control area, ticket machines on platform

1 m = 3.28 ft. 1 kph = 0.62 mph

In West Dade and particularly between the airport, downtown, and the seaport, a higher-speed operation on exclusive right-of-way is envisioned. In particular, the efficient operation of the special airport-seaport service is critical. High-platform stations best serve to keep trackways clear of pedestrians and are critical where third rail power pickup is used. Although barriers between tracks could prevent crossing between platforms where low platforms are used, they are not as effective at keeping people off trackways as a high platform. In addition, high-floor vehicles with standard trucks are better proven to provide reliable service at the higher speeds that are possible between West Dade and the seaport.

Another aspect in which anticipated transit service differs between Miami Beach and the remainder of Miami is service pattern. In West Dade a typical pattern providing service between approximately 5:30 a. m. and 1:00 a. m. 7 days a week with frequent service in the morning and evening peak periods is anticipated. In Miami Beach, however, 24-hr service is anticipated for weekends and possibly 7 days a week to serve the late night entertainment and tourists there. Moreover, it may prove desirable to operate services at different headways in Miami Beach than in West Dade during regular service hours. Although short turn service could be operated on portions of a continuous line, this difference in operating patterns supports the notion of separate lines.

Finally, although free transfers would be provided between an east-west line and a Miami Beach line, distinct fare collection methods and fare policies may be desirable in the two areas. In West Dade paid fare control areas with turnstiles like the existing Metrorail line are anticipated. In Miami Beach, because of on-street integration of stations, a proof-of-payment system is desirable. Also in West Dade, a flat fare system equal to the existing Metrorail fare is anticipated. In Miami Beach, where it is particularly desirable to attract shorter trips, a two-tiered fare may be desirable with a low fare for travel entirely within Miami Beach and a higher fare for trips from Miami Beach to downtown or points beyond.

Given the differences between the transit needs of West Dade and Miami Beach and the requirement that transit in Miami Beach be light rail to operate on streets, the only options available are a through service that is entirely light rail, a through service that is a hybrid of light rail and either heavy rail or an automated guideway transit (AGT) technology, or separate lines. A through service that is entirely light rail would not respond well to the requirements or opportunities in the West Dade to seaport portion of the corridor.

A hybrid technology, with vehicles that can operate from either overhead or third rail power, is an attractive concept. However, the relevant issues go beyond the power pickup method in this case. First, hybrid vehicles would have to have high floors to be compatible with a third rail power pickup and to offer the high-speed operation potential in West Dade, forcing all stations to have high platforms, including those in Miami Beach. Second, all vehicles must be the same width, whereas wider vehicles are desirable in West Dade and narrower vehicles in Miami Beach. Third, given the MacArthur Causeway alignment and an elevated east-west line in downtown, the junction between the two lines requires obtrusive transition tracks that climb from grade level to the high elevated line within downtown Miami and extensive additional right-of-way there. Fourth, hybrid vehicles must negotiate the tight curves required in Miami Beach and therefore must be either short or articulated. Finally, the cost to purchase and maintain hybrid vehicles is expected to be greater than that for either heavy-rail or light-rail vehicles since the hybrid vehicles would require all the capabilities of both systems.

Despite the desire to offer a one-seat ride, the option of using heavy rail or a similar technology for the east-west line from West Dade to the seaport and light rail for a line from downtown Miami to Miami Beach is gaining momentum.

Integration of Miami Beach Line into Transit System

If separate transit lines are chosen for service between West Dade and the seaport and for connecting to Miami Beach, the location and character of the transfer station become important elements in providing an attractive and integrated transit system.

The potential locations for a transfer point between an east-west line and a Miami Beach line depend partly on the alignment chosen to connect Miami Beach to downtown Miami. Two basic routes were studied in the East-West Multimodal Corridor Study: along the MacArthur Causeway or through a tunnel under Government Cut and the Port of Miami. Within these two basic alternatives a number of options were also considered. In any case, in order to provide the special through service from the airport to the seaport, the east-west line would extend to the seaport on Dodge Island.

These alignments provided three primary sites for transfer between the two lines:

- South Pointe, Miami Beach (on First Street),
- The seaport (on Dodge Island), and
- Downtown Miami (in the vicinity of Freedom Tower).

If the transfer point were at South Pointe in Miami Beach, passengers from the Miami Beach light-rail line would have to transfer once to reach downtown Miami. However, passengers from the South Pointe area, which is becoming one of the most densely developed areas in Miami Beach, would not have to transfer to reach downtown Miami or points in West Dade, including the airport. Likewise, passengers from bus routes serving the west side of Miami Beach along Alton Road would only have to transfer once at South Pointe to reach destinations in downtown or West Dade. This option corresponds primarily to the Government Cut tunnel alignment.

If the transfer point were at the seaport, all passengers from Miami Beach would have to transfer once to reach the Miami CBD or points in West Dade, including the airport. Passengers from the South Pointe area would also have to transfer once, whereas passengers from bus routes serving the west side of Miami Beach along Alton Road would have to transfer twice. Moreover, the transfer point in this case would not be a significant destination for many of the daily passengers nor a site for potential development. This option occurs only with the Government Cut alignment.

If the Miami Beach line continues on the MacArthur Causeway to downtown Miami with a transfer on Biscayne Boulevard at Freedom Tower, passengers from Miami Beach would not have to transfer to reach the Miami CBD but would have to transfer once to points in West Dade. Passengers from bus routes serving the west side of Miami Beach along Alton Road and the South Pointe area would have to transfer once to reach downtown and twice to reach the airport and West Dade. Extending the

Miami Beach line a bit further south gives Miami Beach passengers direct access to the inner loop of the Metromover system and puts the heart of downtown Miami within walking distance of the line. If the Miami Beach line ends on Biscayne Boulevard, a second transfer would be required to reach the existing Metrorail line on the west side of downtown, but a proposal to continue the line west on Flagler Street or another route would provide a direct transfer between those lines as well.

Despite the operational advantages of a Government Cut route and issues related to a line along the MacArthur Causeway, the cost of the tunnel and impacts for the Port of Miami during construction were deemed too great, and the MacArthur Causeway alignment was chosen, resulting in a downtown transfer because of difficulties in extending the heavy-rail line across the MacArthur Causeway and building a junction downtown.

Alignment and Design Alternatives

The choice of a route and the specific design of trackways and stations are interrelated issues in Miami Beach. Given the limited width of the avenues, proximity of architecturally historic buildings, and existing traffic problems, the arrangement of tracks, traffic lanes, parking, and stations is a critical issue.

Miami Beach Transit Alignment

Three basic alignment options were considered within Miami Beach: two tracks on Washington Avenue, a one-way couplet on Washington and Collins avenues, and a loop around the South Beach area, operating either in one direction or bidirectionally on Washington Avenue, 17th Street, Alton Road, and First Street.

The one-way couplet concept in which both transit and traffic would operate northbound on Collins Avenue and southbound on Washington Avenue was introduced as a means to reduce the impact of the transit line on traffic flow through Miami Beach and to divide the physical impacts of the rail line between two streets. However, Collins Avenue is narrower, contains more residences and hotels, and is lined by more art deco structures than Washington Avenue. Furthermore, community opinion indicated that these avenues should not be one way and that all parking on one side of each street should not be lost as would be required in that plan. Therefore, Collins Avenue was excluded from further consideration.

The notion of a transit loop in South Beach operating on Washington Avenue, 17th Street, and Alton Road was introduced in the study in response to comments by local Miami Beach residents and representatives. It was suggested that a loop would provide improved service to both the east side of South Beach, which is dominated by commercial and hotel uses, and the west side, which is dominated by high-rise apartment buildings. Some suggested a single track, one-way loop to minimize costs and impacts to streets. For some the idea of a loop seemed inherently good beyond any particular benefits it might present.

On further consideration, the hoped-for benefits of the loop proved more illusory. The single-track loop results in excessive travel times for many of the short trips within Miami Beach that the line is hoped to attract. Since the travel time around the loop is approximately 15 min and travel with a single-track loop would be only in one direction, a person wishing to travel a short distance against the direction of travel would have to travel the long way around the loop. This would be particularly onerous for travel from the Miami Beach Convention Center to points along Washington Avenue, a key travel orientation.

In addition, the majority of trips from the west side of South Beach are unlikely to be oriented directly to the east side of South Beach, except on weekends. Travel to employment areas elsewhere in Dade County is more likely to dominate daily travel patterns in this area. Moreover, for many trips from the Alton Road area to points along Washington Avenue, the loop would not offer a significant advantage over walking because of the circuitousness of the trip. Ridership forecasting supported these patterns and suggested that the loop offers little benefit over existing bus service on Alton Road, connecting with a rail line to downtown Miami at 4th Street and with significant costs and street impacts.

Key information comparing the Washington Avenue alternative with the bidirectional loop alternative is as follows (MB = Miami Beach, O&M = operation and maintenance, system = all future bus, Metrorail, and LRT service in the county):

	Washington Avenue	*Miami Beach Loop*
Capital cost (MB only) ($ millions)	59.3	97.6
Annual O&M cost for MB LRT ($ millions)	8.2	10.6
Net annual O&M cost (system) ($ millions)	271.3	273.0
Passenger boardings on MB LRT (millions)	8.1	8.3
Daily transit person trips (system)	368,500	368,100

The loop option adds significantly to the capital and operating costs of the Miami Beach line while drawing a disproportionate part of its ridership from competing bus services. By serving the primary commercial, entertainment, convention center, and hotel areas, as well as a significant portion of the residential population, the Washington Avenue alignment focuses on the area with the greatest potential to attract transit riders and to support appropriate redevelopment in Miami Beach.

The design of the transit line on Washington Avenue is fully compatible with later development of a loop, a northern extension, or both. Since construction of the Washington Avenue alternative does not preclude completion of the loop, both options were retained for further consideration. However, on the basis of the information presented, it was recommended that only the Washington Avenue alignment be pursued at this time. Extensions to that line, either to complete a loop on 17th Street and Alton Road or to continue farther north on Collins Avenue and Indian Creek Drive, can be investigated in the future.

Configuration of Tracks and Stations on Washington Avenue

Detailed design studies were conducted to determine how best to fit tracks and stations on each of the streets and avenues considered while improving pedestrian circulation and accommodating vehicular traffic and parking. In all cases, in order to provide a high-quality, competitive transit service, it was deemed critical that the rail transit line have an exclusive right-of-way, free of traffic except that crossing at intersections. No sharing of lanes for left turns would be allowed since this would significantly impair the movement of transit vehicles. It is assumed, however, that the guideway would be paved and have mountable curbs to allow its use by emergency vehicles if other lanes are tied up with traffic.

Parking in the lane adjacent to a trackway is deemed infeasible unless a separation of at least 3 ft (1 m) and a pedestrian barrier can be provided. Without the separation, people getting out of vehicles would be in the way of oncoming trains and without a barrier they would be unaware that they had wandered into the trackway.

One of the alignment alternatives studied, the Washington–Collins Avenue alternative, would locate one track on each of those avenues with all trains and traffic traveling northbound on Collins Avenue and southbound on Washington Avenue between First and 20th streets. In this scheme it was decided that the tracks would best be located in an exclusive guideway along the left curb of each avenue (the west side of Collins and the east side of Washington). This configuration would allow the minimum right-of-way since the existing sidewalks would serve as the station loading areas on both avenues. It would also allow right turns to be made off both avenues without interference from trains, and left turns would be signal controlled to protect trains and vehicles. This scheme eliminates parking along the side of each avenue adjacent to the tracks but allows uninterrupted parking on the opposite side of the street. As indicated previously, this alternative was rejected by the community because of the impacts of a rail line on Collins Avenue, which is narrower and has more residential uses than Washington, and opposition to a one-way traffic operation on the avenues and the loss of parking.

The remaining alternatives require two tracks on Washington Avenue, a 100-ft (30.5-m) wide right-of-way with buildings abutting on both sides (Figure 4). The avenue is currently a two-way street with a small median but no left-turn lanes. Although there are two through lanes and one parking-and-loading lane in each direction, standing and loading from the second lane is a common problem, often reducing some blocks to one through lane. The sidewalks are approximately 12 ft (3.65 m) wide but vary somewhat from block to block and have expanded areas using part of the curb parking lane at some intersections. Pedestrian volumes often exceed the capacity of the sidewalks, particularly on Friday and Saturday nights when customers crowd the sidewalks in front of clubs and force pedestrians into the curb lanes.

Three general schemes for placement of double tracks and station platforms were considered on Washington Avenue: both tracks on one side of the street, one track along each curb, and both tracks in the center of the street. In each case variations related to the placement of station platforms, parking, and traffic lanes were considered and an overall best scheme was developed.

The scheme with one track along each curb on Washington Avenue minimizes right-of-way requirements by using sidewalks for station platforms in both directions (Figure 5). However, this arrangement would eliminate parking along both sides of the street unless a separation and barrier were provided on each side. Even if parking was provided, no direct access to stores would be possible since barriers would be required to prevent random crossing of tracks. It was also determined that only low platforms and low-floor vehicles could be used with this scheme because of the minimal space available and the visual impacts of high platforms or high-blocks on adjacent buildings in the historic district. However, even low platforms posed a problem here. Since a typical low-floor car requires a platform approximately 14 in. (35 cm) over rail (street) height and sidewalks are typically about 6 in. (15 cm) over the street, the sidewalks would have to be raised approximately 8 in. (20 cm). On most of Washington Avenue, retail stores front directly on the sidewalk, however, and there is usually no rise in the in-

FIGURE 4 Washington Avenue today.

terior floor height. Thus raising the sidewalk would have unacceptable aesthetic and physical impacts. Raising part of the sidewalk or sloping it would cause serious drainage problems, particularly in Miami Beach, which is subject to heavy showers and hurricanes. Therefore, it was necessary to locate stations on blocks that did not have adjacent buildings with floors at sidewalk level.

The concept of locating both tracks on one side of the street was identified in the original feasibility study (*1*). For most of the length of Washington Avenue, the west side was chosen to avoid utility conflicts on the east side and to leave the street activity on the east side of the transit line so that vehicles making turns to and from Collins Avenue would not cross the transit line (Figure 6). The optimal station layout for this configuration uses the west sidewalk for southbound boarding and a platform along the east side of the tracks for northbound stops. This arrangement allows for either two-way traffic flow on Washington Avenue or a one-way pair with Collins Avenue. The two-way configuration would allow one through lane in each direction, parking along the east side in blocks that do not have stations, but no left-turn lanes. In blocks without stations, the space used by the northbound platform would serve as a through lane in a two-way configuration or as a signal-controlled right-turn lane in the one-way configuration. Although this configuration offers the greatest flexibility for configuration of traffic lanes, it eliminates parking along the west side of the avenue and suffers from the same problems of locating station platforms along sidewalks directly in front of buildings. As with the scheme with tracks on both sides of the street, this scheme requires low-level platforms located on blocks without building conflicts. If high platforms are required, they could be arranged by locating a single high platform between the tracks, but this resnlts in a greater visual impact on nearby buildings.

A configuration with tracks in the center of the street locates the station platform and canopies as far from building facades as possible and affects properties on both sides of the avenue equally (Figure 7). A center platforn arrangement was selected to reduce the overall width required, provide a streamlined appearance, and locate station elements as far as possible from facades along the avenue. This scheme works equally well with high or low platforms and has no effect on buildings, sidewalks, or drainage. With either type of platform, the station platform would slope down to the crosswalks at both ends of the block at each station to provide barrier-free access at both ends of the station. This scheme significantly reduces the traffic capacity of the avenue but

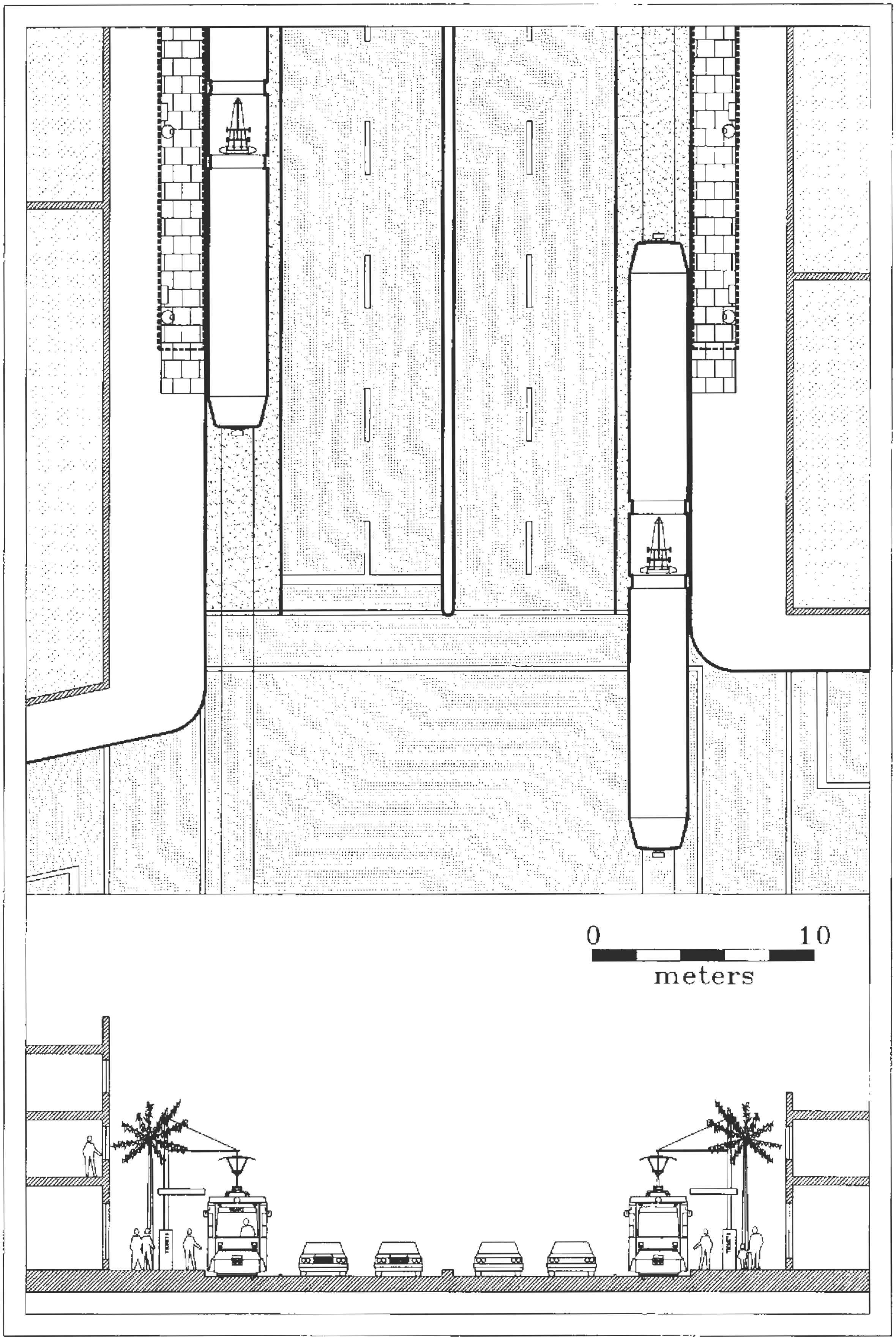

FIGURE 5 Transit on both sides of Washington Avenue.

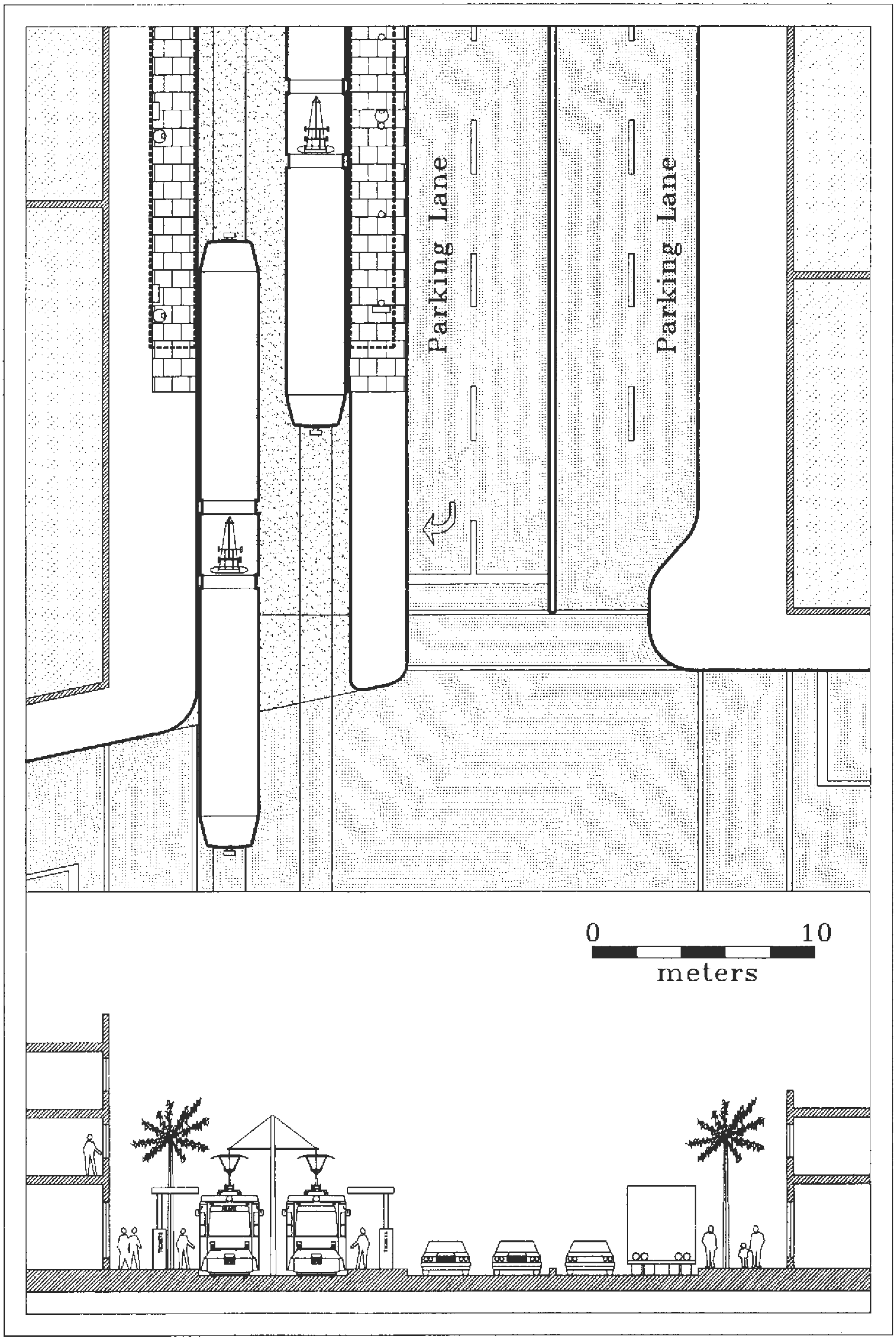

FIGURE 6 Transit on the west side of Washington Avenue.

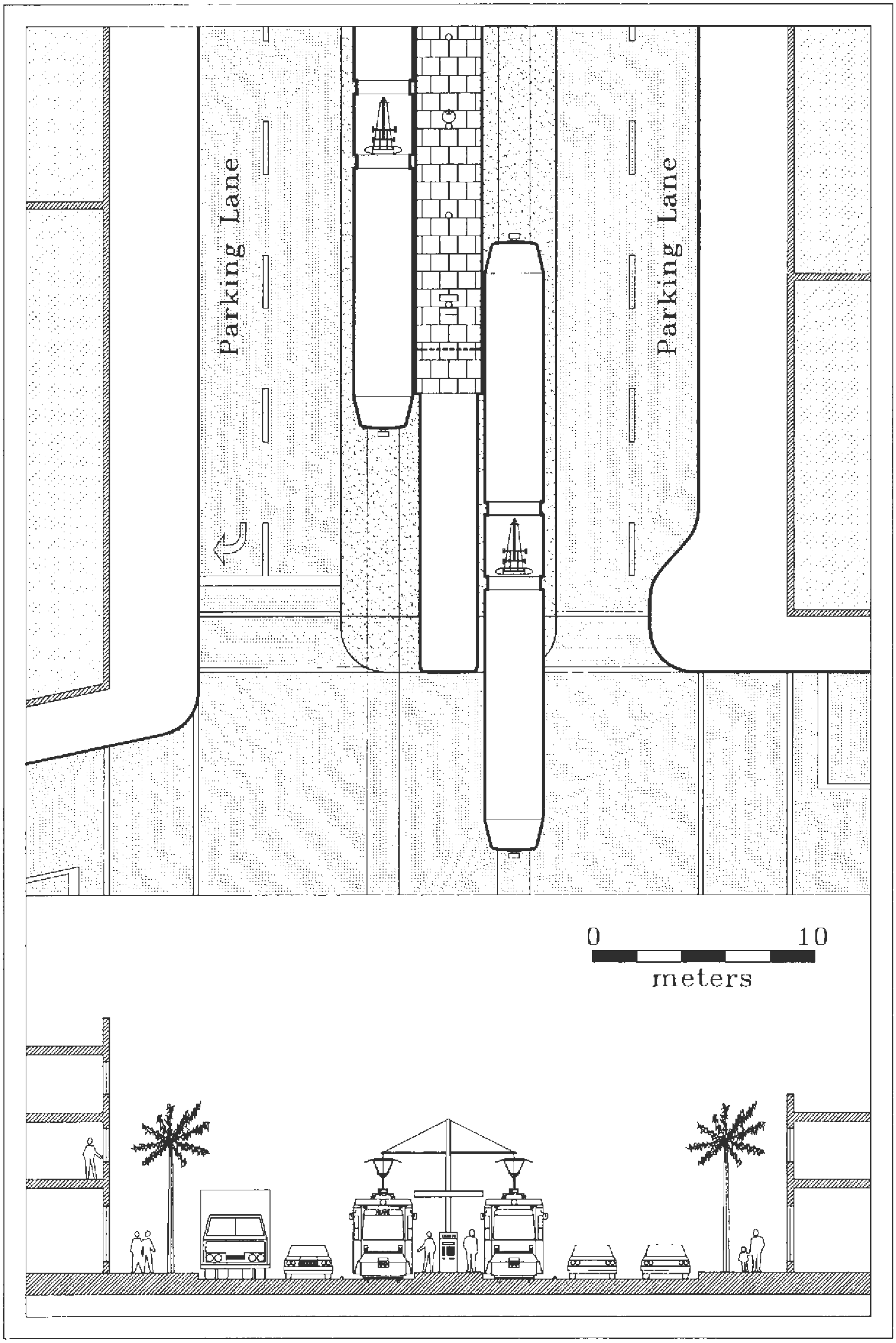

FIGURE 7 Transit in the center of Washington Avenue.

FIGURE 8 Future LRT on Washington Avenue.

creates a slower traffic pattern supportive of the transit-pedestrian focus of the street. One through lane would be provided in each direction. In blocks with stations, no parking or left-turn lanes would he possible. However, the majority of blocks could provide parking and loading along the curb lanes. Left-turn lanes could only be provided in those blocks by eliminating parking near intersections. To avoid train-traffic conflicts and allow maximum parking to remain, it may be desirable to eliminate left turns and require drivers to turn right around the block.

In response to the aesthetic concerns on Washington Avenue and the desire to retain the maximum amount of parking possible, and to keep options for high- or low-floor vehicles open, an alignment in the center of Washington Avenue with center platform stations was selected for further development in Miami Beach (Figure 8).

ACKNOWLEDGMENT

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Integration of Extended Vintage Trolley Operations into New Light-Rail System in Dallas, Texas

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In 1989, restoration and construction of a 2.9-km (1.8-mi) long vintage street trolley system was completed in Dallas, Texas. The system was put into operation between the northern fringe of the central business district (CBD) and a retail and restaurant area immediately north of downtown Dallas. Five years later, plans and preliminary designs were under way to expand this system. At one end of the line, the route is to be extended further into the CBD to another retail, restaurant, and entertainment area and at the other end, to a major mixed-use development of office, housing, and retail activities. More important, these two extensions will then interface with one of the stations for Dallas' 32.2-km (20-mi) light rail transit (LRT) starter system now under construction in the CBD, a downtown bus transfer facility now being designed, and another LRT station serving the mixed-use development north of the CBD. In doing so, the vintage trolley line will become a system connector, providing feeder service to the LRT and bus components of the transit system and serving an area of the city with limited transit accessibility. The evolution of these systems and the status of their development and integration are described.

Beginning as early as 1873, streetcars were the primary mode of transportation in Dallas, Texas, for many years. The first streetcar was a mule-drawn vehicle. Cars drawn by steam locomotives began to be used for public transportation in 1887. Electric cars arrived in 1889, and cable cars were attempted in 1890. The first trolley car appeared in 1884 on McKinney Avenue, a then residential street north of downtown, as part of the Dallas Street Railway Company operation. The line extended along McKinney, providing access between downtown and uptown Dallas. The line along McKinney operated until the 1950s when all streetcar operations were terminated in favor of the more flexible bus service.

Dallas Trolleys Reborn

In the late 1970s, a neighborhood group located along McKinney Avenue persuaded the city of Dallas to participate in a joint venture to improve the streetscape of the Vineyard area (Figure 1). This venture included city funds for removing the asphalt pavement overlay on a section of McKinney Avenue to expose the original brick street. The work was accomplished in 1981.

During the course of street renovation, the trolley tracks were uncovered along with the old brick paving. These original trolley tracks, with minor exceptions, were found to be in excellent condition and suitable for streetcar operation.

At about the same time, a McKinney Avenue restauranteur began investigating the possibility of reestablishing streetcar operations on the old tracks. In late 1982, a group of 36 volunteer trolley enthusiasts led by this businessman prepared a proposal for restoration of trolley service on McKinney.

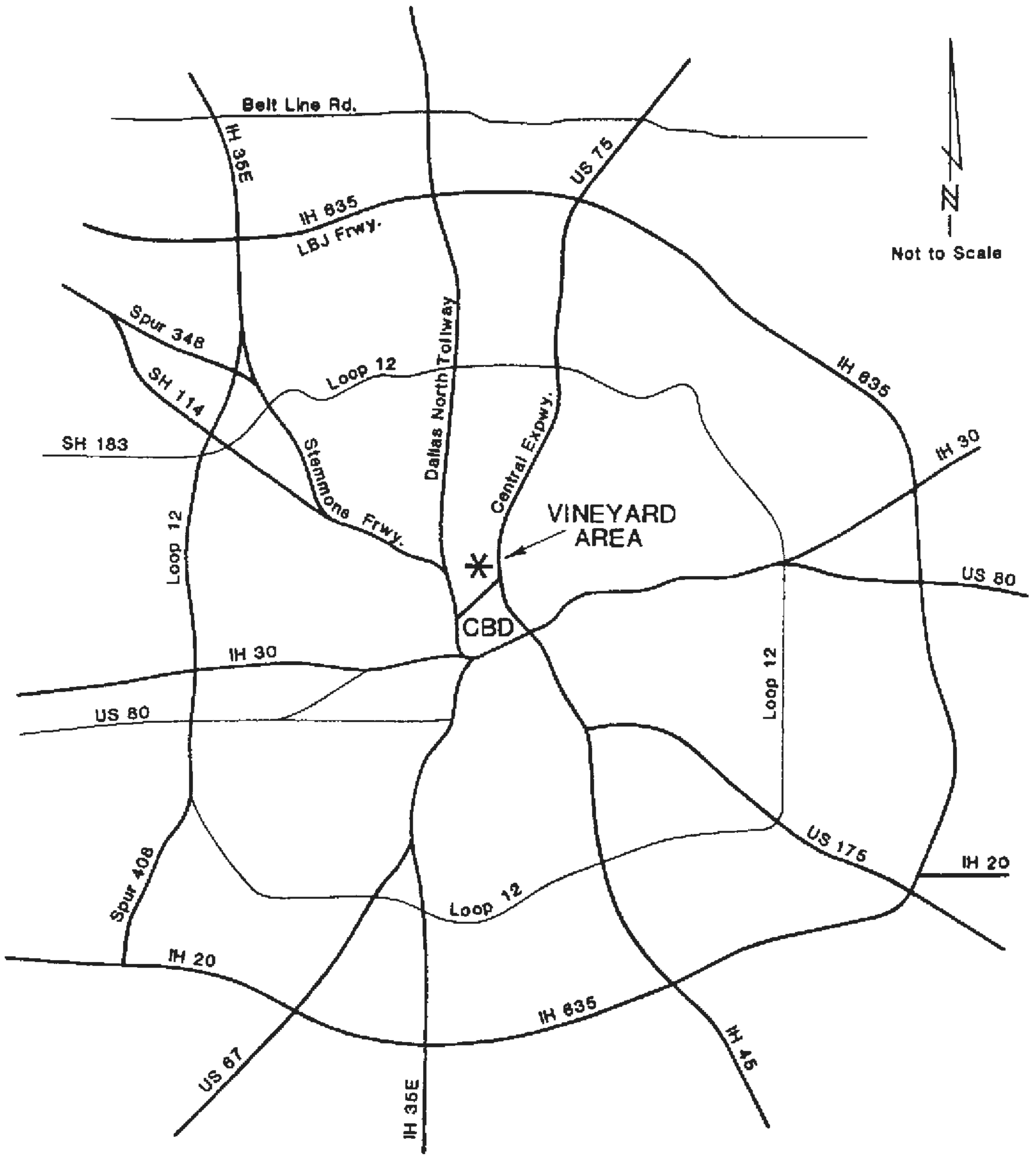

FIGURE 1 Trolley system location.

In February 1983, the McKinney Avenue Transportation Authority (MATA), Inc., a Texas not-for-profit group, was established to provide a corporation capable of obtaining funds and operating a proposed streetcar system.

Financing

In early 1984, a federal grant application was prepared. Support for the application was sought and received from the downtown business association and the local chamber of commerce. The Dallas City Council and the local transit agency approved the grant application in summer 1984 for $1.3 million with an additional $200,000 to be provided by the city of Dallas from a 1976 bond program and $400,000 by MATA from private donations.

In October 1984, the Urban Mass Transportation Administration (UMTA), now the Federal Transit Administration (FTA), initially approved a grant of $50,000 for a feasibility and environmental study. The results of the environmental study were accepted and UMTA approved the grant for system construction in August 1985.

In July 1987, an amendment to the initial grant application was prepared for submission to UMTA. This amended application was made for Section 3 discretionary funds in the amount of approximately $1.2 million. This grant application was approved in March 1988, increasing the total federal participation to over $2.5 million. An additional $2.4 million in local funding was

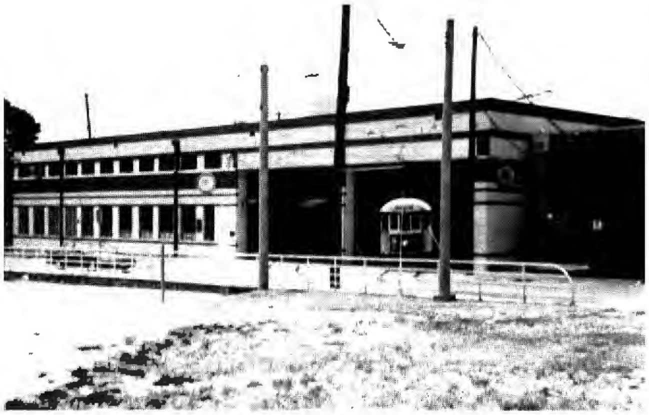

FIGURE 2 Completed car barn reconstruction.

FIGURE 3 Reconditioned Brill car No. 122.

provided through private donations to match the federal grant, purchase and renovate a maintenance and storage facility, and purchase and renovate five vintage trolley vehicles. These efforts increased the total project cost to over $5.5 million.

The Car Barn

Initially, a wooden frame garage behind the streetcar plan originator's restaurant was to serve as a maintenance and storage facility for a one-car trolley system. When it was determined that more vehicles would be needed to provide the desired frequency of service, another facility had to be located. The selected warehouse had an interior truck dock that could be converted into a service pit for the trolleys. It was one block from the proposed streetcar route, however, and the roof had to be raised to provide enough clearance for the trolleys.

The renovation work was begun in May 1987 with a "roof breaking" ceremony. Construction was completed in November of that year with the trolleys to be restored being moved from temporary quarters to the new maintenance and storage facility. The completed car barn is shown in Figure 2. MATA purchased and renovated the car barn for about $760,000 with funds from private donations.

Vehicle Renovation

A decision was made early in the implementation process to renovate existing vintage trolley vehicles rather than building new replicas. This meant that it was going to be necessary to find existing vehicles and parts to use in the rebuilding process, which started with the purchase of one 1920s New Orleans style car that was ultimately sold and used as partial payment on a total of five vintage streetcars that were acquired from a variety of owners and several countries. Two of the cars and their parts were obtained from Portugal and Australia. Two other vehicles were purchased or leased from a local trolley buff, and the fifth car was rescued from demolition just before the land on which it was sitting was sold. The vehicles, in various states of disrepair, were transported to the new trolley barn, where they were carefully restored and reconditioned by volunteer craftsmen. Figure 3 shows one of the vehicles in its fully restored condition.

Trolley System Construction

In early spring 1986, the city of Dallas requested proposals for the engineering of all construction other than the car barn and vehicle renovation. An engineering contract was awarded to a local firm in June 1986 in the amount of $392,820. Once the preparation of plans and specifications was completed, the city advertised for bids; the construction contract was awarded to a local construction company in April 1988 for $4,273,797. Only $2,213,277 of this contract had to be charged against the trolley project. The balance was utility replacement and street reconstruction work that was needed anyway. Construction was completed for the route shown in Figure 4 in about a year.

Trolley Operation

Since MATA is a privately operated system, it was necessary to enter into an agreement to run its vehicles on the publicly owned tracks. No operating agreements of this type existed, so it was necessary to refer back to some of the original operating agreements with railway companies. The operating agreement with Dallas Railway and Terminal Company, which dated back to the early 1900s, was examined. Despite its age, that agreement

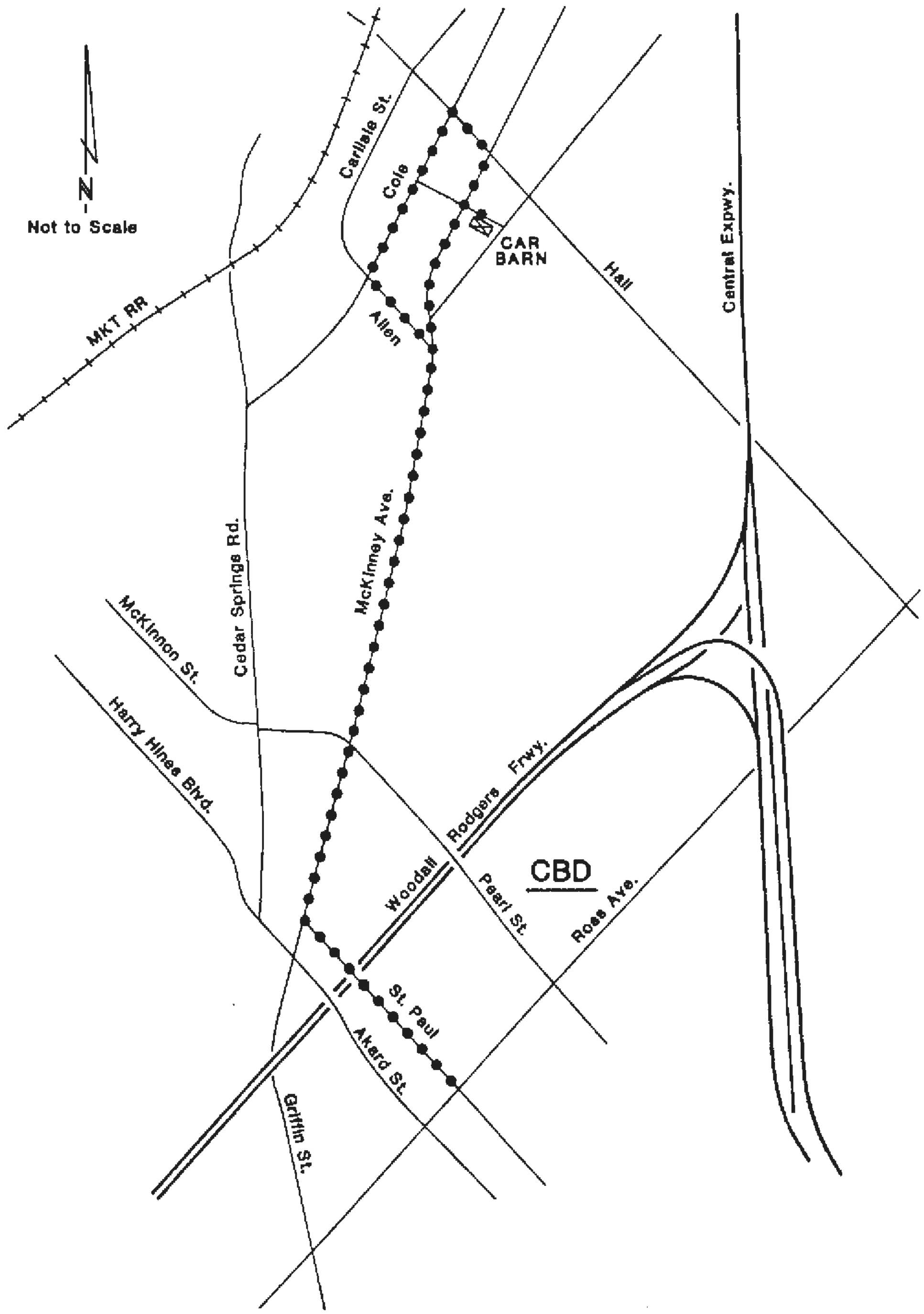

FIGURE 4 Existing trolley route.

served as a model for a new pact. MATA agreed to operate the system at its own expense for 5 years. If during that time the system became financially unable to continue, the city had a first lien on all MATA property.

The system began operation in July 1989. With the exception of shutdowns for maintenance and repairs, the system has been in continuous operation with four restored vintage cars and a largely volunteer work force ever since without requiring public agency financial assistance.

Dallas' Light-Rail System

Starter System

Following its establishment in 1983, the Dallas Area Rapid Transit (DART) regional transportation authority began preparation of plans to develop a light-rail transit (LRT) system to serve the urbanized area. A 108-km (67-mi) LRT system was ultimately approved as part of an integrated LRT, commuter rail, and bus transit system

Rodney W. Kelly

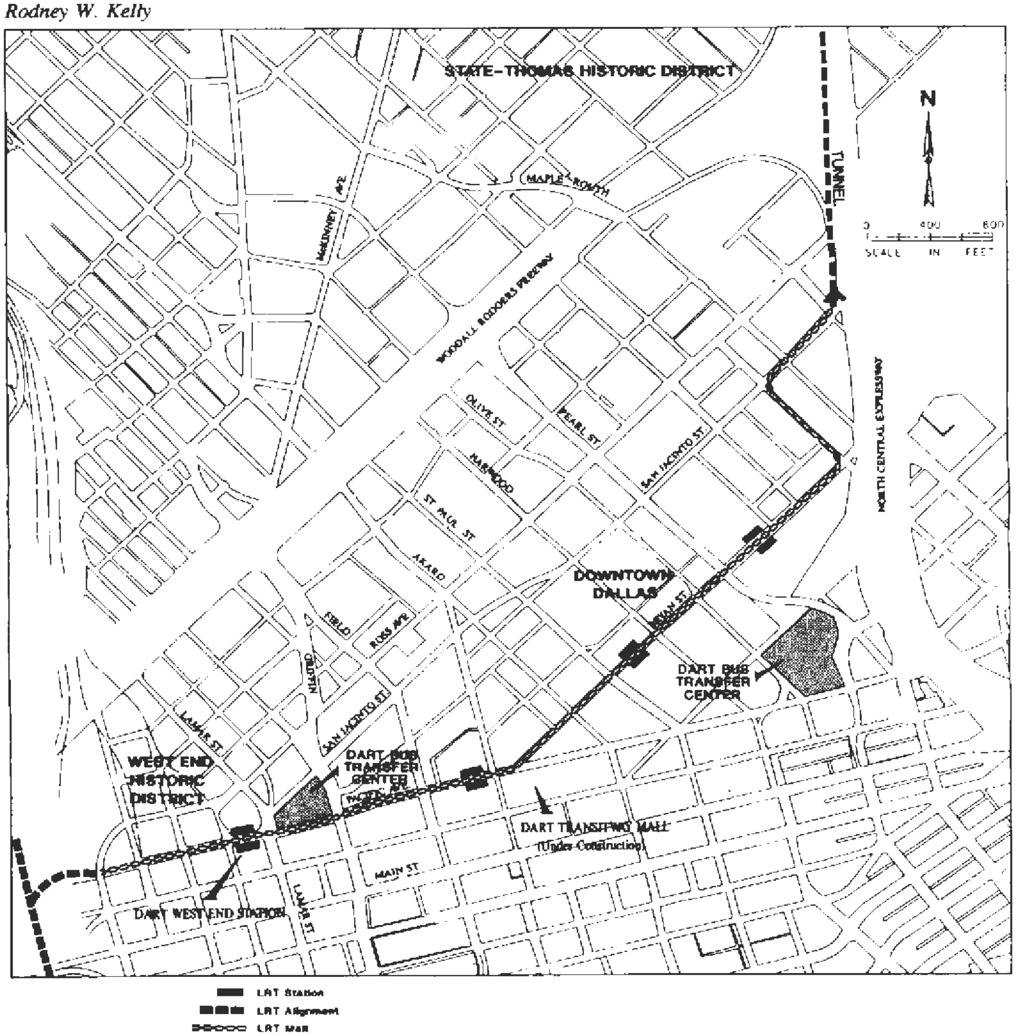

FIGURE 5 Dallas CBD LRT and bus transit facilities.

plan. Preparation of engineering plans led to project implementation, with all of the 32.2-km (20-mi) LRT starter system currently under construction. Operation of the first segment of the starter system is scheduled to begin in mid-1996.

CBD Component

The heart of the LRT system will be located in the downtown area where all of the lines converge. The system will operate along a 3.22-km (2-mi) long at-grade transit mall located on two connecting east-west streets, linking a line to the north and another to the south.

In addition to an LRT mall, there will be two downtown bus transfer facilities at the east and west ends of downtown to serve bus routes that pass through and connect in the CBD. Each of these bus transfer centers will be located next to one of the LRT stations to accommodate bus-to-rail as well as bus-to-bus transfers. The configuration of the LRT mall and the locations of the bus transfer centers are shown in Figure 5.

Trolley Extensions

Even before completion of the existing McKinney Avenue trolley restoration, studies were conducted to evaluate the possibility of a West End link. The West End Association and the Central Dallas Association strongly supported and actively pursued the extension but had not been in a position to advance beyond basic feasibility analysis. More recently, establishment of support for the Downtown Improvement District, the Uptown Public Improvement District, and the CityPlace Tax Increment Financing (T.I.F.) District gave impetus to the possibility of both north and south extensions. In addition, the Intermodal Surface Transportation Efficiency Act (ISTEA) has added a possible alternative for capital funding that the city of Dallas is actively pursuing on behalf of the local supporters of additional restoration of historic trolley service.

Through the cooperative efforts of the city of Dallas, the North Central Texas Council of Governments (NCTCOG), the Central Dallas Association (CDA), the Texas Department of Transportation, DART, and MATA, a study was initiated to examine extensions of the trolley line and linkages with the LRT and bus systems.

Task Force

Early in the project, it was recognized that certain segments of the community had a strong interest and a role to play in any possible extension of the McKinney Avenue Trolley. It was concluded that the knowledge, input, and support of these entities was essential to the success of the project, the measure of that success being enough consensus to result in the necessary support (financial, political, etc.) to carry the project forward as a component of an integrated transit system plan. Therefore, a task force consisting of the following entities (in addition to the consultants and NCTCOG) was created to support, advise, and critique the consultant team: MATA, DART, West End Association, CityPlace, CDA, and the city of Dallas (Department of Public Works and Transportation).

The members of the task force provided or assisted in obtaining facts, figures, plans, and previous reports that were important to the accuracy and completeness of this study. They also met to critique the progress and the interim conclusions of the study team and to engage in dialogue that assisted in identifying issues to be addressed.

Description of Alternatives

The trolley extension study addressed a variety of potential route options that covered two physically separated service areas: the CityPlace options and the West End options. The CityPlace options extended from the northern terminus of the current McKinney Avenue trolley line at McKinney Avenue and Hall Street and are therefore referred to as the north extension alternatives. The West End options extended from the southern terminus of the current McKinney Avenue trolley line at St. Paul Street and Ross Avenue and are therefore referred to as the south extension alternatives. Any combination of north and south extensions is possible because they are physically over 1.5 km (1 mi) apart. Therefore, north and south alternatives were, for the most part, considered independently but compared against nearly identical criteria.

The alternatives investigated were based primarily on the routes included in a report prepared by NCTCOG (*1*). This was essentially a ridership study, and therefore certain operational aspects of the routes were not entirely defined. In order to provide a meaningful comparison in the current study, all of the routes were defined more clearly, which resulted in several subalternatives (modifications of the basic routes). Thus the one north route in the 1992 study became three north alternatives. There were four south alternatives in the 1992 study, all of which were included with increased definition. In addition to these routes, a fourth north alternative and four south alternatives were added based on input from various study participants. These routes are shown in Figures 6 and 7.

System Integration

Northern Extension

Each of the route extension alternatives was designed to interface with both the LRT and the bus systems. The north extension has its proposed terminus within a short walk of a pedestrian access portal to the underground subway station on the North Central Line. With feeder buses also being routed to this station, there would be an opportunity for trolley-to-bus transfers as well as trolley-to-LRT transfers. Because the area around the portal is currently vacant and controlled by a single developer (CityPlace), a member of the trolley extension task force, it was possible to develop a northern route extension with the direct station access needed to afford desirable system interface. The proposed station area is shown in Figure 8.

Southern Extension

All of the southern routes except one pass within one-half block of the proposed West End LRT station and next to a proposed bus transfer center. The trolley tracks are proposed to be located on the opposite (left) side of the one-way street next to the bus transfer center in order to avoid conflict with the high level of bus activity in the right lane. The proposed interface area is shown in Figure 9. With the extensions of the trolley line on both ends to interface with LRT stations, the route will become a system connector between two LRT stations, thus providing access to the transit stations from points in between.

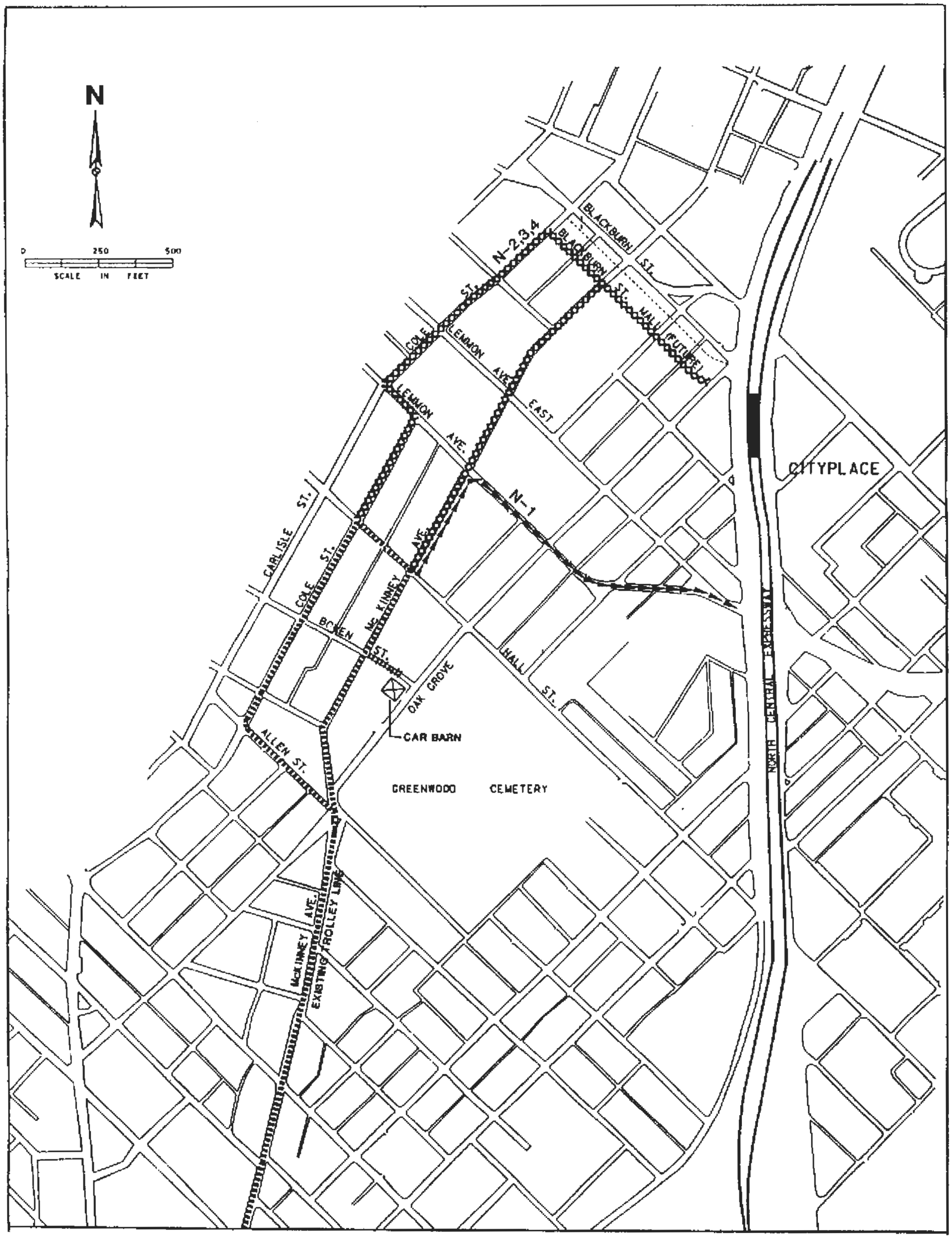

FIGURE 6 McKinney Avenue trolley: north extension alternatives.

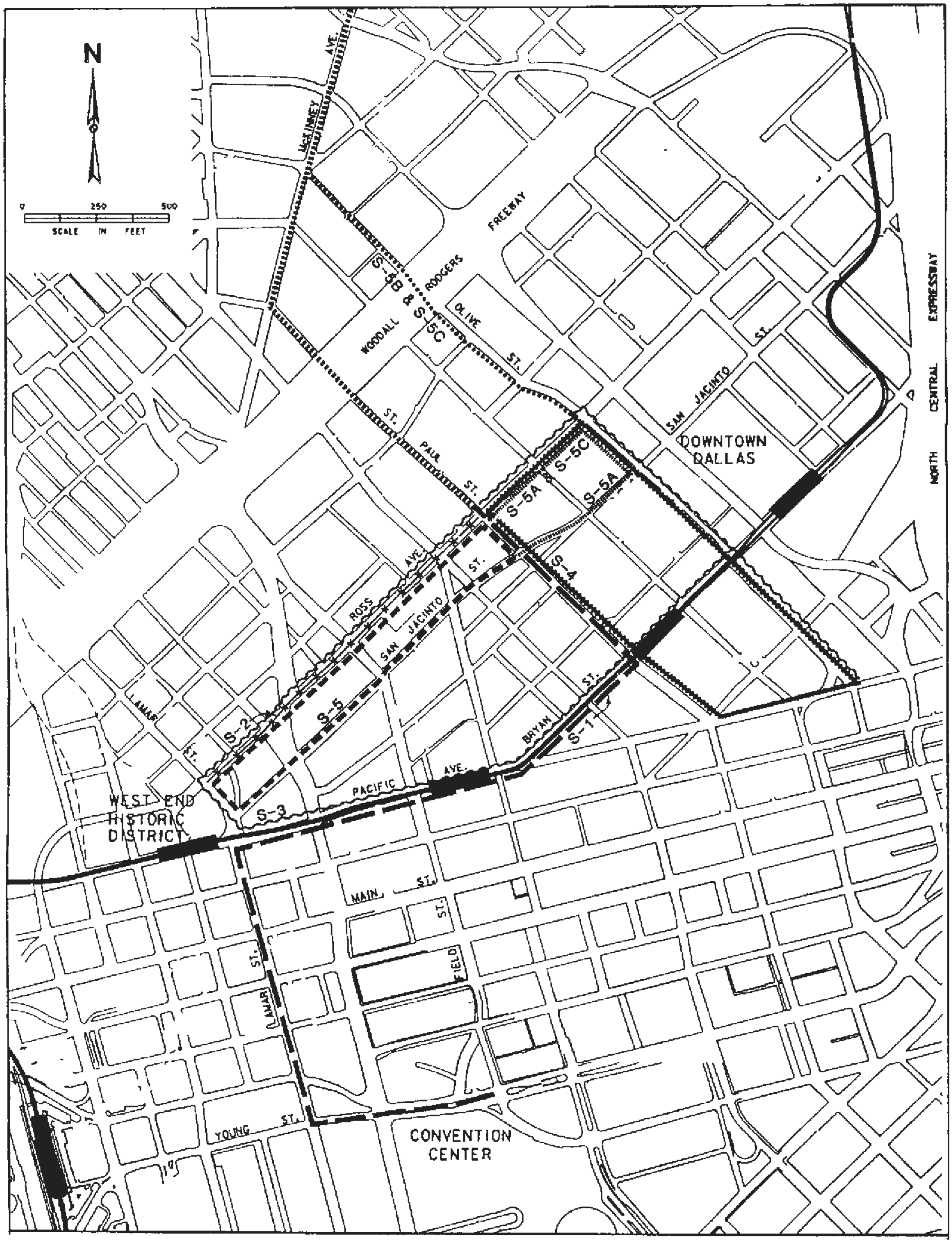

FIGURE 7 McKinney Avenue trolley: south extension alternatives.

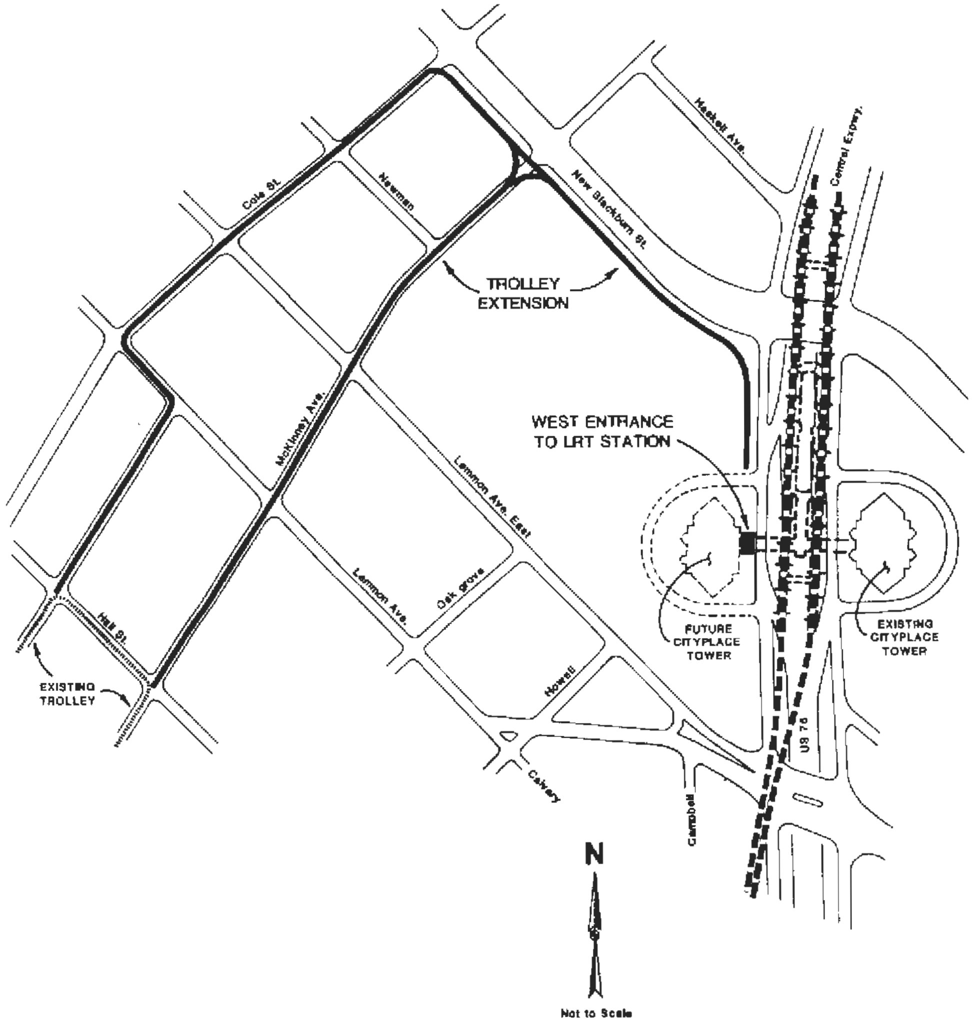

FIGURE 8 McKinney Avenue trolley north extension.

Preliminary Screening

The first level of analysis for potential extensions of the McKinney Avenue Trolley served to reduce the number of options under consideration to those most viable for more detailed evaluation. This phase also established the parameters to be given detailed study and thus also defined the scope of this segment of the study. The study and evaluation processes for the preliminary screening consisted of the following primary elements, which were considered in the determination of the reasonableness and practicality of each option:

- Establishment of evaluation criteria,
- Data collection and review of previous studies,
- Route inspection,
- Analysis of data,
- Establishment of ranking parameters,
- Screening of alternatives (scoring and grading), and
- Recommendations for detailed study.

On the basis of the stated study goals, the consultant team proposed a list of criteria upon which to base the preliminary screening of the alternative routes. This list was presented to the task force and discussed. Recommendations were made, and the consultant team began the evaluation process. As the evaluations proceeded, it became apparent that additional criteria would provide more meaningful results, and the study team expanded the categories. The following criteria were used:

- Potential ridership per meter (foot) of route, existing and future;
- Potential total ridership, existing and future;
- Traffic and parking;
- Technical issues (electrical);
- Proximity to DART;
- Street reconstruction;
- Utility reconstruction;
- Right-of-way required;
- Service to West End or CityPlace;

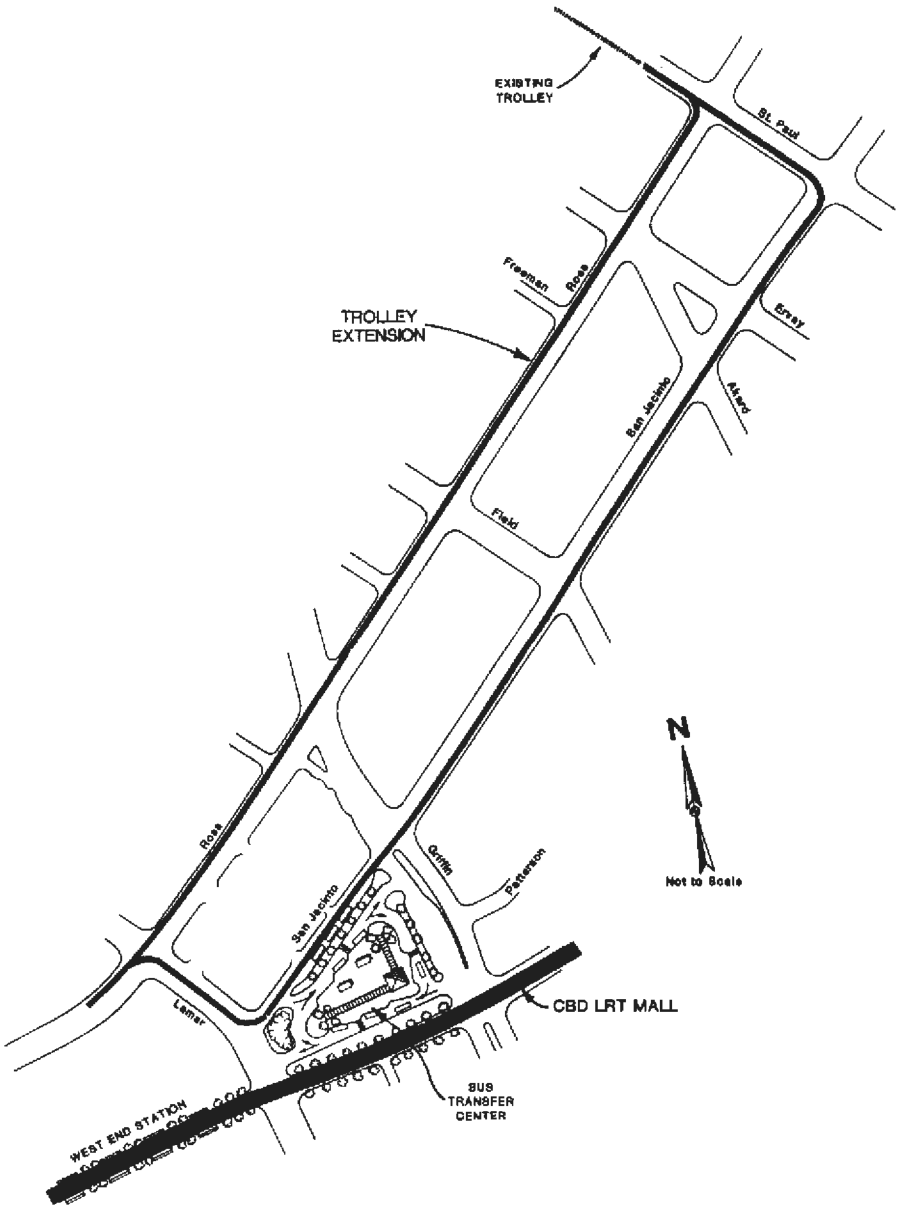

FIGURE 9 **McKinney Avenue trolley south extension.**

- Implementation issues;
- Overall length and cost;
- Service to CBD core;
- Operational issues; and
- Use or crossing of DART facilities

Each criterion was noted as being scored or graded; north routes were scored 1 thru 4 since there were four options. South routes were scored 1 through 5 since there were (initially) five options. Each grading criterion indicates whether it was a negative or a positive criterion. After each applicable criterion was graded, a weighting factor was applied to indicate its relative importance. Most criteria received a weight of 1; however, several criteria were weighted 2 because of their importance. One criterion (service to CBD core) was weighted more lightly because it was considered a secondary goal. Table 1 shows the evaluation application of the criteria.

North Routes

Based on its clearly superior scoring and significant level of support, the N2 route was recommended for further study. Its strengths are in its strong interface with the DART CityPlace LRT station, its favorable operating characteristics, and its residential and work-related ridership potential.

TABLE 1 McKinney Avenue Trolley Extension Study Summary of Preliminary Rankings

	Route								
Criteria	N1	N1A	N2	N3	S1	S2	0	S4	S5
Ridership/Ft. of Route - Existing	2	3	4	1	3	1	4	5	2
Ridership/Ft. of Route - Potential	2	3	4	1	1	5	4	3	2
Total Ridership - Existing	0	0	0	0	4	1	5	3	2
Total Ridership - Potential	0	0	0	0	2	1	5	4	2
Traffic & Parking	-3	-2	-1	-2	-2	-2	-2	-1	-2
Technical (Electrical)	-3	-3	-1	-1	-3	-2	0	-3	0
Proximity to DART	1	1	2	2	3	1	3	2	1
Street Reconstruction (1)	-1	-1	-1	-1	-2	-3	-2	-2	-3
Utility Reconstruction	-2	-2	-2	-2	-1	-1	-2	-2	-2
R.O.W. Required	-1	-1	0	0	-3	-2	-3	0	-2
Service to West End or Cityplace (2)	2	4	6	6	2	6	4	0	6
Implementation Issues	-3	-3	-2	-1	-3	-1	-3	-1	-1
Overall Length / Cost	4	1	2	3	1	5	2	3	4
Service to CBD Core (3)	0	0	0	0	1	0	1	1	0
Operational Issues	-3	-2	-1	0	-3	-1	-3	-1	-1
Use or Crossing of Dart (2)	0	0	0	0	-6	0	-6	-4	0
Score	-5	-2	10	6	-6	8	7	7	8
Rank	4	3	1	2	3	1	2	2	1

(1) - Considers Cross Slope, Longitudinal Slope, and General Condition of Pavement

(2) - Criteria Considered Critical (Either Positive or Negative) and Therefore Weighted More Heavily (X2)

(3) - Criterion Considered Secondary and Therefore Weighted More Lightly

South Routes

On the basis of their direct access to the West End and their probability of expeditious implementation, routes S2 and S5 were recommended for further study. In addition, a variation of S5, S5A, merited further investigation because of its ridership potential and operational characteristics. It was acknowledged, however, that the routes that use DART facilities (S1 and S4) have the greatest ultimate potential for success based on ridership, and the further study of the recommended routes should include provisions for future interconnection with the DART LRT system through the CBD core.

The S1 and S4 routes scored well because their shared use of the DART LRT tracks gave them high ridership potential. However, it was the study team's opinion that an expedient resolution of all of the obstacles to use of DART rail facilities by trolley vehicles was not possible at that time. Therefore, these routes were acknowledged as having the greatest ultimate potential, but not being the most practical alternatives to pursue. It is important to clarify that the use or crossing of DART facilities was not seen as a serious flaw but as a factor that could significantly delay immediate implementation of a trolley extension. On the other hand, given time to address and overcome the issues that complicate the use of DART facilities by the trolley, there is probably no greater potential for success than capitalizing on the ridership base and physical plant investment of the DART LRT system. The issues to be dealt with in order to do so include

- Reconciling the difference between DART's operating power of 750 volts and MATA's use of 600 volts;
- Modifying the trolley wheel profile so that it fits LRT tracks while still operating adequately on trolley tracks;
- Dealing with the safety issues between the historic cars and the LRT vehicles in terms of bumper heights, impact resistance, and so on;
- Satisfying DART operations personnel that the historic trolley's reliability or lack thereof will not impede LRT service;
- Reconciling union versus nonunion and paid versus volunteer operator issues on the same line; and
- Physically retrofitting the LRT with the switches necessary to connect the trolley tracks to DART's system.

It was believed that the foregoing issues were more likely to attract the necessary attention once the DART LRT system is operating. It may be possible at that time to experiment with a trolley car operating on the LRT line to more effectively define and overcome the perceived conflicts. Then, perhaps, future extensions of the trolley can more meaningfully consider use of DART facilities in a positive light.

Detailed Analysis

The Detailed Analysis Phase took the alternative alignments recommended by the Preliminary Screening (Routes N2, S2, S5, and S5A) as well as Routes S5B and S5C, which were added to consider the elimination of contraflow operation on St. Paul, and expanded the evaluation of each in both scope and level of detail. The result was an assessment that primarily addressed physical impacts (traffic, utilities, properties, etc.) of the proposed extensions. Also included was an analysis of potential ridership—patronage forecasts for each of the remaining alternative routes—which in turn generated an evaluation of farebox revenues, operating costs, and maintenance costs resulting in a proposed financial plan. The financial plan also addressed potential sources of funding for the capital investment necessary to design and construct the proposed streetcar extensions.

The result of this phase of the study was a definitive recommendation for the chosen route and specific track alignment for one north extension and one south extension that could be carried forward into conceptual engineering and more detailed cost estimating.

The primary factors that affected the placement of the rails within the roadway were passenger safety, traffic operations, track geometry and space requirements, utility conflicts, on-street parking, and location of existing tracks. These considerations were often in conflict with one another, and the choice of alignment became a balance among the criteria based on engineering judgment.

Each of the route options was reviewed on a block-by-block basis to determine the most appropriate preliminary track alignment. The alignments were considered preliminary because further stages of the study were required to identify physical conflicts and other impacts in detail, with the expectation that adjustments would be made.

Since only one north extension alternative remained, the focus of the impact analysis was on confirming the suitability of the track alignment within the corridor through more in-depth analysis and discussion of traffic issues and physical conflicts, if any. The goal was to reach a level of comfort with the chosen alignment such that all issues could be dealt with using conventional construction methods at a reasonable cost. The proposed route of the CityPlace extension has remarkably few complexities regarding traffic or physical conflicts with existing improvements.

Only one special trolley signal phase was required for the entire route. There would be no loss of on-street parking on the entire northern route. All in all, this route presented no extraordinary expenses or design challenges.

Preferred Alternatives

The S2 alternative and each of the now four variations of the S5 were reviewed against the factors and analyzed in detail, especially with respect to physical construction elements that would lead to excessive cost. Though detailed cost estimates were not developed at this stage of the analysis, the general magnitude of relative cost was apparent from the length of each route and its physical construction conflicts and issues. The results of the analysis led the study team to conclude that Route S2 did not merit further consideration. Further, the team concluded that any of the S5 alternatives would provide adequate service but that each successive version, S5A, S5B and S5C provided a better level of trolley service, greater flexibility of operation, added safety and increased ridership potential, but with a corresponding increase in cost. Therefore, contingent upon the procurement of funding, it was recommended that the West End extension consist of the S5C alternative, eliminating the contraflow operation on St. Paul and incorporating a CBD circulator loop. If funding is not immediately available for this large an investment, the interim route should be S5A so that the circulator loop will be built and the ability to eliminate the contraflow in the future will be maintained. The conceptual engineering plans and cost estimates therefore focused on the S5C option.

Trolley Extension Features

On the basis of recommendations in the preliminary screening and detailed analysis, the extension of the McKinney Avenue Trolley will result in a system totaling approximately 47,500 linear meters (29,500 linear feet) of standard-gauge track operating primarily in city streets that historically contained trolley service. The combination of single and double track will provide the guideway for operation of faithfully restored vintage trolley cars, many of which previously served the city of Dallas. The extension constitutes nearly half of the total track length and will ultimately involve the addition of up to four historic vehicles of varying capacity and manufacture to supplement the four vintage cars currently operated by MATA. Propulsion will be provided by an extension of the overhead power distribution system supplemented by a second rectifier and power source.

Supplementary vehicle storage facilities will be required. Ultimately a separate storage facility and Trolley

Museum could complement the existing car barn, which would continue to serve as the maintenance facility.

The extension of the system includes two separate legs that, when completed, will link the West End Historic District to the CityPlace development area by way of the existing McKinney Avenue-Uptown-State-Thomas corridor.

Vehicles

MATA currently operates four vintage trolley cars and is currently restoring a fifth vehicle. Because of limitations on headways imposed by the contraflow segment of the existing route, no more than three cars can operate at one time and rarely are more than two in service simultaneously. However, with the proposed extensions of the system and the eventual elimination of the St. Paul contraflow segment, as many as five cars will operate on 10-min headways at peak times, plus charters and party cars. In order to meet this need and allow spare cars for maintenance, MATA has options on four additional historic vehicles.

Estimate of Cost

The basis for the estimate of cost to extend the McKinney Avenue Trolley was the quantities developed from conceptual engineering plans. The estimate was built on as many items as possible given the level of detail of the plans. The unit prices were gathered or developed from prices for similar work currently being performed in the Dallas-Ft. Worth area, as well as from inquiries about other recently constructed historic trolley systems around the country. Utility relocation costs were estimated and, under current franchise agreements, could be financed by the various utility companies.

Because of the uncertainty of funding for the trolley extension and the corresponding possibility that one of the lesser-cost alternatives other than Route S5C may have to be constructed, the estimates were separated into four parts: Routes N2, S5, S5B, and S5C. All estimates include a 20 percent contingency to cover items that may not be identified at this conceptual level of design. They also include a 15 percent allowance for surveying needed for design, the final design itself, geotechnical investigation, materials testing during construction, and part-time private construction administration to supplement the city's inspection. The estimates are given in Table 2.

Financial Plan

The existing trolley system's construction was funded by $3 million in private donations, $2.5 million in FTA grants, and $250,000 in bond monies from the city of Dallas (for the relocation work). Two of the four operating cars were donated; they were restored with private donations. A third car was purchased and restored with private donations. The fourth car is leased. The existing system, therefore, represents four sources of possible funding that could be applied to the proposed extension: private donations, federal transit or other federal grants, city capital improvement funds, and in-kind donation of materials, equipment, labor, and so forth. The franchised utility companies and city relocation of their own facilities fall most closely in the last category.

The proposed trolley extension will involve all of the same elements as the previous restoration of historic service, and thus similar funding mechanisms will be sought for certain aspects of the work. However, it is unlikely that private donations will he available to make a significant impact on the substantial cost of the proposal. Therefore the majority of a reduced-scope $10 million in funding is being sought through the Statewide Transportation Enhancement Program under ISTEA in the categories of rehabilitation of historic transportation, preservation of abandoned railway corridors, and historic preservation. As of this writing, MATA has been selected for $1,000,000 of those funds under an application submitted in November 1993. In the fall of 1994,

TABLE 2 Cost Estimates of Alternatives

Extension	Basic Construction Cost	Utility Relocation	Total Cost
N-2 & S-5C*	$10,139,000	$2,445,100	$12,584,100
N-2	$3,591,600	$276,100	$3,867,700
S-5C	$6,493,800	$1,459,800	$7,953,600
S-5	$4,512,200	$1,459,800	$5,972,000
S-5B	$6,265,000	$2,053,300	$8,318,300

* Preferred Alternative

an additional $4.6 million was received in a second award of enhancement funds. To fully finance the project, $1 million has been pledged by the CityPlace development T.I.F. and $3 million has been included in proposed city of Dallas general obligation bond funds.

Transit Service Integration

The first segment of the LRT system from the south into the CBD is scheduled to begin operating to the West End station in June 1996. At the same time, the West End bus transfer center construction will be completed and open for operation. It is expected that the trolley extensions will be built and placed into operation in late December 1997, thus connecting two LRT stations and interfacing with a bus transfer center. With the completion of these three independently operating systems, bus, LRT, and vintage trolleys will be integrated to provide transit service in a truly functional manner.

REFERENCE

1. *McKinney Avenue Transportation Study.* NCTCOG, Dec. 1992.

The Denver Experience: Starting Small

Mark Imhoff, *Carter & Burgess, Inc.*

The Denver Regional Transportation District (RTD) successfully implemented a 5.3-mi (8.53-km) starter light-rail project solely with local dollars on time and under budget. The Central Corridor light-rail line opened on October 7, 1994. The $116 million project was designed and built through the heart of downtown Denver in 4 years. The Central Corridor alignment and operations and how they fit into the RTD system both today and in future planned expansion are described. The focus is on the strategy of using local funds for a starter project and the prospects for completing and implementing the Southwest Corridor light-rail extension (currently near the end of the preliminary engineering and draft environmental impact statement phase).

October 7, 1994, was a day that was 25 years in the making: light-rail transit (LRT) became a reality in the Denver region. The 5.3-mi (8.53-km) Central Corridor light-rail line opened for passenger service on time and on budget.

The Denver Regional Transportation District (RTD) was created in 1969 to provide public transportation for the region. The district encompasses all or part of six counties and spans 2,400 mi^2 (3864 km^2), which is the largest service area of any transit district in the country. A fleet of approximately 870 buses (both RTD buses and RTD-contracted buses) and 11 light-rail vehicles (LRVs) is deployed during peak commuting periods. The system works well, well enough to earn RTD the honor of Transit System of the Year in 1993 from the American Public Transit Association. RTD has enjoyed seven consecutive years of increasing ridership (over 6 percent in 1993), bucking all of the national trends.

However, traffic congestion and air quality in the region continue to worsen. The combination of the Clean Air Act and the Intermodal Surface Transportation Efficiency Act (ISTEA) makes the likelihood of adding major roadways to the region slim. Downtown Denver is by far the largest employment center currently and into the foreseeable future. Therefore, much of the RTD system is focused on the Denver central business district (CBD) and currently carries over 30 percent of the commuters to and from the Denver CBD. In addition, regional growth has produced strong suburban city centers and office parks. Residential growth has occurred in a low-density fashion, primarily around the fringe of the urbanized area. Therefore, it is increasingly difficult for RTD to provide efficient public transportation connecting all activity centers within the entire service area.

Figure 1 shows the seven planned rapid transit corridors, all of which traverse or parallel the most heavily congested roadways within the region. The North and Northwest corridors have been implemented with bus and high-occupancy-vehicle (HOV) solutions. Both corridors have been extremely successful in the early phases and will become increasingly popular as efficiency is improved and expanded with future phases. A problem

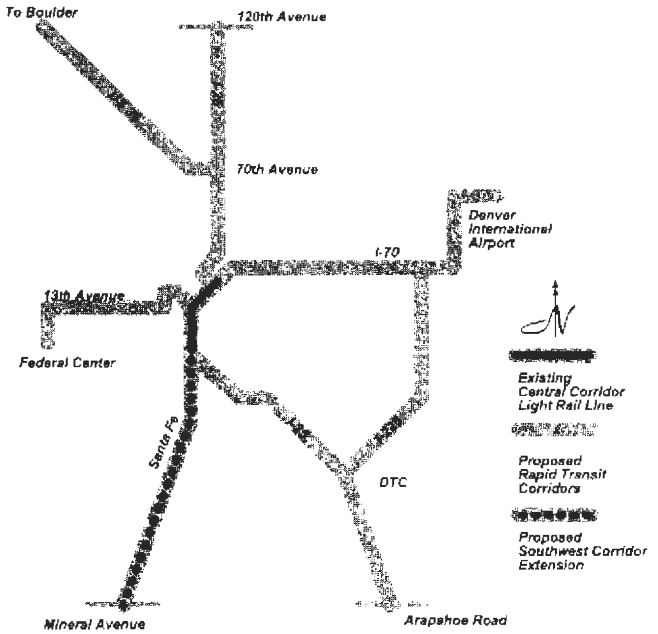

FIGURE 1 **Proposed rapid transit corridors in Denver, Colorado.**

with bus rapid transit solutions is collection and distribution capacity in the downtown as large numbers of buses converge. For example, the current Market Street Station bus facility in downtown Denver will not be able to accommodate all the buses from the combined North and Northwest corridors.

Light-rail technology provides a fast, efficient, and high-capacity solution, thereby offering a viable alternative to many automobile users and replacing buses that currently enter the CBD. Operating costs are reduced and buses are available for other purposes, allowing RTD to utilize the bus fleet to better serve the outlying areas whether it be for LRT feeder service, suburb-to-suburb service, or enhanced local service.

Light-rail technology is flexible to provide high-speed operation between park-and-ride lots and suburban stations and slower operation in mixed traffic in the CBD where stations are closely spaced.

The Central Corridor light-rail line was planned and developed to be a starter line and to act as the hub of a regional light-rail system. By and large, if any of the remaining rapid transit corridors (Southwest, Southeast, West, or East) were constructed, they would include the Central Corridor. The Central Corridor was built totally with local funds. Future corridors will require other funding sources. Federal funds are currently being sought for the Southwest Corridor, which is in the preliminary engineering phase.

The planning and design of the Central Corridor was done so that it could accommodate future corridors. Stations were built for three-car trains, conduit was included for future communications needs, and the interface between traffic signals and train signals was established to easily accommodate future enhancement.

The concept for the Central Corridor was conceived in the summer of 1989, and a feasibility study was undertaken. Engineering and construction took approximately 4 years. The schedule was very aggressive, and few believed that a project of the Central Corridor's magnitude through the center of downtown Denver could be accomplished in a 4-year time frame. RTD created a new department dedicated to the design and construction of the Central Corridor. The team was enhanced by a few committed individuals from the City and County of Denver (CCD) Traffic Division and design and construction management consultants.

The project was very visible and political. The political process took its course and steered the way. The project team focused on the day-to-day activities, problems, and crises. In part, the future of a regional light-rail system rested on the success of the Central Corridor. All were committed to on-time and on-budget performance. The project had to be a showcase for what light rail could be. Construction would be disruptive in the downtown, and therefore impacts on businesses and the traveling public had to be minimized, coordinated, and communicated. Partnering sessions were held including RTD, CCD, contractors, utility companies, railroads, and business interests.

Central Corridor Project

The Central Corridor line is a 5.3-mi (8.53-km) light-rail line with 14 stations and a fleet of 11 LRVs. The project cost approximately $116 million. Implementation of the Central Corridor line was expected to eliminate approximately 560 bus trips a day into the CBD and to carry 14,000 riders a day. As shown in Figure 2, the line begins at the I-25 and Broadway Station in the south with major bus transfer and park-and-ride facilities. The bus transfer facility has 18 bus bays and accommodates 30 bus routes; this operation has been shifted from Civic Center Station in downtown, thus eliminating the bus travel into the CBD. The park-and-ride lot was planned for 220 cars; however, demand required a quick expansion to over 600 spaces.

From the I-25 and Broadway Station the double-track line goes north through the railroad corridor to a second, smaller bus transfer facility at the Alameda Station directly behind the new Broadway Marketplace superstore complex, a community station at 10th and Osage, and leaves the railroad corridor as it passes under the Colfax Viaduct. The railroad corridor stretch of the line is approximately 3.2 mi (5.15 km) long and operates at speeds of up to 55 mph (88.5 km/hr). The high-speed

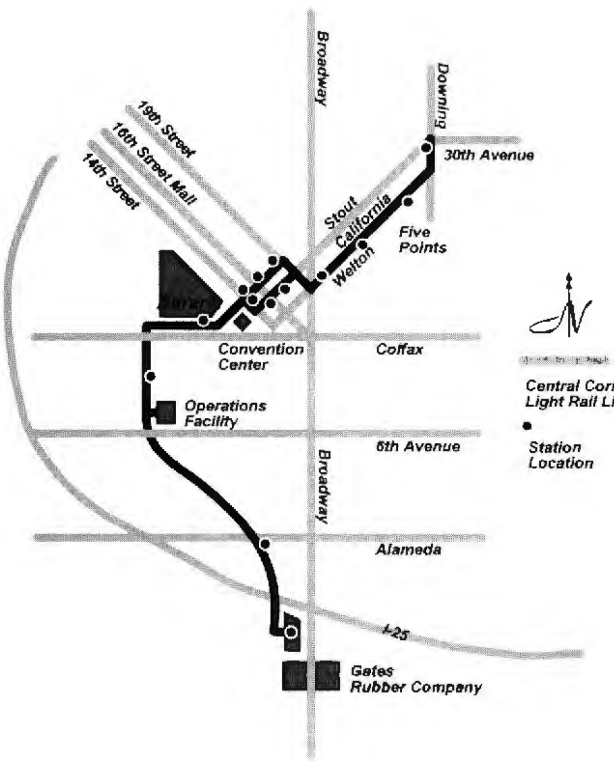

FIGURE 2 Central Corridor light-rail line.

operation is accomplished with a grade separation over Santa Fe and Kalamath streets and protected crossings of Bayaud and 13th Avenues.

From the Colfax Viaduct to the 30th and Downing Station, approximately 2.1 mi (3.38 km), the operation is running in or adjacent to city streets and is controlled by integration with the CCD traffic signal system. Adjacent to Colfax is the Auraria Station, which serves the three-campus, 37,000-commuting-student (no dormitories) Auraria Higher Education Center. The line then crosses Speer Boulevard and Cherry Creek and traverses Stout Street in a double-track configuration to 14th Street. At 14th Street the line splits into a one-way loop through the CBD to 19th Street, northbound along 14th and California streets and southbound along 19th and Stout streets. The loop contains six stations in pairs at the Convention Center (14th Street), the 16th Street Mall, and 18th Street.

The loop becomes double track again at 19th and California streets and continues north along 19th to Welton Street, where it crosses Broadway at the 20th and Welton Station. At 24th Street the line becomes single track with stations bracketing the Five Points Business District at 25th and 29th streets. The single-track section allowed on-street parking to remain. After the 29th Street Station the line again becomes double track to the end of Welton Street and around the corner adjacent to Downing Street to the end of the line at 30th Avenue. The 30th Avenue and Downing Street Station also includes a small bus transfer facility and a 26 car park-and-ride lot.

The in-street running sections in the downtown loop along California and Stout streets and along Welton Street had numerous property access locations that required crossing the tracks at driveways in an unprotected fashion. In the downtown loop, along California and Stout streets, the system was designed for the LRVs to run in a contraflow operation, that is, opposite the direction of traffic. The design was such that the street-LRT operation is done in a "drive right" setting. Therefore, a car making a left turn across the tracks can see the oncoming LRV and make the turn when it is safe.

The Welton Street situation was more difficult to solve. The two-way, side-running LRT operation along one-way Welton Street meant that a northbound LRV would be overtaking a car turning right across the tracks, and this was determined to be an unsafe and unacceptable movement. Therefore, RTD elected to purchase all of the access rights to the property along Welton Street. All of the affected properties have alley access, which was determined to be sufficient for existing uses. (In many cases, however, damages were assessed and paid.) CCD then modified the zoning along Welton Street to accommodate potential future development that would allow off-site parking. In addition, seven cross streets along Welton Street were unsignalized and did not warrant signals. Automated No Right Turn signs were installed at these locations and are activated to flash when LRVs approach.

System Integration and Start-up

The Central Corridor was designed and configured to integrate and interface efficiently with the bus system. Even as the light-rail system is expanded, the bus network will continue to be the backbone of the integrated transit system. Therefore, an enormous amount of planning and coordination was done for the bus interface at the I–25 and Broadway, Alameda, 16th Street transit mall, and 30th and Downing stations. Convenient and efficient passenger transfers between bus and light rail is critical to the success of the system. The Central Corridor was planned and scheduled for 5-min headways in the peak periods, 10-min headways in the off-peak periods, and 15-and 30-min headways in the early morning and late night operations. All connecting bus routes were then modified to interface accordingly.

Testing of the system and training of the operators began in August in preparation for the October 7 grand opening. The experience gained during the testing period revealed necessary modifications to the system. Numerous signing and striping additions and modifications were implemented, continuous adjustments were made to the traffic signal timing interface, and modifications to the operating procedures were made as appropriate. RTD was ready for opening day, or so it was thought.

The grand opening was October 7, 1994, followed by a weekend of free rides and activities. Bad weather had cleared, and Colorado Governor Romer and Denver Mayor Webb were present for the opening ceremony. Free rides for the public began at noon and continued through the weekend. RTD had estimated 50,000 to 70,000 riders throughout the three-day free-ride weekend. The final tally was closer to 200,000. Trains were packed to crush loads for the entire weekend.

Monday morning, October 10, was the actual opening day for revenue service and the integration with the bus system; this was the real test. Additional RTD staff volunteers guided bus riders and answered questions. The operation went fairly well, but heavily loaded trains did not permit the LRVs to remain exactly on schedule, particularly in the afternoon peak. During the first 2 weeks of operation commuters and regular riders were joined by joy riders and interested parties. Light rail was carrying in excess of 16,000 riders per day, nearly 15 percent more than expected. While enjoying the success of the system, RTD management was faced with overcrowded trains, a faltering bus interface, and missed schedules. Regular customers were patient but were beginning to complain. Many commuters were beginning to modify their travel to other park-and-rides or, worse, driving to work.

RTD responded by switching three bus routes back to Civic Center Station to flatten the peak demand on the LRVs as an interim measure. This action helped but did not solve the problem. Continuing operating experience and analysis determined that the real solution to the problem was to increase the LRV fleet from 11 vehicles to 17 vehicles. The additional six vehicles are in production, with delivery to begin in January 1996. In the interim additional bus routes have been diverted to Civic Center Station (with a stop at the I-25 and Broadway Station), and a modification to the LRT schedule has been implemented.

Why Start Small?

As stated earlier, RTD had been debating whether to implement light rail for 25 years. Earlier attempts at a regional system or a full corridor were not successful, primarily because of a lack of funding. The strategy behind the Central Corridor light-rail project was to start small, building the hub of the regional system and, most important, to build it quickly and efficiently with local dollars. RTD wanted to show the Federal Transit Administration and Congress that it was committed to rapid transit and willing to take the initiative to start on its own.

The Central Corridor was designed to provide a useful purpose as a stand-alone project until additional legs of the regional system could be implemented. It was built to show the general public what light-rail technology really is and that it could satisfactorily fit into the surrounding environment. The alignment was conceived with a grade-separated or protected high-speed section and a street-running downtown collection-distribution section to show the flexibility of light-rail technology. The system was also structured to significantly reduce the number of bus trips into the Denver CBD.

The determination of need for a rapid transit system had been made long ago. One of the main objectives was to get started. Building the Central Corridor light-rail project in tandem with the North Corridor bus and HOV project would provide good examples of the two premier rapid transit alternatives for everyone to see and use.

The Central Corridor was made possible as a result of a 1989 Colorado Supreme Court ruling to the effect that any entity collecting a sales tax (RTD has a dedicated 0.6 percent sales tax) was also entitled to a "use tax" for goods purchased outside the district but used within the district. Consequently, the use tax generated approximately $10 million per year in additional revenue. The RTD Board of Directors dedicated the use tax windfall to rapid transit development. At this time the options were evaluated, and it was decided by the RTD Board of Directors not to continue to accumulate capital reserves as matching dollars for desired federal funds but to combine the use tax revenues with available capital reserves to finance a $115 million to $125 million locally funded starter system.

In conjunction with the design and construction of the Central Corridor, planning progressed on the regional system. In December 1992, the Southwest Corridor Alternatives Analysis was initiated; the Southwest Corridor was the region's priority corridor to pursue federal funding. However, timing was not such that the region could attain authorization for the Southwest Corridor through ISTEA. In the meantime, the alternatives analysis was modified per ISTEA to a major investment study (MIS) and completed with light rail as the locally preferred alternative as an extension of the Central Corridor. Currently, preliminary engineering and the environmental impact statement for the Southwest Corridor are being prepared through an FTA Section 9 grant.

During the 1994 legislative session RTD worked closely with the Colorado delegation in pursuing authorization for the Southwest Corridor light-rail project through the National Highway System (NHS) bill. In the House of Representatives version, RTD was able to get the Southwest Corridor included, plus secure language crediting the majority of the Central Corridor and prior expenditures in the Southwest Corridor as a local match. In addition, the House version would have earmarked approximately $13 million for final design and early action construction activities. This would have been a great step forward for the project and the region and was exactly where RTD wanted to be. However, the Senate version of the NHS did not include any unauthorized projects, and a conference committee hearing never occurred.

A similar strategey was taken by RTD during the 1995 legislative session. The House of Representatives indicated that they would begin their deliberations on the NHS bill where they had left off in 1994. RTD had progressed in the Southwest Corridor well into preliminary engineering and completed the draft environmental impact statement (DEIS). In addition, the city of Englewood had structured a deal with a major developer adjacent to the Hampden Station for the demolition and redevelopment of a major shopping mall (Cinderella City), including the integration of a light-rail station, bus transfer facility, and park-and-ride lot as a joint development component. Therefore, RTD was able to solidify a $15 million request package for fiscal year 1996 that included final design, purchase of the remaining right-of-way, contribution of the RTD share for the public-private joint development at the Hampden Station, and a significant portion of the required railroad relocation.

As of this writing, RTD had presented two rounds of testimony in March 1995 before congressional committees for the requested $15 million 1996 earmark, both with positive response. RTD remains optimistic about the chance to attain the 1996 earmark and subsequently to secure a full funding grant agreement for the 8.7-mi (14-km) extension of light rail in the Southwest Corridor.

PART 2
LIGHT-RAIL TRANSIT ISSUES

Pedestrian Control Systems for Light-Rail Transit Operations in Metropolitan Environments

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Pedestrian considerations should be included with other considerations in the planning and design of light-rail transit (LRT) systems. If pedestrians' needs are inappropriately accounted for, the LRT agency could experience higher-than-average experience with collisions between light-rail vehicles (LRVs) and pedestrians, leading to necessary and expensive system retrofits or reduced LRV operating speeds, which would negatively affect LRT operations and potential ridership. Pedestrians interact with the LRT environment at stations and pedestrian crossings and in LRT-pedestrian malls. This interaction is unique in that (*a*) pedestrians are not always completely alert to their surroundings, (*b*) LRVs are unable to stop quickly or swerve to avoid colliding with a pedestrian, and (*c*) the injuries to the pedestrian are usually severe and often fatal. Thus, special pedestrian traffic control devices (including relevant pedestrian striping, signs, and signals) and pedestrian crossing control treatments (including pedestrian automatic gates, swing gates, Z-crossings, and bedstead barriers) are necessary to help pedestrians become alert to the dynamic LRT environment. Future research should be conducted to develop specific application guidelines for each of the pedestrian crossing control treatments. The potential methodology for selecting one or more pedestrian crossing control treatments for installation at a given pedestrian crossing location should be expanded and quantified through this research.

Light-rail transit (LRT) has become a reality in North America. Some 19 cities in the United States and Canada have systems in operation, in addition to several short starter-line segments (*1*). Because light-rail vehicles (LRVs) travel in a wide range of environments (both on street and in separate rights-of-way), attract passengers, and have large capacities, LRT is an increasingly viable public transportation option in many urban areas.

As new systems are planned and existing systems are extended, planning and design of LRT systems and extensions or retrofits to existing systems must consider the interaction of LRVs with motorists and pedestrians. Planning and design of new LRT systems (alignments, geometries, and traffic control devices) have traditionally focused on meeting only the minimum requirements for the interface between LRVs and motor vehicles. Pedestrian-related design issues in the vicinity of the LRT alignment have not received as much attention, sometimes leaving pedestrians exposed to potential accidents.

According to data obtained by the authors from 10 North American LRT agencies (Baltimore, Boston, Buffalo, Calgary, Los Angeles, Portland, Sacramento, San Diego, San Francisco, and San Jose) for the Transit Cooperative Research Program (TCRP), Project A–5 (Integration of Light-Rail Transit into City Streets), on average about 8 percent of all LRV collisions involve a pedestrian. Although this percentage is relatively small when compared with the percentage of LRV collisions involving motor vehicles, LRV-pedestrian collisions are usually more severe and often fatal. Therefore, it is critical that LRT agencies consider pedestrian movements and actions during the early stages of LRT system planning and design.

Further, interactions between pedestrians and LRVs are significantly different from those between motorists and LRVs. In general, as operators of motor vehicles, motorists tend to be more aware of their dynamic environment. Conversely, pedestrians, traveling largely in the relatively safe venue of protected sidewalk areas, do not routinely share the same continuous, attentive edge. When crossing the travel path of motor vehicles or LRVs, pedestrians should shift to a state of awareness similar to that exhibited by motorists. However, this shift does not always occur. Moreover, unlike motor vehicles, LRVs cannot swerve or stop quickly enough to compensate for pedestrians who are errant or disobedient of traffic control devices.

Accordingly, various pedestrian crossing environments and characteristics associated with each are described; then some recommended pedestrian traffic control devices for LRT systems are discussed along with some pedestrian design considerations and types of pedestrian crossing control treatments. Last, a possible approach to developing application guidelines for these pedestrian crossing treatments is presented.

Pedestrian Crossing Environment

Pedestrians interact with and cross LRT alignments at three distinct locations:

1. Pedestrian crossings of LRT semiexclusive, separate rights-of-way,
2. Mid-block or intersection crossings where LRVs travel in the median (or on the side) of a street, and
3. LRT-pedestrian mall environments.

At pedestrian crossings of semiexclusive, separate rights-of-way, LRVs usually operate through the crossing at speeds up to 90 km/hr (55 mph). Because of this relatively high crossing speed, these types of crossings are usually controlled by flashing-light signals (flashing red lights and bells), appropriate pedestrian warning signs and striping, and, in some instances, automatic gates. Examples of this type of pedestrian crossing can be found along the San Diego LRT system East Line to Santee, near Glen Burnie on the Baltimore LRT system, and along the Folsom Line on the Sacramento LRT system.

The second type of pedestrian crossing is perhaps the most common to existing LRT systems. Here, LRVs travel in the median or on the side of a parallel street. Pedestrians cross the LRT alignment either at mid-block locations or at street intersections. LRVs can operate through the crossing at speeds up to about 90 km/hr (55 mph) if the intersection uses motor vehicle automatic gates and up to about 55 km/hr (35 mph) if the intersection is controlled by standard traffic signals. These types of pedestrian crossings typically have pedestrian signals (displaying the Walk/Don't Walk aspects) and may also have flashing-light signals if LRVs operate at higher speeds (above 55 km/hr). This type of pedestrian crossing can be found at virtually all of the North American LRT systems.

In LRT-pedestrian malls, pedestrians may cross the LRT tracks at any location; therefore, LRV speeds in a mall-type environment are usually limited to about 25 km/hr (15 mph). The LRV dynamic envelope (the clearance on either side of a moving LRV in which no contact can take place from any condition of design wear, loading, end or middle ordinate overhang, or anticipated failure such as air-spring deflation or normal vehicle lateral motion) is typically delineated by contrasting pavement texture and color such as the tactile warning strip approved by the Americans with Disabilities Act (ADA). Examples of LRT-pedestrian malls can be found on North First and Second streets at the San Jose LRT system, on K Street at the Sacramento LRT system, and on First Avenue near downtown at the Portland LRT system.

Pedestrian Traffic Control Devices

As part of TCRP Project A-5 (Integration of Light-Rail Transit into City Streets) and ongoing participation on the National Committee on Uniform Traffic Control Devices (Highway-Railroad Grade Crossing Technical Committee, LRT Task Force), recommendations have been developed to aid traffic, safety, and LRT engineers in determining appropriate pedestrian traffic control devices for the three pedestrian crossing environments described in the previous section. The pedestrian traffic control devices presented here fall into two major categories: LRV dynamic envelope delineation and pedestrian signs and signals.

LRV Dynamic Envelope Delineation

The dynamic envelope of an LRV should be delineated at all pedestrian crossings of semiexclusive, separate right-of-way and all pedestrian crossings where LRVs travel in the median (or on the side) of a street. The LRV dynamic envelope should also be delineated along the

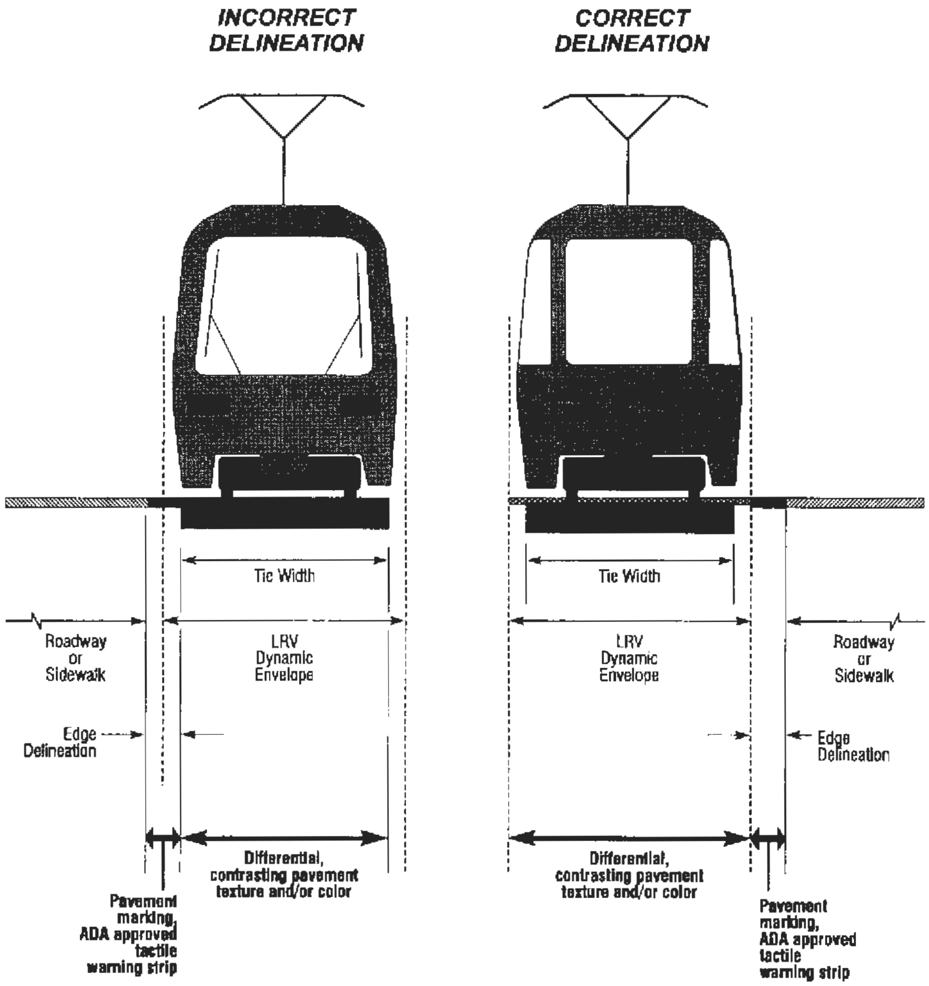


FIGURE 1 **LRV dynamic envelope delineation.**

entire length of LRT-pedestrian malls. Pavement markings that delineate the dynamic envelope of an LRV serve two purposes: to provide the LRV operator with the clearance limits for pedestrians and to indicate to pedestrians where the LRV may encroach on their path.

The preferred method of delineating the LRV dynamic envelope is by differential, contrasting pavement texture, color, or both. Alternatively, a solid line 100 mm (4 in.) wide may be used. Any crossing material or contrasting pavement texture or color used to delineate the track area should always encompass the LRV dynamic envelope. Further, as shown in Figure 1, where delineation (e.g., ADA-approved tactile warning strips) is used to mark the edge of the LRV dynamic envelope, it should always be completely outside of the envelope.

Pedestrian Signs and Signals

At crossings of LRT rights-of-way where pedestrian movements are controlled by pedestrian signals, the primary warning sign should be the W10-5 LRT crossing sign (see Figure 2). At unsignalized pedestrian crossings (crossings where pedestrians are not controlled by pedestrian signals) of semiexclusive, separate, LRT-only rights-of-way where LRVs operate in both directions, the W10-5a sign should be used. The pedestrian signal is the primary regulatory device, and the warning sign alerts the pedestrian of the increased risk associated with violating the pedestrian signal. According to the *Manual on Uniform Traffic Control Devices* (MUTCD) (2), Section 2A-13, an optional sign (educational plaque) displaying the legend TRAIN may be installed below the W10-5 or W10-5a signs.

When flashing-light signals (see Figure 3) serve as the primary warning device, that is, when the red signals are flashing alternately and the audible device is active, the pedestrian is required to remain clear of the track area (outside of the LRV dynamic envelope), as per the *Uniform Vehicle Code*, Section 11-513 (3).

At gated LRT-only crossings where LRVs operate in both directions, a flashing-light signal assembly should

FIGURE 2 LRT crossing signs [colors: symbol, arrow, legend, and border—black (nonreflecting); background—yellow (reflective); dimensions in millimeters; 25.4 mm = 1 in.].

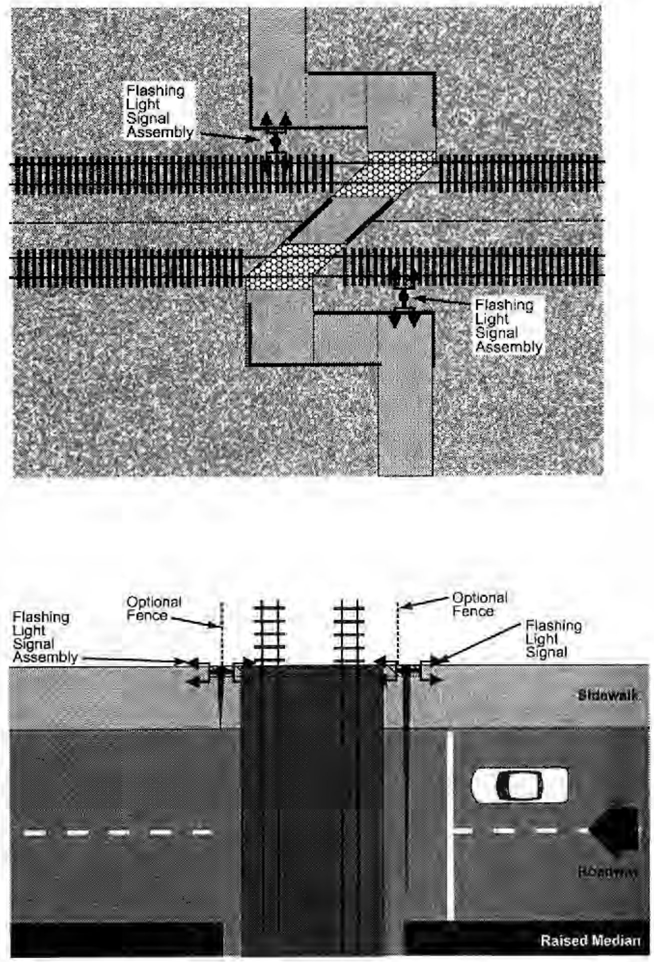


FIGURE 3 Typical placement of flashing-light signal assemblies: *top*, isolated pedestrian-only crossing of LRT-only right-of-way; *bottom*, pedestrian crossing of LRT-only right-of-way.

also be installed adjacent to the pedestrian path (e.g., the sidewalk) in the two quadrants without vehicle automatic gates, as shown in Figure 3.

At nongated, unsignalized pedestrian crossings where LRVs operate in both directions in the median (or on the side) of a street, the W10-5a sign should be the primary pedestrian warning.

An LRV-activated, internally illuminated matrix sign displaying the pedestrian crossing configuration with multiple tracks may be used as a supplement to the W10-5 sign to warn pedestrians of the direction from which one or more LRVs may approach the crossing, especially at locations where pedestrian traffic is heavy (e.g., near LRT stations). This active matrix sign (see Figure 4) should animate the pedestrian to look both ways as LRVs are approaching the crossing. Further, the relative speed of all LRVs (or railroad trains) as they approach the pedestrian crossing should be depicted. This sign should be used in combination with the W10-5 sign in lieu of the W10-5a sign. It should not be used with the W10-5a sign since it permanently displays a double-headed arrow and the legend LOOK BOTH WAYS.

Alternatively, an LRV-activated, internally illuminated flashing sign displaying the legend SECOND TRAIN—LOOK LEFT (or RIGHT) may be used as a supplement to the W10-5 to alert pedestrians that a second LRV is approaching the crossing from a direction that might not be expected (see Figure 5). The sign warns pedestrians that, although one LRV has passed through the crossing, a second LRV is approaching and that other active warning devices (e.g., flashing-light signals and a bell) will remain active until the second LRV has cleared the crossing.

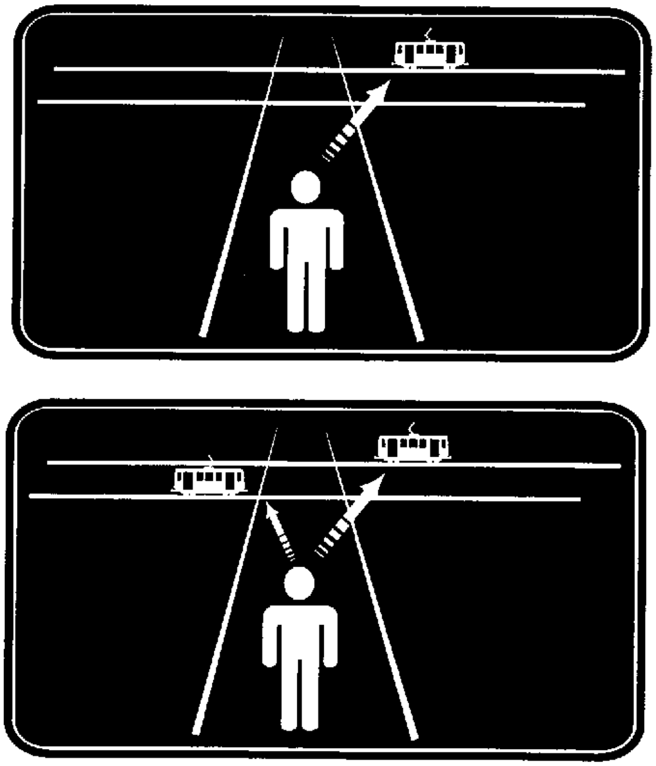
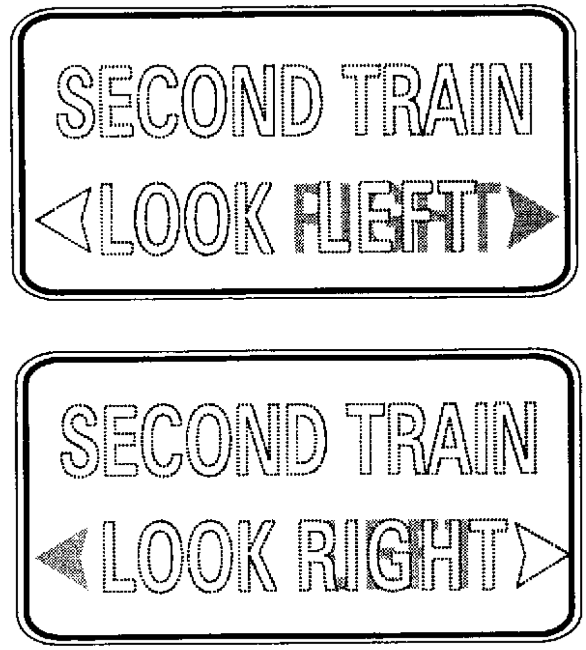


FIGURE 4 Active matrix train-approaching sign (approximately 760 by 460 mm): *top,* one LRV approaching pedestrian crossing; *bottom,* multiple LRVs approaching pedestrian crossing [colors: pedestrian, crossing, rail, and LRV—amber (active matrix); background—black (nonreflective); 25.4 mm = 1 in.].



W10-7
(Proposed)

FIGURE 5 "Second Train" internally illuminated sign (760 by 460 mm) [colors: legend—amber (fiber-optic illumination); background—black (nonreflective); only one direction illuminated at any time; 25.4 mm = 1 in.].

When this sign is activated, only one direction is illuminated at any time and only one arrow (to the left of LOOK or to the right of RIGHT) is illuminated at any time, the arrow that points in the direction of the approaching second LRV. If two LRVs are very closely spaced so that they will pass through the pedestrian crossing almost simultaneously, this sign should not be activated since there would be no opportunity for pedestrians to cross between the successive LRVs.

These LRV-activated warning signs should be placed on the far side of the crossing (and also on the near side of the crossing if necessary for added pedestrian visibility), especially when the crossing is located near an LRT station, track junction, or multiple-track alignment (more than two tracks). All pedestrian warning signs should be mounted as close as possible to the minimum height above the ground set by the MUTCD (2), Section 2A–23 [1.5 or 1.8 m (6 or 7 ft)], or pedestrians will often not see or simply ignore them. They should be mounted lower than the minimum height only if pedestrians are restricted from entering the area where the signs are installed. Usually, the W10-5 or W10-5a sign should be mounted so that the clearance to the bottom of the sign is 1.8 m (7 ft). If a supplemental active matrix sign or SECOND TRAIN—LOOK LEFT/RIGHT sign is used below the W10-5 sign, the bottom of the supplemental sign should be at least 1.5 m (6 ft) above the ground.

Pedestrian Crossing Design Considerations

At pedestrian crossings of semiexclusive, separate right-of-way and at mid-block or intersection pedestrian crossings where LRVs travel in the median (or on the side) of a street, adequate, safe queueing areas for pedestrians should always be provided. These areas should be clearly marked (with contrasting pavement texture and color or striping) on both sides of the tracks between the parallel roadway (if present) and LRT tracks. Where the pedestrian crossing is wide (e.g., more than two track alignments) and LRVs or other trains operate in multiple directions, a clearly designated area between the sets of tracks should be provided (if space is available) as a safe place to queue in case multiple LRVs or trains approach the crossing while pedestrians are within the rail alignment.

Furthermore, if these safe queueing areas are not provided and pedestrians are not adequately channeled across the LRT tracks at designated locations (along separate rights-of-way or the median or side of the street alignments), LRV speeds through the crossings would have to be substantially reduced, forcing LRVs to operate as if they were in an LRT-pedestrian mall environment.

Possible treatments for the channelization and control of pedestrian crossings of LRT separate rights-of-way or median or side-of-street alignments include

- Grade separation or crossing closure,
- Pedestrian automatic gates,
- Swing gates,
- Z-crossings, and
- Bedstead barriers.

The last four pedestrian crossing control systems, as well as appropriate application of each, are described in the following sections.

Pedestrian Crossing Treatments

One possible solution to address pedestrian crossing concerns is to either grade separate or close the crossing. Although grade separation (e.g., a pedestrian-only tunnel under or a bridge over the LRT alignment) may completely solve the conflict between pedestrians and LRVs, it is not always feasible for LRT agencies because of economic, construction, security, or environmental reasons.

Further, closing the pedestrian crossing may, in some instances, make the potential for an LRV-pedestrian collision greater. One of the overriding planning principles developed by TCRP Project A–5 suggests that LRT system planning and design should respect the urban environment that existed before LRT implementation. Because pedestrians (and motorists) grow accustomed to their urban environment, LRT systems that operate in these environments should conform as much as possible to the behaviors (and pedestrian movements) that have already been established. Accordingly, unless a specific urban design change is desired (e.g., changing a street into an LRT-pedestrian mall), pedestrian traffic and travel patterns should be maintained. If pedestrian crossings are simply closed without considering impacts on out-of-direction travel patterns, pedestrians may attempt to cross the LRT alignment despite fences and other barriers that discourage these actions.

Because grade separation and pedestrian crossing closure are not usually feasible, for economic and safety reasons, respectively, the other pedestrian crossing control treatments listed earlier, which are designed to warn, channelize, or block pedestrians from crossing the tracks when LRVs are or may be approaching the crossing, have proven effective for both controlling and channeling pedestrians across the LRT track environment.

Pedestrian Automatic Gates

Pedestrian automatic gates are the same as standard automatic crossing gates except that the arms are shorter. They are used to physically discourage pedestrians from crossing the LRT tracks when the automatic gates are activated by an approaching LRV. When LRV stopping sight distance is inadequate, these gates should always be used.

The preferred method for pedestrian automatic gate installation is to provide them in all four quadrants; where right-of-way conditions permit, the vehicle automatic gate should be located behind the sidewalk (on the side that is away from the curb), so that the gate arm will extend across the sidewalk, blocking the pedestrian crossing in two of the four pedestrian quadrants (see Figure 6, Option A, and Figure 7, Option A). Longer and lighter gate arms make this installation feasible. However, experience suggests a maximum gate arm length of 11.5 m (38 ft) for practical operation and maintenance. At those crossings requiring the gate arm to be longer than 11.5 m, a second automatic gate should be placed in the roadway median. To provide four-quadrant protection, two single-unit pedestrian automatic gates should also be installed behind the sidewalk across the tracks opposite the vehicle automatic gates. This option is preferred to the option described next because it keeps the pedestrian path clear and minimizes roadside hazards for motorists.

Alternatively, the pedestrian automatic gate may share the same assembly with the vehicle automatic gate (near the curb of the sidewalk), as shown in Figure 6, Option B, and Figure 7, Option B. In this case a separate driving mechanism should be provided for the pedestrian gate so that if it fails, it will not affect the vehicle automatic gate operations. To provide four-quadrant protection, two single-unit pedestrian automatic gates should also be installed on the curbside of the sidewalk across the tracks opposite the combination vehicle-pedestrian automatic gates.

The possibility of trapping pedestrians in the LRT right-of-way when four-quadrant pedestrian gates are installed should be minimized. Clearly marked pedestrian safety zones and escape paths within the crossing should be established.

Pedestrian automatic gates have been successfully installed on the St. Louis Metrolink LRT system, the Chicago Transit Authority "Skokie Swift" electrified passenger rail line, the CalTrain commuter railroad line from San Jose to San Francisco, the Long Island commuter railroad line in New York, the Southeastern Penn-

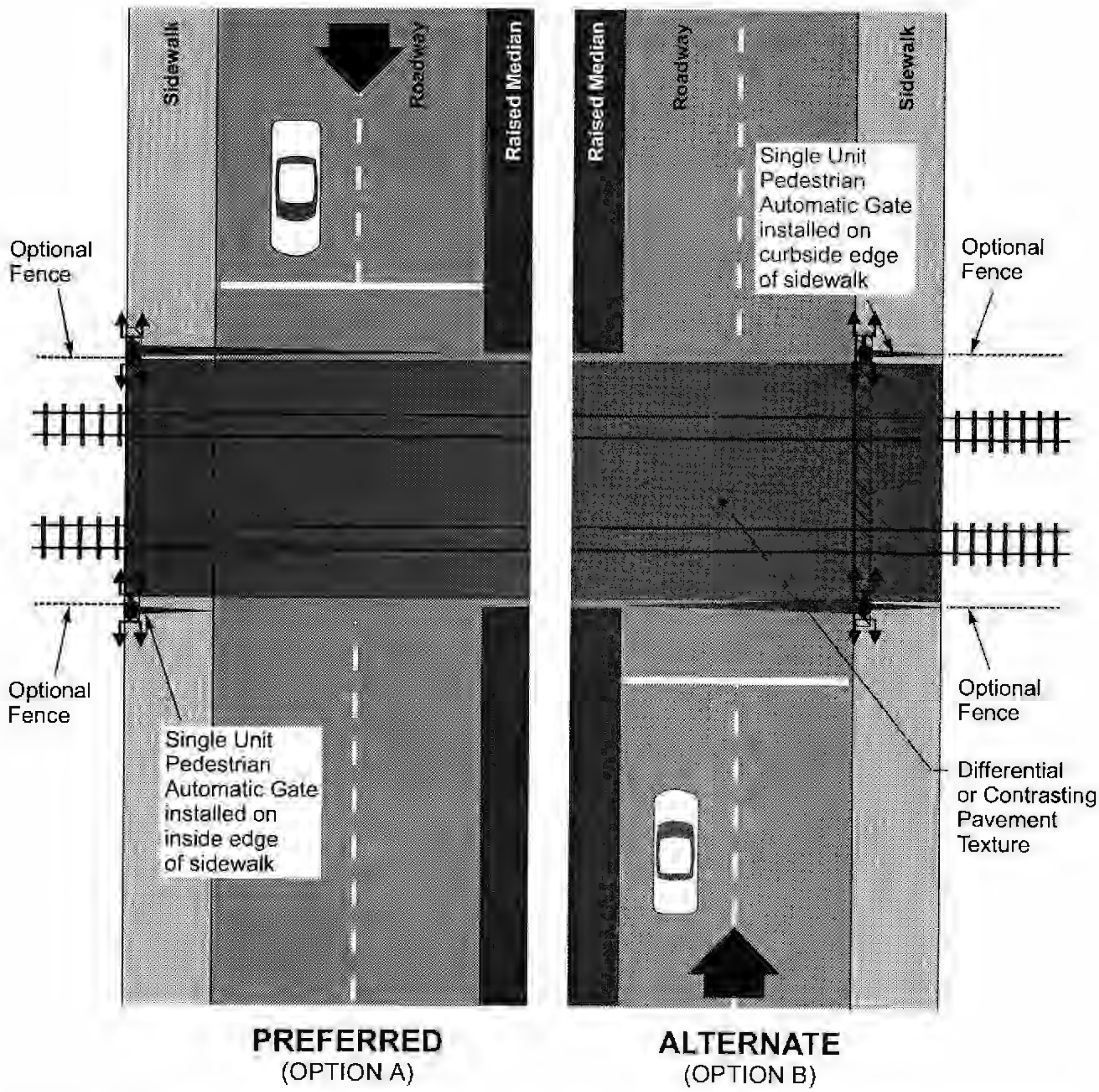


FIGURE 6 Placement of pedestrian automatic gates: Option A—gates installed on inside of sidewalk extending across sidewalk and roadway; Option B—gates installed on curbside of sidewalk with separate pedestrian gate arm.

sylvania Transportation Authority commuter railroad line, the Santa Fe railroad through Holbrook, Arizona, and the Southern Pacific railroad through Reno, Nevada.

Swing Gates

The swing gate (usually used in conjunction with flashing-light signals and bells) is a pedestrian crossing control treatment that alerts pedestrians to the LRT tracks to be crossed and forces them to pause, thus preventing pedestrians from running freely across the LRT tracks and restricting the exit from the LRT right-of-way (see Figure 8). The swing gate requires pedestrians to pull the gate in order to enter the crossing and to push the gate to leave the protected track area; therefore, a pedestrian cannot enter the track area without pulling and opening the gate. Swing gates should be designed to return to the closed position after passage of the pedestrian but should never lock in the closed position to avoid potentially trapping a pedestrian within the LRT right-of-way.

FIGURE 7 Pedestrian automatic gate examples: *top,* Option A, Skokie, Illinois; *bottom,* Option B, Holbrook, Arizona.

Swing gates may be used at pedestrian-only crossings, on sidewalks, and near stations (especially if the station is a transfer point with heavy pedestrian volumes). They may be used at pedestrian crossings of either single-track (one-or two-way operations) or double-track alignments.

Although initially there were some concerns about the potential to trap pedestrians (especially those with disabilities) on the trackway, research conducted by the authors as part of TCRP Project A-5 (which included interviews with safety officers from three LRT agencies that have installed swing gates) suggests that swing gates not only have not increased the risk of accidents at those crossings where they have been installed but also have proved effective in reducing collisions between pedestrians and LRVs. They are currently installed at various locations on the Calgary LRT system, especially at stations; on the San Jose LRT system (at the Ohlone-Chynoweth Station); and on the Los Angeles LRT system (at the Imperial Transfer Station). In fact, the Los

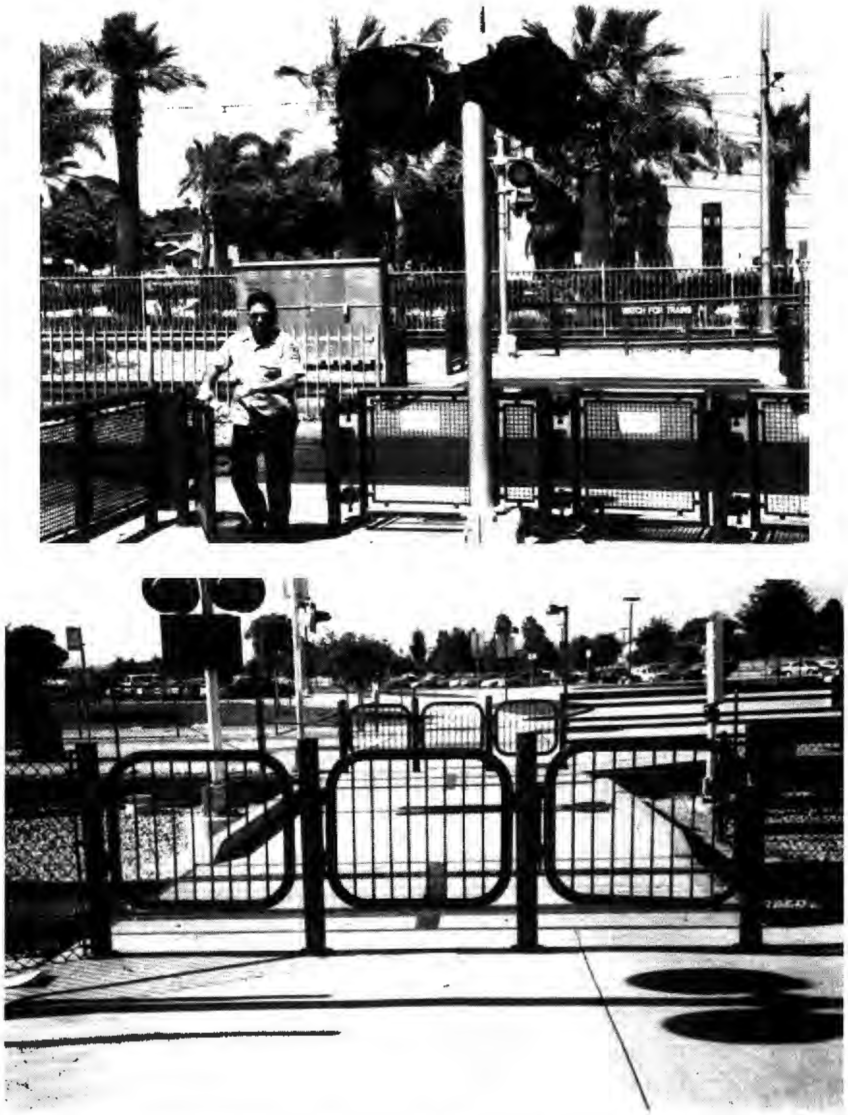


FIGURE 8 Pedestrian swing gate examples: *top,* Los Angeles LRT system; *bottom,* San Jose LRT system.

Angeles County Metropolitan Transportation Authority (LACMTA), operating agency of the Los Angeles LRT system, recently conducted a survey of swing gate users at the Imperial Transfer Station in which it was indicated that pedestrians found the swing gates easy to use and appreciated the barrier between them and the fast-moving LRVs and railroad trains.

Z-Crossings

The Z-crossing channelization controls movements of pedestrians who are approaching the LRT tracks. Its design and installation turn pedestrians toward a potentially approaching LRV before they cross each track, forcing them to look in the direction of oncoming LRVs (see Figure 9, *top*).

Z-crossing channelization may be used at crossings where pedestrians are likely to run unimpeded across the tracks, such as isolated mid-block, pedestrian-only crossings. Z-crossing channelization used with pedestrian signals creates a safer environment for pedestrians than when Z-crossings are used alone. This type of channelization device may also be used in conjunction with pedestrian automatic gates and bedstead barriers if LRVs operate at high speeds or the pedestrian volumes are heavy.

The Z-crossing channelization should not be used where LRVs operate both ways on a single track because pedestrians may be looking the wrong direction in some instances. In a double-track alignment during reverse-

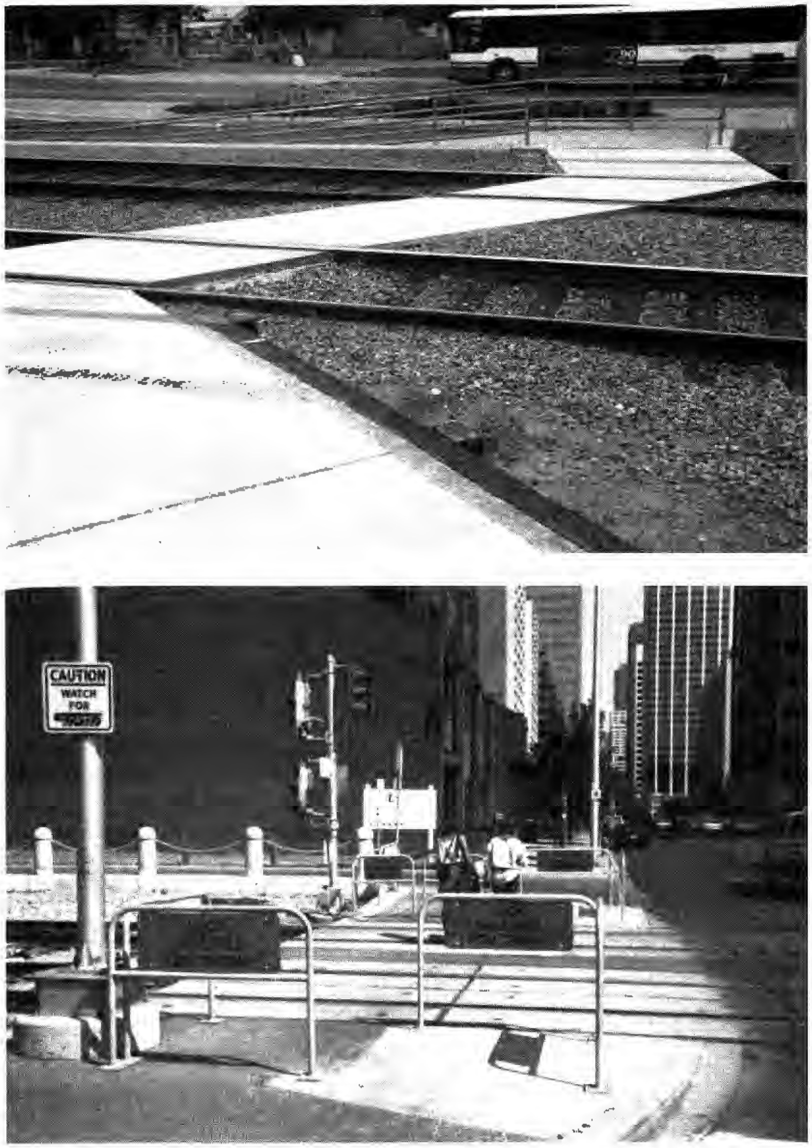


FIGURE 9 *Top:* Z-crossing, San Diego LRT system, East Line to Santee; *bottom:* bedstead barrier, Calgary, Alberta, LRT system, Seventh Avenue transit mall.

running situations, pedestrians may also look in the wrong direction; however, because reverse-running is performed at lower speeds, it should not be a deterrent to installing this channeling approach.

Z-crossing channelization is currently being used by the Portland LRT system along East Burnside Street, by the San Diego LRT system on the East Line to Santee, and by the San Francisco LRT system on the South Embarcadero MUNI Metro Extension.

Bedstead Barriers

Bedstead barriers may be used in tight urban spaces where the LRT right-of-way is not fenced in, such as a pedestrian crossing at a street intersection. The barriers are placed in an offset, mazelike manner that requires pedestrians moving across the LRT tracks to navigate the passageway through the barriers, which should be designed and installed to turn pedestrians toward the potentially approaching LRVs before they cross each track, forcing them to look in that direction (see Figure 9, *bottom*). These barriers should also be used to delineate the pedestrian queueing area on both sides of the track area. These same effects could be accomplished by using bollards and chain.

Bedstead barriers may also be used in crossings where pedestrians are likely to cross the tracks unimpeded, such as at stations or transfer points. The barriers should be used in conjunction with one or all of the following:

flashing-light signals, pedestrian signals, and appropriate signing. Bedstead barriers may also be used in conjunction with pedestrian automatic gates.

Bedstead barriers should not be used where LRVs operate both ways on a single track because pedestrians may be looking in the wrong direction in some instances. In a double-track alignment during reverse-running situations, pedestrians also look in the wrong direction; however, because reverse-running is performed at lower speeds, it should not be a deterrent to installing this channeling approach.

Bedstead barriers are used at numerous locations on the Calgary LRT system at or near station locations and intersection crosswalks.

Combined Pedestrian Crossing Control Treatments

The pedestrian crossing control treatments described in the foregoing sections may be used in combination, as shown in Figure 10, depending on the level of risk of a collision between a pedestrian and an approaching LRV at the crossing. Moreover, pedestrian safety and queueing areas should always be provided and clearly marked.

Pedestrian Crossing Control Treatment Applications

To date, no guidelines have been developed for determining when to use one or more of the pedestrian crossing control treatments as a function of the level of risk for pedestrians at a crossing. Theoretically, selecting the most appropriate pedestrian crossing control treatment would follow the conceptual process shown in Figure 11. First the level of risk should be established, typically as a function of pedestrian volumes, LRV speed, crossing configuration, stopping sight distance, adjacent land use (e.g., schools, senior citizen facilities, etc.), existence of passenger transfers to other modes, and other factors that may affect pedestrian safety. A potential risk value could be determined as a function of the foregoing factors (f_i) weighted according to their relative importance (w_i):

$$R = \Phi\ (w_i\ , f_i) \tag{1}$$

Once the potential risk value is determined and the cross street traffic control device is established, the appropriate pedestrian crossing treatment can be selected as per Figure 11. Further research is needed to quantify pedestrian risk values and develop the best equations

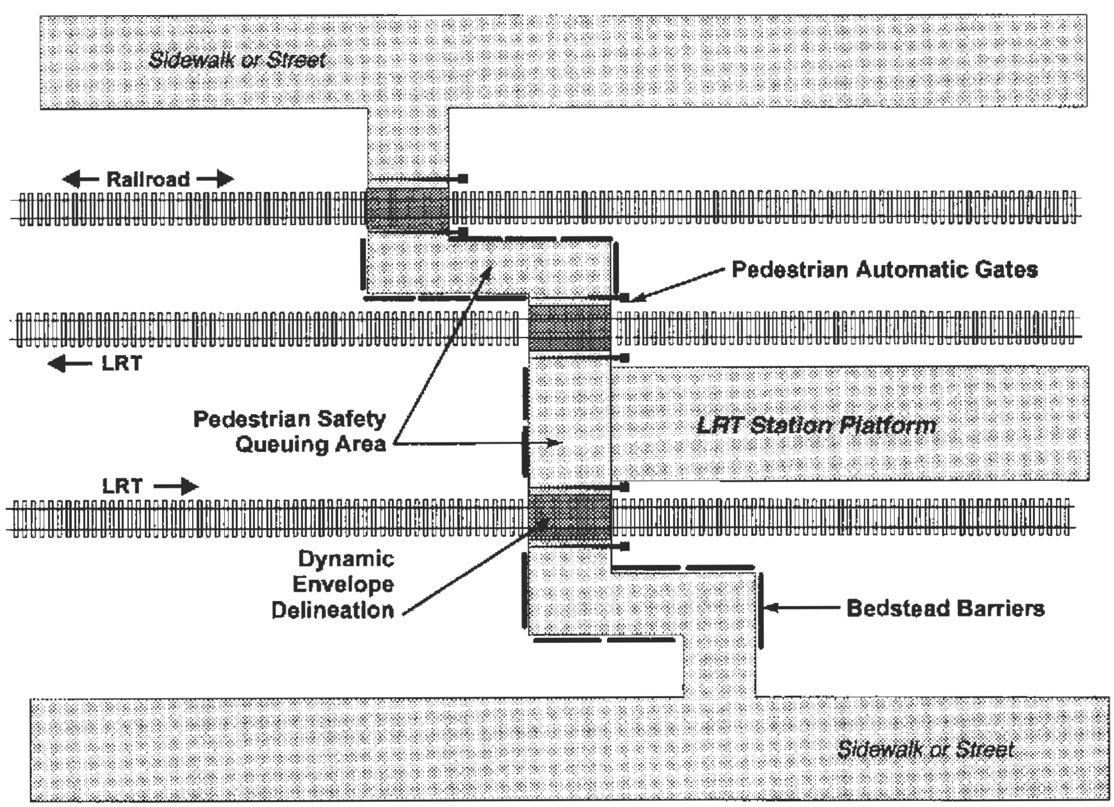


FIGURE 10 Illustrative pedestrian treatment in combined railroad and LRT corridor (not to scale).

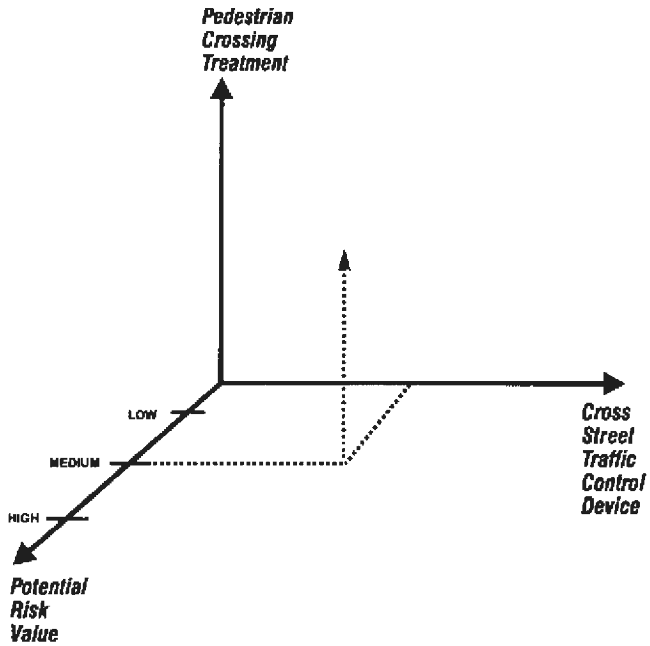


FIGURE 11 Conceptual process for selecting pedestrian crossing treatment.

and appropriate weights for each safety factor. Moreover, through additional research each pair of risk value and cross street traffic control devices has to be related to the most appropriate pedestrian crossing treatment.

In practice, to simplify this process for possible inclusion in LRT design or traffic engineering manuals, a pedestrian crossing treatment selection diagram (Figure 12) could be developed. Once the risk value has been determined using Equation 1 and the cross street traffic control device has been selected, the most appropriate pedestrian crossing treatment can be selected by means of the discrete risk value curves ($R1$, $R2$, $R3$, . . . in Figure 12). The shape of the risk value curves would be determined as a function of the research described above.

Conclusions and Recommendations

Each of the gate and channelization devices described above should be used with appropriate signaling (flashing-light signals, pedestrian signals, or both), signing, and pavement markings. As described, the dynamic envelope of the LRV should be clearly delineated by contrasting pavement texture and color (or alternatively by striping) at every pedestrian crossing. Further, the LRV dynamic envelope should be continuously delineated in an LRT-pedestrian mall (by contrasting pavement texture and color, ADA-approved tactile warning strips, or other approved pavement marking).

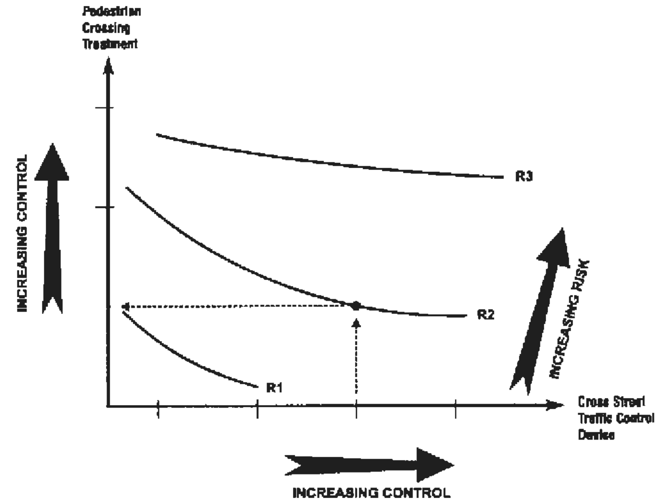


FIGURE 12 Pedestrian crossing treatment selection diagram.

The gate and channelization devices presented in this paper should be used to alert pedestrians of the increased risk associated with crossing an LRT track alignment. Future research is needed to develop specific application guidelines and an appropriate selection methodology for each pedestrian crossing control treatment or combination of treatments.

Last, pedestrian considerations should be included with other considerations in LRT system planning and design. If pedestrians' needs are inappropriately accounted for during system planning and design, the LRT agency could experience a higher-than-average rate of collisions between LRVs and pedestrians (leading to necessary and expensive system retrofits) or reduced LRV operating speeds, which would negatively affect LRT operations and potential ridership.

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Overview of Light-Rail Train Control Technologies

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The various modes of operation of current U.S. light-rail transit (LRT) systems, the limitations of conventional train control technologies, and the capabilities and basic components of more advanced and emerging technologies are described. The operational constraints experienced by some LRT operators as well as the progress in applications of advanced control and communication technologies are also discussed.

Light-rail transit (LRT) systems have been enjoying growing popularity because they are considered socially and environmentally attractive and often incur lower operating costs compared with other transit modes while providing medium capacities [2,000 to 25,000 persons per hour per day (pphpd)]. Most of the 18 transit agencies operating LRT systems in the United States are planning to expand their systems. LRT is also being considered by many cities that do not have the size and density to justify conventional heavy-rail systems.

Despite the advantages offered by LRT, many systems have been experiencing problems related to safety and capacity. Many systems have reached or are anticipated to reach full capacity because of rising ridership. Increasing the capacity beyond the design limit is, however, not easily achieved because of, for example, speed constraints imposed by track geometry, outdated equipment conditions, or mixed traffic operations.

To alleviate the aforementioned problems, new technologies are needed that offer a cost-effective way to ensure safety and add system capacity without requiring significant investments in infrastructure. Avanced train control and communications technologies form one group of such technologies. Transit authorities in North America, such as the San Francisco Municipal Railway (MUNI), Los Angeles County Metropolitan Transit Authority (LACMTA), Metropolitan Transportation Authority New York City Transit (MTA New York City Transit), Toronto Transit, Southeastern Pennsylvania Transportation Authority (SEPTA), Metropolitan Boston Transit Authority (MBTA), and others, are investigating and evaluating alternative train control and communications technologies. The major incentives to upgrading or replacing the existing control and communications systems are increased safety, higher reliability, and greater operational flexibility compared with the existing fixed-block and wayside technologies.

According to a 1992 report prepared by the Office of Policy under the Federal Transit Administration (*1*), approximately $1.52 billion was spent between 1983 and 1991 on "improvements" to U.S. rail transit systemwide control components including signals, cables, relays, and other equipment necessary to provide control, communication, and supervisory functions. A before-and-after assessment showed that although there were some improvements to control systems that were considered in excellent condition, there was considerable deterioration in the control systems that were assessed to be in good, fair, or poor condition. As a result, the percentage of control systems in good condition decreased from 54 to 33 percent, resulting in an increase in the number of control systems in fair or poor condition (from 28 to 46 percent). The number of communications and supervisory-and-control systems in fair or poor condition increased from 63 to 82 percent and from 20 to 30 percent, respectively. It was concluded that most deterioration in condition occurred in light-rail vehicles (LRVs). The outdated condition of the current light-rail control systems coincided with the 59.5 percent increase in the LRT operating expenses during the period between 1984 and 1993, a substantial increase compared with the 33.6 percent increase in operating expenses for bus transit and 29.3 percent for heavy-rail transit (2).

Selection of equipment has proved a difficult decision because of the lack of performance and communication standards for specifying guideway transit equipment. Much time and money have been spent by both transit operators and suppliers to find new technologies with a high degree of interchangeability and the capability of being overlaid on existing technologies. In this paper, operating modes of current LRT systems, the operational constraints experienced by LRT operators, and the limitations of conventional train control technologies are discussed. The capabilities and components of more advanced and emerging control and communication technologies, and the progress in their applications are also reported.

Existing LRT Control Technologies

Table 1 provides a summary of the current control systems and some operating statistics for 16 LRT systems in 15 U.S. cities. It may be seen that even when highly sophisticated electronic control systems are available in today's market, the majority of the LRT systems in the United States are still manually operated, sometimes with the "improved and safe" speed control system. Both operating modes described in this section, manual train operation and manual train operation with speed control, incur large costs for operation, maintenance, repair, and equipment replacement.

Manual Train Operation

Manual train operation relies completely on the operator and the operator's experience and judgment in obeying the signals. It requires the driver to respect wayside speed and light signals. One of the major problems with this mode is the high maintenance and replacement costs for equipment and labor. In addition, the train driver does not have a way of determining train berthing, speed of the lead train, and station dwell time.

Manual Train Operation with Speed Control

In manual train operation with speed control the train driver also has full control of the train, but the speed is automatically supervised and constantly displayed to the driver by the automatic speed regulation (ASR) system. ASR is accomplished with fixed-block and wayside equipment that transmits the speed command that is prewired for each track section to the onboard equipment. The fixed-block technology, having been proved over several years, requires the installation of track circuits and offers speed control and stop protection on the line. Speed command selection depends on the number of clear blocks ahead and is calculated on the basis of interlocking information, traffic, train location, speed rating, and braking potential. This operating mode is most commonly used in U.S. LRT systems. The major drawback of this operating mode is the lack of long-term reliability of mechanical relays, the need for recalibration every 5 years, and the performance limitations of the equipment.

Operating Constraints Experienced by LRT Operators

In this section the operating constraints experienced by four LRT operators are described. The information was obtained from reports, interviews with personnel from the transit agencies, and from authors' observations.

San Francisco Municipal Railway

MUNI trains are manually driven with speed control. LRVs operate in the subway under the train operator's control with cab signal supervision. The train driver controls the doors, platform berthing, direction, coupling and uncoupling, onboard announcements, and radio communications to the central control. Train dispatching is managed by supervisory personnel at trackside in communication with central control.

A conventional railroad-type signal system provides interlocking control, wayside route indications, and manual cab signals. Over-speed protection is provided for only three speeds: 16, 32, and 43 km/hr (10, 20, and 27 mph). In the normal direction of travel, wayside signals approach clear, but the central control has the ability to manually operate the five subway interlockings during emergencies with an overlaid centralized traffic control system.

In the subway, train direction and movement below 16 km/hr (10 mph) are not restricted by the signal system. There is no zero-speed command, cab signal stop indication, or wayside trip-stop system. LRVs are

TABLE 1 Operational Characteristics of Selected LRT Systems (*2*)

Cities	Minimum Headway (minutes) Designed	Minimum Headway (minutes) Operated	Average Operating Speed (km/h)*	Train Control System	Operating Expenses/ Veh. Rev. Km[c] (1993$)	Operating Expense/ Pass-Km[c] (1993 $)	Unlinked Pass-Trip/ Veh. Rev. Km[c]
Los Angeles							
Blue-Line[a]	3	6	34	M, ATP	9.50	0.25	2.56
Green-Line[b]	2	5	n/a	ATC	---	---	---
Portland	3	3	31	M, ASC	4.83	0.42	3.21
Baltimore[a]	15	15	n/a	M, ASC	6.32	0.32	1.76
Buffalo	2	5	19	M, ASC	8.82	0.41	5.64
Denver	n/a	5	48	M, ASC	---	---	---
Sacramento	15	15	34	M	5.80	0.30	2.44
San Diego	2.5	4.25	20	M	2.80	0.11	2.31
St. Louis	5	7.5	48	M, ASC	---	---	---
Boston[a]	n/a	7.5	21	M, ASC	11.20	0.43	11.45
New Jersey	n/a	2	29	M, ASC	4.62	0.32	2.88
Philadelphia[a]	n/a	3	32	M	8.33	0.27	8.22
San Fran.[a]	2.5	10	18	M, ASC	10.11	0.37	6.30
Cleveland	2	6	29	M, ASC	6.93	0.25	2.63
Pittsburgh	3	3	23	M	8.35	0.42	2.69
San Jose	n/a	10	32	M	7.06	0.29	2.25

Notes: *M* — *Manual Operation*
ATC — *Automatic Train Control*
ATP — *Automatic Train Protection*
ASC — *Automatic Speed Control*
[a] *Systems considering advanced train control systems*
[b] *Systems considering fully automated control system*
[c] *To obtain MPH and/or Veh. Rev-Mile multiply by 1.61*

equipped with deadman control, spin-slide control, blended friction and dynamic grid disk brakes, electric track brakes, and sanders.

For MUNI, three major constraints limit rhe system's capacity and the ability to maintain schedule adherence: the terrain, aging signal control and vehicle equipment, and transitions between surface and subway operations. The specific problems include the following (*3*):

- Collision avoidance in the subway when speed is below 16 km/hr (10 mph) relies on the train operator's adherence to rules and use of good judgment;
- The design characteristics of the existing over-speed protection system, combined with few speed commands and the steep grades, frequently result in unnecessary emergency brake applications when trains are operating at the maximum commanded speed; and
- Since the signal system has a limited fault tolerance, virtually any failure dramatically reduces system performance.

SEPTA Light-Rail System

The SEPTA system consists of three currently inactive surface lines and five subway-surface lines. Each track of the double-track system is signalized for unidirectional movements. There are neither passing sidings nor crossovers between the two main tracks. Slowing or stopping of traffic at any point inside the tunnel, especially during peak periods, has a ripple effect on the rest of the traffic as well as on overall vehicle flow within the tunnel. The existing signal system consists of three types of signals (*4*):

- Automatic block signals: These provide conventional two-block, three-aspect protection (red, yellow, and green), which governs the entry into a typical signal block.
- Speed control signals: These are electrically timed and are actuated on the approach to a signal. The function of these signals is to restrict speeds for curve and grade conditions or to maintain a reduced speed through several consecutive blocks. The signals require the vehicle operator to reduce speed until the signal displays a more favorable indication. These speed control signals are used to increase the safety level but tend to cause an overall decrease in operating speed.
- Call-on signals: These are primarily used for vehicles entering a station to allow more than one vehicle to berth at that station platform. This is accomplished by dividing the platform track into two track circuits, front and rear.

SEPTA has experienced the following problems:

- Minimum scheduled headways on some routes are 3 min and 30 sec in the tunnel, and cannot be decreased further. The present line capacity during peak periods with 50 to 60 cars per hour has reached its limit for safe operation in the tunnel.
- During peak hours, the demand for service exceeds supply on certain routes. As a result of peak operating conditions, SEPTA is able neither to improve the schedules nor to inform the passengers of delays.
- The most serious deficiency of the existing signal system is the lack of speed enforcement. There are no onboard devices that will actuate automatically if the car operator ignores a wayside indication. The chances of human error in this situation are much higher than with an automatic system.
- There are no signals from 15th Street to 22nd Street except for clusters of short blocks in certain areas.
- The signal system in the tunnel reflects the operating demands and philosophy of the 1950s when a heavy concentration of vehicles operating on a close headway of 20 to 30 sec at slow speed was needed to carry passengers through the tunnel.
- Speed control signals were installed to improve safety following incidents such as derailments or rear-end collisions, which have further reduced operating speeds.

San Diego Trolley

The system is modeled after western European systems with a rolling stock that is composed of German type U2 articulated LRVs. Parts of the system operate on freight tracks. The San Diego Trolley is a manually driven system, with the operator controlling the vehicle speed and a dispatcher controlling the track switching. The system operates with rail switches and signal lights that have remained essentially unchanged from century-old railroad technologies.

The system is experiencing several problems (5):

- Operation of the San Diego Trolley in the downtown area is constrained by street block lengths that accommodate only two-car trains without overhang. During peak hours, however, four-car trains are needed. Although train length is reduced to three cars at the Imperial transfer station before the train enters the downtown, pedestrian traffic is still impeded at intersections in the downtown area.
- Traffic control signals in downtown are synchronized to allow the progression of LRVs through signalized crossings. This progression is accomplished only if the train operator leaves the station at the beginning of the green phase of the first intersection in downtown. At this intersection, there is a countdown device that informs the operator that the light will change in 15 sec. When the light turns green, the operator has to close the doors and be ready to start running the train to catch the "green wave."
- Ridership in the downtown area is increasing, but service frequency is limited to 90-sec headways to synchronize LRT system operation with the control signal.

Boston-MBTA Green Line

The Green Line system operates over 37 route-km (23 route-mi) that is a combination of exclusive right-of-way (ROW) (subway and elevated), reserved ROW that interfaces with traffic at street crossings, and mixed ROW. The system consists of four lines with 70 stations, four of which are connected with heavy-rail lines and one of which is connected with the commuter rail.

Three of the four lines operate with a 5-min peak headway, and the remaining line operates with an 8-min headway. The four lines pass through the 12.4-km (7.7-mi) Central Tunnel, which allows a minimum headway of 65 sec only during special events and 83 sec during regular peak hour operation.

There are two problem areas—traffic management and the signal control system (6):

- LRVs that interact with traffic operate with no special signal timing or signal preemption. Parts of the signal system in the private ROW predate World War II. Traffic engineers at MBTA are testing a device that detects a stopped train at an on-street station and turns the upstream signal red to alert automobile drivers not to pass the LRV and to allow the passengers to alight onto the street. This device provides only marginal safety for passengers and causes unacceptable congestion for street traffic.

• The system uses a type of automatic vehicle identification (AVI) that provides partial train supervision and route control. However, a train is identified only when it is passing a loop. There is no information about the train location between the loops. Communication with a train can be achieved only when it is over the loop and if the vehicle initiates the communication. If the vehicle fails to communicate, the control center will be unaware of the vehicle's current position.

• The system relies completely on the operator to obey the signals. Human error is the most prevalent cause of incidents and accidents.

• The system is supposed to operate with 83-sec headway, but because of vehicle bunching, the headways are less than 45 sec. Vehicle bunching causes all trains to make a mandatory stop before entering the North and Lechmere stations.

New Technologies in LRT Operation

In recent years, new technologies in train control systems have been developed rapidly with the well-defined goals of increasing capacity, enhancing safety, and providing a high degree of interchangeability for mixed-mode operation. Table 2 describes the most important functions of different control technologies. In Table 3 information about North American train control equipment suppliers is provided.

Automatic Train Control Systems in Conjunction with Train Attendants

Automatic train control (ATC) system technology with train attendants is considered a mature technology since it has been used in heavy-rail system operation for many years with positive results to solve capacity and safety problems. Currently, ATC technology is considered the

TABLE 2 Functions and Capabilities of Train Control Technologies

	LRT Systems Control Technologies				
Operating Mode Functions	Manual with Wayside Signals	Wayside Fixed Block	Fixed Block & Cab-Signaling ATO, ATP	Comm-Based & ATO, ATP	Overlaid Comm-Based & ATO, ATP
Train detection	Limited	Yes	Yes	Yes	Yes
Safe train separation	Limited	Yes	Yes	Yes	Yes
Over speed protection	No	No	Yes	Yes	Yes
Broken rail detection	Limited	Limited	Limited	Limited	Limited
Minimize headway & max. throughpnt cap.	No	No	Limited	Yes	Yes
Centralized dispatching, identification & schedule adherence capability	Limited	Limited	Yes	Yes	Yes
Provides ATS	Limited	Limited	Yes	Yes	Yes
Interface with ROW intrusion detection	Limited	Yes	Yes	Yes	Yes
Public information on real-time basis	No	Limited	Yes	Yes	Yes
Ease of train operation	No	No	Yes	Yes	Yes
ATP compatibility	Limited	Limited	Yes	Yes	Yes
ATO compatibility	No	Limited	Yes	Yes	Yes
ATS compatibility	No	Limited	Limited	Yes	Yes

TABLE 3 Control and Communications Technology Suppliers in North America

Suppliers in North America	Type of Equipment Supplied										
	Mechanical	Electrical/ Electronic	Track Circuits	ATC & Train Stops	Multiplexing	Level crossings	Marshalling yards	Software	Cables/fiber optics	Automated transit	Lineside equip.
Amtech				✓							
CMW Systems		✓	✓	✓	✓	✓	✓	✓	✓		
Electro-Pneumatic Corp.		✓	✓			✓		✓			
General Railway Signal	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Harmonc Industries		✓			✓						
Safetran Systems	✓	✓	✓	✓		✓					
Siemens Transp. Systems		✓	✓	✓			✓	✓		✓	✓
Transcontrol Corp.		✓	✓	✓		✓	✓				
Ultra Hydraulics							✓				
Union Switch & Signal	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Western-Cullen-Hayes	✓	✓				✓	✓				
ALCATEL, Canada		✓	✓	✓	✓	✓		✓	✓	✓	
GEC/ALSTHOM, Canada		✓	✓	✓	✓	✓		✓	✓	✓	

Source: Railway Directory, 1995

most suitable alternative to expand and upgrade LRT systems.

For a heavy-rail system with ATC, the train driver's functions are limited to providing information to passengers at stations, operating vehicle doors, and controlling the trains if the automatic system fails. In fact, the door operations could also be accomplished by ATC, but because of safety considerations, it remains a manual process. Trains are routed by signal indication, with continuous display in the cab to keep the train attendant informed of operating conditions. Vehicle operation is totally commanded from the control center. Control consoles in the center are used for the remote control and monitoring of all interlockings. The routes of individual trains may be monitored with reference to their train identification numbers.

An ATC signaling system interfaces with most vehicle functions, including traction motors, brakes, and public address systems. The three major subsystems of ATC are automatic train protection (ATP), automatic train operation (ATO), and automatic train supervision (ATS).

Automatic Train Protection

The train operator has command of the train operation, but his or her actions are supervised automatically in real time with data from the signals, blocks, and switches. The ATP system continuously checks that the train can proceed safely in reference to the next stopping or slowing point. The train operator receives an alarm whenever the authorized speed is violated, and a predetermined time is allowed for the operator to request a full-service brake rate before the ATP system invokes a full-service brake penalty to zero speed.

Automatic Train Operation

The decision about whether the train is to run under an automatic control system is made on the vehicle by the train operator. ATO provides the basic operating functions such as controlling the running and headways of trains, managing stops in stations, controlling the opening and closing of train doors, and providing audio and visual information to passengers. Generally, the fixed-block system concept is used for train separation.

Automatic Train Supervision

ATS functions include routing of trains, train dispatching, train tracking, adjustment of train performance levels, generation of alarms and indications for both vehicles and wayside, generation of operational and vehicle maintenance reports, control of station dwell times, and identification of trains. The ATS subsystem consists of a computer, console and displays, and a communications control center. The computer system's function is primarily to optimize operating efficiency. It controls and supervises departure times, routing, dwell times, and other corrective strategies. In addition, the computer monitors the operation of interfacing systems such as escalators, passenger gates, fans, vents, and the power distribution network. Through the control center, ATS monitors the position and adjusts the performance of all trains (*7*).

Although an ATC system is capable of operating trains without drivers, it does not have adequate safety features (see discussions on fully automated systems below) to allow the fully automated operations that make on-board drivers unnecessary. Because of the diverse LRT system operating environments, the presence of drivers is essential, and they may need to perform more functions than those that a heavy-rail train operator typically does. Using the ATC system for LRT operation in mixed ROW requires implementation of LRT-road interface management to control traffic signals at crossings. Infrared devices may be installed on the vehicles, which will preempt street traffic lights accordingly, giving priority to LRVs. This function may also be accomplished by using induction loops in the tracks or automated traffic surveillance and a control system that detects a train approaching an intersection and adjusts the signal progression to allow the train to pass through the next intersection without stopping.

Fully Automated System

With a fully automated control system, a train is operated automatically, including starting, stopping, driving, coupling, towing, and door opening and closing, eliminating human error in the operating process completely. No on-board drivers or attendants are necessary. All functions are integrated. For instance, ticket sales may control the traffic capacity and number of trains needed. A fully automated train control system includes the same functions as the ATC system but with added fail-safe measurements that permit the removal of on-board human drivers. For a fully automated system, ATP is the most important function, providing the basic safety operations, including safe spacing of trains, over-speed protection, switch controls and interlocks, and door control interlocks. ATO is responsible for vehicle speed regulations within the safe envelope set by the ATP subsystem, which also governs station stopping programming, vehicle and door timing control, and command coordination between stations and the central control. ATS operates within the constraints of the ATP system by means of an integrated set of equipment, which includes the central computer, train control and power distribution displays, control consoles, and communication equipment.

The complete system equipment for the control subsystems (ATP, ATO, and ATS) is located at the central computer complex, at the stations, along the guideway, and on board the vehicles. Interactions of the subsystem functions are very complex, and sophisticated interfaces are required between them. If there is a failure in the central system and no manual mode is available, the entire line will stop operating.

In addition to the complex equipment, a fully automated system requires 100 percent exclusive ROW, often resulting in a significant increase in the capital costs. The benefit, however, is a better level of service, including high speed, short headways, high reliability, and enhanced safety.

Communications-Based Technologies

The term *communications-based* refers to a train control system that uses an intensive two-way or bidirectional communication data link between the wayside and the train to detect continuously the position and speed of the train as well as the trains preceding and following it, allowing for decreased headways and increased throughput. The system is also called a transmission-based signaling (TBS) system or communications-based signaling (CBS) system. CBS does not require track circuit hardware. Instead, a wireless system is used to transmit information either from vehicle to vehicle or from vehicle to wayside or central office. It creates a phantom block or a shadow between the rear of a preceding train and the front of a following train. Depending upon how fast each train is moving, the size of the shadow can be changed, allowing the distances between train to vary for different types of trains operating at different speeds, hence the name *moving block*. At slow speeds, less space between trains is needed. At higher speeds, greater braking distance is required, thus a longer block. CBS is a proven technology over the last 12 years and has been applied primarily in Europe. As of 1996, it will also become available to the U.S. market.

In a CBS configuration, the train must determine its location on the wayside. Several technologies can be used for this function, including tachometers, radar, loop transposition detection, transponders, Global Positioning System (GPS), digital maps, and inertia measuring devices (gyroscopes and accelerometers). Once a vehicle determines its location on the wayside, it transmits its location back to the wayside via RF data radio or low-frequency inductive coupling. RF data radio is currently being explored by many companies (*8*).

Advanced Train Control Systems

An advanced train control system (ATCS) is a fault-tolerant, wireless train control system that utilizes microprocessors and digital data communications to connect elements of the railroad, vehicles, track forces, and wayside devices to the dispatcher's office. In addition, it will link data to key railroad managers through an information management system. The ATCS eliminates dependence on human compliance with signal indications, operating rules, and written instructions to achieve safe speeds and train separation. It allows increased traffic capacity and equipment utilization and maximizes electrical and labor savings.

Information management is one of the two principal functions of the ATCS: it issues work orders, monitors system health, calls crews, records events, and plans dispatching strategies. The other principal function is vital and nonvital train control: throwing switches, moving trains, and stopping trains. Some of the most important benefits of ATCS are as follows:

- Increasing traffic capacity on existing tracks by decreasing headways, mitigating the need for additional track;
- Decreasing the number of cars required for revenue operation by allowing trains to run faster; reduced trip times require fewer trains to maintain the same headway;
- Reducing brake rates, resulting in reductions of energy usage and trip times;
- Providing multiple-train coordination, decreasing peak power demand and the size of propulsion substations;
- Allowing easy installation and overlay on existing systems, permitting mixed operation modes; and
- Ensuring that all train movements are safe, valid, and observed, eliminating all possibility of human error.

Today, ATCS is considered the train control technology with the greatest potential to solve safety and capacity problems and at the same time offer savings on capital and operating costs.

Positive Train Control Systems

Positive train control (PTC) is the Federal Railroad Administration's term for what has previously been called positive train separation (PTS) to denote collision avoidance. PTC is a highly capable technology, not only for preventing train accidents and casualties, but also for preventing violation of permanent and temporary speed restrictions, including restrictions that protect on-track workers and their equipment.

When a CBS system is overlaid on an existing, vital traditional fixed-block system, it becomes a PTC system. The total safety of the combined system is enhanced as compared with the traditional signaling system. It is possible to develop PTC technology that provides varying levels of operation, depending on how much or how little of the current signal and control system is to be retained. A PTC system that is overlaid on an existing signal system and provides enforcement of occupancy and speed restrictions is called basic PTC. An enhanced PTC system is vital (with fail-safe characteristics) and is capable of replacing fixed-block signal systems.

PTC systems have the potential for improving the management of train operations in various ways and at lower costs than conventional ATC. With a PTC system, the brakes would be applied automatically, if necessary, to keep trains apart, enforce a permanent or temporary speed restrictions, or stop the train short of a switch not properly aligned for that train or other known obstructions such as on-track maintenance equipment (*8*).

Advanced Railroad Electronic Systems

The advanced railroad electronic system (ARES) was designed by Burlington Northern Railroad (BN). In conjunction with Rockwell International, BN implemented a test bed for ARES in Minnesota from 1988 through 1993. ARES is an integrated command, control, communications, and information system, designed to control rail traffic with a high degree of efficiency, precision, and safety. The data link uses the railroad's existing microwave and VHF radio frequencies to communicate information, instructions, and acknowledgment between the control center and a train or other track vehicles. To determine position and speed, ARES uses GPS to provide the control center with highly accurate three-dimensional vehicle position, velocity, and time data (*8*).

State-of-the-Art GPS-Based Control Technology

For service monitoring within noncommunicating territories, GPS may be used for a state-of-the-art LRT information management and control system using maps as a common reference frame. GPS is a satellite-based technology used to determine the position of a point anywhere on the earth's surface. Basically, a GPS-based control system includes two main components, a vehicle location and tracking system and a scheduling support system. Vehicle tracking is performed through a sequential polling process that provides automatic updates of vehicle location on the map display. These two components provide dispatchers with the necessary tools to make safer operating decisions and monitor operator or vehicle performance. Some important applications may be vehicle location, vehicle identification, passenger information, schedule adherence, and emergency response.

Implementation of New Technologies

New Control Technology for MUNI Metro System

Operational studies and computer modeling performed by MUNI demonstrated that the capacity problems could be solved if (3)

- The time necessary to turn trains at Embarcadero Station was minimized,
- Limitations associated with the existing signaling system and LRV train reversal functions were mitigated, and
- All train movements in the subway were globally controlled, coordinated, and optimized.

MUNI determined that the technology had to have at least 2 years of proven applications and actual in-service use for a mass transit system in at least one city. Subsequently, an ATCS was determined to be the most suitable technology to mitigate the existing constraints.

The primary objectives for implementing the ATCS are

- Eliminating as much as possible manual operations and decisions;
- Improving safety by eliminating human error and equipment or system failures as potential causes for accidents and injuries;
- Increasing reliability and availability and lowering maintenance costs by replacing existing maintenance-intensive equipment with equivalent service-proven equipment that requires less maintenance;
- Allowing flexible operation to permit additional shuttle service and improve management and recovery in the event of equipment failures or other emergencies;
- Providing additional operational flexibility and fully automated control of new track area associated with the MUNI Metro Turnback, which is under construction;
- Enhancing passenger information systems and improving right-of-way security against intrusions;
- Providing capability for mixed-fleet and dual-mode operation and for future expansion projects; and
- Providing capability for 60 trains per hour per direction and the ability to control 40 trains at any one time.

The ATCS project funding information obtained from MUNI ATCS Systems Coordination Department (Patricia G. DeVlieg, project engineer) is given in Table 4.

TABLE 4 Funding for MUNI's New Control System

Category	Funding ($)
Project Management, Administration, Test & Start	4,963,250
Consultant Services	6,851,425
Construction Contract	52,725,465
Sales Tax	2,717,232
Contingency	1,221,710
Project Total	**68,479,082**

Improving SEPTA Light-Rail Control System

In addition to solving the capacity problem, the new technology was expected to satisfy the following criteria :

- It is a proven technology used on a transit property with demonstrated results;
- It has distinct advantages in terms of operations, control, and maintenance functions;
- It has sufficient redundancy to operate trains safely and efficiently under normal and contingency conditions;
- It offers all automatic train control features such as ATO, ATP, and ATS, while allowing manual operation;
- It allows mixed operation with the ability to enable communication between new and existing vehicles about their locations; and
- It is able to perform all existing functions such as call-on, multiple berthing at stations, civil speed restrictions, and interlocking operations.

After reviewing eight different systems (three fixed block and five moving block) offered by seven suppliers, SEPTA found that moving-block technology offered continuous train control with minimal wayside equipment and could handle the close headway of 60 sec required in the tunnel. The initial investment was considered to be reasonable and maintenance costs could be reduced. As a result, SEPTA proposed to prepare performance specifications for a moving-block system including communications-based technology.

Improving Boston Light-Rail Control System

The goal of MBTA is to regulate traffic as it enters the downtown tunnel. The technology should provide the proper train separation and keep headways above 1 min. It should also place the trains in proper sequence so that the correct berthing at Park Street can take place. The most important requirement is that the technology be able to make automatic adjustments to correct deviations in schedules. For longer delays, the system must be

TABLE 5 Estimated Costs of MBTA's Central Tunnel Communications-Based Train Control System (6)

Phase Description	Cost ($ million)
Computer Analysis	0.5
Design	4.0
Construction Phase Services	4.0
Replace Signal System	25.0
Install ATS	15.0
Incorporate Traffic Management System	5.0
Overlaid Communications-Based System	45.0
Total Cost	**98.5**

able to use the track and signal system to short-route and deadhead cars.

The system to be adopted by MBTA requires four system components: a new interlocking device and signal equipment, an ATS system, a traffic management system (TMS), and an overlaid communications-based train control system. These systems need to be integrated into one system including the associated vehicle-borne equipment. According to the information provided by MBTA during the International Conference on Communications-Based Train Control on May 9–10, 1995, in Washington, D.C., the project is estimated to cost $98.5 million, which does not include force account moneys. A breakdown of the cost is given in Table 5.

Dallas Area Rapid Transit Light-Rail Starter System

In 1992, construction began for the Dallas Area Rapid Transit (DART) LRT starter system, which consists of 32 km (20 mi) of double track and 20 stations at a cost of $841 million. DART's LRT system is scheduled to open its first segment of 16 km (10 mi) and 10 stations in June 1996, the second segment of 11.3 km (7 mi) and 7 stations in late 1996, and the third, 4.8-km (3-mi) segment in June 1997. The system will run in diverse operating environments including a 5.6-km (3.5-mi) segment in deep twin tunnels, a 2.4-km (1.5-mi) bridge spanning the Trinity River, a semi-grade-separated private right-of-way, within a street median, and through a vehicle-restricted transit mall in the central business district (CBD).

The control and communications equipment for DART's LRT system will be housed in a control center. The control system will provide full monitoring and remote control capabilities such as train stopping, vehicle movements on the mainline, revenue service delivery and control, delay management, ROW access, and emergency response coordination.

The signal system is designed to accommodate a 90-sec headway at a maximum operating speed of 105 km/hr (65 mph) with restrictions of 72 km/hr (45 mph) in unprotected line-of-sight territory and 32 km/hr (20 mph) through the CBD. There are 54 grade crossings, 34 of which are fully protected with warning gates. Activation of the gates is accomplished through one of all of the following: standard approach circuitry, train-to-wayside communications, and absolute block—traffic signal interface. Movement of LRVs in the CBD will be controlled by green light signals synchronized with the central traffic management signal system.

The components of the train control system include

- A communications transmission system to provide a link between the control center and locations within communicating territories via a fiber-optic cable; communication between the control center and locations within noncommunicating territories is via copper cable or dial-up telephone lines;
- A supervisory control system to transmit and receive status change indications and control signal devices and ventilation equipment;
- A central computer network consisting of a system overview display and control consoles for main-line operations, yard operations, and system management;
- A train stop control system to provide penalty stop protection for the trains in signalized segments;
- A train-wayside communication system to provide remote control capability for switch operation and commands to the signal system;
- Wayside absolute block signals to protect train movement within signalized areas; in nonsignalized territory, line-of-sight operating rules will apply; and
- Fully automatic couplers at both ends of the vehicle for all mechanical, pneumatic, and electrical connections between cars in a train, remotely controlled from the operator cab.

Conclusions

A major advantage of LRT systems is their capability to operate in diverse environments. The manual operation mode of LRT, however, has resulted in a larger number of train-vehicle and train-train collisions when compared with other fixed-guideway transit modes. Future LRT control technologies must therefore provide capabilities to monitor and control the entire fleet that operates on different rights-of-way and alignments. The train control systems should be capable of providing real-time, constant communication between the vehicle-track, vehicle-control center, track-control center, passenger-control center, and vehicle-operator and vehicle-control center for safe operation and maximum utilization of the track.

Current LRT systems equipped with ATP and with ATO and ATS are operating with shorter headways, increased capacity, and enhanced safety. An example is the Los Angeles Green Line, which runs on an exclusive right-of-way equipped with an ATC system and has drivers on board the vehicles who keep constant communication with the central control to provide for safer train operation.

Advanced technologies such as ATCS promise to allow economical, efficient, and safe train operation by incorporating a collision avoidance system that is capable of detecting and preventing impending collisions between vehicles for safer train movements, a feature that may solve the major LRT safety problem. Currently, the only LRT system operating with ATCS is the fully automated, driverless SkyTrain in Vancouver, Canada.

Additional effort in the development of advanced LRT control technologies for at-grade LRT operation with mixed traffic is needed. It is imperative to develop an improved on-board and wayside system to provide automatic location tracking and automated transmission of movement authorization coordinated with track sensors and traffic signals. Because most existing LRT systems will need to upgrade or replace their control and communication systems in the future and given the fact that funding is limited, it is also important that the new technologies be flexible enough to be compatible with the existing equipment, to allow phased improvements. To develop technologies and equipment that will significantly enhance LRT safety and performance requires transit equipment suppliers and LRT operators to work together to identify the needs, constraints, market potentials, and opportunities in technologies and financing.

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Sensitivity of Hudson-Bergen Light-Rail Transit System Model Forecasts

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Travel demand modeling and forecasting that were completed as part of the evaluation of a proposed light-rail transit (LRT) system in New Jersey's Hudson River waterfront area are described. The modeling required a unique approach because of several characteristics of the study area. The market for the proposed service includes those commuting into New York City from New Jersey as well as travelers within the waterfront area. This area has a complex mix of existing transit service, which the proposed LRT system would complement. The travel demand models were developed initially as part of a New Jersey Department of Transportation project. A residential choice model was added to the conventional four-step process, and a nested logit-based mode and path model was developed. The nested logit model estimates shares among existing and new modes, accounting for different levels of competition as observed among subsets of the modes. The model system was used to prepare a Draft Environmental Impact Statement for the proposed LRT system. In preparation of the Final Environmental Impact Statement, the model was refined, updated, and validated to 1990 conditions. The mode-choice model was adapted to better reflect elements of travel behavior that were observed in focus groups and a stated-preference survey. Data from a 1990 trans-Hudson survey were used to reestimate mode-choice coefficients using a specification suggested by the stated-preference surveys. Forecasting experiments are shown to illustrate the overall sensitivity of model forecasts to policy variables and future scenarios. Estimates of the ranges in forecasts that result from sampling error in the choice model estimation process are given.

In 1989 the New Jersey Department of Transportation (NJDOT) commissioned a project to create a new set of travel forecasting models that would replicate the travel patterns within the northern New Jersey area that extended across the Hudson River and capture the very important share of the travel market with destinations in New York City. The Federal Transit Administration (FTA) required this work be expanded in an Alternatives Analysis/Draft Environmental Impact Statement (AA/DEIS) for the Hudson River waterfront study for two reasons. First, the majority of trips headed to New York from west of the Hudson exit through Hudson and Bergen county portals. Second, rapid and current projected development along the Hudson River waterfront beginning in Bayonne, New Jersey (Hudson County), and ending in Edgewater, New Jersey (Bergen County), indicated the potential for a new transit investment to increase existing transit capacity and reduce congestion.

The enormous size and complexity of the New York City region required development of travel forecasting models that differ from conventional models. The length of commuter trips that employed individuals within the region are willing to make and the number of transportation modes that may be used defy comparison with other regions of the country. Even social patterns are quite different than those experienced elsewhere. For instance, households with relatively high incomes within New York City itself do not conform to the traditional relationships among income, automobile ownership, and transit usage. Consequently, it was necessary for the patronage forecasting model developed for the Hudson-Bergen Light Rail Transit System's (HBLRTS) AA/DEIS process to use innovative travel forecasting procedures. The initial model had to respond to the special needs of the Hudson River waterfront area, and more generally, the unique travel patterns of the New York City metropolitan area.

Initial Model Structure

To develop the initial HBLRTS model, the traditional four-step process of trip generation, distribution, mode choice, and trip assignment was employed, with two important modifications. First the distribution component for work trips was modified through the use of a residential location-choice model, which mirrors real-life choices by assuming that households select their place of work first and then choose a place to live on the basis of the location of the work site and a broad spectrum of social, economic, and travel time variables. Conversely, the conventional model approach distributes trips from home to work, implicitly assuming that people first chose where they will live and then chose where they will work.

By reversing the decision assumption, the residential location-choice model better predicts travel patterns for the Hudson River waterfront study through a feedback loop of transportation characteristics that were considered in the residential selection process. This model feature reflected the broad use of transit as a principal mode of travel for work trips for many people in the region. Mode shares for work trips during a 24-hr period into Manhattan are 43 percent automobile and 57 percent transit according to the 1990 All Modes Trans-Hudson Survey (*1*), and approximately 35 percent automobile to 65 percent transit for work trips into the waterfront according to the 1990 Waterfront Employee Survey (*2*). The share of transit is higher in both markets during peak periods.

The mode-choice model was extended to include both primary and access modes as "transit paths." Because of the highly competitive transit options available in the New York–New Jersey metropolitan area, it would be inaccurate to assume that all transit trips used the same "best" transit path between two pairs of zones. Consequently, the "mode and path" choice model was structured into 13 separate mode-path options, permitting the estimation of separate trip tables for each option. These separate tables allowed analysis to occur with the trip tables before assignment to the networks. This process provided a greater degree of precision in refining forecasts. It also provided an opportunity for insights into travel behavior that could not be easily achieved when the final decision on modes and submodes was left to the network assignment process. Finally, the nesting feature of the mode-path choice model allowed the grouping of those alternative mode-path options that most closely compete. Within each nest, the model estimates the probability that each alternative in the nest will be chosen.

In addition to the need to analyze the multipath options available, the opportunity to evaluate transit service capacity is also important. This evaluation occurred outside the model process in an iterative fashion through service equilibration. The model did not consider capacity constraints such as delays caused by crowded trains or delays caused by waiting for the next train if the first is full.

Nonwork travel patterns were modeled using a conventional approach. Nonwork distribution was estimated with a gravity model, which uses the person trips to and from each zone produced by trip generation, the zone-to-zone minimum time paths from the highway network, and friction factors indicating willingness to travel a certain distance. *K*-factors were introduced into the model to compensate for crossing volumes of the bridge between New York and New Jersey, which carried more trips than the model predicted. The model was unable to account for the effect of bridge crossing on travel patterns. Because it was assumed that nonwork trips are generally less likely to use transit than home-based work trips, a gamma function of travel time was used to estimate nonwork trips as a share of work trips. The gamma function assumes there is a progressive unwillingness to use transit for nonwork trips as the length of the trip increases. The gamma function used distance as the prime variable in explaining variation.

Model parameters for this initial HBLRTS model (*3*) were estimated using 1980 and 1983 transportation and land use data, including data from the 1980 U.S. census. Validation was performed using available 1986 and 1989 observed data.

Current Status of Model

The initial HBLRTS model was used to evaluate alternative transportation investment proposals and estimate their associated traffic and environmental impacts. Once a locally preferred alternative was selected, refined forecasts were needed for a final environmental assessment. After a model refinement and upgrade process, the initial model was transformed into its current version.

Specific model refinements include network, zone, and land use changes as well as enhancements to model structure and parameters. An extensive update of both the highway and transit networks resulted in the receipt of more highway detail required for more precise rail, bus, and ferry mode analysis. All state bighway facilities and major county road facilities are coded in the highway network. In addition, many local arterials are used in the network, especially in the urbanized areas within New Jersey. In Hudson and Bergen counties, there is even more local detail to capture very localized complexities. Additional transit detail has led to more accurate line-haul and transfer volumes. Because the previous model indicated significant interaction between the proposed new light-rail transit (LRT) and other transit modes, particularly at major transit interchanges, detailed modal analysis is now provided at these major transfer hubs.

Accompanying changes were also made to the model's zone structure. Zones within Hudson and Bergen counties are now all based on census tracts, and some zones, particularly in the waterfront development areas, are as fine as actual development sites. This level of detail became necessary to evaluate the impact of alternative LRT alignments in and around actual or planned developments.

Both base- and future-year land use data were updated. The 1990 census, the 1990 All Modes Trans-Hndson Survey, and 1990 statistics on employment and population were used to develop and calibrate a 1990 base for the refined HBLRTS model. The source of land use in 2010 was regional forecasts prepared by Urbanomics for NJDOT and the New Jersey Office of State Planning. In addition, waterfront development expectations were updated and incorporated into the 2010 forecasts.

Model parameters and structure were reviewed, and four important modifications occurred. First, a distinction that was made in the mode-choice model between long and short drives to transit was omitted and replaced by one "drive-to-transit" definition. This new definition avoids a sudden shift at the arbitrarily defined breakpoint between long and short and instead relies more on observed park-and-ride catchment areas for the various transit modes revealed in the 1990 All Modes Trans-Hudson Travel Survey. Next, the modal definitions for trans-Hudson service were expanded. Since ferry has become a viable trans-Hudson alternative, it has been added to the model structure as a separate mode. This change enables the analysis of LRT-to-ferry transfers as an alternative to LRT-to-Port Authority Trans-Hudson (PATH) for trips destined to midtown or lower Manhattan.

The nonwork model was also modified by replacing a gamma function with a simple look-up tahle of factors based on the 1990 All Modes Trans-Hudson survey. The current approach to modeling nonwork trip patterns recognizes that the number of observations for nonwork trip purposes is not as robust as that for work trip purposes; therefore, a calibrated nonwork logit model would be less robust. Since the work model is calibrated from a robust data base, the resnlts of the home-based work mode-choice model are more reliable, and pivoting off such a model limits the magnitude of error in forecasting transit share for nonwork purposes. Inherent in this current approach is the assumption that the main difference in mode shares for nonwork is due to the inherent difference in trip purpose between work and nonwork travel. This difference is captured by pivoting off the home-based work mode-choice model using mode shares from the 1990 All Modes Trans-Hudson survey to obtain nonwork travel.

Stated-Preference Research

The last model enhancements were improvements to mode-choice coefficient estimates. Under the AA/DEIS model version, the value of time was extremely high, in the vicinity of $45/hour. This value of time implied that riders were relatively insensitive to travel costs as compared with travel times. Further, riders also appeared insensitive to the number of transfers. Since both results seemed counter to past findings, a stated-preference survey (SPS) (*4*) was initiated to assist in refining the model. The SPS was also utilized to challenge the overall nesting structure of the model and to develop a "mode bias" constraint for the LRT mode.

The stated-preference data generally support the model specification, result in a value of time of $15/hour, and reveal that transfers have a significant perceived penalty. The transfer penalty was found to be equivalent to approximately 10 min of in-vehicle travel time and increasing in marginal value for each additional transfer. An additional finding of the SPS is that the LRT mode bias constant is very similar in value to the PATH constant and is therefore a reasonable surrogate for the "new LRT mode" constant. Otherwise, statistical estimation of model coefficients with the stated-preference data produced values very close to those in the original mode-choice model.

Recommendations from the SPS are incorporated into the current HBLRTS model, though model coefficients were estimated using approximately 4,100 revealed-preference observations from the 1990 All Modes Trans-Hudson Survey. The number of transfers is included as an explicit variable with increasing marginal disutility, and the value of time estimated by the new model is similar in value to the SPS value of time. As a result, the current HBLRTS model reflects greater sensitivity to travel cost and a greater resistance to travel paths that increase the number of transfers required. The expected outcome of the SPS was a reduction in LRT use by trans-Hudson commuters because of the new sensitivity to transfer and costs.

The model results mirror this expectation as follows:

	HBLRTS Market Share (%)	
Market Area	*Original Model*	*Current Model(S)*
Trans-Hudson	51.3	48.9
West-of-the Hudson	48.7	51.1

Market and Land Use Analysis

Description of Market Area

The New Jersey Hudson River waterfront is in the stages of major redevelopment, with far-reaching potential for waterfront municipalities and the state in terms of jobs and revenues. Historically, the waterfront housed heavy industry and railroad-related uses, but over the past few decades, industrial and railroad use vacated the waterfront properties, leaving hundreds of acres of abandoned and rusting rail yards, decaying piers, and remnants of warehouses and factories.

During the past several years, interest in the waterfront has been rekindled and redevelopment is occurring, but primarily for nonindustrial or residential uses. Developers seeking to capitalize on the region's housing and office markets have proposed a number of waterfront projects that include office buildings, apartment houses and condominiums, retail centers, restaurants, marinas, parks, and entertainment and recreation centers. Collectively, these projects could create a whole new city along the waterfront.

In nearly all socioeconomic categories, the immediate study area is divided into two distinct parts: the Bergen County section and the Hudson County section. The Bergen County municipalities are generally more affluent (1990 median household income of $49,249 versus $30,917 in Hudson County) but have similar household size (2.67 per household in Bergen County and 2.64 per household in Hudson County); working residents tend toward white-collar, professional occupations, whereas Hudson County was more blue collar. Housing values and median rents in the Bergen towns far exceed those in Hudson County. The Hudson County area is more racially and ethnically diverse, and its residents are younger.

Overall, the area population for Bergen and Hudson counties decreased between 1980 and 1990 by 2.4 percent and 1 percent, respectively. However, employment grew respectively by 22 and 9 percent between 1980 and 1990. Growth is expected in employment and population in both counties through the year 2010. Bergen County is projected to grow in employment by about 1 percent per year and is expected to remain about the same in households to the year 2010. Hudson County's household growth is expected to be 0.898 percent per year to the year 2010. Primarily because of the substantial expected waterfront development, the number of jobs available in Hudson County will grow by 1.2 percent through the year 2010.

Along the waterfront development areas, the 1990 employment level was 22,651 and is expected to grow at 9 percent per year to 43,475 in 2000 and then slow down to 6 percent per year through the year 2010. The number of housing units in 1990 was 10,437 and will grow to 29,181 by 2010.

Development Forecasts

A significant amount of the land surrounding the LRT alignment is vacant today, especially in the core sections of the alignment in downtown Jersey City, Hoboken, and Weehawken, as well as nearby sections of West New York along the waterfront. Although major development plans have been proposed for most of the vacant land, future development patterns are not really known today. The recent decision of the cotton, sugar, and other commodity exchanges to remain in Lower Manhattan instead of relocating 3,200 jobs to Colgate illustrates the volatility associated with future land use forecasts and development patterns. However, estimates of future development at waterfront sites were developed for 2000, 2005, and 2010 to enable the determination of future LRT ridership for those years. The forecasts include estimates of future office space, retail space, and housing units, which have been converted into office jobs, retail jobs, and resident population.

Several sources (6, Appendix D) were used to develop these forecasts to take into account both current conditions in the Hudson River waterfront development environment and current thinking about the economic growth potential in the New York metropolitan area, including Manhattan and Hudson County. These sources were used to develop estimates of total future growth for the area and estimates of growth for each of the individual developments in the waterfront area.

Demand Analysis

Application of the refined HBLRTS model presents an opportunity to assess its reasonableness. In addition, by varying assumptions in the model, it can be shown how sensitive the model is to these changes and the level of confidence of the model. These issues will be addressed by providing a benchmark patronage forecast for review and analysis, various sensitivities and elasticities of alternative model assumptions, confidence intervals around the benchmark, and finally a comparison of the elasticities against local and regional experience.

Benchmark Description

The 2010 benchmark LRT system used for this analysis is the locally preferred alternative, which has two branches, the Bayonne Branch and the Westside Branch (Figure 1). The Bayonne Branch begins at 5th Street in Bayonne and converges with the Westside Branch at the Gateway Park-Ride at Liberty State Park in Jersey City. The Westside Branch begins at Route 440 in Jersey City. In this benchmark system, both branches are scheduled to operate on a 9-min headway and terminate at the Vince Lombardi Park-Ride in Ridgefield. This operation produces an effective headway of 4.5 min between the Gateway Park-Ride and Vince Lombardi LRT stations. The assumed LRT fare is a flat rate of $1.00 with no discounting for intermodal transferring and multiride tickets or other discounts such as that for senior citizens.

The bus service for this benchmark system assumes modifications to both NJ Transit and private carrier routes to feed the LRT service and has not been fully dimensioned in cost or difficulty of implementation, but barring any constraints, it is "feasible" (7).

In addition to bus feeder service, the benchmark sys-

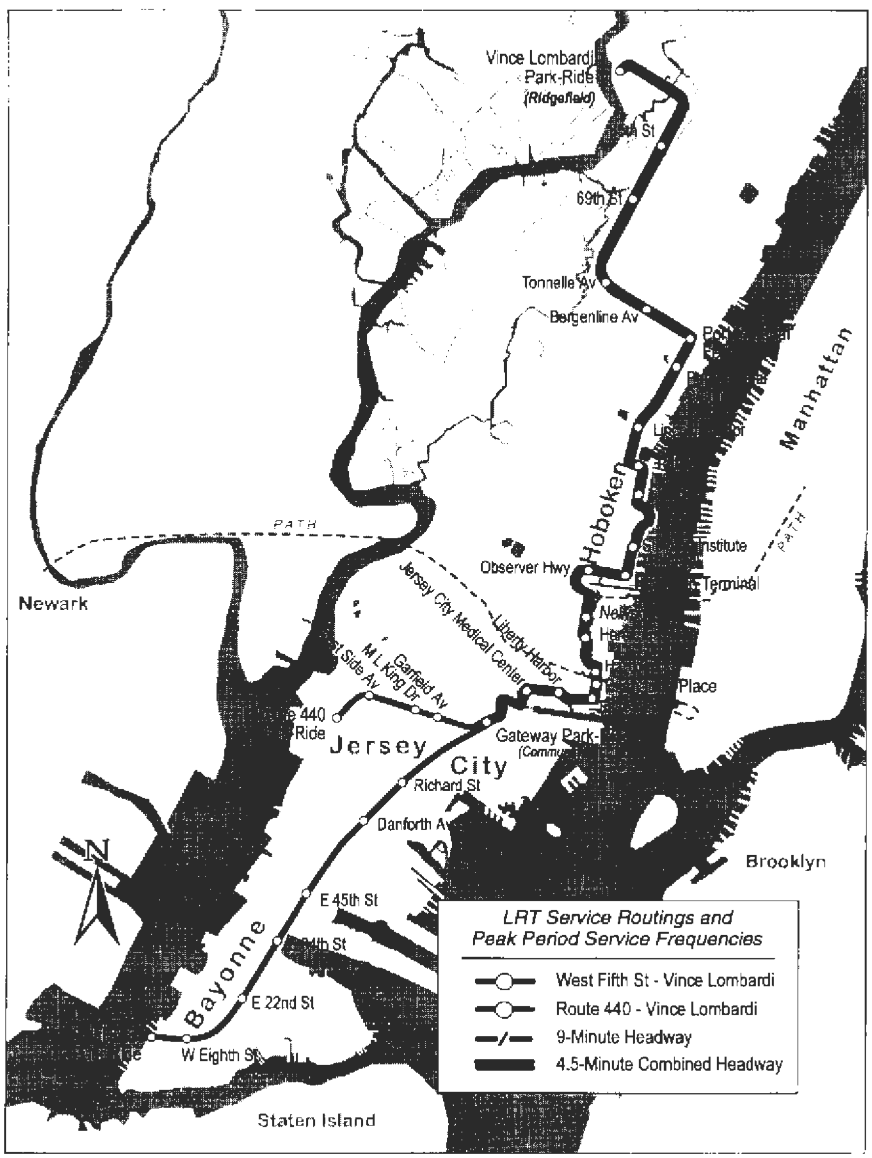

FIGURE 1 LRT alignment.

tem features a series of LRT park-and-ride or "drive-to-LRT" locations. There are 13 LRT park-and-ride locations among each of three branches: Westside, Bayonne, and Northern. Although projected demand for spaces at Liberty State Park would surpass capacity, there is no occurrence of serious undercapacity with respect to the number of daily parkers and the availability of parking spaces. Park-and-ride locations at 5th Street, Liberty State Park, and Vince Lombardi would represent more than 60 percent of the total parking demand. On the basis of nominal parking fees, the minimum expected revenue that the LRT park-and-rides would generate is slightly more than $2.3 million.

Market Share Summary and Patronage Forecast

The total patronage projected for the 2010 benchmark LRT system is 90,200 daily LRT riders. Approximately 48 percent of this patronage is the trans-Hudson market and the remaining 52 percent remain west of the Hudson. The expected annual revenue generated by this patronage is approximately $27 million. The combined revenue generated by LRT ridership and the $2.5 million additional revenue expected from park-and-ride lots brings the total expected LRT revenue to $29.5 million.

When compared with other modes in the region, the benchmark LRT system captures a significant share of transit trips. Approximately 10 percent of all transit trips beginning or ending west of the Hudson and around 6 percent of the transit trips into New York are made on LRT. For transit trips with destinations only to Hudson County, 24 percent, or 43,000, are made on LRT, and transit trips originating in Hudson County have a 20 percent LRT share, or 60,000 LRT riders. Finally, the highest LRT transit share is for intra-Hudson County trips at approximately 27 percent, reflecting 36,400 trips on LRT.

The principal origin markets targeted for the HBLRTS can be defined as Staten Island, southern Hudson County, downtown Jersey City, northern Hudson County, northern Bergen County, and southern Bergen County. Over 40 percent, or 38,000, of all benchmark LRT trips have destinations in either midtown or lower Manhattan. Approximately 28 percent, or over 25,000, are destined to new development areas along the waterfront—downtown Jersey City and other parts of the waterfront in Hoboken or Weehawken.

Southern Hudson County

Although close to 30 percent of the LRT trips that begin south of Hoboken go to Manhattan, over half of the LRT trips from these areas involve local trips between or within Staten Island, Bayonne, southern Jersey City, and downtown Jersey City. This result reflects a significant amount of short-distance, local LRT trips. The LRT serves residents of southern Hudson County well by affording a viable alternative for making local trips, the largest percentage of which occurs in downtown Jersey City. Of the total 7,050 trips originating in downtown Jersey City, approximately 60 percent remain in the downtown area. When the entire waterfront is considered, 8,666 of the 15,339 trips that would originate in the waterfront are local waterfront LRT trips.

Northern Hudson County

In contrast to southern Hudson County, approximately 9,215 LRT trips, representing over 50 percent of the 16,665 LRT trips from northern Hudson County markets, are Manhattan-destined trips, whereas 5,149, slightly less than 30 percent, reflect local or waterfront trips. The largest market for trans-Hudson LRT trips is Bergen County. Over 80 percent, or 9,981 of the LRT trips from this market, end in Manhattan locations.

Comparison with Other Scenarios

Patronage forecasts produced for the LRT benchmark system were systematically compared with results from over 20 different scenarios (6, Appendix F) selected to demonstrate the importance of key variables: LRT run time, LRT frequency, fare policies, and land use assumptions. In addition, a 1990 base year along with a future-year build scenario were selected to demonstrate growth and diversion impacts. The results of these scenarios are shown in Table 1. The scenarios are defined as follows:

1. 1990 base year: no build assumptions, only existing conditions,
2. 2010 build without LRT: all build assumptions such as heavy rail in major corridors but no LRT,
3. 2010 baseline: build assumptions with LRT,
4. Fare: increase in LRT fare from $1 to $2,
5. Frequency: decrease frequency from 9 to 12 min,
6. Run time: increase run time on LRT alignment in mixed traffic,
7. 1990 land use: assumes all build assumptions including LRT but no economic growth, and
8. Development: assumes 100 percent development near LRT stations.

The analyses for the scenarios that did not involve land use changes were performed without rerunning the residential location model. The results thus reflect mode-choice and network equilibration effects only.

TABLE 1 Benchmark and Selected LRT Trips by Market Type

Market:	TRIPS WITH DESTINATION IN HUDSON COUNTY							
		2010						
		BUILD	2010					
	1990	WITHOUT	LRT	LRT	LRT	LRT	LRT - NO	LRT -DEVOLPMENT
MODE	BASE	LRT	BASELINE	FARE	FREQ	RUNTIME	GROWTH	GROWTH
Total Walk to Transit	77.4	136.0	124.2	126.2	126.0	126.2	84.8	141.0
Total Drive to Transit	10.2	22.0	15.0	15.2	15.4	15.4	8.4	18.2
Walk to LRT	0.0	0.0	37.8	33.0	33.8	34.0	17.4	44.8
Drive to LRT	0.0	0.0	5.2	4.8	5.0	5.0	3.4	5.6
Total LRT	0.0	0.0	43.0	37.8	38.8	39.0	20.8	50.4
Total Transit	87.6	158.0	182.2	179.2	180.2	180.6	114.0	209.6
Auto	1096.0	1336.0	1314.0	1318.0	1316.0	1316.0	1094.0	1260.0
Total Trips	1183.6	1494.0	1496.2	1497.2	1496.2	1496.6	1208.0	1469.6
Market:	TRIPS WITH ORIGIN IN HUDSON COUNTY							
		2010						
		BUILD	2010					
	1990	WITHOUT	LRT	LRT	LRT	LRT	LRT - NO	LRT -DEV
MODE	BASE	LRT	BASELINE	FARE	FREQ	RUNTIME	GROWTH	GROWTH
Total Walk to Transit	152.6	220.0	196.4	200.0	199.2	199.6	146.4	209.8
Total Drive to Transit	43.6	62.0	49.2	50.2	50.0	50.2	35.4	50.6
Walk to LRT	0.0	0.0	54.0	47.0	48.8	48.8	30.4	60.0
Drive to LRT	0.0	0.0	6.6	6.0	6.2	6.2	4.8	6.8
Total LRT	0.0	0.0	60.6	53.0	55.0	55.0	35.2	66.8
Total Transit	196.2	282.0	306.2	303.2	304.2	304.8	217.0	327.2
Auto	1188.0	1428.0	1408.0	1412.0	1410.0	1410.0	1182.0	1260.0
Total Trips	1384.2	1710.0	1714.2	1715.2	1714.2	1714.8	1399.0	1587.2
Market:	HUDSON COUNTY TO HUDSON COUNTY TRIPS							
		2010						
		BUILD	2010					
	1990	WITHOUT	LRT	LRT	LRT	LRT	LRT - NO	LRT -DEV
MODE	BASE	LRT	BASELINE	FARE	FREQ	RUNTIME	GROWTH	GROWTH
Total Walk to Transit	54.4	100.0	90.4	92.0	92.2	92.0	62.0	101.2
Total Drive to Transit	4.6	12.0	6.0	6.2	6.2	6.4	3.0	7.4
Walk to LRT	0.0	0.0	32.6	28.2	28.8	29.2	13.2	39.0
Drive to LRT	0.0	0.0	3.8	3.4	3.6	3.6	2.6	4.0
Total LRT	0.0	0.0	36.4	31.6	32.4	32.8	15.8	43.0
Total Transit	59.0	112.0	132.8	129.8	130.8	131.2	80.8	151.6
Auto	738.0	926.0	911.0	912.0	912.0	912.0	738.0	870.0
Total Trips	797.0	1038.0	1043.8	1041.8	1042.8	1043.2	818.8	1021.6
Market:	TRIPS TO NEW YORK CITY - - INCLUDES STATEN ISLAND							
		2010						
		BUILD	2010					
	1990	WITHOUT	LRT	LRT	LRT	LRT	LRT - NO	LRT -DEV
MODE	BASE	LRT	BASELINE	FARE	FREQ	RUNTIME	GROWTH	GROWTH
Total Walk to Transit	292.8	370.0	351.6	353.6	352.4	353.0	268.0	351.4
Total Drive to Transit	219.0	300.0	285.2	286.6	285.6	286.0	213.8	282.8
Walk to LRT	0.0	0.0	28.0	24.6	26.0	25.4	23.0	27.4
Drive to LRT	0.0	0.0	15.2	13.2	14.2	13.8	12.4	15.0
Total LRT	0.0	0.0	43.2	37.8	40.2	39.2	35.4	42.4
Total Transit	511.8	670.0	680.0	678.0	678.2	678.2	517.2	676.6
Auto	1452.0	1842.0	1838.0	1840.0	1840.0	1840.0	1440.0	1840.0
Total Trips	1,963.8	2,512.0	2,518.0	2,518.0	2,518.2	2,518.2	1,957.2	2,516.6

Note: Two directional, 24-hr service; values are in thousands.

1990 Base Year

The primary destination markets, trans-Hudson and Hudson County, are evaluated. Between the 1990 base year and the 2010 LRT benchmark, the market share of total transit increases for trips destined to Hudson County, originating in Hudson County, as well as for intra-Hudson County and remains relatively constant for the trans-Hudson market.

The direction and magnitude of change in automobile versus transit shares are expected. Since there already exists an array of transit services into Manhattan, the transit-to-automobile share is not expected to change significantly with development of the HBLRTS. Instead, shifts between transit modes are more likely to occur in the Manhattan-destined trip market. For instance, modal shifts between PATH and ferry will occur because ferry is now competing with PATH, and the LRT will serve as a feeder to both systems.

Expected future development along the waterfront, even without a seamless north-south transit distributor along the waterfront, explains the increase in transit shares for trips to, from, and within Hudson County. The reasonable magnitude of the increase in trips to, from, and within Hudson County, respectively 5, 4, and 6 percent, reflects existing PATH and local bus competition. As a result, the LRT would divert some PATH and bus users but would also attract some automobile users who are currently not well served by existing transit services.

2010 Build Without LRT

The major difference between the 2010 LRT benchmark and the 2010 build without LRT scenarios is the change in automobile, PATH, and Port Authority Bus Terminal (PABT) bus volumes. As shown in Table 1, the 2010 LRT benchmark would decrease 24-hr daily automobile volumes by 22,000 for trips destined to Hudson County, by 20,000 for trips originating in Hudson County, by 15,000 for intra-Hudson County trips, and by 4,000 for Manhattan trips. Table 2 shows that 24-hr daily PATH volumes would increase by more than 20,000 trips.

This last result is the effect of the LRT-to-PATH relationship, which becomes evident when the LRT is included. What also shows up is the reduction in the use of PABT buses to enter Manhattan because commuters would exercise the option to use LRT-to-PATH or LRT-to-ferry routes. For instance, at Hoboken Terminal, in the 2010 build without LRT scenario, there are approximately 48,000 daily transfers to PATH, and in the 2010 LRT benchmark, which includes the LRT, there are around 72,800 daily transfers to PATH. The additional PATH transfers generated in the LRT benchmark are a result of the LRT.

TABLE 2 Ridership Boardings by Mode

MODE	1990 BASE 24-HR ONE-DIR	2010 BUILD WITHOUT LRT 24-HR ONE-DIR	2010 BUILD WITH LRT 24-HR ONE-DIR
Hoboken Rail	32,500	61,047	60,294
Newark Rail	50,083	77,810	77,182
Ferry			
Hoboken	1,635	2,329	2,147
Port Imperial - Midtown	4,431	6,681	7,772
Port Imperial - Downtown	53	178	46
Colgate	na	1,156	1,133
PATH (Trans Hudson)			
North Tunnel	39,869	42,437	50,675
South Tunnel	53,739	72,456	75,478
Total PATH:	93,608	114,892	126,152
Bus			
Route 9	8,401	12,057	12,326
PABT (Trans Hudson)	83,258	91,644	86,632
LRT	na	na	45,617

Land Use Impacts

The impacts of various land use assumptions can be observed best by evaluating impacts in specific markets. Two land use scenarios were analyzed. The first scenario assumed that there would be no economic growth in the region but that all capital rail improvements would be made, inclusive of the LRT. The other scenario assumed that 100 percent of proposed development would occur in or near the vicinity of LRT stations.

No Growth

Even in the absence of economic growth, the LRT would still generate over 60,000 daily trips. Market-specific impacts of importance include the following:

1. A diversion from automobile to transit would occur as compared with the 1990 base year. There would be 2,000 and 6,000 fewer daily automobiles for trips with destinations or origins, respectively, within Hudson County, and 12,000 fewer automobiles into New York. Because the 1990 base year and the no growth scenarios assume the same economic conditions, this result clearly demonstrates that an LRT option greatly benefits current commuters.

2. When compared with the 2010 benchmark scenario, the no growth scenario results in an increase in the portion of LRT trips that go into Manhattan from

43 to 54 percent and a corresponding decrease in the portion of LRT trips to the waterfront. In addition, approximately 6,700 of the 30,000 loss in LRT trips caused by no growth occurs in the Manhattan trans-Hudson market.

3. An additional 20,500 reduction in LRT trips along the waterfront occurs in the absence of growth. This loss accounts for slightly over two-thirds of the difference in LRT ridership between the 2010 LRT benchmark and the 1990 no growth scenarios. The remaining trips would be lost to and between other locations.

100 Percent Development near LRT Stations

An expected result is that greater development within waterfront locations at or near LRT stations would shift the share of LRT trips bound for Manhattan versus those bound for the waterfront as the New Jersey Hudson River waterfront increases its share of housing and jobs in the region. A comparison between the 2010 LRT benchmark and 100 percent development scenarios verifies this expectation. Although the net gain in LRT trips is 6,800, 100 percent development around LRT stations increases LRT trips to the waterfront by more. In fact, LRT trips to waterfront locations increase by approximately 9,000 as other locations realize a net loss in LRT trips. Conversely, LRT trips from waterfront locations increase by more than 3,000. These results demonstrate the impact of transit accessibility in the choice of work and residence locations.

Fare

Compared with the 2010 LRT benchmark scenario, a \$1.00 increase in the LRT fare causes a 12 percent decrease in ridership but an increase in revenue of 76 percent, or \$20.4 million. The changes are evenly distributed throughout the various markets as well as among the various LRT boarding segments. Daily weekday LRT trips into Manhattan decrease by 4,800, but annual revenue increases by around \$8.7 million. LRT trips into waterfront locations decrease by 3,000 but revenue increases by approximately \$5.8 million. Total annual revenue increases by \$20.4 million and daily weekday LRT ridership decreases by 11,000.

Frequency

Decreasing frequency from 9 to 12 min over the 2010 LRT benchmark has the effect of reducing overall LRT ridership by approximately 8 percent, or 7,400 daily riders, and produces a corresponding 9 percent decrease in revenue, or \$2.2 million. The distribution of LRT ridership to and from targeted markets remains relatively constant as compared with the 2010 LRT benchmark. The change in LRT frequency has less impact on ridership and fares than a change in LRT fare policy, and much less impact than that resulting from a change in economic growth.

Run Time

An increase in LRT run time decreases LRT ridership only slightly more than a decrease in frequency: an additional 900 riders would be lost accompanied by an additional \$200,000 loss in revenue. The effects of the change in LRT run time also occur proportionately as the market shares remain relatively constant against the 2010 LRT benchmark.

Sensitivity of Forecasts to Policy

Over 20 alternative policy assumptions were made to produce different LRT scenarios. Table 3 shows some of these scenarios and the associated policy assumptions, ridership result, percentage change over the LRT benchmark, and elasticity where appropriate. The impact of the LRT fare policy is roughly symmetrical. Total LRT riders have an elasticity of −0.12 when fare is either increased or decreased. However, for trans-Hudson only LRT riders, the fare elasticity ranges from −0.18 to −0.25. For intra-New Jersey LRT riders the elasticity is −0.12. This means that trans-Hudson riders are more sensitive to changes in fare policy, primarily because this market has more transit options, and the absolute dollar change of the total cost is greater for this market than it is for intra-New Jersey riders (i.e., trans-Hudson riders generally pay multiple fares and have a higher total fare).

The park-ride fare policy is not symmetrical. When only drive-access trips to the LRT are considered, elasticity increases to around 0.08 for drive-access LRT riders (Table 4). The elasticity for a frequency policy is slightly greater when the wait time is shortened: −0.24 versus −0.25.

All elasticities move in the expected direction. The greatest ridership change occurs when assumptions regarding economic growth are changed. Changes in fare policy have the next most significant impact, although not as substantial as changes in growth assumptions. LRT run time and frequency assumptions have the least impact within the range explored. LRT ridership is not greatly affected by policy changes on other modes except in the instance of feeder buses, in which case the extent to which feeder bus service is within the control or influence of the LRT operator will affect ridership and revenue benefits expected from the LRT system.

TABLE 3 Sensitivity and Elasticity

Scenario No.	Description	Ridership	% Change	Elasticity
0	Baseline Scenario	90,167		
1	Increase LRT fare: $2.00	79,149	-12.22	-0.12
2	Decrease LRT fare: $0.50	95,381	5.78	0.12
3	Employ distance based LRT fare:	86,881	-3.64	n/a
4	Increase non-LRT fare: PATH $2.00	86,043	-4.57	0.05
5	Increase non-LRT fare:Ferry 25%	89,645	-0.58	-0.02
6	Increase non-LRT fare: Bus 25%	90,839	0.75	0.03
7	Increase LRT frequency: 12 min	82,808	-8.16	0.24
8	Decrease LRT frequency: 6 min	97,566	8.21	0.25
9	Increase LRT park-ride cost 100%	88,075	-2.32	-0.02
10	Decrease LRT park-ride cost: 100% (free parking)	91,707	1.71	0.02
11	Increase non-LRT park-ride cost: PATH 25%	90,449	0.31	0.01
12	Increase non-LRT park-ride cost - Ferry 25%	90,081	-0.10	0.00
13	Change feeder bus headway: NJ Transit only	80,224	-11.03	n/a
14	1990 landuse and 2010 network	60,112	-33.33	n/a
15	Increase LRT run time: non fixed guideway segment	81,917	-9.15	n/a
16	Increase auto highway and "drive-to" time 10%	89,707	-0.51	-0.05
17	Increase Hudson River Crossing Tolls: 25%	90,903	0.82	0.03
18	Increase auto parking cost in Waterfront downtown:25%	90,185	0.02	0.00
19	Different regional forecasts of population &employmt	97,271	7.88	n/a
20	100% development at projects adjacent to LRT station	96,976	7.55	n/a

Note: Baseline scenario—9-min frequency, $1.00 fare, feeder bus plan.

TABLE 4 Sensitivity and Elasticity by Market Type

	TRANS-HUDSON LRT/PATH RIDERS			
Scenario	Description Scenario	Ridership	% Change	Elasticity
0	Baseline Scenario	47,121		
101	Increase Trans-Hudson Total Transit Fare:$1	41,325	-12.30	-0.25
	DRIVE ACCESS TRIPS ONLY			
No.	Description	Ridership	% Change	Elasticity
0	Baseline Scenario	21,759		
109	Increase LRT park-ride cost 100%	19,972	-8.21	-0.08
110	Decrease LRT park-ride cost: 100% (free parking)	23,780	9.29	0.09

Note: Baseline scenario—9-min frequency, $1.00 fare, feeder bus plan.

Sensitivity of Forecasts to Model Sampling Error

It is generally not possible to specify a precise confidence interval for forecasts from a travel demand modeling system such as that developed for HBLRTS. Even for a single component such as a statistically estimated mode-choice model, there are several possible sources of error, not all of which can be quantified. A confidence interval representing sampling errors can in theory be constructed for the HBLRTS mode-choice model. To do that for the full model requires a relatively complex set of calculations. A simple alternative is to estimate the range in forecasts that would result from variations in the individual model coefficients within their statistical confidence levels.

Table 5 shows the changes in LRT forecasts that result from variations in mode-choice model coefficient values within 2 standard deviations from the estimated values. Results are shown for each of the model variables and for the structural parameters of the nested logit model. They are also shown both with and without iteration through the residential-choice model (fixed versus non-fixed trip tables). The greatest ranges in estimates come from the transfer variable and the coefficient for the nest

TABLE 5 Sampling Error

Coefficient Name	Coefficient Value	Standard Error (SE)	Original Model Result	Fixed Person Table +2*SE	Fixed Person Table -2*SE		Non-Fixed Person Table +2*SE	Non-Fixed Person Table -2*SE
Transfer	-0.423400	0.0546	90,167	93,494	86,086		94,955	85,804
Cost/Income	-0.007361	0.000587	90,167	87,496	91,622		88,343	91,681
In-Vehicle	-0.047360	0.00212	90,167	88,515	90,776		87,149	92,766
Emp Density	-0.001398	9.06E-05	90,167	88,093	91,173		88,032	92,131
Nest 1	0.560500	0.0211	90,167	84,605	95,423		83,538	97,437
Nest 2	0.794600	0.0621	90,167	90,196	88,798		90,554	89,122
Nest 3	0.283000	0.0252	90,167	87,131	92,423		86,736	93,776
Nest 4	0.493300	0.0404	90,167	90,569	88,571		90,930	88,744

that includes walk to LRT. Generally, however, the sampling errors from individual coefficient values result in only approximately 5 percent variations in forecast LRT patronage.

Local and Regional Experience

LRT fare elasticity ranges from −0.18 to −0.25 for trans-Hudson commuters and is −0.12 for intra-New Jersey commuters as compared with the elasticities on local or interstate bus and rail, which fall within a range of −0.2 to −0.3. This result can be attributed to the fact that roughly 55 percent of the LRT passengers transfer to another mode to complete the entire trip, and therefore the actual change in fare is less.

The overall PATH elasticity estimated from the model is very close to historic PATH elasticities calculated by Regional Plan Association (RPA) in 1989. Based on actual ridership data, these elasticities were between −0.04 and −0.06. The 95 percent confidence interval indicated that the elasticity could range up to −0.19.

The fare elasticity of the New York City subway system appears close to the LRT elasticity. Charles River Associates estimated a fare elasticity of −0.166 covering the period 1975–1984. Other subway elasticities range from −0.09 to −0.209.

The model's elasticity of ±0.245 is almost an exact match to RPA's historic data on subway frequency of 0.24 for an increase in service frequency.

Conclusions

Forecasting experiments are shown to illustrate the overall sensitivity of model forecasts to policy variables and possible future scenarios. The refined and reestimated HBLRTS model is appropriately sensitive to cost, transfers, and frequency. Patronage results are within reasonable ranges and generally have a 95 percent confidence level. The LRT elasticities are consistent with historic New York subway, PATH, local bus, and interstate bus experience. Major findings of the analysis are as follows:

- Important destination markets for the HBLRTS are Manhattan and waterfront locations. Respectively, these destination areas account for approximately 42 and 28 percent of the LRT trips.
- Important origin markets for the HBLRTS include Staten Island, Bayonne, southern Jersey City, the waterfront, northern Hudson County, and Bergen County. Combined, these areas are the source of over 74,000, or 82 percent, of the total 90,167 LRT trips.
- Forty percent of the HBLRTS ridership is a strong, local, intra-Hudson County commutershed. Of the total 90,167 LRT riders produced by the 2010 LRT benchmark scenario, 36,400 are intra-Hudson County trips.
- Southern Hudson County is an important LRT market for waterfront-destined trips, whereas northern Hudson County and Bergen County have predominately LRT riders for New York–destined trips. Both southern and northern Hudson County are also strong local LRT markets.
- Expectation regarding employment growth is the most critical factor for projected HBLRTS ridership and revenue. Comparing a model run that assumed 2010 employment and population growth projections with a model run that assumed only 1990 economic conditions but 2010 transportation facilities shows a variance of 30,000 LRT riders over the 2010 benchmark result.
- Economic development around LRT stations will shift the share of Manhattan- versus waterfront-bound LRT trips. When 100 percent development is assumed around LRT stations, the share of commuters to Manhattan fell from 0.43 to 0.39 and the share of trips to the waterfront increased from 0.28 to 0.36. In addition, the 100 percent growth assumption resulted in an additional 20,500 LRT riders over the 2010 benchmark scenario.
- Four other policy variables that are important in projecting LRT ridership and fare levels are, in order

of importance, LRT fare, LRT run time, and LRT frequency.

• An LRT feeder bus system will enhance patronage of the system. The ability to control and influence the feeder service will affect the degree and consistency to which this enhancement can be accomplished.

• LRT fare elasticity is higher for trans-Hudson commuters using the LRT than it is for intra-New Jersey LRT riders.

• All LRT elasticities move in the expected direction and are consistent with historical local and regional experience.

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Networkwide Approach to Optimal Signal Timing for Integrated Transit Vehicle and Traffic Operations

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An intermodal networkwide strategy is presented for the determination of optimal traffic signal timings in locations such as reserved transit malls in central business districts where light-rail transit (LRT) vehicles are subject to the same traffic controls as motor vehicles. The determination of optimal signal timings is crucial for public transit since delay at signals contributes significantly to passenger dissatisfaction with the system. Some jurisdictions have little or no coordination of traffic signals with LRT movements, whereas others use some priority systems, often signal preemption, that can seriously disrupt the flow of other traffic at intersections. The strategy considered here is unique because it is both integrated and networkwide, thereby balancing the needs of public transit with those of private vehicles. Traffic and LRT, including all intersections and stations, are treated as one intermodal system for which traffic signal timings are optimized to minimize delay and maximize throughput. The methodology is based on a neural network that determines, in real time, the parameters that control the traffic signal timings. It extends a previously developed methodology, a fundamentally new approach to signal timings for motor vehicular traffic, to the integrated LRT and traffic network. The approach is illustrated by a prototype simulation of part of the Baltimore central business district.

One of the major concerns in the design and operation of light-rail transit (LRT) is the interaction between LRT and other traffic. LRT operations are common on grade level in the central business district (CBD) of many cities, sometimes operating directly on city streets but more frequently using reserved transit malls. Such malls can take several forms. They may consist simply of a portion of a street reserved for LRT with painted lane markings separating the light-rail vehicles (LRVs) from other vehicles, as on Howard Street in Baltimore. Alternatively, such malls may consist of the median strip of a major street (the northern part of First Street in San Jose, for example), or the entire street may serve as a transit mall (the southern part of First Street in San Jose or C Street in San Diego, for example). Although all such malls are successful in keeping LRVs separate from motor vehicle traffic between intersections, the LRVs are subject to the same traffic signal system as other traffic. Although there may be separate phases for LRT at traffic signals, LRVs must often stop for cross traffic. Thus, in addition to the time spent stopping at stations, LRT is subject to significant delays at traffic signals. Because of heavy use of LRT by the general public, such delays significantly reduce person throughput and increase travel time, thereby contributing, in some degree, to public dissatisfaction with public transit. This is a significant problem to address in the LRT planning process.

Approaches to the problem of interaction between LRT and motor vehicles at signalized intersections attempt to give LRT some priority over motor vehicles. There are several methods of giving such priority to LRT, ranging from minor changes in the signal phases to accommodate LRT to more extreme measures such as signal preemption. Although there are many specific implementations of signal preemption, the basic idea is for the LRV approaching a signalized intersection to communicate its proximity to the controller unit at the intersection and then for the controller timer either to extend the green phase to allow the LRV to go through or to force a red phase on cross-street traffic. Either method provides the LRV with a green phase.

There is a good deal of literature on priority systems. For example, some of the considerations involved in the design and planning of priority systems are discussed by Stone and Wild (1). One of their main recommendations is that in designing priority systems, particularly signal preemption, total delay should be considered, including both delay for motor vehicle users and delay for LRT passengers. In addition, simulated results showing the effect of preemption on total delay are provided. Radwan and Hwang (2) discuss methods of evaluating the preemption system with respect to passenger delay, and some simulation results are given. In addition to the work by Stone and Wild and by Radwan and Hwang, the effects of preemption systems on the throughput and delay of motor traffic are discussed by Gibson et al. (3), Celniker and Terry (4), and Yagar and Han (5). As these authors show, the effect of preemption on the integrated system of traffic and LRT is mixed. Clearly, preemption can speed the passage of LRT, but it can also have unexpected and sometimes adverse effects on cross traffic. In fact, in San Diego [see discussion by Gibson et al. (3)], studies conducted soon after the opening of the LRT system in 1981 indicated that preemption had very little negative effect on other traffic, whereas later studies there [see discussion by Celniker and Terry (4)] did show a negative impact. These results prompted a change from a preemption system to a more passive system of priority for LRVs.

In this paper a significantly different approach to the interaction of LRT and traffic at signalized intersections along a transit mall is presented. The approach produces, in real time, signal timings that are tuned to approach optimality relative to a measure of effectiveness (MOE) that accounts for both LRT and motor vehicle traffic. The MOE reflects total traffic and transit passenger delay in the system and is calculated with real-time sensor data from both the LRT and traffic components of the system. This approach is very different from an approach based purely on preemption because, from the outset, the signal operation here will be responsive in real time to the needs of the total intermodal traffic and transit system rather than to the needs of transit alone. Although this approach is perhaps most useful on transit malls where preemption is a less popular alternative, it can still be used in conjunction with preemption. For example, at times of heavy traffic, when preemption might cause large queues to build up on cross streets, preemption could be suspended and this approach used. Again it is to be emphasized that this approach is designed to mitigate delay in the combined transit and traffic network in an integrated way, emphasizing the tradeoffs between LRT and motor vehicle traffic.

In this approach, the networkwide traffic control methodology of Spall and Chin (6) is combined with a simple but realistic model for LRT movements on reserved malls to obtain a strategy for signal timing control in the integrated system. In the methodology of Spall and Chin, traffic sensor data are used to obtain networkwide signal timings without having to use a detailed flow model for the traffic network. Attempts to obtain reliable models for real-time traffic control on a networkwide basis have been unsuccessful (6,p. 1868; 7,p. 258), largely because of the complexity of vehicular interaction in a large network and the inability to model driver behavior. Thus, an approach not dependent on large-scale models is a desirable feature. The traffic control strategy, as discussed by Spall and Chin, applies to motor vehicle traffic. In order to extend its applicability to the intermodal traffic and LRT system, a model for LRT movements is developed in this paper. In contrast to the difficulty of modeling traffic on a networkwide basis, modeling of LRT, at least on reserved malls as considered in this paper, is simpler. On the reserved malls being considered, interactions with traffic take place only at intersections, and therefore LRT moves with predictable regularity. (In this paper, interaction between LRT and pedestrians is ignored.) Therefore, in contrast to modeling general traffic flows, modeling such LRT movements is a reasonable task.

This paper is organized as follows: The integrated signal control strategy is described, showing how the results of Spall and Chin (6) are extended to include LRT. The LRT model, which is critical in such an extension, is discussed in more detail next. Prototype simulation results, showing how the approach could be used on a portion of the Baltimore CBD, and a summary are provided.

Signal Timing Control Strategy

In presenting the signal timing strategy, first a discussion of the strategy as it pertains to motor vehicle traffic alone is given, as it was originally developed by Spall and Chin (6). Then its extension to the joint LRT and traffic network is given.

As discussed earlier, the signal timing strategy uses real-time traffic flow data to produce signal timings that are optimized relative to a predetermined MOE. The MOE used here is person delay. Results of simulation studies using this strategy and MOE are provided by Chin and Smith (8). However, the approach has the additional advantage that it is readily adaptable to other MOEs. The mathematical techniques are based on use of a neural network (NN) as an approximation to the true, but unknown, mathematical function that controls the signal timings. Performance of the NN depends upon accurate estimation of a large number of parameters called *weights*, which, together with current traffic flow data, determine the signal timings. Accurate estimation of the weights is accomplished by optimization of the MOE using the method of simultaneous perturbation stochastic approximation (SPSA), a general optimization tool well suited for multivariable problems. Optimization of parameters is performed by efficiently extracting information from repeated applications of small, simultaneous perturbations to all the estimated parameters over a period of several days. The timings and associated weights are estimated to apply to a large range of per-cycle traffic fluctuations that vary from light to congested conditions and from smooth to surge traffic behavior. The weights are updated from day to day by SPSA in a gradually adaptive process that proceeds to optimize the signal timings relative to the prescribed MOE calculated from traffic sensor measurements. The real-time traffic flow data are used in two ways. The first is to update the NN weights from one day to the next. The second is to calculate the most appropriate signal timings for the immediate signal cycle using the most recent set of NN weights.

In extending this approach to cover the intermodal system of LRT and traffic, the two main issues are determining what real-time data are to be used and determining what the MOE is to be. Whereas a wealth of real-time traffic data is available from sensors, the same may not be true for LRT. However, it is reasonable to expect that some measurements are available of the times at which the LRV passes a few known points along the transit line. Therefore all that is required are these measurements.

The transit model described in the next section then "fills in" estimates for intermediate times along the route. There are several means of obtaining such measurements. One such way, which is becoming popular in the transit industry, is the Global Positioning System (GPS). Other vehicle location systems, such as scanners on utility poles, would also be adequate for the measurements that are needed in this process. [Several such systems are discussed in Vuchic's text (*9*, p. 288).] Even with modern automatic vehicle location systems such as GPS, it is still necessary to have a model for LRT for those times when data from the vehicle location system are not available. (This may occur when the GPS signal is blocked by tall buildings, for example.) In addition to time measurements, detailed measurements of passenger loads are useful. In their absence, however, rough, average values could be used as an alternative.

Analogous to traffic flow data, the information provided by the transit model is used in two ways. First, this information is used to update the NN weights from one day to the next and then to actually determine the signal timings at the current time. The latter is a particularly important use for the model because the timings change depending on the presence of an LRV, and it is the model that provides the information about the location of the LRVs.

In order to accommodate LRT as well as traffic, the MOE used in the traffic control strategy is augmented with terms reflecting delay in transit. Delay is with respect to a target schedule, namely, a schedule that could be reached with minimal delay time at traffic signals. Thus, a target schedule is somewhat more optimistic than the usual public transit schedule. To compute the MOE, the procedure is first to determine, at each intersection, whether an LRV will arrive there according to the model. If so, a delay term for the LRV is computed as

$$\text{Delay}_{\text{LRV}}(t) = n(t)[S(t) - M(t)] \tag{1}$$

where

$S(t)$ = time from the point of most recent measurement according to the target schedule,
$M(t)$ = corresponding time as computed by the model, and
$n(t)$ = number of passengers (or average number of passengers if the exact figure is not available).

The delay term in Equation 1 is squared and summed over all LRVs in the network and added to the delay terms for traffic queues. The combined delay expression is then used in the mathematical optimization routine. Similar to the traffic count data used as input by the NN control process as described by Spall and Chin (*6*), the combined traffic and LRT control process uses these data plus LRT real-time location data to determine signal timings for the next traffic signal cycle.

Time and Location Model for LRT Movements on Reserved Malls

In this section a more detailed description of the model for LRT movements is provided. As stated earlier, this model is a history of locations and corresponding times that the LRV passes each location. The locations are known, the arrival times at one or more previous locations are known exactly, and the model estimates the time component of LRV arrival at each new location.

The time component of the transit model is obtained by estimating the time that the LRV spends at stops, including both traffic signals and stations, and the time it takes for the LRV to travel from one stop to the next. Because only movements on a reserved transit mall (rather than movements on a city street) are considered, it is reasonable to suppose that traffic signal and station stops are the only stops the LRV makes. (The same would be true on a private right-of-way away from the CBD, with even fewer traffic signals.) The procedure is repetitive, starting at a point with an available accurate measurement and estimating along the way until reaching the next point with a new accurate measurement, and then beginning the process again. This leads to a time history at all traffic signal and station stops. The model assumes constant start-up acceleration, constant speed during cruising, and constant braking. Therefore, it is a straightforward matter to compute times at locations intermediate to the stops. The approach is stochastic in nature, and therefore random variability in these physical parameters can be incorporated into the model.

To estimate the time spent in motion from one stop to the next, the regimes-of-motion method discussed by Vuchic (9, pp. 159–174) is followed. When the distance between stops is long enough for the LRV to reach maximum speed, the stop-to-stop time is

$$t_{\text{stop-to-stop}} = \left[\frac{D}{V} + \frac{V}{2}\left(\frac{1}{\bar{a}} + \frac{1}{\bar{b}}\right)\right] \tag{2}$$

where

D = distance (m) between stops,
V = maximum speed (m/sec),
$\bar{a}$ = acceleration rate (m/sec^2), and
$\bar{b}$ = braking rate (m/sec^2).

When the distance between stops is shorter and the LRV does not reach maximum speed, the stop-to-stop time is

$$t_{\text{stop-to-stop}} = \sqrt{\frac{2(\bar{a} + \bar{b})D}{\bar{a}\bar{b}}} \tag{3}$$

where D is again the distance between stops.

The time t_{stopped} (sec) that the LRV spends at stops, both signals and station stops, as indicated in Figure 1, is now estimated. If the LRV arrives during the red phase with r sec remaining until the next green phase begins, then $t_{\text{stopped}} = r + t_s$, where t_s (sec) is the start-up (or reaction) time, the time it takes the LRV to start once given the green indication. When the LRV stops at a station, the time it spends stopped is the sum of the lag time t_L (sec) from when the vehicle stops to when the doors open; the dwell time t_D (sec), that is, the passenger ser-

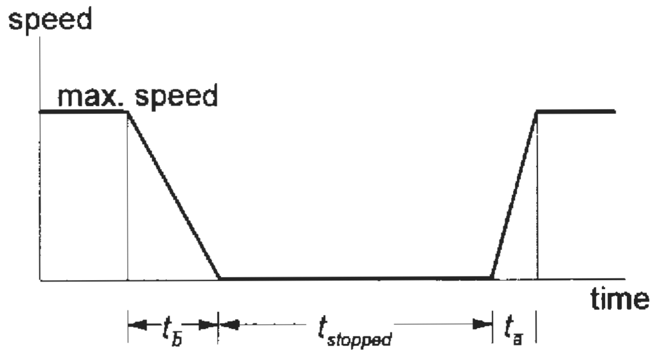

FIGURE 1 Model time profile for LRT stop cycle (does not include start-up time).

vice time; and start-up time t_s, described above. Thus, $t_{\text{stopped}} = t_L + t_D + t_s$. The time spent accelerating t_a (sec) and the time spent braking t_b (sec) in Figure 1 are included in the stop-to-stop time discussed earlier. The *Highway Capacity Manual* (10, Chapter 12) provides nominal values for these times, although in practice they can be determined in field tests.

The model for LRT movements is now complete. Starting with a point where an accurate measurement of time is available, the time to all stops and potential stops (i.e., green traffic signals) can be calculated. Equations 2 and 3 are used to estimate the time that the LRV is moving, and the discussion in the previous paragraph is applied to estimate the time the LRV is stationary. Mathematically this can be expressed as follows. If the stops (stations and traffic signals) are denoted as stop (0), stop (1), stop (2), and so on, the time that the LRV arrives at stop (k) is

$$T_{\text{stop}(k)} = \sum_{j=0}^{k-1} \left\{ t_{\text{stop}(j)\text{–to–stop}(j+1)} + t_{\text{stopped[stop}(j)]} \right\}$$

To fill in at other locations between stops, Equations 2 and 3 can also be used. It is important to emphasize that knowing the exact location at all points is not critical because the stochastic (SPSA) nature of the approach allows the control algorithms to accommodate random variations in all parameters in the model. For clarity, terms representing random variations have been omitted from the discussion.

Baltimore Prototype Simulation

The integrated transit and traffic control strategy is now illustrated with a prototype simulation study of a portion of the Baltimore CBD. The configuration of the simulation area is shown in Figure 2. There are 17 signalized intersections with 38 queues, whose timings are controlled in this simulation. Although there are other

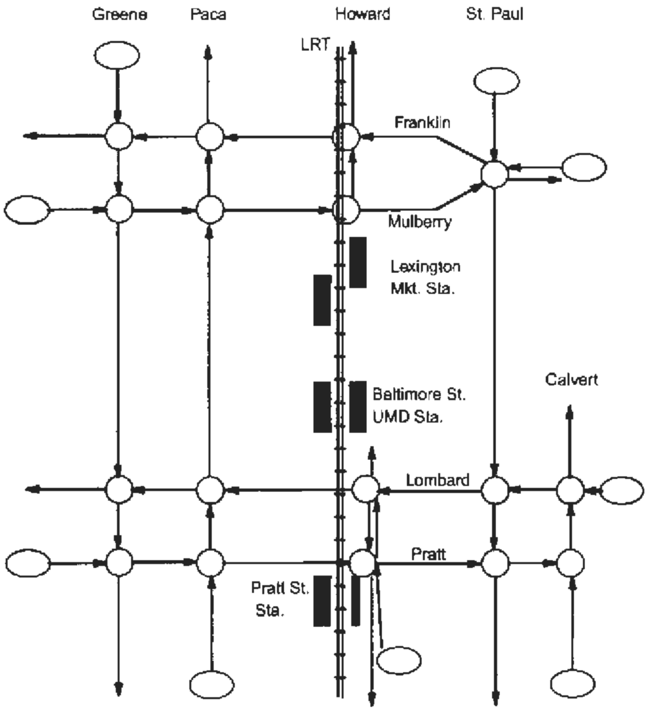

FIGURE 2 Baltimore simulation configuration. Circles denote signalized intersections and ovals denote input nodes.

streets with signalized intersections within the grid, the chosen streets are the major thoroughfares within the Baltimore CBD. Four of these intersections include LRT, which operates double-tracked on Howard Street. Motor vehicle traffic is heavily restricted on Howard Street, and therefore the only traffic flows considered there are those shown in Figure 2. Three LRT stations are shown in Figure 2; actually only the Baltimore Street and Lexington Market stations are within the simulation grid, and the Pratt Street station is on the border of the grid.

The simulation period covers the evening peak period from 4:00 to 6:00 p. m. Traffic flows and initial signal timing information used in the simulation were derived from data supplied by the Baltimore Department of Transportation. Saturation conditions are present on all portions of the east-west streets. Peak-period cycles are 110 sec, and the splits generally favor east-west traffic (*11*, p. 5). In particular, splits on intersections on Howard Street, north of Lombard Street, provide the green signal to east-west traffic about 70 percent of the time. In the simulation (and in practice), LRT trains with three cars operate every 15 min at a maximum speed of about 32 km/hr (20 mph).

The integrated LRT and traffic control strategy was used to determine signal timing splits for the 17 intersections in the simulation network throughout the simulation period. As mentioned earlier, the timing splits are determined by NN weights; for this scenario 1,033 of these weights, with two hidden layers, were estimated. (The greater versatility afforded by two hidden layers as opposed to one is required because the transit and traffic system is not linear.) Although the estimated timings change continuously (cycle-to-cycle) depending on traffic flow and LRV position and load, the underlying NN weights are changed in an optimal adaptive manner over a longer-term basis (days and weeks). In this scenario, this adaptive process lasted about 3 months.

Table 1 shows the average person delay over the 2-hr simulation period at the end of the adaptive process for both the traffic and transit components of the network. Results are shown for three cases: (*a*) fixed signal timings, similar to the current system (baseline); (*b*) timing splits determined by the integrated transit and traffic strategy discussed in this paper, and (*c*) timing splits determined by a simulation of preemption without the integrated strategy. For traffic, person delay is simply the expected time spent waiting at red signals for all motor vehicles in the network times 1.4, which was used as an average value of persons per vehicle. For LRT, delay is as given by Equation 1 relative to a target schedule and reflects the passenger load, consistent with the MOE as discussed earlier. The target schedule is computed using the time and location model and is the fastest possible schedule. (Preemption provides a 10-sec slower schedule since it is assumed that the operator will have to slow down to ensure having the green indication. Therefore, the delay with preemption is small, but not zero.) Passenger load was derived from data supplied by the Mass Transit Administration, Maryland Department of Transportation.

As shown in Table 1, the SPSA-based integrated transit and traffic control strategy is very effective in reducing person delay in the network both for traffic and for LRT.

TABLE 1 Person Delay for Integrated Transit and Traffic Control Strategy Compared with Other Approaches

	Person Delay (hours)		
Method	LRT	Traffic	Total
Fixed Signal Timing (Current Baseline)	42	288	330
LRT Preemption Only	4	318	322
Integrated Transit and Traffic Strategy	33	272	305

When compared with signal preemption, the integrated strategy (and the baseline) is, as expected, less effective than preemption for the LRT portion alone. However, as shown in Table 1, preemption can significantly increase delay to motor vehicle traffic. This increase is 17 percent above the integrated approach and 10 percent above the baseline. When applied to the total network, therefore, preemption shows a 6 percent increase in delay above the integrated approach and slight (2 percent) decrease in delay compared to the baseline. Compared with the current baseline, the integrated approach reduces LRT delay by 21 percent and traffic delay by 6 percent. For the total network, this translates into an 8 percent reduction in delay with the integrated approach.

SUMMARY

A networkwide strategy for the determination of optimal traffic signal timings that balances the needs of LRT and motor vehicle traffic is provided. It operates in real time, using information about the LRV's position and traffic flow data. Through prototype simulations, it showed the capability to significantly decrease delay in the total (LRT plus traffic) network when compared with either the fixed-interval-type controller (currently used) or the preemption method that is popular with several LRT systems.

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Application of Light-Rail Transit Flexibility: Dallas Area Rapid Transit Experience

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The planning, design, and construction of a light-rail transit (LRT) line require that a wide range of complex issues be resolved. Although no one mode of transit can serve as the best alternative for every corridor, light rail has significant advantages in many applications. A unique feature of LRT is its flexibility, versatility, and ability to develop incrementally. It can be adapted to a wide variety of geographic and topographic conditions, financial capabilities, rights-of-way, and existing infrastructure. In addition, this flexibility can have a direct impact on the design of light-rail stations and the vehicle to be operated on the system. The Dallas Area Rapid Transit (DART) initial three line operating environments are described. DART's application and implementation of LRT technology in a variety of complex operating environments are summarized, and the paper concludes with a status report on the light-rail starter system construction program. Almost every segment of the 32.2-km (20-mi), 21-station starter system presents a different situation, ranging from on-street to grade-separated conditions. The starter system includes a new Trinity River Bridge, grade separations, aerial alignments, a subway, a central business district mall, joint use of a utility corridor, median running, and standard railroad environments. This flexibility has also been incorporated into the specifications for the light-rail vehicles and the stations that will be served. Revenue service is expected to begin in June 1996.

The planning, design, and construction of a light-rail transit (LRT) line require that a wide range of complex issues be resolved. Although it is recognized that no one mode of transit can serve as the best alternative for every corridor, light rail has significant advantages in many applications. A unique feature of LRT is its flexibility, versatility, and ability to develop incrementally. It can be adapted to a wide variety of geographic and topographic conditions, financial capabilities, rights-of-way, and existing infrastructure. Moreover, light rail can be developed incrementally; it can be expanded as demand and the ability to pay for it increase. This incremental feature of light rail is especially important in view of changing public-sector financial abilities. Finally, LRT in many cases is less costly than rapid transit. It does not have the overall high performance and capacity requirements of conventional rapid transit; consequently, construction and operating costs are lower. This lower cost makes LRT economically justifiable in urban areas where conventional rapid transit is not feasible because of cost or demand factors. In addition, this flexibility can have a direct impact on the design of light-rail stations and the vehicle to be operated on the system.

Although most LRT systems are, in fact, much less costly than rapid transit to construct, the Dallas Area

Rapid Transit (DART) did not find this to be true with its starter system. At approximately $26 million per kilometer ($42 million per mile), the DART system incorporates features not normally associated with LRT, a direct result of selecting alignments that required a wide variety of applications for their ability to address the many challenges that were presented.

DART has incorporated this flexibility into the design and construction of its LRT system. Summarized here are DART's application and implementation of LRT technology in a variety of complex operating environments, concluding with a status report on the light-rail starter system construction program. Almost every section of the 32.2-km (20-mi), 21-station starter system presents a different situation, ranging from on-street to grade-separated conditions. The starter system includes a new Trinity River Bridge, grade separations, aerial alignments, a subway, a central business district (CBD) mall, joint use of a utility corridor, median running, and standard railroad environments. This flexibility has also been incorporated into the specifications for the light-rail vehicles (LRVs) and the stations that will be served.

Background

The DART Board of Directors approved the Transit System Plan on June 27, 1989. The 1989 Transit System Plan was a major revision of DART's original plan adopted in 1983. The 1989 Transit System Plan recommended 106.3 km (66 mi) of LRT and 29 km (18 mi) of commuter-rail service and that an LRT starter system be constructed to serve CBD-oriented, medium-to-long work trips during the peak commute periods. The DART Board of Directors recently approved an update to the 1989 Transit System Plan. The revised plan will result in a total of 85.3 km (53 mi) of LRT and 59.6 km (37 mi) of commuter rail by 2010.

DART maintains and operates a fleet of 1,000 vehicles including buses and paratransit vans for mobility-impaired customers. Every weekday, up to 160,000 passengers board buses to reach destinations throughout the 1,813-km^2 (700-mi^2) service area. With the introduction of rail service, the bus system will be reoriented to provide fast, convenient service to new rail stations and transit centers.

Like many cities, Dallas has a number of railroad alignments leading to the downtown that parallel many of the commuter corridors of the city. Although many of these tracks are still in use by the railroads, this rail network has served as a reasonable starting point on which to plan the light-rail system. As a result of system planning, DART purchased approximately 219 km (136 mi) of right-of-way varying in width from 9.15 to 91.5 m (30 to 300 ft) during the period April 1988 through February 1992. Even with this aggressive purchasing program, DART has been unable to acquire all the necessary right-of-way from rail operators to make a continuous system. As a result, DART has selected various light-rail applications for implementation that will fill in the gaps and make the necessary connections to complete the system.

LRT Project Overview

The LRT starter system now under construction consists of approximately 32.2 km (20 mi) of radially oriented LRT lines connecting the Dallas CBD with north and south activity areas (Figure 1). The three lines are divided into five LRT corridors: North Central (NC), Central Business District (CBD), Oak Cliff (OC), South Oak Cliff (SOC), and West Oak Cliff (WOC). Provisions for future system expansion (funded from the build-out budget) are included for the Garland, Richardson, and Pleasant Grove connectors, as well as the Service and Inspection Facility. The LRT starter system project also includes the design and construction of three bus transit centers as part of the following: Illinois Station on line section SOC-1; Hampton Station on line section WOC-2; and Ledbetter Station on line section SOC-2.

Opening day ridership for the first 19.3 km (12 mi) and 14 stations opening in June 1996 is expected to be approximately 15,000 revenue passengers. When all of the starter system stations are open by May 1997, ridership is expected to be approximately 33,000 per day. (The CityPlace Station is expected to open in January 1999.)

Commuter-Rail Project Overview

DART's LRT project gets most of the attention, but another rail project now being developed by DART and the Fort Worth Transportation Authority (The T) is under construction. As planned, two-to four-car trains will operate peak-period service between Dallas and Irving. The service will eventually extend to Dallas-Fort Worth (D/FW) International Airport and Fort Worth. The DART Board approved the purchase of 13 rail diesel cars (RDCs) from VIA Rail Canada. The cars are being remanufactured for use on the DART commuter-rail system. They are scheduled to arrive in Dallas for testing in the fall of 1995. Each car will have the capacity to carry 96 seated passengers. Opening day ridership is expected to be approximately 1,000.

The commuter-rail project is segmented into three phases, with hours of service and capacity expected to increase as each phase is completed. Phase 1 of the

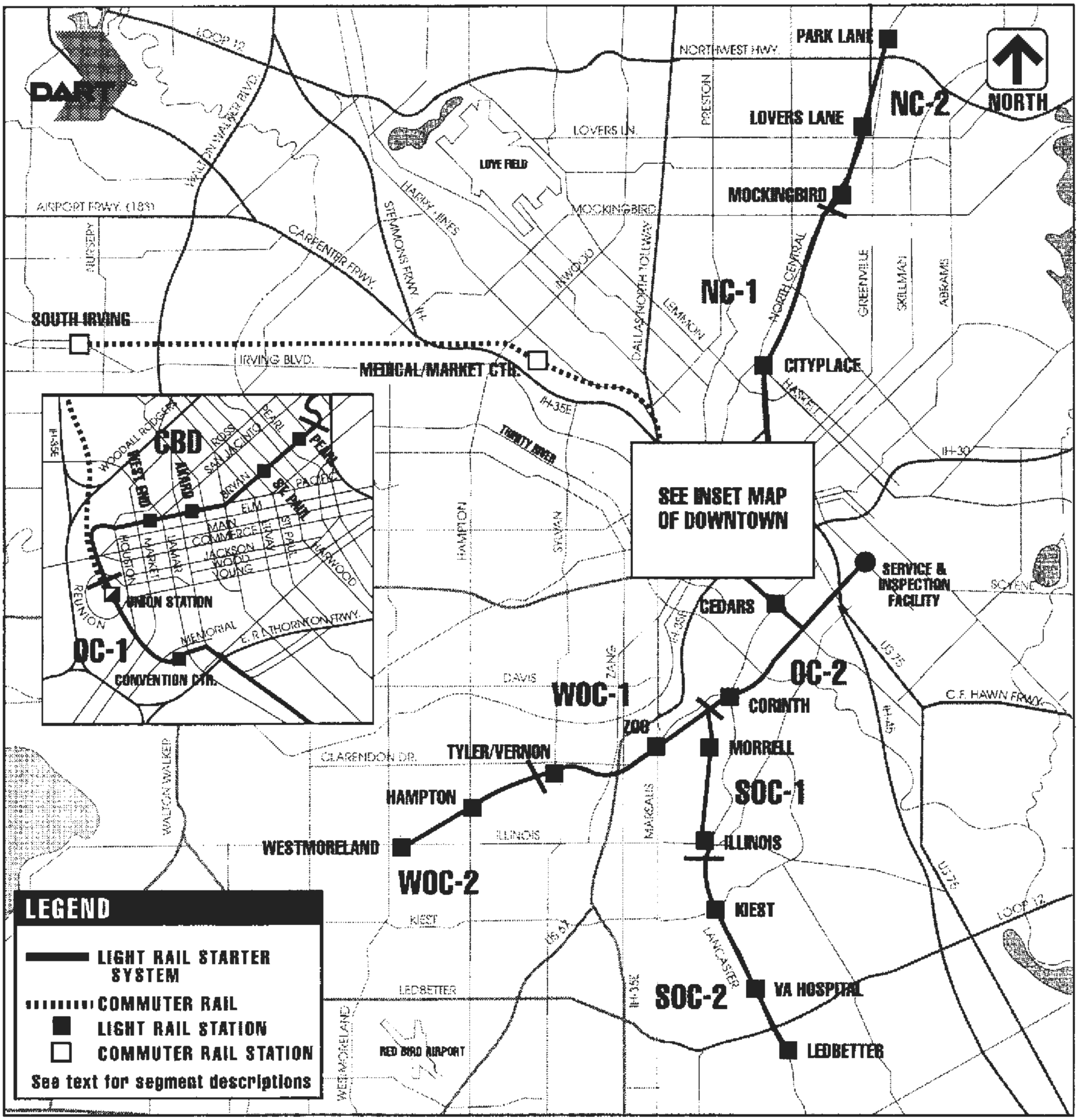

FIGURE 1 DART light-rail and commuter-rail starter system.

commuter-rail system consists of 16.1 km (10 mi) of passenger service between Dallas and Irving connecting three stations: Union Station in downtown Dallas, Medical Center/Dallas Market Center, and the existing South Irving Transit Center (Figure 1). Future phases will extend service to Fort Worth in several subphases, to D/FW International Airport, and possibly to the Dallas Convention Center. An equipment maintenance facility, including storage tracks, will be located in Irving and will be partially funded by The T.

The light-rail and commuter-rail systems have been planned to complement each other by sharing a passenger stop at Union Station, which will allow passengers to transfer between the two rail networks or use a bus to travel to a downtown destination. Union Station will become a true multimodal station, serving buses and three types of rail systems (LRT, commuter-rail service, and Amtrak).

DART Alignment and Application

Special Attributes of LRT

LRT has a number of special attributes that have a direct influence on the planning and design of this particular mode. LRT is extremely flexible in its geometry and therefore may have many route options. LRVs can negotiate much sharper curves and steeper grades than heavy-rail rapid transit and can utilize a wide variety of rights-of-way.

Light-rail service can efficiently utilize many kinds of right-of-way, depending on cost, availability, and condition. Circumstances will dictate which type, or what combination, should be applied to a given corridor or route. The seven rights-of-way used in Dallas are

- Center street, with as much transit priority as is feasible;
- Park strip, median, or boulevard (similar to the first type but exclusive and with crossing safety features);
- Jointly used light-density railroad trackage;
- Power line;
- Aerial structures at highway, railroad, or river crossings, with private right-of-way between crossings;
- Subway, or below-grade; and
- Abandoned railroad corridor.

The vertical alignment of a light-rail system is perhaps the single most important issue in that it largely determines the cost of the project. An at-grade line is considerably less expensive to build but may lower operating efficiency and increase traffic conflicts. Although LRT is somewhat suited for mixed traffic operations, operations over long routes must have priority over automobile traffic in order to avoid slow run times, unreliable schedules, and consequently poor operational performance. Underground and elevated alignments, on the other hand, raise costs significantly and fail to capitalize on the flexibility of LRT technology. If the LRT line is completely grade separated, it duplicates a typical rapid transit heavy-rail system and the cost may exceed the benefits.

Early in the planning process DART identified, defined, and tested the many available route options to permit selection of an optimum route. The testing to prove or disprove the functional viability of each route was conducted to ensure that the selected alternative was the best available. The results of the testing led DART to consider and develop a variety of route applications in its light-rail system.

A discussion of DART's starter system alignment and the variety of light-rail applications follows.

North Central Line

The North Central line extends northward 10.8 km (6.7 mi) from Routh Street in the CBD, roughly paralleling the North Central Expressway, to Park Lane. The North Central Expressway (US–75) is a major suburban city–central city commuter route. Revenue service is projected for December 1996. The North Central line contains two line sections.

The NC-1 line section extends 5.6 km (3.5 mi) from Routh Street in the CBD rransit mall through a double tunnel under the North Central Expressway to Mockingbird Lane. The alignment enters a portal at Ross Avenue and remains grade separated in a cut-and-cover configuration under the North Central Expressway frontage road to Woodall Rodgers Freeway. North of the Woodall Rodgers Freeway, the alignment enters a 4.8-km (3-mi) tunnel and exits through a portal north of Mockingbird Lane. There will be one underground station at CityPlace (a joint development venture of CityPlace Corporation and DART), located between Lemmon and Haskell avenues.

Upon surfacing north of Mockingbird Lane, the NC-2 line section follows the former Southern Pacific right-of-way purchased by DART in 1988. The alignment continues northward approximately 4 km (2.5 mi) along the DART right-of-way to Park Lane. North of Mockingbird the right-of-way is at grade with aerial crossings at Lovers Lane. An 8200-m (2,500-ft) aerial alignment is used from Southwestern to Caruth Haven. The aerial alignment returns to grade before it rises again to cross Northwest Highway. Aerial crossings were selected to avoid interfering with the high traffic volumes (in the range of 30,000 per day) and the relatively short distance available between the North Central Expressway frontage roads and Greenville Avenue with an operating rail right-of-way in between, resulting in a short queue length. Stations are located at Mockingbird Lane (750 parking spaces and four bus bays), Lovers Lane (no parking and two bus bays), and Park Lane (532 parking spaces, plus temporary leased parking until the line is extended, and eight bus bays). The alignment ends on the south side of Park Lane at a temporary at-grade station; however, a new station will be built on the north side in conjunction with the extension of the North Central line over Park Lane.

North Central Tunnel

In the early planning stages for this corridor, various alternative alignments were under consideration. Use of a nearby railroad right-of-way was eliminated early because of neighborhood opposition. The Dallas City Council passed a resolution that removed any chance of using the rail right-of-way. This action was significant because DART's enabling legislation requires the approval by a city of any alignment through that city. Therefore, the 1989 Transit System Plan reflected an undefined configuration within the North Central Expressway right-of-way. When planning and design began on the reconstruction of the expressway by the Texas Department of Transportation (TxDOT), several alternatives were evaluated. An aerial alignment in the median of the expressway was considered briefly but discarded because of neighborhood opposition on the grounds of neighborhood intrusion. At grade in the median was not selected because of wider right-of-way requirements for the roadway project and high cost and impact.

After further planning and analysis, twin-bore tunnels were selected in conjunction with fewer freeway lanes as the preferred alternative. Later, it was changed to cut and cover under the frontage roads because of the perceived high cost of deep-bore tunnels. DART became increasingly concerned about the uncertain schedule for the freeway reconstruction, which would have resulted in unacceptable delays and cost increases. At the same time, TxDOT was having great success in boring a large drainage tunnel below the expressway. The area geology consists of Austin Chalk (limestone), which is very conducive to deep-bore tunneling. After additional analysis and cost estimates for the cut-and-cover options, the decision was reversed to the deep-bore twin tunnels beneath the roadway based in part on the success of TxDOT and new cost data.

With a 290-Mg (320-ton) boring machine, work started on the 4.8-km (3-mi) twin tunnels at Mockingbird Lane on the northern end of the southbound tunnel on November 4, 1992. Delays were encountered caused by pockets of petroleum products and methane gas. The southbound bore was completed on August 17, 1993. Tunneling work was then started on the northbound tunnel, which was completed on January 3, 1994.

The North Central light-rail tunnels consist of two 6.5-m (21-ft 6-in.) diameter tunnels running underneath the North Central Expressway from Mockingbird Lane to the Woodall Rodgers Freeway interchange at depths varying from 12.2 to 36.6 m (40 to 120 ft), a short cut-and-cover box section under Woodall Rodgers Freeway, cross passages every 244 m (800 ft), and a number of underground rooms for mechanical and electrical equipment. There is to be one subway station—CityPlace—which will not be in service until 1999, pending final contractual discussions with the CityPlace developer. Another station midway between Mockingbird and CityPlace has been caverned out but is not budgeted for completion at this time. Work on the tunnel is scheduled to be complete by the early part of 1996. At that point, the tunnels will be turned over to DART for installation of the rail system components.

Central Business District

Early plans called for a subway through the downtown area. Because of the number of stations and related costs, plans for the subway were dropped and a surface transitway was proposed.

The CBD Mall line section extends from the NC-1 tunnel transition section near the intersection of San Jacinto Street and Routh Avenue along Bryan Street and Pacific Avenue through downtown Dallas. The CBD Mall section will serve the commercial and high-rise office complexes, Arts District, and the West End. The Mall will allow limited parallel vehicular access but no through traffic, although most cross streets remain open. Four stations are located on this section: Pearl, St. Paul, Akard, and West End. Construction of all four stations is on schedule and they are expected to open for revenue service in June 1996.

CBD Mall

The CBD Mall line section extends from the NC-1 tunnel transition section near the intersection of San Jacinto Street and Routh Avenue along Bryan Street and Pacific Avenue for a distance of 1.9 km (1.2 mi) through the West End Historic District. The transitway mall connects the north and south light-rail lines to the CBD. The mall will be pedestrian-friendly, with restricted automobile traffic, wide sidewalks, benches, trees, decorative artwork, and other features. There are four stations: Pearl, St. Paul, Akard, and West End. Each station has been designed to complement the surrounding architecture and features passenger amenities, covered waiting areas, benches, information displays, and special access facilities. In the CBD, light-rail trains will operate every 5 to 10 min. The mall is expected to stimulate the downtown economy as retail shops and restaurants open there to serve rail passengers. Interest in redevelopment has already begun around the Pearl and West End stations. The West End Historic District currently contains more than 100 restaurants, specialty shops, and nightclubs housed in turn-of-the-century warehouses. Street vendors, sidewalk cafes, and surrey rides add to the district's appeal. Recent additions include a 10-screen movie theater and Planet Hollywood. The West End Historic District mitigation plan avoids Section 110 conflicts with the John F. Kennedy Assassination National Historic District and preserves the historic nature of the district.

The CBD Mall generally requires rebuilding the existing street and sidewalk and relocation of utilities. The design includes placement of embedded double-track girder rail, installation of brick and concrete pavers, and placement of trees and lights along the street. Benches, trash receptacles, and the vehicle power system (catenary) have been designed to complement the architectural standards of the area. Local traffic and emergency access needs are included in the design. Through traffic on the affected streets is diverted to nearby streets. Most cross streets remain open, with the traffic signals coordinated with the light-rail operation. The mall begins at the intersection of Pacific Avenue and Houston Street in the West End Historic District, follows Pacific Avenue to Bryan Street, where it turns to follow Bryan Street to Hawkins Street. The line turns north on Hawkins Street to San Jacinto and then east across Routh Street to the North Central portal. Additional right-of-way is required to transition in and out of Hawkins Street. The remainder of the mall is generally within the public right-of-way. A future connection to the proposed Pleasant Grove LRT line is being constructed near the intersection of Bryan and Hawkins streets, and the future Carrollton connection will occur at the West End.

There are several parking garages and off-street loading docks along the CBD Mall that require access to and from Pacific Avenue or Bryan Street. As a result, some blocks continue to have at least one lane for vehicular access. Otherwise, only emergency traffic is accommodated along the mall. Minor streets such as Austin, Crockett, Federal, and Hawkins will be closed. Other existing streets crossing Pacific Avenue and Bryan Street will remain open.

Oak Cliff Line

The Oak Cliff line is being developed in two segments, designated OC-1 and OC-2. The OC-1 line section runs from the western end of the CBD Mall through Union Station and Convention Center to a point beyond The Cedars (Lamar) Station. The OC-2 line section includes the segment that runs from below The Cedars Station to the Yard Lead for the Service and Inspection Facility and south along the Santa Fe corridor to the junction with the West Oak Cliff and South Oak Cliff lines. Completion of the Oak Cliff line is on schedule, and revenue service is expected to begin in June 1996.

The OC-1 line section extends from Houston Street at the edge of the CBD Mall south 2.9 km (1.8 mi) past Dealey Plaza on the Triple Underpass and through the railroad Right-of-Way District behind Union Station. The alignment turns east to go under the expanded Dallas Convention Center and then turns southeast along the old City Spur of the Atchison, Topeka, and Santa Fe Railroad to cross the R. L. Thornton Freeway (I–30) on an existing Santa Fe Railroad bridge. Following the Atchison, Topeka, and Santa Fe corridor, the line joins the OC-2 line section between The Cedars Station and the Yard Lead. Stations are located at Union Station, Dallas Convention Center, and The Cedars (Lamar). The Convention Center Station will have provision for three bus bays and no parking. The Cedars Station will have no parking and three bus bays. The OC-1 alignment was selected because the City Spur was very lightly used by the Atchison, Topeka, and Santa Fe Railroad and was clear of the Right-of-Way District, which was still heavily used. Union Station was the only logical choice for a station, and the alignment could be acquired at a reasonable price and provided the needed connection with the south side of Dallas.

The 4.3-km (2.8-mi) OC-2 line section continues from east of The Cedars Station over Lamar Street to the Yard Lead, where it turns to the north to enter the Service and Inspection Facility and to the south as a new double-track aerial structure over the main lines of the Right-of-Way District and then over the Trinity River and its floodplain. After crossing the Trinity River, the line crosses Eighth Street at grade and continues to Corinth Street, which it crosses on a grade-separated structure. There is one station on this section, Corinth Station, which is located between Corinth and Eighth streets. Initially, this station will have 86 parking spaces, with the potential of expanding to approximately 500 parking spaces, and three bus bays.

Trinity River Bridge

The 1.6-km (1-mi) Trinity River Bridge is part of the 4.3-km (2.8-mi) OC-2 line section from Moore Street east of the Texas Utilities Electric (TUE) right-of-way. A new double-track aerial structure was constructed over the river and its floodplain between the levees and the main lines of the Right-of-Way District south of the CBD. The right-of-way and existing single-track bridge were purchased from the Santa Fe Railroad (along with the yard for the Service and Inspection Facility and the West Oak Cliff line) to provide a river crossing. To facilitate the sale, DART entered into agreements with the railroad to allow the displaced trains to use other DART-owned rail right-of-way and paid for connections to those lines. DART had originally considered utilizing the existing one-track bridge. This option was discarded early on because of the heavy use the corridor would receive as the trunk line of the system with frequent headways. The single-track bridge would have restricted operations below DART service standards. As a result, a new double-track bridge was approved. As it crosses the river, the alignment is entirely within the former Santa Fe Railroad except for a short 152.5-m (500-ft) section that spans a portion of the TUE easement of Trinity Park (part of the city of Dallas Greenbelt). The alignment then crosses the existing underpass at Lamar Street before returning to grade. The bridge and yard lead have been used as an on-site test track for new LRVs. The bridge was completed in July 1995.

Union Station

Two at-grade rail platforms are located at Union Station between the Reunion Boulevard bridges. The first platform (nearest to Union Station) will be used exclusively by northbound LRT passengers. The second platform will be shared by RAILTRAN commuter-rail passengers and southbound LRT passengers. Also serving the station on a third platform is Amtrak. Mainline freight traffic will be situated west of the three platforms.

West Oak Cliff Line

The West Oak Cliff corridor extends from the South Oak Cliff—Oak Cliff junction along the former Atchison, Topeka, and Santa Fe right-of-way to the Westmoreland Station, passing the Dallas Zoo en route. The right-of-way was purchased from the railroad in 1992. This corridor was considered the easiest to plan and construct within the starter system primarily because of the existing right-of-way and the high potential for ridership. Aside from a problem with contaminated soil on city-owned property at one station, this branch has encountered few difficulties. Development in the area is primarily older, single-family residential units with limited industrial activity. Completion of the West Oak Cliff line is on schedule with revenue service expected in June 1996.

The 4.0-km (2.5-mi) WOC-1 line section includes the segment between the junction of the West Oak Cliff and South Oak Cliff lines and the Dallas Zoo and Tyler/Vernon stations. The Dallas Zoo Station will serve the regional population by providing direct access to a popular destination in the area. The station has five bus bays and no parking. The Tyler/Vernon Station is located adjacent to a former industrial site. This site has a tremendous opportunity for redevelopment with direct access to the station. Like the Zoo Station, park-and-ride spaces are not provided.

The WOC-2 line section extends from Polk Street west along the Atchison, Topeka and Santa Fe right-of-way corridor 3.4 km (2.1 mi) to Westmoreland Road. Stations are located at Hampton and Westmoreland roads. The Hampton Station opened as a bus transit center in January 1995. The station has 550 parking spaces and five bus bays. The Westmoreland Station will have over 1,000 parking spaces and six bus bays.

South Oak Cliff Line

The South Oak Cliff corridor extends from the junction of the Oak Cliff and South Oak Cliff lines to the Ledbetter Station just beyond Loop 12. This corridor utilizes three distinct rights-of-way in its 6.4-km (4-mi) length. Construction of the South Oak Cliff line is on schedule with revenue service expected on SOC-1 in June 1996 and SOC-2 in May 1997.

The SOC-1 line section extends from the Atchison, Topeka and Santa Fe right-of-way along the TUE transmission line right-of-way (formerly the Texas Electric Railroad right-of-way) 2.4 km (1.5 mi) to Illinois Avenue. Stations are located at Morrell Street and Illinois Avenue. The Morrell Station does not provide parking and has two bus bays. The Illinois Station opened as a transit center in July 1994. The Illinois Station will have approximately 350 parking spaces (with an additional capacity of 260 spaces) and nine bus bays.

Below the Illinois Station, the SOC-2 line section extends from Illinois Avenue south 4.7 km (2.9 mi) to Arden Road in the Lancaster Avenue median past Ledbetter Drive, where it veers onto an exclusive guideway to the terminus at Ledbetter Station. Stations are located at Kiest Boulevard, Veterans Administration Hospital, and Ledbetter Drive. The Kiest Station will have 474 parking spaces and two bus bays, Ledbetter Station will have 400 parking spaces and six bus bays. The VA Hospital Station will have no parking or bus bays.

Utility Corridor

The SOC-1 section line begins at the junction with the Oak Cliff line and continues south along the former Texas Electric Railroad right-of-way shared with relocated TUE high-tension transmission towers. The Texas Electric Railroad alignment was acquired by TUE during the 1940s. During construction of the DART system in this corridor, the utility lines were relocated onto new poles spaced closer together and placed off to one side. The alignment is partially flanked by Moore Street on the west and Woodbine Street on the east. The alignment from Iowa Avenue to Compton Street is at-grade construction.

From Iowa Avenue, the alignment parallels the west side of the relocated TUE transmission towers. The existing towers were removed and replaced with poles that have the capability to provide the same capacity in less space. The required horizontal and vertical clearances of the rail line to the poles and the final typical section were developed with the approval of the local TUE authority. A new 106.8-km (350-ft) long street on the west side of the alignment required additional right-of-way between Stella Road and Edgemont Avenue. This alignment was selected because of the availability of the corridor and lower cost associated with development of light rail in the right-of-way. Because of the alignment, three streets end in cul-de-sacs on the east side of the TUE right-of-way. At-grade crossings are provided at Stella Road and Edgemont Avenue.

The next at-grade crossing is at Lynn Haven Avenue. Proceeding northward, at-grade crossings are provided at Waco Street and Morrell Avenue, and three streets—Galloway, Strickland, and Hendricks—are closed at the DART/TUE right-of-way and the final grade crossing at Compton Street.

Lancaster Road

The area between the Illinois and Ledbetter stations is an automobile- and bus-oriented commercial corridor along both sides of Lancaster Road and is referred to as the Lancaster Commercial District. A few residences and several public facilities including the Kiest Library and the Veterans Administration Hospital are located within the district. The median of Lancaster was selected during the planning phase for several reasons. The former Texas Electric Railroad right-of-way was not selected because the line did not go through the commercial area (it was located several blocks west) nor was it close enough to the VA Hospital.

The 4.7-km (2.9-mi) alignment consists of at-grade double track located within the rebuilt median of Lancaster Road with one aerial crossing at Illinois Avenue. Between Illinois Avenue and Ledbetter Road, Lancaster Road has been transferred from the state highway system to the city of Dallas. South of Ledbetter Road, Lancaster Road is a state highway (SH–342). Both sections have a narrow median. Numerous driveways and median crossings provided local access across Lancaster Road, which is striped for four lanes; two parallel parking lanes provide width capacity for six lanes. The median will be widened to accommodate the double-track rail line, and Lancaster Road will retain the same number of traffic lanes that are presently provided; however, on-street parking has been eliminated on both sides of Lancaster Road to preserve as much of the commercial development as possible and to provide for the rail right-of-way. At-grade crossings are provided at all major and secondary thoroughfares crossing Lancaster Road. Certain median openings at minor-street crossings are closed because of safety and access concerns. Eight major cross streets will remain open. Additional right-of-way is required along some sections of the street adjacent to signalized intersections to provide separate left-turn lanes for Lancaster Road approaches.

Proceeding southward from Illinois Station, the at-grade alignment parallels Denley Drive adjacent to the TUE substation. Continuing southward, the alignment becomes aerial as it crosses Illinois Avenue and turns to cross the southbound lanes of Lancaster Road at the point where Lancaster Road splits right to meet Corinth Street Road and left to meet Montana Avenue. The alignment returns to grade and continues in a new median with two lanes of traffic in each direction. The alignment remains within the median south to the Ledbetter Station passing the Kiest and VA Hospital stations. After crossing Ledbetter Drive, the alignment turns to the west, crosses the southbound lanes of Lancaster Road, and enters an exclusive right-of-way.

LRVs

A contract was awarded to Kinki-Sharyo for 40 LRVs. Given the choice between a futuristic design and a more conventional one, the DART Board chose the former, with end caps sloping back at a much greater angle than is the case in most other North American LRVs. The LRVs were specifically designed to function in the wide range of operating environments found within the DART system. The cars are double ended, articulated, with six axles, high floors, and four sets of sliding doors per side. Each car measures 28.2 m (92 ft 8 in.) over coupler faces, with a width of 2.7 m (8 ft 10 in.) and a height of 3.8 m (12 ft 6 in.) from the top of the rail. The car body is lightweight welded steel. The vehicles weigh no more than 49 940 Mg (110,000 lb) without passengers, making them the heaviest LRVs to be delivered in North America. The articulated section is weatherproof and does not degrade lighting or air-conditioning or heating performance in the interior. Seating capacity is provided for 76 persons with an additional 76 standing. Each car can accommodate a crush load of 200 persons. Power is provided by a 750-volt DC overhead catenary system. The cars are designed for speeds of 105 km/hr (65 mph), with an average of 40 to 56 km/hr (25 to 35 mph). Final assembly is taking place at a facility in the Dallas area. The cost per car is $2,500,000. About 21 percent of the vehicle cost will be funded by the Federal Transit Administration. The complete system will require 125 cars.

The first two LRVs were delivered in mid-1995 for testing. Each car will accumulate 6,440 km (4,000 mi) during the testing phase running up to the 105 km/hr (65 mph) top speed on 4 km (2.5 mi) of track. The test track consists of the yard lead for the Service and Inspection Facility, a portion of the light-rail system in Oak Cliff that runs over the Trinity River Bridge to the Corinth Station. Forty light-rail cars will be tested during 1995 and 1996, arriving in increments of four per month.

Station Facilities

Twenty-one stations will be built along the initial 32.2-km (20-mi) starter system. Light-rail station facilities range from individual shelters along the transit mall to major subway stations. The CBD stations consist of an 8-in. raised platform (sidewalk extension) with shelters for weather protection. These shelters are easy and inexpensive to maintain, and in all cases, security is heightened because of the visibility provided. Away from downtown, the station design includes arching canopies over both tracks. Platforms are designed for either side of the tracks or center placement. The typical side platform measures 91.5 m (300 ft) long and is 5.2 m (17 ft) wide; center platforms are 8.5 m (28 ft) wide. Both station types are equipped with a 30.5-m (100-ft) canopy. Additional space is provided at all non-CBD station platforms to accommodate a future 30.5-m (100-ft) length extension. Finishes include wind screens, benches, landscaping, and artwork. Landscaping will be employed to enhance the appearance, to control and passively direct the movement of patrons within station sites, and to enhance or improve microclimates at the stations. High-level platforms for the mobility impaired are located at the forward end of each platform.

Patron access and egress at stations vary by location because of site conditions. Eight stations will be built with integral park-and-ride facilities, providing an initial capacity of nearly 4,450 spaces. Kiss-and-ride facilities are provided at 13 of the stations. Generally, access and egress treatments are hierarchical. First priority is given to bus patrons using the drop-off lanes. Second priority is given to short- and long-term parking for mobility-impaired and kiss-and-ride patrons. Third priority is to long-term commuter parking patrons. Patrons accessing stations on foot are provided the most direct circulation available to the adjacent land uses.

Service and Inspection Facility

The heart of DART's light-rail system is the new, $30 million state-of-the-art Service and Inspection Facility, situated just south of the R. L. Thornton Freeway near Fair Park. The three-story, 8277-m^2 (89,000-ft^2) facility houses the staff and equipment necessary to test and maintain the forthcoming fleet of LRVs. The facility can be expanded to 14 973 m^2 (161,000 ft^2) to accommodate an increased fleet size. The building includes a down-draft paint booth equipped with lifts and fresh air supply, environmentally controlled work areas including electronics, and a brake shop designed to prevent contaminants and contains an integrated bus and rail operations control center. The 10.9-ha (27-acre) tract includes two-track servicing areas for interior and exterior cleaning.

Project Costs

The light-rail starter system is estimated to cost $840 million (inflated dollars) or approximately an average of $26 million/km ($42 million/mi). However, the tunnel and bridge construction contracts awarded by the DART Board are below estimates by several millions. The North Central Tunnel was bid at $86.8 million to construct—$35 million below staff estimates. The contractor for the Trinity River Bridge construction submitted a price of $18.6 million—5 percent under staff estimates. The Federal Transit Administration has agreed to reimburse 19 percent, or $160 million, of the total cost of the starter system. The starter system's 40 LRVs are being built for $105 million.

As of August 31, 1995, the LRT project was within budget overall, with approximately $811 million, or 94 percent, committed; approximately $544 million, or 63 percent, was expended as of July 31, 1995.

Summary

It should be apparent that a general discussion of the experience of one system cannot answer the many planning and design questions concerning a light-rail system and site-specific applications. DART evaluated numerous alternatives in each of the light-rail corridors and decided to use LRT because of its flexibility, versatility, and ability to be developed incrementally. In addition, this flexibility has had a direct impact on the design of the light-rail stations and the vehicle to be operated on the system.

DART's 32.2-km (20-mi) starter system presents a different operating situation in nearly every kilometer of its total length. DART has found that the light-rail mode fits the complex operating environments found within the region that require installation of a versatile fixed-guideway system. Light rail can effectively utilize six kinds of right-of-way, depending on cost, availability, and condition. It can be completely grade separated, segregated horizontally from other traffic, within a mixed-traffic stream, in a transitway mall, and designed to operate in power-line corridors. Because of cost, elevated systems, subways, and bridges must be limited to the highest-density locations or key bottlenecks. Light rail is intended to be a lower-cost alternative, and an excess of fully grade-separated structures or tunnels can quickly eliminate most of the cost advantage. However, there is no other practical way to cross a river, highway, or railroad of major importance.

DART is currently in the final months of a construction program to build the initial starter system. Vehicles are being tested, and revenue service is planned to begin in June 1996. DART intends to expand the service to the north and east within the next several years. Even then, the system will not be complete—several other extensions are being planned, grade-separation projects are being designed, and operating enhancements are to be implemented.

DART's starter system project is but an increment of a larger LRT plan. By incorporating the flexibility of LRT and the proven technical and operational experiences of other light-rail systems into the DART experience, a new direction for improved public transit service in the region has been provided.

Evaluating Efficiency of Transit Alternatives in Griffin Line Corridor, Hartford, Connecticut

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Elizabeth S. Riklin, *Capitol Region Council of Governments, Hartford*
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The Greater Hartford Transit District, in cooperation with the Capitol Region Council of Governments, has completed the Griffin Line Corridor Major Investment Study (MIS), which is an extensive evaluation of the Griffin Line Transit and Economic Development Project. The project considers five different transit alternatives to improve transportation and economic development conditions in the corridor. In conformance with Federal Transit Administration (FTA) guidance, the evaluation of alternatives considers the effectiveness, efficiency, and equity of an investment in each of the five alternatives. The efficiency evaluation of each of the alternatives considers the alternative's cost-effectiveness in terms of cost per trip and its operating efficiency in terms of operating costs per hour, mile, and passenger and its FTA cost-effectiveness index. To ensure that the efficiency evaluation measures fully reflect the projected and potential benefits of each alternative, the Griffin Line Corridor MIS includes the concepts of ***new service trip*** and ***bus-equivalent*** hours and miles. Furthermore, a critical element of the evaluation of alternatives in the Griffin Line Corridor is the analysis of the cumulative impacts of alternative transit supportive policies and alternative transit operating assumptions on the relative cost efficiency of the alternatives. The cumulative impact analysis includes an Operating and Maintenance Cost Sensitivity Study, which is an examination of the impact of different levels of ridership (represented as percentage increases or decreases compared with the baseline ridership forecast) on the projected annual operating and maintenance costs for each alternative.

The Greater Hartford Transit District, in cooperation with the Capitol Region Council of Governments, has completed the Griffin Line Corridor Major Investment Study (MIS), which is an extensive evaluation of the Griffin Line Transit and Economic Development Project. The project considers five different transit alternatives to improve transportation and economic development conditions in the corridor. In conformance with Federal Transit Administration (FTA) guidance, the evaluation of alternatives considers the effectiveness, efficiency, and equity of an investment in each of the five alternatives. This paper focuses on the evaluation of the efficiency of each of the alternatives.

The efficiency evaluation of each of the alternatives considers the alternative's cost-effectiveness in terms of cost per trip and its operating efficiency in terms of operating costs per hour, mile, and passenger and its FTA cost-effectiveness index. To ensure that the efficiency evaluation measures fully reflect the projected and potential benefits of each alternative, the Griffin Line Corridor MIS includes the concepts of ***new service trip*** and ***bus-equivalent*** hours and miles. Furthermore, a critical element of the evaluation of alternatives in the Griffin Line Corridor is the analysis of the cumulative impacts of alternative transit supportive policies and alternative transit operating assumptions on the relative cost efficiency of the alternatives. The cumulative impact analysis includes an Operating and Maintenance Cost Sensitivity Study, which is an examination of the impact of different levels of ridership (represented as percentage increases or decreases compared with the baseline ridership forecast) on the projected annual operating and maintenance costs for each alternative.

Griffin Line Corridor

The Griffin Line Corridor is a 15-mi (24-km) corridor connecting two major economic and transportation generators in the region—downtown Hartford and Bradley International Airport. The corridor, illustrated in Figure 1, includes the city of Hartford; the towns of Bloomfield, Windsor, and East Granby; and the state-owned Bradley International Airport in Windsor Locks. The initial Griffin Line transitway under consideration in the MIS connects the Union Station Transportation Center on the west side of downtown Hartford, several Hartford neighborhoods (Clay Arsenal, Asylum Hill, Upper Albany, Blue Hills), St. Francis Hospital and Medical Center, the Albany Avenue retail district, the University of Hartford, Weaver High School, the COPACO Shopping Center, Bloomfield Town Center and High School, and the Griffin Center Office Park. This initial 9-mi (14-km) segment of the Griffin Line Corridor between Hartford and Bloomfield includes the existing 8.5-mi (13-km) abandoned rail right-of-way known as the Griffin Line. The right-of-way was purchased by the Connecticut Department of Transportation in 1981 and 1989 under the State's Rail Banking Program to reserve the right-of-way for potential use as a mass transit facility.

Transportation Alternatives Considered

Five alternatives are under consideration to meet the future public transportation and economic development needs of the Griffin Line Corridor. The alternatives con-

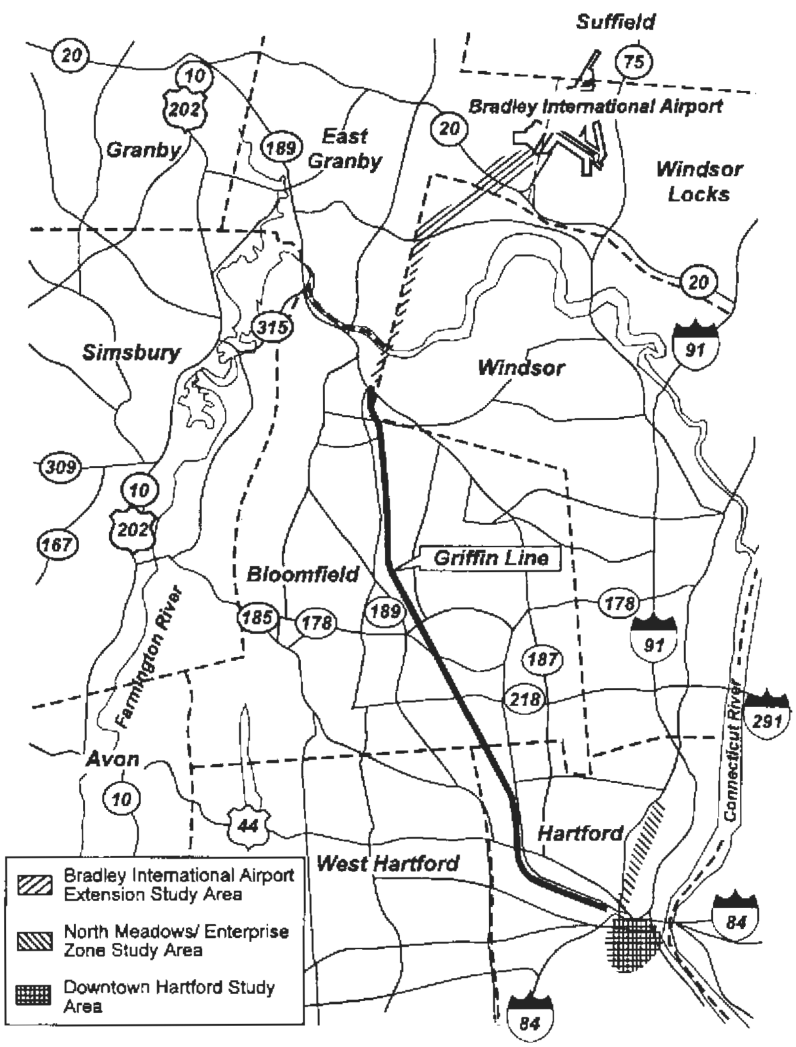

FIGURE 1 Griffin Line corridor including area studied for possible expansions.

sist of "no-build," which essentially maintains current conditions; a transportation system management (TSM) alternative consisting of low-cost, operationally oriented transportation improvements; and three build alternatives, the bus bypass, the busway, and the light-rail transit (LRT) alternative. The "no-build" alternative is shown in Figure 2, and the other four alternatives are shown in Figure 3. Brief summaries of each alternative follow.

No-Build Alternative

The no-build alternative includes the existing 1994 bus service in the Hartford area, with additional bus service on routes that are projected to exceed capacity by 2010. This alternative maintains the existing radial route structure centered on downtown Hartford. It also maintains the current mixture of local and express routes, with the express routes serving the outlying areas from a number of park-and-ride lots.

TSM Alternative

All service improvements identified in the no-build alternative will be provided; the primary components of the TSM alternative are new routes linking downtown Hartford to the growing suburban employment centers in the Griffin Line Corridor, particularly in the area between Bloomfield and Bradley International Airport.

Bus Bypass Alternative

The bus bypass alternative consists of an exclusive (bus only) roadway of 4.7 mi (7.5 km) in the Griffin Line right-of-way beginning at Church Street in the vicinity of Union Station in downtown Hartford to Park Avenue in Bloomfield. No stations or stops would exist along the bypass. The major purpose of the bypass roadway would be to provide shorter travel times between Hartford, Bloomfield Center, and the Griffin Center Office Park. One new route, linking Hartford to Bradley In-

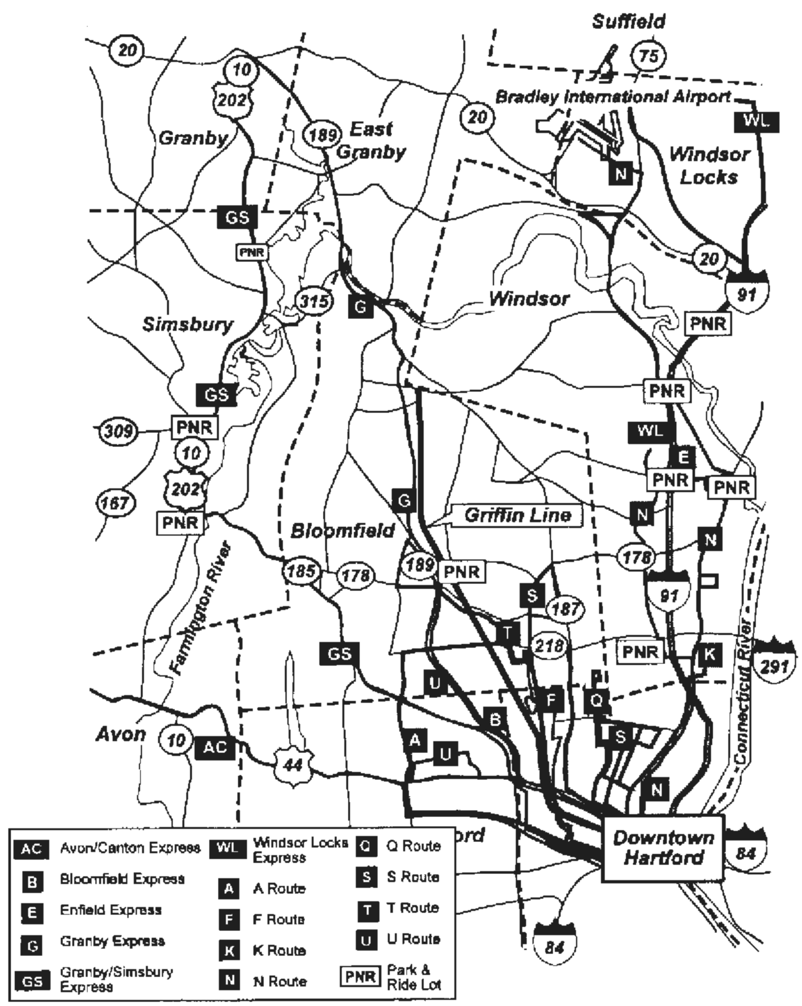

FIGURE 2 No-build alternative: existing bus routes.

ternational Airport via the Griffin Line Corridor, is included. Selected existing transit routes would also be diverted to the bypass to reduce travel times. The alternative also includes route and headway changes to selected corridor routes and the same service improvements identified in the no-build alternative, specifically those required to provide adequate capacity on routes with projected ridership increases to the year 2010.

Busway Alternative

The busway alternative consists of an exclusive (bus only) roadway of 8.4 mi (13.5 km) in the Griffin Line right-of-way between Church Street in the vicinity of Union Station in downtown Hartford to Prospect Hill Road in Bloomfield. A total of eight stations would be built along the busway, and bus access to the guideway would be provided at four sites. The northernmost station, Griffin Center Office Park, would be accessible by existing streets from the fixed-guideway terminus. One new local bus route, with stops at all busway stations, would be added. Six existing local routes (or branches) would be modified to provide feeder service to the busway, and two existing express routes in the Griffin Line Corridor would be diverted to the busway to provide a faster trip in and out of Hartford. Finally, shuttle bus routes would operate between the busway and major employment areas. This alternative also includes the same service improvements identified in the no-build alternative, namely, those required to provide adequate capacity on routes with projected ridership increases to the year 2010.

LRT Alternative

The LRT alternative consists of the construction of an LRT line in the Griffin Line right-of-way from Union Station in downtown Hartford to the Griffin Center Of-

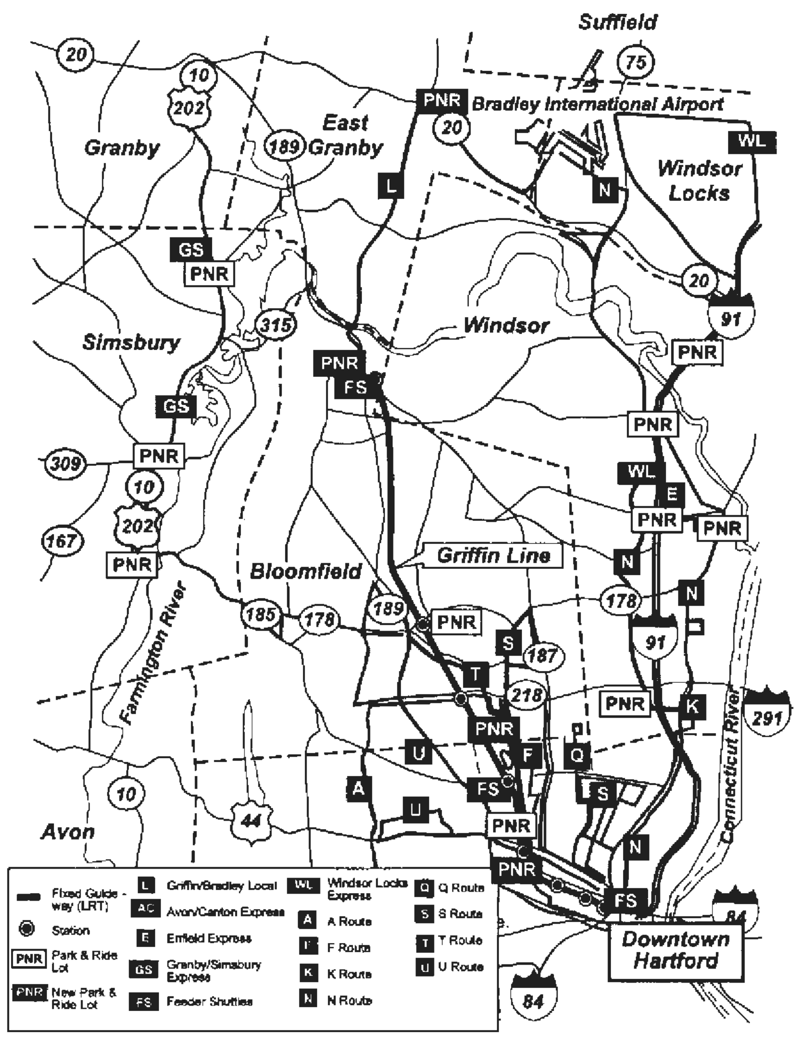

FIGURE 3 LRT alternative: supporting bus routes.

fice Park, a distance of about 9 mi (14 km). The LRT vehicle is a modern trolley electrically powered with overhead catenary, similar to those in recent systems in Sacramento, Portland, and San Diego. Eight LRT stations would be built at the same locations as those proposed for the busway stations. The alternative also includes a number of changes and improvements to the bus service operated in the corridor, including new feeder services, the conversion of one current express route into an LRT feeder, and modifications to the routing of six existing local routes (branches) to allow them to function as LRT feeders. Shuttle bus routes would operate between the LRT and major employment areas. This alternative also includes the same service improvements identified in the no-build alternative, namely, those required to provide adequate capacity on routes with projected ridership increases to the year 2010.

Capital, Operating, and Maintenance Cost Estimates

The capital and operating and maintenance cost estimates for the alternatives are summarized as follows:

Alternative	*Total Capital Cost ($ millions)*	*Annual Operating and Maintenance Costs (beyond No-Build) ($ millions)*
No-build	2.2	—
TSM	8.1	2.0
Bus bypass	44.7	1.6
Busway	95.0	4.8
LRT	176.5	6.7

Operating and Maintenance Costs

The annual operating and maintenance costs range from $33.0 million for the no-build alternative to $39.7 million for the light-rail alternative. By comparison, the total annual budget (1994) for operations and maintenance for the CT Transit, Hartford Division, was $30.5 million. The no-build alternative, then, represents an approximate 8 percent increase from the 1994 budgeted amount.

TSM Alternative

The total annual operating and maintenance cost for the TSM alternative is $35.0 million, approximately $2.0 million higher than the no-build alternative. The increase in operating costs can be directly attributed to service improvements and expansion planned as part of the TSM alternative. These improvements and expansion include reduced headways on one express route and the addition of one new route.

Bus Bypass Alternative

The annual cost for operating the baseline definition of the bus bypass alternative would be $34.7 million (FY 1994 dollars). This total is $1.7 million higher than the cost of the no-build alternative but $0.4 million less than the cost of the TSM alternative. The operating costs for the bus bypass alternative would be lower than the costs for the TSM alternative because the higher operating speeds afforded by the use of the exclusive right-of-way would require fewer buses to operate the same general service levels.

Busway Alternative

The annual cost for operating the baseline definition of the busway alternative would be $37.8 million (FY 1994 dollars). This total is $4.8 million higher than the cost of the no-build alternative and $2.7 million higher than the cost of the TSM alternative. The operating costs for the busway alternative are higher than the costs for the TSM alternative because of the increased express bus service and related stops at eight new busway stations along the Griffin Line. Facilities maintenance costs for the eight proposed stations would be incurred if the busway alternative were implemented. In addition, several existing bus routes would be improved and the new local bus route would be implemented with a higher frequency of service.

LRT Alternative

The annual cost for operating the baseline definition of the LRT alternative would be $39.7 million (FY 1994 dollars). The cost for bus service would be $33.7 million and the cost for the light-rail service would be $6.0 million. The total costs (bus and light rail) are $6.7 million higher than the costs of the no-build alternative and $4.7 million higher than the cost of the TSM alternative. The increased costs can be attributed to the introduction of light-rail service and the additional personnel and facilities related to it. The operating cost for the bus service would be lower for this alternative compared with all other alternatives, with the exception of the no-build alternative. Some express routes would be converted to light-rail feeders, whereas other routes would be modified slightly to improve service to the proposed light-rail stations. Project policy implemented by the working group (including CT Transit, Connecticut Department of Transportation (CTDOT), Capitol Region Council of Governments, and Greater Hartford Transit District), which minimized any significant bus service modifications or reductions in the level of service, limited any further savings in bus costs associated with the LRT alternative at this time. More detailed treatment and scheduling analyses can be completed in the future phases of the project to introduce cost savings and efficiency measures while maintaining transit service quality.

Operating and Maintenance Cost Methodology

Separate operating and maintenance cost models have been developed for each of the two transit modes (bus and light rail) proposed for implementation in the Griffin Line Corridor. The transit cost models were constructed to conform with the FTA's most recent technical guidelines for transit alternatives analysis (*1*). The operating and maintenance cost models were developed to be disaggregate, resource build-up models, consistent with the above FTA guidelines. Staffing requirements, labor costs, and nonlabor expenses were calculated on the basis of the projected quantity of service supplied (e.g., peak vehicles, revenue vehicle-miles) and the physical size of the system (e.g., route-miles, number of stations).

Bus Operating and Maintenance Cost Model

The bus operating and maintenance cost model was based on CT Transit's current organization, which consists of three service units (maintenance, transit, and administrative) in three operating divisions. Operating and maintenance costs were estimated for each service unit within the Hartford division only since this is the division that would be affected by the implementation of the transit alternatives. Furthermore, operating and maintenance costs were estimated for Finance and Marketing and Planning and Scheduling within the Administrative Services unit in the Hartford division. Since some administrative costs are shared by all three operating divisions, shared costs were allocated to the Hartford division based on its share of vehicle miles proposed in CT Transit's FY 1994 budget.

Actual salary and wage data for each position (e.g., money counter) were not available for use in the bus operating and maintenance cost model. Salary ranges for specific salary groups were used instead (e.g., seven positions make up the Clerical and Support salary group). There are eight salary groups within CT Transit. For purposes of estimating labor costs, 65 percent of the top salary in each salary group was used as a reasonable estimate of annual labor costs for all positions within each group.

The ability of the cost model to estimate bus operating and maintenance costs accurately for the study alternatives was tested and calibrated by applying the model to FY 1992 and FY 1993 actual data and to CT Transit's FY 1994 budgeted data. Input variables and actual operating and maintenance costs for FY 1992 and FY 1993 were obtained from CT Transit's Section 15 reports. Input variables and budgeted operating and maintenance costs for FY 1994 were obtained from CT Transit's 1994 operating budget.

Light-Rail Operating and Maintenance Cost Model

Hartford does not currently have light rail; therefore, comparable Section 15 cost data for other similar at-grade independently operating light-rail systems were used to develop the light-rail operating cost model. The model was adjusted for local sensitivities, including the use of CT Transit wage and fringe benefit rates and Northeast Utilities energy costs and local material costs, to develop light-rail operating cost estimates.

The structure of the light-rail model is similar to the bus cost model, with line-item costs tabulated for specific light-rail service units (e.g., light-rail administration, operations, and maintenance). Specific line items were provided for unique labor positions, such as electromechanic or train operator, and also for unique nonlabor expenses, such as traction power or vehicle spare parts. Each labor and nonlabor expense item was modeled as a separate line item to ensure that the equations that estimate expenses were mutually exclusive and covered all operating costs. Operating and maintenance costs were calculated from the quantity of service supplied and other system characteristics.

The light-rail cost model reflects CT Transit wage and fringe benefit rates. Overhead expenses were allocated to light-rail operations based on CT Transit's FY 1994 operating budget. CT Transit's overhead costs include functions not directly associated with transit operations, such as marketing and customer services. The ratio of budgeted administrative overhead costs to budgeted bus operating costs was applied to light-rail direct operating costs. It should be noted that most of the administrative costs for the light-rail system are variable (i.e., they adjust with the size of the system), whereas other costs are based on a fixed percentage (overhead). Since most of the variability in administrative costs was accommodated by the light-rail cost model, it was reasonable to assume that the light-rail overhead rate was similar to the bus overhead rate.

The operating and maintenance cost model developed for the Griffin Line Corridor light-rail operations was similarly calibrated with actual operating budgets for six U.S. LRT systems.

Projected Demand for Transit Alternatives

Ridership forecasts are presented in terms of projected daily boardings in 2010. The ridership analysis considers demand forecasts for each alternative under various policies and operating assumptions in addition to under baseline conditions. Figure 4 illustrates the ranges of projected demand for each of the transit alternatives.

The range of forecasts for each alternative from baseline to implementation of the downtown Hartford employers' market price parking policy is as follows:

- TSM: 2,000 to 2,200 boardings per day,
- Bus bypass: 2,500 to 4,800 boardings per day,
- Busway: 10,900 to 15,200 boardings per day,
- Light rail: 8,700 to 14,800 boardings per day.

Analysis demonstrates that ridership forecasts for the busway and light-rail alternatives are similar when operating plans include comparable service frequencies along the corridor. In addition, the range of ridership forecast for the complete light-rail service from downtown Hartford to Bradley International Airport is 11,600 to 18,000 boardings per day. This range encompasses Union Station as a major transfer node (lower bound) and the implementation of the downtown Hartford employers' market price parking policy (upper bound).

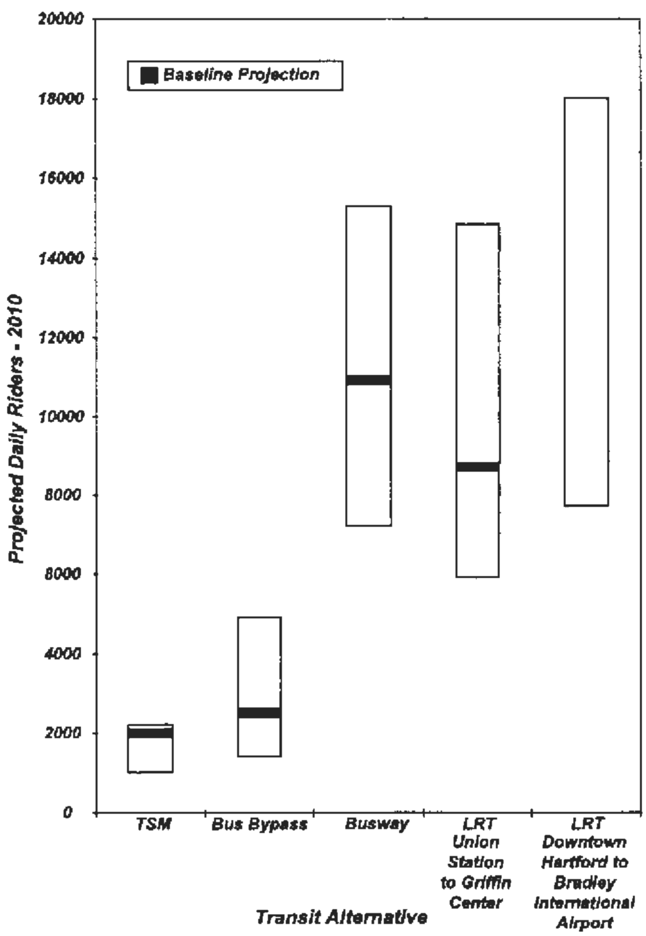

FIGURE 4 Projected daily ridership in 2010 for Griffin Line alternatives.

Evaluation of Alternatives

The Griffin Line evaluation framework adheres to FTA and CTDOT technical procedures. Federal transportation legislation, the 1991 Intermodal Surface Transportation Efficiency Act, dictates that all major transportation investments under consideration be analyzed, evaluated, and selected following guidelines and procedures outlined in the Metropolitan Planning Regulations.

Evaluation Framework

Each alternative is evaluated on the basis of five major elements:

1. **Effectiveness (goals achievement):** How effective is each alternative at achieving the stated goals and objectives of the Griffin Line Transit and Economic Development Project ?
2. **Efficiency (cost-effectiveness):** How efficient and effective is each alternative in providing transportation and mobility, economic and community development, and long-term environmental benefits in relation to the projected capital and operating costs ?
3. **Equity considerations:** How are the benefits and costs of each alternative distributed? (Affected groups include transit users, socioeconomic categories, neighborhoods, businesses, political jurisdictions.)
4. **Trade-off analyses:** What are the key differences between the alternatives?
5. **Financial analyses:** What are the anticipated federal and other capital and operating expenditures, annual cash flow requirements, and potential public- and private-sector funding sources for each alternative?

The evaluation addresses several key long-term issues for the corridor and the Capitol Region including the following:

- **Mobility and accessibility:** Does the alternative improve mobility in both the city and suburban communi-

TABLE 1 Evaluation of Baseline Transit Alternatives

	BASELINE TRANSIT ALTERNATIVES				
EVALUATION MEASURES	No-Build	TSM	Bus Bypass	Busway	LRT
Cost Effectiveness (1994 dollars) in 2010					
Total Cost Per Trip* (Total System)	$1.66	$1.74	$1.86	$2.11	$2.51
Total State Subsidy Per Trip* (Total System)	$0.82	$0.89	$0.90	$1.00	$1.17
Total O&M Cost Per Trip (Total System)	$1.65	$1.71	$1.70	$1.77	$1.88
Total O&M State Subsidy Per Trip (Total System)	$0.82	$0.88	$0.87	$0.93	$1.04
Net O&M State Subsidy Per New Service Trip	—	$3.75	$2.32	$1.30	$2.40
** includes annualized capital (7%) and annual O&M*					
Operating Efficiency					
Operating Cost (1994$) Per Train/Bus Hour	$68.02/hr	$67.64/hr	$68.26/hr	$70.64/hr	$369.97/hr
Operating Cost (1994$) Per "Bus Equivalent" Hour	$71.00/hr	$70.98/hr	$71.48/hr	$74.59/hr	$75.21/hr
Operating Cost (1994$) Per Vehicle/Bus Hour	$5.30/mi	$5.25/mi	$5.14/hr	$5.09/mi	$11.48/mi
Operating Cost (1994$) Per "Bus Equivalent" Mile	$5.64	$5.61	$5.50	$5.52	$5.40
Operating Cost (1994) Per Passenger (Total System)	$1.32/pass	$1.39/pass	$1.36/pass	$1.41/pass	$1.46/pass
Operating Cost Per Guideway Passenger Place -Mile	NA	NA	$0.22	$0.28	$0.12
Efficiency-Ridership/O&M Cost Sensitivity Study					
Operating Cost Per Passenger (Total System) at:					
80% of Baseline Ridership	NA	$1.44	$1.40	$1.45	$1.50
120% of Baseline Ridership	NA	$1.35	$1.33	$1.39	$1.41
160% of Baseline Ridership	NA	$1.34	$1.33	$1.37	$1.36
FTA Cost Effectiveness Index					
FTA New Riders	---	1,600	1,600	4,800	4,000
Total FTA "Cost Per New Rider" @ 4.9%	—	---	<0	$7.27	$19.30

ties? Does the alternative improve job accessibility, particularly for the transit dependent?

• **System build-out and transit network development:** Can the alternative lead toward development of a more extensive transit network and be integrated with potential transit investments in the corridor? What are the long-term cost-effectiveness and efficiency of the alternative in relation to a potential system build-out and transit network?

• **Regional development and transportation:** Can the alternative lead toward efficient and attractive development within the corridor, the Capitol Region, and its transportation network? Is the alternative consistent with regional development and transportation policies?

• **Economic and community development:** How will the corridor communities be developed? Will the alternative attract quality investment to station areas, the corridor, and the region? What is the economic impact? Will "permanent" jobs and sustained economic growth be created?

• **Local land use policies and transit-oriented development:** Is the alternative consistent with local land use and development policies? Will the alternative complement urban redevelopment initiatives and suburban growth management strategies? Will transit-oriented investments be realized? Will urban sprawl and reliance on the automobile continue or be reduced?

Evaluation Measures

The evaluation of the five Griffin Line alternatives considers how efficiently each alternative would support mobility and accessibility, economic and community development, and long-term economic benefits in relation to each alternative's capital and operating costs. The efficiency or cost-effectiveness of each alternative assumes the baseline operating plans and policies. Four key efficiency parameters are summarized in Table 1.

Cost-Effectiveness

Several measures of cost-effectiveness are presented for each alternative under baseline conditions and forecasts. Measures include

• Total cost per passenger trip for total transit system, including annualized capital and annual total operating and maintenance (O&M) costs;

• Total state subsidy per passenger trip for total transit system (including state share of annualized capital and annual net system O&M costs);

• Total O&M cost per passenger trip for total transit system (total O&M costs);

• Total O&M state subsidy per passenger trip for total transit system (net system O&M costs); and

• Net O&M state subsidy per new service trip (net new service O&M costs).

The baseline data illustrate that, generally speaking, the general cost-effectiveness parameters—total cost per trip, total state subsidy per trip, total O&M cost per trip, and total O&M state subsidy per trip—are higher with increased levels of service. The no-build and TSM alternatives have the lowest costs per passenger, whereas the busway and particularly the LRT alternative exhibit the highest costs per passenger. However, the range between the highest and lowest values for O&M cost parameters is only about 14 percent. Values of total cost and total state subsidy per trip are higher for the busway and LRT alternatives because of the inclusion of annualized capital costs for the new fixed-guideway infrastructure and related equipment and facilities.

The relative effectiveness of the alternatives changes when the alternatives are evaluated with respect to net O&M costs per new service trip, which is simply the number of daily trips (not boardings) made on the new transit services. With this concept, the cost-effectiveness of the busway and LRT alternatives compares favorably with the TSM and bus bypass alternatives in terms of net O&M state subsidy per new service trip. These "build" alternatives represent more efficient operations, particularly the baseline busway alternative.

Operating Efficiency

Several measures of operating efficiency are presented for each alternative under baseline conditions and forecasts. Measures include

• Operating cost per train/bus hour,
• Operating cost per train/bus mile,
• Operating cost per passenger (total transit system), and
• Operating cost per system capacity (passenger place mile).

Analysis of the baseline data illustrates that, generally speaking, operating efficiency parameters are reasonably similar across alternatives with the exception that light-rail hourly and per mile costs are higher. This difference is due to the disparity in mode and carrying capacity.

When alternatives are compared on a "bus-equivalent" hourly and mileage basis, where a "bus equivalent" reflects a single standard CT Transit bus (capacity = 55), the analysis normalizes express buses and LRT vehicles to an equivalent bus in terms of capacity. The resulting hourly and mileage data are very consistent between LRT and other alternatives. Indeed, the LRT cost per bus-equivalent mile is lower than that of all other alternatives.

Sensitivity Analysis of Ridership Versus O&M Cost

The cumulative impacts of alternative transit supportive policies and alternative transit operating assumptions on the operating efficiency of each of the five transit alternatives are examined with a sensitivity analysis of operating efficiency of each alternative at various ridership levels. The sensitivity analysis examines the impact of different ridership levels (represented as percentage increases or decreases compared with the baseline ridership forecast) on annual O&M costs for each alternative. The O&M cost model, calibrated to the CT Transit-Hartford Division operations, was used to project the O&M costs of the five alternatives under various ridership scenarios.

Assumptions The sensitivity analysis, or parametric study, was undertaken with the following assumptions and study parameters:

• Baseline ridership forecasts (100 percent) for each alternative were varied at set increments from a low of 50 percent of baseline to a high of 200 percent of baseline.
• Ridership changes were assumed to be evenly spread across all routes and services.
• The O&M cost model applied in the estimation of the baseline cost estimates was applied with adjusted operating inputs (vehicles, hours, miles) required to serve the alternative ridership demand levels studied in the analysis.
• Capital improvements (vehicle purchases, station expansion, etc.) were not included.

Results The results of the sensitivity analysis are shown in Figure 5. The analysis illustrates that the O&M costs of the bus-oriented alternatives (TSM, bus bypass, busway) increase at a fairly linear rate above the baseline ridership. This rate of increase reflects additional O&M staff required with increasing ridership, given limited capacity per bus and per bus operator. Below the baseline ridership, the O&M cost curve flattens for these alternatives. As ridership decreases, costs can only be decreased by reduction in service levels. Policy decisions that were outside the scope of the study determined that service reductions would not be implemented and hence are not reflected in the O&M cost model.

The LRT alternative shows significant economies of scale as the baseline ridership increases, primarily because of the efficiency benefits associated with the larger-capacity vehicles and the capability to operate multivehicle consists with one operator. It is also interesting to

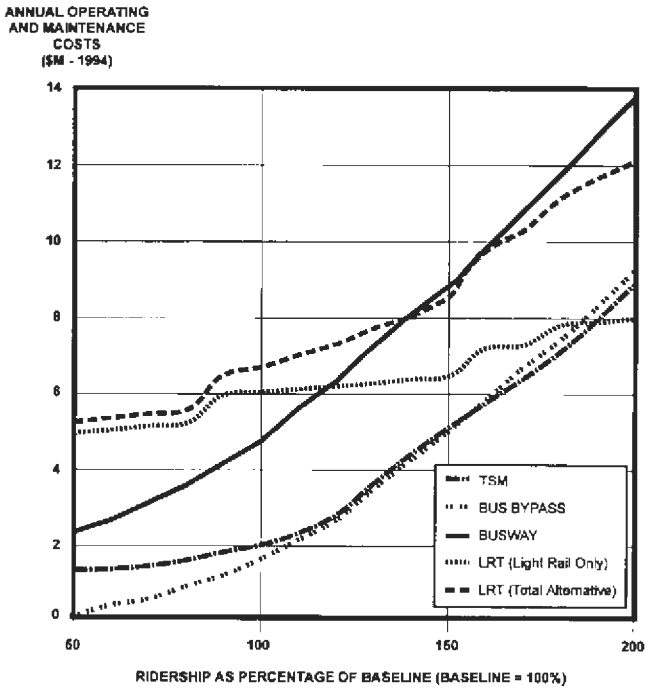

FIGURE 5 Sensitivity analysis of O&M cost versus ridership.

note the difference between the two LRT measures reflected on the sensitivity analysis graph (Figure 5): one reflects O&M costs for LRT operations only, whereas the other reflects LRT operations and supportive bus feeder operations.

O&M costs for the light-rail-only case exhibit a low rate of increase with additional ridership, whereas light rail and bus services exhibits a relatively high rate of increase (though not as high as the bus-only alternatives). This again illustrates the longer-term efficiencies of the higher-capacity light-rail operation, since the increase in the case of light-rail and bus services reflects increased bus costs more than increased light-rail costs. In practice, the actual rate of increase for the light-rail alternative (including supportive bus services) would likely be in the mid-range of the two light-rail cases illustrated. As ridership levels increased, routing and scheduling efficiencies would likely be introduced for the supportive bus services to take advantage of the higher capacity of the light-rail alternative.

FTA Cost-Effectiveness Index

The FTA cost-effectiveness index is intended to provide one measure of the relative attractiveness of various transit alternatives. The method of calculation for this index, the cost per new rider, is documented elsewhere (*1*).

Conclusion

The evaluation of the relative efficiency of the five transit alternatives analyzed in the Griffin Line Corridor Major Investment Study strives to ensure that the costs of each alternative are considered in the context of each alternative's benefits. Through the concepts of new-service-trip and bus-equivalent measures, the costs of each alternative are compared in the context of the benefits of the alternative.

The sensitivity study results reinforce the need to evaluate operating efficiencies over a range of anticipated operating scenarios. Relative efficiencies will change with varying operating scenarios. As the operating conditions will likely vary considerably over the useful life of the transportation investment, the investment should be evaluated for the changing conditions it will likely undergo.

Postscript

On July 12, 1995, CRCOG, the designared metropolitan planning organization, formally selected the LRT alternative as studied in the Griffin Line Corridor Major Investment Study and directed the Greater Hartford Transit District to complete a detailed plan to finance and implement the service. The link between transit investment and sound land use and economic and community development played a significant role in the region's decision to select light rail. Although the evaluation of alternatives indicates that, at initial ridership levels, the busway alternative would be a more cost-effective alternative to achieve the mobility goal, the CRCOG resolution states that "the Griffin Line [LRT alternative] would contribute to important State and regional goals including mobility improvements for urban and suburban residents, economic and community development and sound land use, air quality and energy policies."

The region's decision to select LRT followed formal recommendations by the city of Hartford, Town of Bloomfield, and numerous community and business organizations emphasizing the economic and community development benefits of transit investment. The Hartford City Council resolution selecting light rail as the locally preferred alternative agrees: "The economic and community development impacts of the Griffin Line are as important as the improvements in transit." The Bloomfield Town Planning and Zoning Commission "sees the light-rail alternative as the best way to promote the Town's long-range community and economic development goals" and continued its commitment to implement proactive growth management policies and zoning regulations to direct new development to light-rail station areas while preserving open space in other parts of town.

ACKNOWLEDGMENTS

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Application of Simulation and Animation To Analyze Light-Rail Transit Operations

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Application of computer simulation and animation to analyze light-rail transit networks is described using a case study of the city of Calgary to investigate alternative alignment strategies. Features of the microcomputer-based simulation method are also described. The model includes an animation display that allows the planners to visually monitor a transit system in a laboratory setting. Trajectory diagrams and level-of-service estimates are also available from the proposed simulation method.

The development of simulation models for analysis of transit operations has been attempted in a number of cities. In order to analyze relative merits of various improvement strategies, the public transit operator needs to estimate the level of service provided by a particular operation when changes are made. The proposed simulation approach has the attraction that complex relationships among various operational characteristics can be realistically modeled. The simulation model also allows for experimentation and fine-tuning of operational procedures.

However, the simulation approach has not yet achieved widespread acceptance because of deficiencies such as the site-specific nature of the models (*1,2*), validation difficulties, and lack of portability of the simulation models available to transit operators (*3,4*).

Andersson (*3*) showed a new direction for simulation modelers by incorporating the ability to output graphic frames that display the instantaneous location of vehicles along the route. This output enhancement was a major improvement to the simulation approach, because the ability to visually monitor the simulated operation has largely eliminated the black box nature of the model. The model presented in this paper has advanced the graphic frames concept to the animation stage by exploiting microcomputer technology.

Simulation applications of various degrees of complexity have been reported for tram operations in cities such as the Hague, Melbourne, and Toronto (*4–6*). However, their dependency on mainframe computers makes demonstration difficult at locations not linked to the particular computer. A common feature of these models is that they have been developed for specific projects at specific sites.

Simulation Model

The simulation model described in this paper, LRTSIM, is applicable to light-rail transit (LRT) operations. Light-rail trains often interact with street traffic because exclusive right-of-way may not be available throughout the transit system. Therefore, there are similarities between a tram operation and an LRT operation from the point of view of simulation modeling. As a result, the basic structure and concepts included in the TRAMS package (*6*) is found to be useful in the development of the LRT simulation model. However, LRTSIM is developed on a microcomputer (IBM-compatible) using BASIC computer language, whereas the TRAMS package was based on a minicomputer using FORTRAN-77. Furthermore, significant modifications have been incorporated into the two submodels included in the simulation package described here. These submodels relate to processing of passengers and traffic signals and are described in detail in a later section.

Both software portability and application portability are considered in the development of the simulation package. Software portability is ensured by developing the program on a well-accepted microcomputer. Application portability is ensured by the data-base structure, which allows specification of new networks and operational scenarios. Other useful features such as animation facilities and the self-contained data handling system are described in the next section.

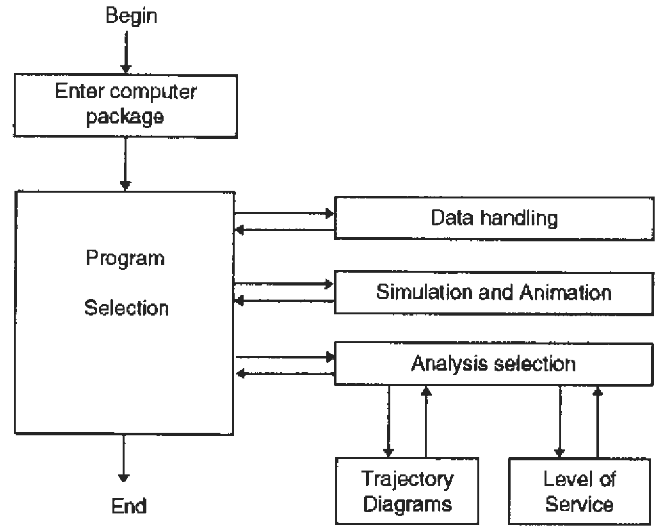

FIGURE 1 **Simplified flowchart of LRT simulation package.**

Components of LRTSIM

The computer program developed for simulation of LRT operations consists of three main components, responsible for data handling, simulation and animation, and analysis. Generally, the modeling activities take place in the above order. The method of conducting the activities in the context of the simulation package is described in the following sections.

The overall simulation consists of seven modules as illustrated in the flowchart shown in Figure 1. Upon entering LRTSIM, the user sees the initial identification screen and enters the module for the selection of modeling activity. The menu displayed by the above module allows the user to activate the desired modeling activity. Once a particular modeling activity is completed, program control goes back to the modeling activity selection module, and the program user can then select a different activity or exit the program.

Figure 1 also shows that the analysis section consists of three program modules. They are the analysis selection program module, the program module for developing trajectory diagrams, and the program module for computing the level of service provided by the simulated transit operation.

Data Handling Component

The data handling component is developed for efficient management and editing of files. The program user is able to create and modify all data files within the program environment. The color graphics display, extensive use of menu systems, and onscreen instructions are combined to ensure that the data entry process is a pleasant and efficient task. Furthermore, the data handling section allows the program to manage a number of data bases. For each operational scenario, there are nine data files describing the route, transit demand, vehicle, and operational characteristics. The simulation package is readily applicable to LRT operations in any city by modifying the data base using the data handling component.

Simulation and Animation Component

The simulation and animation component is responsible for simulation of the LRT operation described by data files created in the previous section. An important addition to the simulation model is the animation interface, which displays the current status of the simulation on the computer monitor. Animation allows the analyst to visually monitor the simulated operation. Validation of the model is simplified by the use of animation because programming inaccuracies are readily detected on the animation display.

The color graphics animation display contains zooming capabilities as well. Thus the planner can concentrate on a particular section of the network on the animation display while the networkwide simulation is being carried out.

Animation can be used to display the following: (*a*) the transit network (in line diagram form) showing the routes, station locations, and signal locations; (*b*) current location of trains; (*c*) prevailing traffic signal phases, and (*d*) simulation clock.

The program automatically selects the scales for the network display to make use of approximately 95 percent of the computer screen. Therefore, in general, the scale selected for the north-south direction of the display often differs from the scale adopted for the east-west direction. Nevertheless, the program allows the user to modify animation display scales by activating the appropriate menu item. The program also selects the spacing of animation update locations along the routes to ensure relatively smooth animation of train movement.

Simulation and animation can be temporarily suspended at any time in order to select one of the following options: (*a*) switch animation on or off, (*b*) zoom in to a particular area of the transit network, (*c*) select from one of the scaling options for the animation display, (*d*) use equal scales in both north-south and east-west directions of the network display, or (*e*) stop the simulation and exit from that particular section of the program.

The program collects and stores data from the simulated operation according to the specifications stipulated in the data base. For example, if data are required to construct time-distance trajectory diagrams of the operation, the program stores data related to time at which trains are observed at each animation update location. Additional information related to passenger loadings, passenger waiting time, and train arrival and departure times at stations is collected if level-of-service measures are also required.

Analysis Component

As stated earlier, the analysis section of the program provides (*a*) trajectory diagrams and (*b*) the estimation of measures of service related to the simulated transit operation. Measures of service such as the mean and standard deviation of travel time, vehicle occupancy, and waiting time of passengers are reported.

Simulation Method

The event update simulation method used ensures that the events are processed in chronological order of occurrence in the transit operation. The method uses an event selector, an event scheduler, and a number of event processors. The various event processors submit future events to the event scheduler, which sets them up in a queue of events in chronological order so that the event selector can choose the next event to be processed. An efficient method of event scheduling particularly suitable for microcomputer-based simulations is included in the simulation model. The above method uses two data arrays, one for the chronologically ordered events in the near future and the other to store all other events in the order of their submission.

There are seven submodels that simulate the following features of the transit operation: (*a*) route characteristics, (*b*) vehicle characteristics, (*c*) dispatching of vehicles, (*d*) boarding and alighting of passengers from multiple-door trains, (*e*) progression of vehicles, (*f*) traffic signal characteristics, and (*g*) LRT interactions with other traffic.

The two submodels described below are significantly different from the TRAMS model mentioned in an earlier section.

Passenger Boarding and Alighting

The submodel for passenger boarding and alighting accounts for passenger handling at the stations of the transit operation. This submodel satisfies the behavioral characteristics described by Wirasinghe and Szplett (7). Figure 2 provides a schematic description of the method of computing passenger handling time at stations. It is assumed that passenger handling time at a particular station is determined by passenger queue processing time at the train door with the longest passenger queue. The passenger queue consists of boarding passengers as well as alighting passengers. It is shown in Figure 2 that the

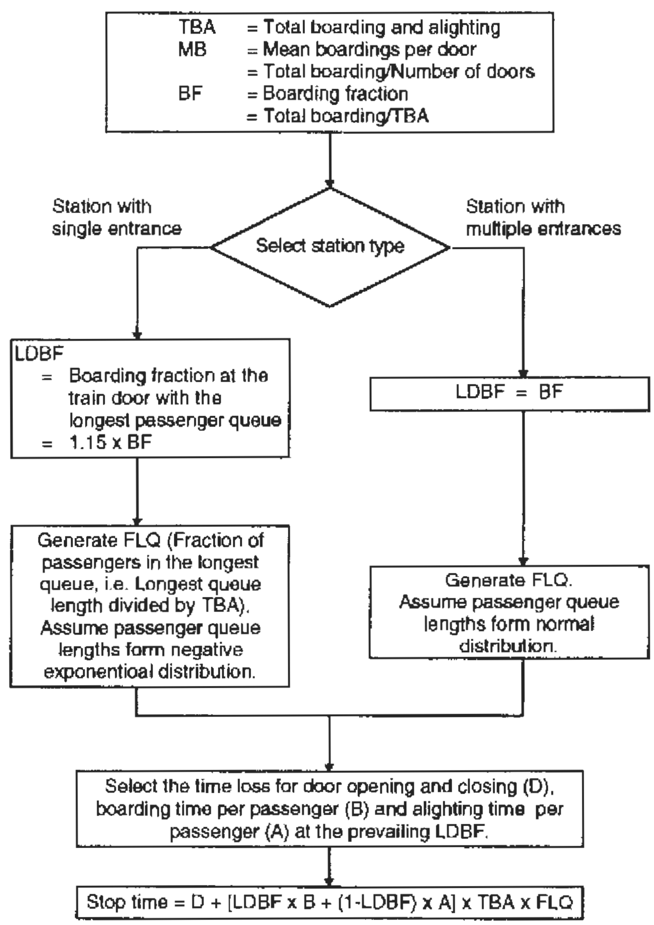

FIGURE 2 Method of computing passenger handling time at stations.

determination of the longest passenger queue during the simulation depends on the type of station. Stations with multiple entrances have passenger queue lengths that follow a normal probability distribution, whereas stations with a single entrance have passenger queue lengths that follow an exponential probability distribution. It is also observed that the fraction of passengers boarding from the longest queue is not significantly different from the fraction of all passengers boarding the particular train when there are multiple entrances leading to the station platform. However, when there is only a single entrance to the station platform from the outside, the fraction of boarding passengers in the longest queue is on average 15 percent greater than the fraction of all passengers boarding the train.

Traffic Signal Characteristics

The simulation model is able to account for three types of traffic signals, as described in the following.

Conventional Street Traffic Signals

Conventional street traffic signals control the progress of light-rail trains when the train operation shares the right-of-way with street traffic. For the purpose of the simulation model, the amber phase is disregarded by including it in the red phase of the traffic signal. The street traffic signal controller in the program allows for fixed cycle phase arrangements and the specification of phase offsets from adjacent traffic signals.

Train Signals

The simulation model also allows for train signal block operations. When a train enters a route segment between two train signals, the signal leading to that particular segment is set to the red phase. At the same time, the signal leading to the route segment just vacated by the train is set to the green phase. The above method protects any other trains entering the route segment occupied by a particular train.

Interlocking Train Signals

Interlocking train signals form a special category of train signals. They are installed in the proximity of train route merge and intersection locations. This particular type of signal prevents more than one train from occupying a merge area of an intersection. Therefore, when a train enters an interlocking segment, all signals on approaches to the particular interlocking segment are set to the red phase to ensure conformity with safety requirements.

Comparison with Field Observations

Comparison of actual field conditions with results from the simulation following existing operating conditions have shown that LRTSIM is able to make reliable estimates of the level of service. Table 1 shows some parameters considered during the validation of the model using data from the Calgary LRT system. The 1987 network was selected because the field data used for comparison were collected in that year. To assist in the comparison of simulation results and field data, critical significance levels for means to be equal were also computed and are shown in Table 1.

For example, the mean travel time in the morning peak traffic conditions on the first route shown in Table 1 is only 1 percent lower than the mean value obtained by the simulation. Comparison of travel time results obtained from the simulation model and the field data for

TABLE 1 Comparison of Simulation Results and Field Data

	Field data		Simulation		
	mean	standard deviation	mean	standard deviation	Critical significance[a]
Travel Time (minutes)					
1. Anderson to University	33.90	2.44	34.23	1.91	0.60
2. Whitehorn to 10 Street S.W.	22.64	1.07	23.43	0.95	0.05
Departure Headways (minutes)					
1. Whitehorn	7.72	3.04	6.01	1.99	0.10
2. Anderson	5.36	1.39	5.01	0.59	0.40
Arrival Headways (minutes)					
1. 10 Street S.W.	7.81	3.29	6.19	3.13	0.16
2. University	5.40	3.72	4.99	1.66	0.60

[a]Critical significance level for means to be equal.

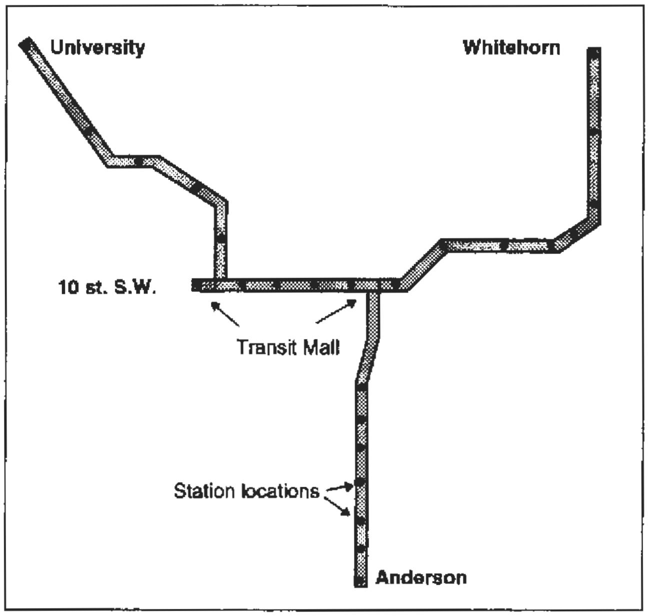

FIGURE 3 LRT routes in Calgary.

the second route shown in Table 1 shows that the mean travel time can be considered equal at a level of significance of 0.05. Table 1 also shows the realistic nature of the mean departure headway available from the simulation model at the first station of each route and the arrival headway at the last station.

Route Alignment Selection Applications

The Calgary transit operation in 1987 consisted of light-rail train routes approaching from three directions (northeast, south, and northwest) and converging at a 2-km-long surface transit mall in the city of Calgary (Figure 3). The simulation model is applied to investigate the effect of the transit mall on the level of service provided to transit passengers. According to the current practice in Calgary, trains on the transit mall share the right-of-way with conventional buses. In a typical peak-period operation, trains from the northeast are turned around at the end of the transit mall (forming Route 202). The northwest and southern routes are operated as a single continuous route (Route 201).

The current practice is compared against two alternatives. The first alternative operation consists of two transit malls that would operate on two adjacent parallel east-west streets. The right-of-way on the two streets mentioned above was preserved for future LRT use by the city of Calgary in 1976. It is assumed that equal amounts of bus traffic will use the two malls. Furthermore, it is assumed that one transit mall will be served by trains to and from the northeast corridor (Route 202). The other transit mall is assumed to be used by the continuous route formed by the south and northwest corridors (Route 201).

The second alternative analyzed assumes that trains will operate in underground tunnels below the present transit mall. The city of Calgary owns tunnel space that has been earmarked for future underground operations in the downtown area (*8*).

In addition, three different demand characteristics are considered for each of the above alternatives. The present demand conditions as well as future conditions when passenger demand increases by 50 and 100 percent are used as simulation scenarios. It is assumed that the operator would increase the vehicle dispatch rate to cater to increased passenger demand. Therefore, for future scenarios, train headways are assumed to be approximately inversely proportional to the square root of the total passenger demand (*9*). The train headways selected for the two routes are as follows (present demand level = 1):

	Headway (min)	
Demand Level Factor	*Route 201*	*Route 202*
1.0	5	6
1.5	4	5
2.0	3	4

The vehicle characteristics of the alternative operations are assumed to be the same as those in the present operation.

The simulation results reported below were computed by repeating the simulation of the morning (two hours) operation toward University Station in the northwest. Ten repetitions were performed. Thus the results reflect the mean values that can be anticipated from peak-period operations spanning 2 weeks.

Figures 4 and 5 show the travel time information available from the simulated operations. Figure 4 relates to the morning peak-period travel time on Route 202 (see Figure 3), and Figure 5 relates to the travel time of Route 201.

In the three demand scenarios simulated, introduction of the second mall reduced travel time by approximately 5 percent. This reduction in travel time can be used for a significant saving in fleet size in this particular LRT system. For example, fleet size can be reduced by two trains when travel time is reduced by 5 percent. A further travel time reduction of similar magnitude is available when the transit malls are eliminated and trains avoid interaction with street traffic by using underground tunnels.

There is no significant difference in the mean waiting time experienced by passengers in the above alternative operations for a given demand level for Route 202, as shown in Figure 6. The reduction in the waiting time with increased level of demand is in agreement with the

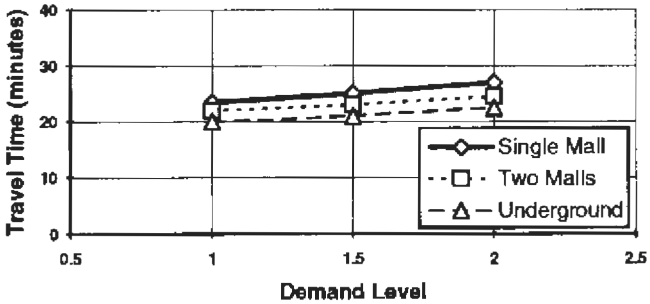

FIGURE 4 Mean travel time of trains on Route 202.

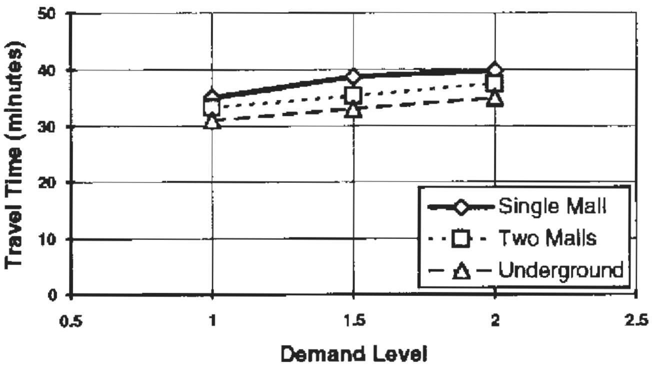

FIGURE 5 Mean travel time of trains on Route 201.

increase in the vehicle dispatch rate. For the purpose of this analysis, the waiting time is considered to be the time spent since the passenger arrival time at the train station till the departure time of the train that the passenger is able to board. Insensitivity of waiting time on this particular route is due to the effects of congestion in the mall area, because the route terminates at the end of the mall. However, planned extension of the route to the west should be designed with care because congestion effects will be carried over to stops away from the mall as shown for passenger waiting time on Route 201 (Figure 7).

The mean waiting time of passengers on Route 201 shows that the single-mall option consistently results in increased waiting time for passengers compared with the other two options. As mentioned before, the above increase in mean waiting time is a result of the congestion at the transit mall, which affects the waiting time of passengers at downstream stations. Generally, the single-mall option shows a higher level of bunching on the trajectory diagram of distance versus time (not shown here), which supports the above results.

The simulation model provides other level-of-service measures related to occupancy and train headways. For example, the maximum occupancy for Route 202 is shown in Figure 8, in which a general increase in crowding and number of standing passengers with the increase in passenger demand level can be seen. However, there

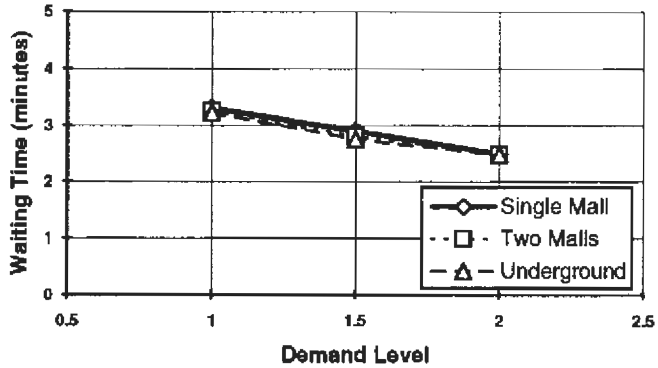

FIGURE 6 Mean waiting time of passengers on Route 202.

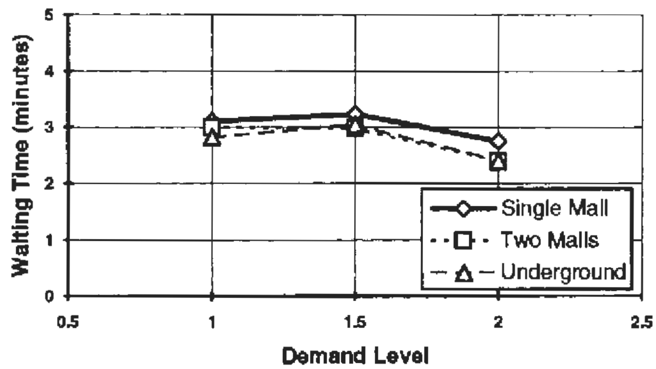

FIGURE 7 Mean waiting time of passengers on Route 201.

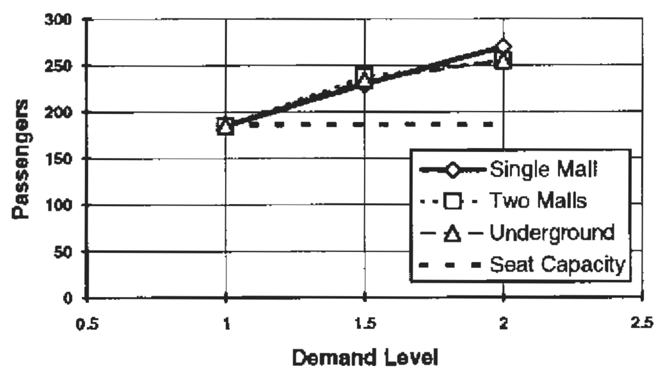

FIGURE 8 Maximum occupancy of Route 202.

is no significant difference in the maximum occupancy among the different operating alternatives at a given demand level.

Conclusions

The simulation model application to the LRT system in Calgary has shown that travel time reductions of approximately 5 percent can be achieved with a two-transit-mall operation compared with the present single-mall operation. The model also predicts a further reduction of similar magnitude in travel time if interactions with other street traffic are removed by operating the LRT system in underground tunnels in the city area. Effects of passenger demand increase in the future have also been investigated. The level-of-service measures investigated during the reported analysis cover waiting time, travel time, headways, and occupancy.

LRTSIM, a microcomputer-based simulation model useful in estimating the level of service provided by LRT operations is described. The animation of the simulated operation is a significant advantage from the point of view of validation and the ease of understanding the simulated operation. The in-built data handling section is designed to allow the model to be readily applied to LRT systems in different cities.

The simulation method provides an effective technique in estimating the level of service of an LRT operation. Microcomputer-based simulation allows the inclusion of animation features and graphical features such as trajectory diagrams that allow planners to readily comprehend the features of the transit operation under investigation. Furthermore, detailed analysis of the operation is made feasible because the program can be readily instructed to track passengers as well as vehicles of the simulated operation and retrieve the required data.

Collection of similar data from field experiments is difficult, if not impossible, because of the associated survey costs and possible disruptions to the service during experimentation. On the other hand, repeated application of the simulation model provides an efficient method for collection of data representing successive days of operations. Therefore, the statistical significance of the estimates can be improved with little additional cost.

ACKNOWLEDGMENT

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PART 3
FUTURE OF RAIL TRANSIT

Progression or Regression: Case Study for Commuter Rail in San Francisco Bay Area

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Commuter rail, once a transit option in many cities, is currently experiencing a resurgence in popularity in this country. A case in point is the Bay Area Rapid Transit District's (BART's) plan to return commuter rail to the East Bay Area. BART is now considering a plan that will return commuter rail to the Bay Area in the form of a 322-km (200-mi) regional commuter rail system in the East Bay Area. This system would use existing rail infrastructure and provide service to five counties. BART developed this program as a near-term and cost-effective transportation solution for relieving highway congestion and maximizing limited financial resources for new rail extensions in the Bay Area. The BART Commuter Rail Program could begin service within 2 years after funding sources have been secured. Short-term implementation is possible because the existing infrastructure and facilities can support service today. The BART Commuter Rail Program would be coordinated with existing regional transit services and provide an integrated and coordinated regional transportation system. Compared with other proposed rail transit and highway expansion projects in the region, the BART Commuter Rail Program is a cost-effective and efficient use of the region's financial and physical resources. In addition, the expected operating performance of the program is within the industry range of performance levels experienced by new-start commuter rail systems across the nation.

Commuter rail, once a transit option in many cities, is currently experiencing a resurgence in popularity in this country. A case in point is the Bay Area Rapid Transit District's (BART's) plan to return commuter rail to the East Bay Area. Critics consider this plan regressive for a state-of-the-art system such as BART and believe that it may eliminate established and committed local projects. This paper will examine how commuter rail, in the San Francisco Bay Area, is determined to be a progressive and cost-effective solution within a context of dwindling resources and urban decentralization.

Since 1992, BART has evaluated the opportunity of implementing a 322-km (200-mi) regional commuter rail system in the East Bay. The system would use existing rail infrastructure and provide service in the counties of Solano, Contra Costa, Alameda, San Joaquin, and Santa Clara, as shown in Figure 1. BART developed this program as a near-term, cost-effective transportation solution to increasing highway congestion and limited financial opportunities for rail extensions in the Bay Area.

Background

BART currently operates a 114-km (71-mi) rapid transit system in three counties (Alameda, Contra Costa, and San Francisco). In 1991 BART embarked on a $2.5 billion rail extension for its Phase I program, which includes the addition of 60 km (36 mi) of new rail and 11 new stations, as shown in Figure 1. The Phase I extensions are expected to be complete and in revenue service by 1996, serving over 100,000 daily riders (*1*). Whereas the new extensions are expected to address significant

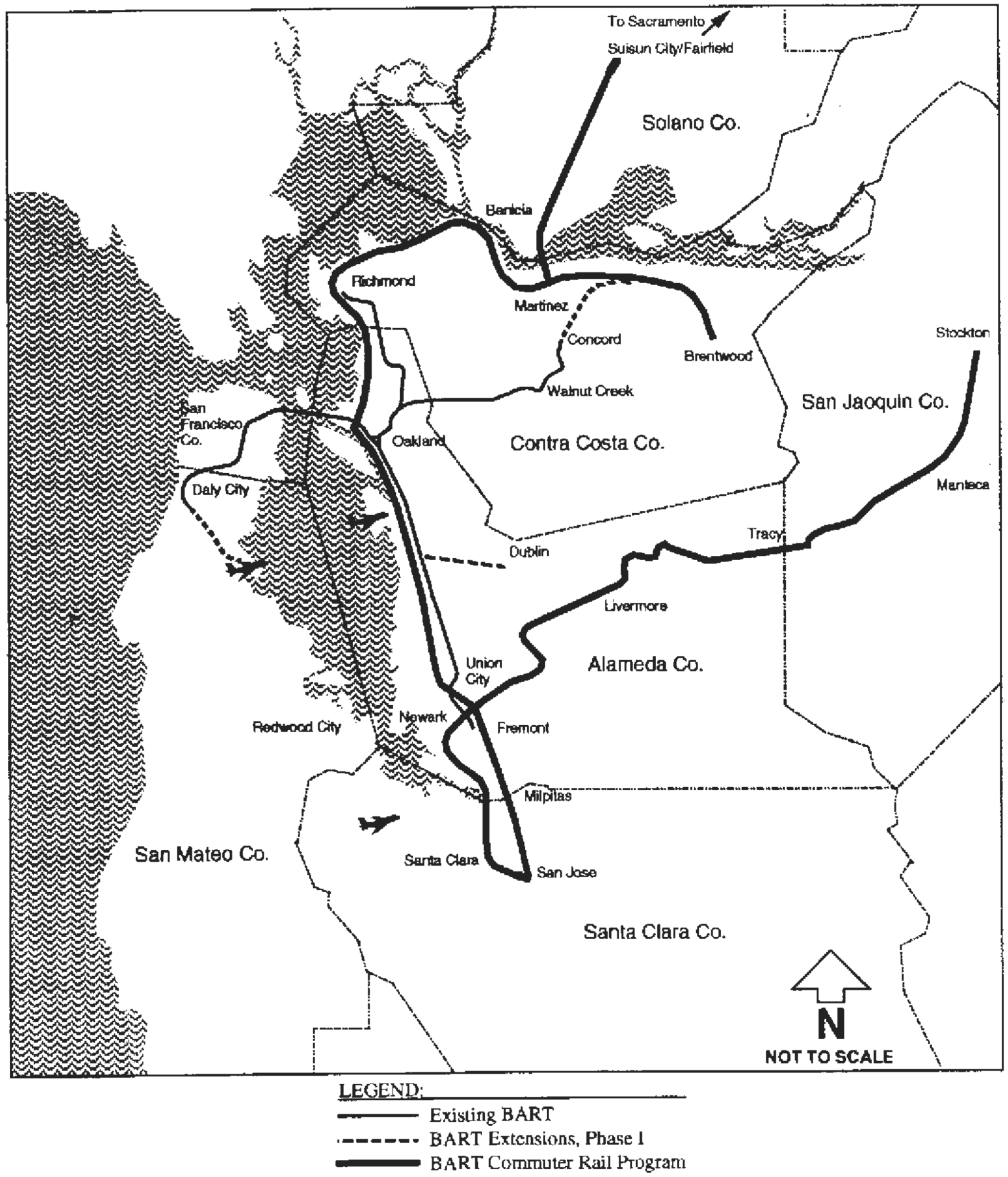

FIGURE 1 BART system and Commuter Rail Program.

travel needs for the region, they cannot meet them all because of rapidly changing travel characteristics and markets.

Several studies that examine other rail opportunities in the Bay Area have been prepared. These studies, which include an intercity rail corridor study (*2*) and commuter rail studies between Solano and Alameda counties (*3*) and between San Joaquin and Santa Clara counties (*4*), determined that there is an immediate need for additional rail service in the region's most heavily traveled corridors. With BART extensions estimated to cost between \$48 million and \$129 million (1994 dollars) per kilometer (\$30 million to \$80 million per mile) (*1*) and the estimated time to plan, design, and construct a BART extension ranging from 5 to 10 years, future BART extensions are considered long-term solutions.

In 1992 and 1993, the Union Pacific Railroad (UP) and the Southern Pacific Transportation Company (SP) made separate proposals to provide their rights-of-way, currently used primarily for freight, for commuter service in the East Bay Area. The UP offered its right-of-way between San Joaquin and Alameda/Santa Clara counties, and the SP offered its right-of-way between Solano, Alameda, and Santa Clara counties. In each case the rail company's proposal included the opportunity to lease or purchase existing rail rights-of-way and infra-

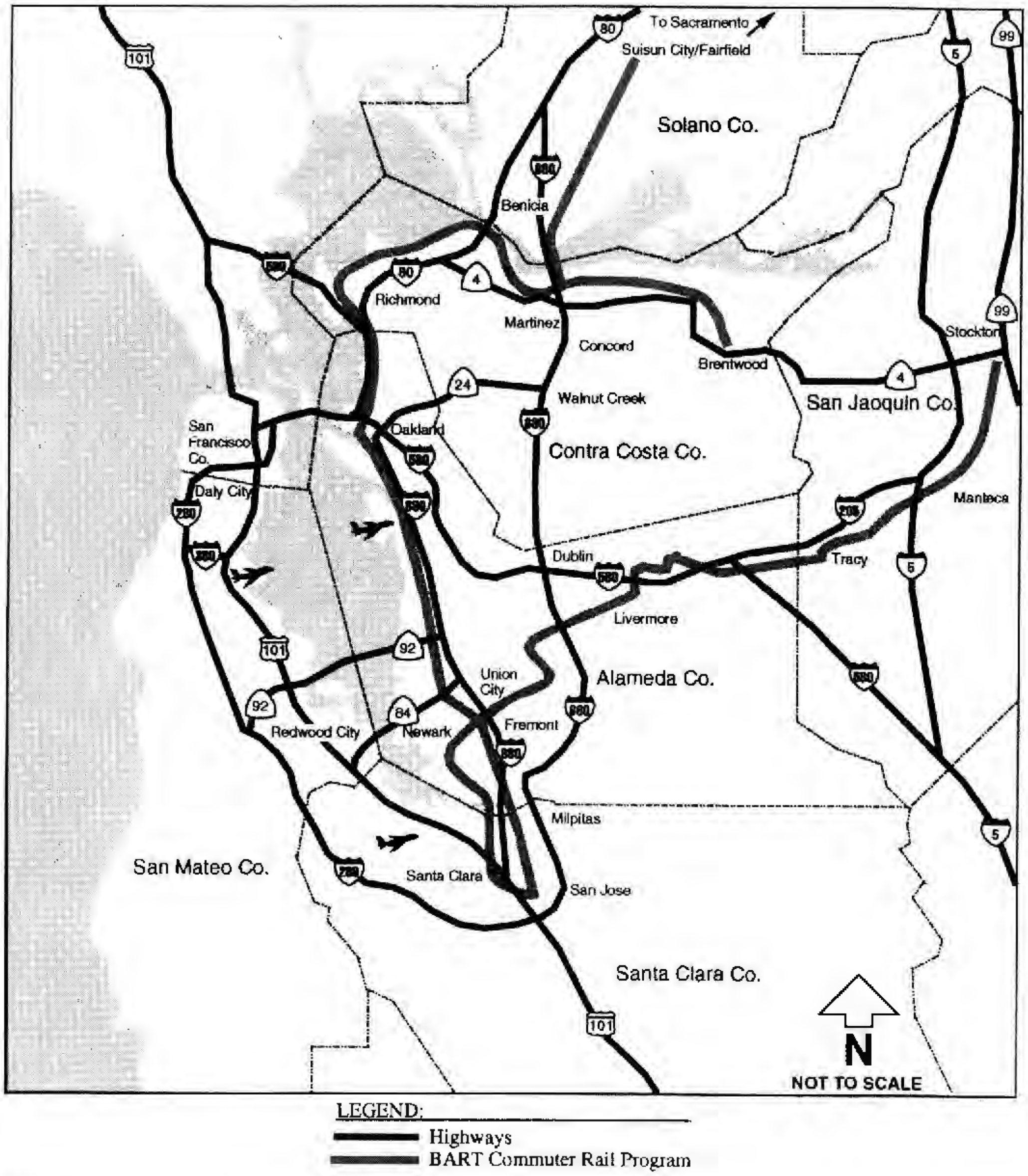

FIGURE 2 Highway corridors.

structure (rail, signals, dispatching) for potential commuter services. The envisioned commuter service along these corridors would replace historical travel routes and could take advantage (for a fee) of existing stations, layover, maintenance, and other facilities. The recently announced proposed merger of the UP and SP offers potential benefits to commuter rail service in the region. If the merger is approved, the Bay Area and surrounding region will be served by only two Class 1 railroads, the newly combined Burlington Northern-Santa Fe and UP-SP. The potential benefits to commuter rail service could include efficient management of freight movements on shared rights-of-way, consolidation of and access to infrastructure capacity, and the opportunity to purchase excess rail rights-of-way at competitive prices.

Travel Need

The Bay Area's travel markets are increasingly defined by new residential construction in areas farther from the urban core and the development of dispersed suburban employment centers. Urban decentralization has a dramatic effect on the East Bay. New travel markets between Solano, Contra Costa, San Joaquin, and Alameda counties have been created, while demand in the traditional travel markets serving San Francisco and the Peninsula has declined. As a result, more residents are traveling from communities farther from the urban core than ever before, and the highway corridors that connect these areas, as shown in Figure 2, are becoming increasingly congested.

TABLE 1 Increase in Daily Work Trips, 1987 to 2010 (5)

Travel Corridor	Primary Highway	Number	Percent
Solano - Contra Costa	I-80	15,000	55%
Contra Costa - Alameda	I-80	23,000	18%
San Joaquin - Alameda	I-580	38,100	140%
San Joaquin - Santa Clara	I-580/880	10,000	92%

The population in Solano and Contra Costa counties is expected to increase by more than 200,000 each (a 60 percent and a 36 percent increase, respectively) between 1990 and 2010, and by 380,000 (a 75 percent increase) in San Joaquin (5). The average population growth during this period for the entire Bay Area is projected to be about 24 percent (5). As a result of these high levels of growth in outlying areas, it is estimated that between 1987 and 2010 the number of daily work trips along the proposed rail corridors will increase by 18 to 140 percent, as indicated in Table 1 (5). The increase in population results in existing and future congestion on the region's major travel corridors. As indicated in Table 2, traffic volumes at key screenlines along these travel corridors will increase by 16 to 57 percent and result in severe congestion (Level of Service F) by 2010 (6,7).

There are relatively few programmed improvements capable of bringing short-term relief (within 5 years) to existing and projected congestion along the I–80, I–880, and I–580 corridors (which parallel the SP and UP rights-of-way) (3). The BART extensions currently under construction will not be able to address the travel needs of these corridors, and planned extensions would be implemented too far in the future to gain any short-term mitigation. However, a commuter rail alternative in these corridors would provide near-term additional passenger capacity and a viable alternative to driving on congested freeways.

Funding and Institutional Issues

In the Bay Area, there is consensus on the need to relieve traffic congestion, but there is disagreement on what that relief should be. The disagreement stems more from a financial concern than a technical one. The current funding picture for the region is equivalent to a zero-sum game: $1 spent on a new project means $1 less for projects already programmed. Therefore, agencies and jurisdictions typically are not willing to give up their projects' funding for a new regional initiative.

Rail alternatives historically are capital intensive and require long-term implementation. However, the commuter rail system being considered in the Bay Area would use existing infrastructure along established travel routes. This would significantly reduce the need for extensive planning and environmental clearances, right-of-way purchases, and major capital investments. A number of local, state, and federal financing opportunities have been reviewed to fund a proposed commuter rail program. In addition to pursuing the inclusion of the program in the Regional Transportation Plan, new sources of financing and strategies to deploy existing funds are being evaluated and identified. For instance, ways to link the BART Commuter Rail Program with other regional and local projects are being investigated to leverage funding opportunities and maximize the benefit from both projects.

TABLE 2 Highway Traffic Volumes, 1995 and Projected for 2010 (6,7)

Travel Corridor & Screenline	Year 1995	Year 2010[1]	% Increase
North Bay - I-80 Westbound AM Peak			
Emeryville/Oakland	9,000	12,000	33.3%
Richmond	5,900	8,500	44.1%
Carquinez Bridge	5,400	7,400	37.0%
Fairfield	7,100	10,700	50.7%
Altamont Pass - Daily			
I-580 @ Pleasanton	157,000	182,000	15.9%
I-580 @ Livermore	140,000	168,300	20.2%
I-580 @ Altamont Pass	103,000	161,400	56.7%
I-205 @ Tracy	65,000	100,600	54.8%

1. These screenlines are projected to be operating at severe congestion (Level of Service F) in the year 2010.

Currently, there are more than 25 transit agencies in the Bay Area (including BART) providing transit services. The Metropolitan Transportation Commission (MTC), the region's metropolitan planning organization, is the Bay Area's transportation planning and funding clearinghouse. One of MTC's charges is to ensure coordinated and efficient provision of transportation services for the Bay Area. MTC has participated in discussions with BART and other agencies to consider commuter rail as an opportunity to consolidate and integrate transit services in the Bay Area with a single operator, fare structure and transfers, and schedules.

BART, a multicounty and multimodal transit operator (BART operates express bus and rapid rail transit service), is well positioned to manage the planning and operation of a commuter rail operation. However, current statutory restrictions prohibit BART from operating any service outside of its three-county district (Santa Clara, Solano, and San Joaquin counties are outside of the BART district). The formation of a joint powers agency or legislative reform is necessary to enable BART to manage, administer, and operate commuter rail service outside of its district.

BART Commuter Rail Program

In response to the initial studies and issues described, BART prepared a commuter rail program (8). The program consolidates the rail alternatives described in the previous studies into a comprehensive regional rail system consisting of 322 km (200 mi) of commuter rail on existing rail lines in five counties, as shown in Figure 1. This section summarizes the BART Commuter Rail Program and the preliminary operating plan.

Program Description

BART developed the regional commuter rail program as an essential component of an integrated regional public transportation network. To ensure successful implementation, BART also developed service standards and refined patronage estimates for the proposed program.

Service Standards

Service standards were developed to define the commuter rail program and specify systemwide equipment and facilities requirements (*8*). The standards established the program's basic infrastructure commitment and a methodology for implementation. They were developed to ensure rapid start-up of service with minimal capital investment. The five major service standard concepts are summarized in this section.

Service Concept It was determined that the service will be operational within 2 years after receiving funding. The service will offer weekday morning and evening peak-hour line-haul service that closely integrates BART and other regional transit services. Initially, the service will not include off-peak or weekend service. However, it is anticipated that alternative rail and bus services that operate in the corridors during off-peak and weekend periods will be marketed to passengers and, wherever possible, integrated into the schedule and fare information. Wherever feasible, stations will be provided with park-and-ride and kiss-and-ride facilities and will be served by local bus systems. Maximum performance, reliability, and equipment availability goals will be established to ensure high-quality service. Commuter service travel times will be competitive with the automobile, with an on-time arrival target similar to BART's (95 percent of trains arrive within 5 min of scheduled times).

Infrastructure Rights-of-way and grade crossings will be protected and controlled in accordance with existing legislation and each railroad's existing standards. Station platforms will be constructed to handle five-car trains and positioned to allow future expansion. Stations will not be staffed and will include only basic passenger amenities (i.e., shelters, lighting, seats, and fare collection equipment). Additional station amenities may be provided by local jurisdictions. Sufficient parking will be provided to meet the expected demand.

Fare Collection A simple, single fare instrument that is compatible with BART and other transit systems will be used to integrate and coordinate transfers. Fares will be based on a zone and proof-of-purchase system. Discounts will be offered for multiride fares, people with disabilities, and seniors.

Rolling Stock The commuter rail rolling stock will be leased or purchased and will meet all Federal Railroad Administration requirements. The rolling stock will be state-of-the-art equipment and will be capable of providing push-pull operation. Diesel-electric locomotives are expected to be capable of pulling at least five passenger cars at the maximum allowable speeds. High-capacity (bilevel) passenger coach and push-pull cab cars will be used.

Accessibility All elements of the program (facilities and rolling stock) will meet current Americans with Disabilities Act requirements.

Corridor Descriptions

Three corridors have been studied independently for possible commuter rail service, including the North Bay, South Bay, and Altamont Pass corridors, as shown in Figure 3 (*8*). BART conducted a complete reconnaissance survey of the existing lines to determine the condition of the facilities and found they were all capable of accommodating commuter operations consistent with the service standards described earlier. Each of the corridors is described briefly in this section.

North Bay Corridor This corridor generally parallels I-80, serving the emerging residential communities in Solano County and the traditional employment centers in Oakland and San Francisco. It is 76 km (47 mi) long and would provide service between Solano County and West Oakland (with a direct connection to BART for transfers to San Francisco and other points in the East Bay) on the SP Sacramento Line. Branch service could also be provided on a 43-km (27-mi) corridor between Martinez and Brentwood on the SP Mococo Line in Contra Costa County. There are four existing intercity rail stations in this corridor that could be used by a commuter service: Suisun City/Fairfield, Martinez, Emeryville, and Richmond (also a BART station).

South Bay Corridor This corridor would serve residents in Alameda County traveling to the emerging employment centers in Santa Clara County and the Silicon

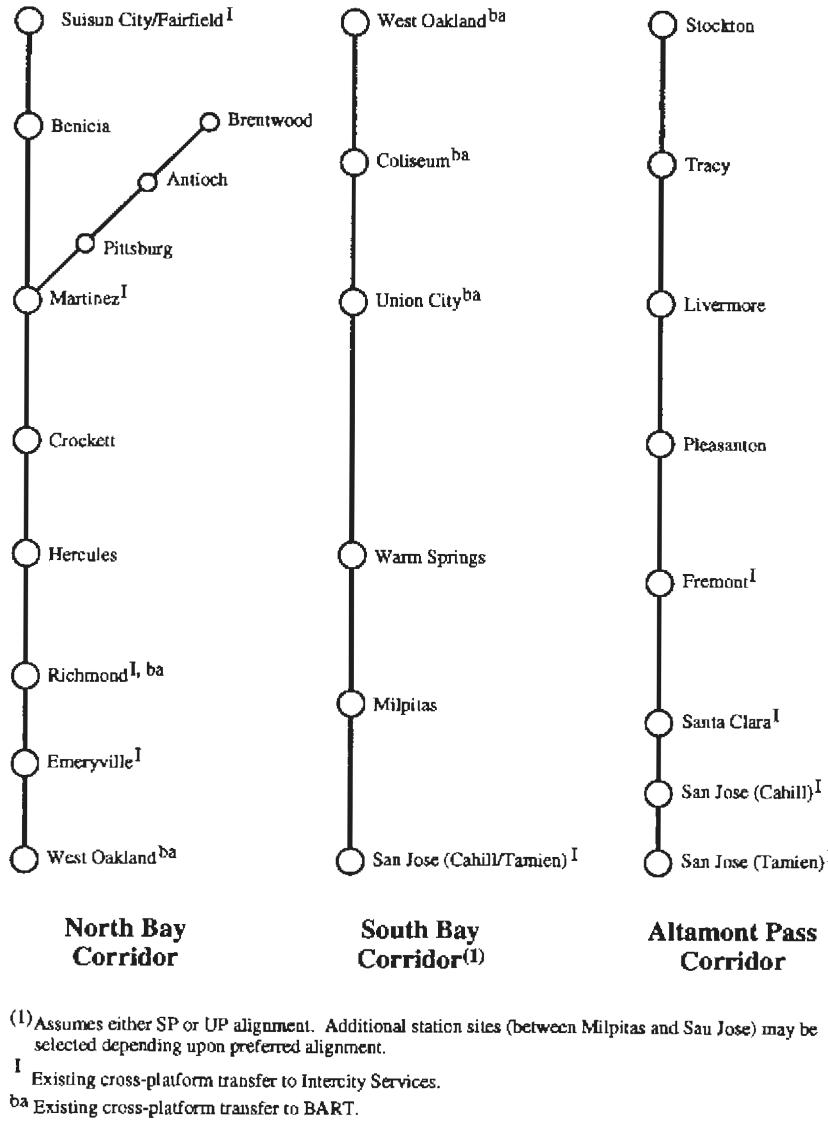

FIGURE 3 Commuter rail corridors.

Valley. Service in this 68-km (42-mi) corridor, which generally parallels I-880, would be provided between West Oakland and San Jose on either exclusive SP or UP rights-of-way or a combination of the two. The selection of the preferred right-of-way will be determined on the basis of local preferences and future funding and implementation conditions. There are two existing stations in this corridor located in San Jose: the Cahill joint Amtrak/Caltrain station in downtown San Jose (used by several intercity rail services and the Caltrain Peninsula Commute service) and the Tamien station (which serves Caltrain and the Santa Clara Transportation Authority light rail transit).

Altamont Pass Corridor This corridor would serve residents in the emerging residential communities in East Alameda and San Joaquin counties and the employment centers in East Alameda and Santa Clara counties. It generally parallels the I-580 and I-880 corridors with service provided on the UP and SP rights-of-way. Four stations currently provide intercity rail service, including Stockton, Fremont, Santa Clara, and San Jose (Cahill).

Patronage Estimates

The service plan also evaluated and refined initial patronage estimates for each of the corridors and prepared a systemwide estimate along all three corridors (*8*). Patronage estimates for 2000 were developed on the basis of a regional planning model and travel data, and the program is expected to serve about 3.73 million passengers annually, as indicated in Table 3.

TABLE 3 BART Commuter Rail Patronage Estimates: Total Daily and Annual Trips in 2000 (*8*)

Corridor	Daily	Annual
North Bay	6,400	1,600,000
South Bay	5,520	1,380,000
Altamont Pass	3,000	750,000
Total	14,920	3,730,000

Preliminary Operating Plan

A preliminary operating plan was prepared on the basis of the service standards, physical infrastructure conditions, and travel demand data of the three potential commuter rail corridors (*8*). The preliminary operating plan is summarized in Table 4. The basic premise of this plan is to maximize the operating potential of this service while ensuring a rapid start-up and minimal capital investment.

Economies of Scale

It was determined that significant economies of scale could be gained by implementing the entire system at once rather than phasing in one corridor at a time. The preliminary operating plan qualitatively identified economies of scale to be achieved through consolidation of maintenance functions, rolling stock requirements, crew and staffing needs, and maximizing integration of fares and service schedules.

Service Plan

An effort was made to find a cost-effective balance between passenger requirements and optimal equipment and crew utilization among the three corridors. On the basis of preliminary discussions with the UP and SP, it was determined that an operations window for the commuter service could be established to minimize conflicts between freight and passenger movements.

In all cases, the resulring optimum service plan was based on patronage estimates and existing infrastructure conditions. The service plan assumed 22 stations within the entire rail network (7 exist). Service schedule scenarios were tested using a rail operations simulation program, which estimated run times on the basis of required track speeds, other rail operations (freight and passenger services), scheduled station stops and dwell times, and crew changes and train turn times.

A fundamental operating strategy assumed that schedules would accommodate business travelers and provide reasonable arrival and departure times in San Francisco, Oakland, and San Jose. The schedules also assumed sufficient time for transfers to connecting bus/rail services. As indicated in Table 4, the optimum service schedules included up to six peak-direction trips (a.m. and p.m.) in the North Bay and South Bay, and two peak-direction trips (a.m. and p.m.) in the Altamont Pass Corridor. The initial service plan does not include off-peak service. After the successful initiation of the service, additional midday, evening, and weekend off-peak service will be considered and added to the schedule and incorporated into the operating plan.

Competitive Travel Times

Estimated travel times of automobile and commuter rail service for origin and destination pairs for 2000 were compared (*9*). As indicated in Table 5, it is estimated that the commuter service would provide travel time savings of up to 24 percent compared with the automobile.

Rolling Stock Requirements

Rolling stock requirements were based on the service standards and preliminary service schedules described earlier (*8*). The basic train set includes a locomotive, three bilevel passenger coaches, and a bilevel cab control car, for a total capacity of 580 passengers per train. The total rolling stock requirement is 15 locomotives, 46 coaches, and 16 cab cars. These estimates include a 15 percent spare requirement for locomotives and a 20 percent spare requirement for coach and cab cars, consistent with industry standards (*8*). On the basis of an industry survey, it was determined that these rolling stock requirements could be met within a 2-year time frame through either a lease or a purchase option (*8*).

Capital and Operating Costs

The estimates of capital and operating costs for the commuter rail service were based on the assumptions that equipment would be used on multiple corridors, joint maintenance and layover facilities would be shared, and labor costs could be reduced through these and other staff and crew efficiencies (*8*).

Capital Costs Capital costs for infrastructure are based on an inventory of the corridors and estimates for the improvement of tracks and signals, layover and maintenance facilities, and stations. Estimates for rolling stock and right-of-way access fees were based on an industry survey and discussions with the railroads. Station costs were based on the assumption that existing facilities would be used or that minimal stations would be constructed, as described earlier. It was also assumed that the commuter rail program would use existing maintenance facilities or would share the Amtrak, Cal-

TABLE 4 Preliminary Operating Plan (Peak-Period Service Only) (8)

	AM Peak Period		PM Peak Period	
Service Corridor	Trains	Headway (minutes)	Trains	Headway (minutes)
North Bay				
Suisun/Fairfield to West Oakland	3	30 - 60		
Brentwood to West Oakland	3	30		
W. Oakland to Suisun/Fairfield			3	40 - 60
W. Oakland to Brentwood			3	40 - 45
South Bay				
W. Oakland -Union City - San Jose	1		2	55
Union City to San Jose	3	20 - 25		
San Jose -Union City -W. Oakland	2	30	1	
San Jose to Union City			3	30
Altamont Pass				
Stockton to San Jose	2	60		
San Jose to Stockton			2	40

TABLE 5 Comparative Travel Times and Speeds, 2000 (9)

	Automobile			Rail			
Selected Pairs	Miles	Time (min.)	Speed (mph)	Miles	Time (min.)	Speed (mph)	Travel Time Savings (%)
Fairfield-W. Oakland	44.8	92	29.2	49.0	75	39.2	18
Pittsburg-W. Oakland	31.8	79	24.2	41.5	61	40.8	23
Martinez-W. Oakland	23.8	57	25.1	28.0	47	35.7	18
Warm Spring-W. Oakland	32.9	58	34.0	36.9	47	47.4	19
San Jose-W. Oakland	43.4	77	33.8	50.9	71	43.2	8
Fairfield-San Francisco	50.6	111	27.4	54.9	90	36.6	19
Pittsburg-San Francisco	38.9	100	23.3	47.4	76	37.4	24
Martinez-San Francisco	30.8	78	23.7	33.9	62	32.8	21
Livermore-San Jose	42.6	84	30.4	42.0	71	35.4	15

trans, and Peninsula Commute Service Pullman maintenance facility to be located in San Jose. Maintenance facility costs are based on a prorated share of use. The capital costs presented in this paper assumed purchase of rolling stock. The initial capital costs for the program are estimated to be about $340 million (1994 dollars) total or $1.06 million per kilometer. They are summarized in Table 6.

Operating Costs Annual operating and maintenance costs for the commuter service include crew, fuel, facility and equipment maintenance, administrative, and associated costs. The costs were based on a survey of similar costs for other new-start and traditional commuter rail systems (*8*). In particular, the experiences of the Peninsula Corridor Caltrain service in the Bay Area and the new Metrolink service in Southern California were used as a baseline reference to approximate local conditions. Total annual operating costs for the system were estimated to be up to $17.2 million (1994 dollars).

Fare Revenue Projections and Net Operating Costs

A distance-based "zone" fare structure was assumed for the commuter rail service (*8*). The fare program was assumed to be integrated with the BART fare system, requiring only a single payment for trips originating on the commuter rail service and transferring to the BART system. Discounts were assumed for multirides, people with disabilities, and seniors. The annual revenue generated from passenger fares is estimated to be about $5.2 million (1994 dollars). Applying these fare-box revenues to operating costs, the net operating cost of the commuter rail service would be $12 million (1994 dollars), resulting in a fare recovery ratio of 30 percent.

Implementation Issues

Once funding is secured, it is expected that the entire system could be operational within 2 years (*8*). This

TABLE 6 Preliminary Capital Costs, BART Commuter Rail Program (8)

Cost Item	1994 Dollars (millions)
Track and Signal Modifications	$24.79
Layover facilities	2.12
Station modification/construction	30.74
Maintenance facilities	4.00
Rolling Stock	128.00
Track Access Fees	150.00
Total Capital Costs	$339.75

includes a realistic estimate of the planning and implementation phase of the program. A 2-year start-up was considered realistic because it is estimated that railroad negotiations and infrastructure improvements (track, signals, and facilities) could be completed within the 2 years. In addition, it was determined that the project may qualify for a categorical exemption under the California Environmental Quality Act because it would establish rail service along rail lines already in use. The exemption could significantly expedite the environmental review process. On the basis of discussions with railcar manufacturers, it was determined that a 2-year lead time was required for procurement and delivery of new commuter rail equipment. It was assumed that leased equipment could be used on a temporary basis until the new equipment was delivered if the lead time requirement could not be met.

Service implementation options were developed as an alternative to implementing the entire network immediately. Unforeseen financial, jurisdictional, and institutional issues may make it impossible to implement the entire network in one phase. For instance, funding for the BART Commuter Rail Program has not been identified. However, BART, in coordination with other local and regional agencies and other interested parties, is developing strategies to identify partial and full funding options such as highway mitigation funds, state and federal rail funds, and local sources. Therefore, these service options could allow implementation of a portion of the service while other funding sources for the remainder of the network are identified. The trade-off of implementing the service in phases is immediate start-up of some service versus the benefits of economies of scale of the entire system. A summary of these alternatives is discussed next.

Service Within the BART District

The commuter rail service could initially be provided within the BART District only, including Contra Costa and Alameda counties. This would minimize institutional constraints and maximize immediate service implementation. For instance, service could be provided in the North Bay Corridor between West Oakland and Martinez and Brentwood, in the South Bay Corridor between West Oakland and Fremont, and in the Altamont Corridor between Livermore and Fremont. Service in the South Bay Corridor would parallel and augment existing BART service along the Fremont line with express service (BART serves 10 stations and Commuter Rail would serve 2 stations between Fremont and West Oakland) and provide additional capacity to a rapidly growing travel corridor.

This alternative would prohibit service to other areas where passenger demand is high (i.e., Solano, Santa Clara, and San Joaquin counties). In addition, providing service within the BART District only would limit transit coordination and integration opportunities.

Service Within a Single Corridor

A single corridor (e.g., the North Bay, South Bay, or Altamont Pass) could be identified for near-term implementation. This corridor would be selected on the basis of its operational, economic, and political feasibility to begin service sooner than in other corridors. For instance, as community consensus and support develops within a corridor, funding could be identified to initiate service in that corridor.

This alternative would have to address institutional and jurisdictional constraints that could delay service initiation. Also, the previously identified economies of scale could not be realized with single-corridor service.

Service on Selected Alignments and Segments

Service could be implemented on selected alignments and segments only. For instance, service may initially be implemented in the North Bay between Suisun City/Fairfield and West Oakland, in the South Bay between Union City and San Jose, and in the Altamont Pass between Livermore and San Jose. These alignments and segments could be operated as an initial phase individually or as a system that could be developed into the comprehensive regional system.

As with single-corridor service, this alternative would limit the ability to maximize cost savings through economies of scale. In addition, the service plan would limit opportunities for regional transit integration and coordination.

COMPARATIVE ANALYSIS

This section compares the BART Commuter Rail Program with (*a*) rail transit projects in the Bay Area and (*b*) new-start commuter rail systems elsewhere in the United States. The purpose is to test the level of performance and the feasibility of the BART Commuter Rail Program

TABLE 7 Proposed Rail Transit Projects in San Francisco Bay Area

Proposed Rail Transit Project	Implement Schedule	Capital Costs [1994 $]	length [km]	Annual O&M Costs[1994 $]	Annual ridership [Yr 2010]	Capital costs per km [$/km]	O&M Costs per rider [$/trip]
Tasman LRT[1]	5 years	$494.4M	19.3	$20.4M	1.48M	$25.62M	$13.88
BART Warm Springs Extension[2]	5 years	$540.9M	8.7	$11.3M	2.12M	$62.17M	$5.23
BART Commuter Rail-South Bay[3]	2 years	$50.5M	35.4	$2.60M	1.00M	$1.43M	$2.60
BART Commuter Rail[4]	2 years	$339.8M	322.0	$17.2M	3.73M	$1.06M	$4.61

M = million(s); km = kilometer(s); O&M = Operating and maintenance

[1] Locally Preferred Alternative identified in *Tasman Corridor Final Environmental Impact Statement/Final Environmental Impact Report (December 1992)*. All costs were adjusted to 1994 dollars by applying a 3% annual escalation factor.

[2] Alternative 5 (aerial in park design option) identified in *BART Warm Springs Extension Final Environmental Impact Report (November 1991)*. All costs were adjusted to 1994 dollars by applying a 3% annual escalation factor.

[3] Segment of BART Commuter Rail Program-South Bay Corridor (Union City-San Jose) that would serve a similar region as the proposed Tasman LRT and BART Warms Springs Extension projects.

[4] BART, 1994.

against other modes and similar commute rail systems nationally.

Analysis of Proposed Rail Transit Projects

Table 7 provides a comparison of current proposed rail transit projects in the Bay Area. The figures appearing in the table were obtained from published planning and environmental documents (*10,11*). The Tasman LRT (Light Rail Transit) project would provide rail transit service in the north San Jose area, whereas the BART Warm Springs Extension would provide BART (heavy rail) transit service to southwest Alameda County via a southern extension from the existing Fremont BART Station (*10,11*). For purposes of this analysis, these projects are compared with the entire 322-km (200-mi) BART Commuter Rail Program and to a segment of the BART Commuter Rail South Bay Corridor (Union City–San Jose). The segment of commuter rail between Union City and San Jose is 35.4 km and would serve a region and passenger market similar to those of the other proposed projects.

The comparative information for the proposed regional projects includes implementation schedule, capital/construction costs, system track length, annual costs to operate and maintain the service (O&M costs), and annual ridership. All costs were adjusted to 1994 levels by applying an escalation factor of 3 percent per year. As indicated in Table 7, commuter rail (either the 322-km system or the 35.4-km South Bay Corridor segment) could be implemented in less time than the other proposed rail transit projects at about 5 percent of the capital cost per kilometer and about 20 percent of the operating and maintenance cost per rider.

Comparing the feasibility and effectiveness of commuter rail with a highway project is more complicated. However, in terms of capital cost, the BART Commuter Rail Program appears to be cost-effective. The range of costs for 1 km of a freeway lane can vary from $1.68 million (based on a recent study prepared by Northern Virginia Transportation Commission) (*12*) to as high as $25.76 million (for a stretch of I–80 between Alameda and Contra Costa counties) (*13*). These costs are significantly greater than the capital costs of $1.06 million per kilometer for the proposed BART Commuter Rail Program.

In terms of performance, commuter rail also compares favorably with highways. The peak-hour capacity of an additional mixed-flow Interstate highway lane is estimated to be about 1,955 persons per hour (1,700 vehicles/peak hour × 1.15 persons/vehicle); that of a high-occupancy vehicle (HOV) lane is about 4,000 persons per hour (1,700 vehicles/peak hour × 2.35 persons/vehicle) (*14*). The operating peak-hour passenger capacity of the BART Commuter Rail Program can be as high as 3,480 persons per hour (6 trains/hour × 4 cars/train × 145 seats/car). Therefore, the peak-hour throughput capacity of the BART Commuter Rail Program is greater than a mixed-flow highway lane and approximates an HOV highway lane at a fraction of the estimated capital cost.

Comparison of Existing New-Start Commuter Rail Systems

Table 8 compares the effectiveness and feasibility of the proposed BART program with existing commuter rail systems that have begun service within the last few years in the United States (telephone interviews with staff at Virginia Railway Express, Tri-Rail, and Metrolink, April 1995). New-start commuter rail systems were selected to avoid any bias or prejudice that would result from using

TABLE 8 Comparison of New-Start Commuter Rail Operating Performance Measures, Fiscal Year 1994

Performance Measures	BART	VRE[1]	Tri-County[2]	Metrolink[3]
Data				
Annual O&M Costs	$17.20M	$11.82M	$20.89M	$42.90M
Annual ridership	3.73M	1.80M	2.91M	4.60M
Annual revenues	$5.16M	$7.49M	$5.18M	$11.00M
Passenger-km	173.39M	92.61M	155.65M	277.42M
Vehicle-km	2.65M	1.55M	3.95M	4.84M
Performance Indicators				
Annual O&M cost/rider	$4.61	$6.57	$7.17	$9.33
Annual subsidy/rider	$3.23	$2.41	$5.39	$6.93
Fare-box ratio	30.0%	63.3%	24.8%	25.6%
O&M cost/vehicle-km	$6.49	$7.63	$5.29	$8.86
O&M cost/passenger-km	$0.10	$0.13	$0.13	$0.15
Passenger-km/vehicle-km	65.43	59.75	39.41	57.32
Revenue/vehicle-km	$1.95	$4.83	$1.31	$2.27

M = million(s); km=kilometer(s); O&M=Operating and maintenance
1. Virginia Railway Express, Virginia; Stafford, Prince William, Fairfax, and Arlington counties.
2. South East Florida; Palm, Dade and Broward counties
3. Southern California; Riverside, Ventura, San Bernardino, Los Angeles and Orange counties

Source: BART, Northern Virginia Transportation Commission (NVTC), Tri-County Commuter Rail Authority, Southern California Regional Rail Authority (SCRRA), 1995.

performance measures of older, established systems that serve mature markets. According to Table 8, the projected performance indicators for the BART Commuter Rail Program are within the range, or better than, the levels experienced by new-start commuter rail systems throughout the nation. For example, the annual operating and maintenance cost per rider for the BART Commuter Rail Program is $4.61, which is considerably less than the other new-start systems, which range between $6.57 and $9.33. However, BART's revenue per vehicle kilometer is $1.95, which is within the range ($1.31 to $4.83) of the other systems.

Conclusion

Some may view the BART Commuter Rail Program as regressive in terms of state-of-the-art transit technology and the elimination of established and committed local projects. However, the analysis summarized in this paper has shown that commuter rail for the Bay Area is a progressive solution that provides a cost-effective and near-term transportation system that will relieve the region's most congested travel corridors and could be compatible with other transportation projects.

An initial evaluation of the BART Commuter Rail Program indicates that commuter rail could begin service within 2 years after funding sources have been secured. Short-term implementation is possible because the infrastructure and facilities can support service today. With a relatively small capital investment (compared with new highway and rail projects), the Bay Area could profit from a safe, reliable, and efficient regional commuter rail service. The BART Commuter Rail Program would be coordinated with existing regional transit services and would provide an integrated regional transportation system.

Compared with other proposed rail transit and highway expansion projects in the region, the BART Commuter Rail Program is a financially feasible and effective transportation option that can provide additional travel capacity in the near term. The expected operating performance of the BART regional commuter rail service is within the industry range of performance levels experienced by new-start commuter rail systems across the nation.

Funding for the BART Commuter Rail Program has not been identified. However, BART, in coordination with other local, regional, and state agencies and other interested parties, is developing strategies to identify funding options. The options include highway construction mitigation funds, state and federal rail funds, and local sources. BART is confident that the funding and institutional challenges facing commuter rail can be overcome by building consensus and an understanding of the benefits of commuter rail compared with the true costs of other projects, and that commuter rail will be a reality in the near term.

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Analysis of Suburb-to-Suburb Commuter Rail Potential: Metrolink in Southern California

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As urban regions continue to decentralize, most travel growth occurs in suburb-to-suburb markets, lessening the relative importance of suburb to central business district (CBD) commuter rail lines. To remain viable in the longer run, commuter rail services need to tap at least some of the growing suburban markets, but it is unclear whether demand exists for suburban-oriented commuter services. The market for suburb-to-suburb commuter rail services is addressed. The potential number of work trip riders between every pair of stations of two Los Angeles area commuter lines operated by Metrolink is determined. Using the actual patronage between each pair of stations, a ratio of actual to potential riders, which indicates market penetration, is computed. The ratio is cross-classified by distance and by suburb-to-suburb or suburb-to-CBD status. Results suggest that short-distance suburb-to-suburb markets have considerable potential but negligible penetration; long-distance suburb-to-suburh markets have much smaller potential but surprisingly large penetration, though neither is as large as for suburb-to-CBD markets. The results suggest that commuter rail lines that serve edge city–type developments could generate substantial traffic.

This paper examines the relative strengths of suburb-to-suburb commute markets inadvertently served by two new regional rail commuting lines (Metrolink) in the polycentric Los Angeles basin. Patronage potential and the depth to which the potential is tapped in such markets are compared with potential and market penetration of more traditional suburb-to-downtown Los Angeles markets. The purpose is to gain insight into the question of whether public policy should attempt to encourage the expansion of commuter rail service into more suburb-to-suburb markets, where most growth in metropolitan travel has occurred in the past half century.

Background

As urban regions continue to decentralize, most travel growth occurs in suburb-to-suburb markets. As early as the 1920s, jobs began leaving central business districts (CBDs) to follow middle class residential dispersion originally facilitated by streetcar expansion and set up smaller centers in suburbia (*1,2*). Convenience retail, manufacturing, wholesaling, and by World War II large-scale specialty retailing continued the trend to the newest and ever-more-distant suburbs. For years only finance, insurance, and real estate jobs appeared immune from the decentralization trends, but in the 1980s even many of these activities moved to the suburbs. Over a 5-year period in the early 1980s, the percentage of national office space located in downtowns areas declined from 57 percent to 42 percent as up to 90 percent of all new office construction took place in suburbs (*3*). By the beginning of the 1990s, larger metropolitan regions were characterized by suburban centers, now known as edge cities, containing specialty retail, high-rise office buildings, hotels, movie houses, and even theaters, each rivaling or surpassing CBDs in magnitude of employment and activities offered (*4,5*). Not surprisingly, most of the spectacular growth in automobile travel since World War II, and particularly during the past decade, took place in the suburban arena and consisted of traffic that both began and ended in the suburbs (*6–10*).

Such demographic changes lessen the relative importance of suburb-to-CBD commuter rail lines, even though absolute patronage may increase. Whereas commuter rail ridership has been increasing on a nationwide basis, and even has been growing faster than bus transit patronage, as a percentage of metropolitan travel it has been declining (*8,11*). The Urban Mass Transit Administration (now Federal Transit Administration) Section 15 data indicate that in 1982 rail rapid transit carried 8.6 billion passenger miles, increasing to 12.0 billion in 1989. Streetcars carried 0.4 billion passenger miles in 1982, rising to 0.5 billion in 1989. Commuter rail carried 6.5 billion passenger miles in 1985, rising to 7.2 billion in 1989. Motor buses carried 19.1 billion passenger miles in 1982, falling to 17.7 billion in 1989. Yet transit's share of urban traffic continues to decline.

Many policy analysts argue the inevitability of commuter rail decline, because they believe that commuter rail cannot operate effectively in any but the traditional suburb-to-CBD role (*2*). Suburban trip ends are too dispersed to be connected with single fixed-route rail lines in such a way as to create sufficient passenger densities to justify construction and operation of the lines. Indeed, similar arguments are applied even to the operation of bus lines in the suburbs (*10,12*).

Others counter by arguing that it is possible to supply the suburbs efficiently with rail and bus service. To do so requires planners to think in terms of networks of interconnecting routes that feed suburb-to-suburb as well as suburb-to-CBD passengers into each other. Such thinking stands in contrast to the usual concept of transit as collections of individual routes and their feeder, each serving CBD-bound trips from different suburban areas, but with little transferring of passengers between routes from each sector and no suburb-to-suburb riding in any sector. Networks of transit routes, if well conceived, have scope economies that accumulate passenger densities on each link, even in areas of thin demand. Scope economies account for the trends toward market concentration in the deregulated airline and trucking industries, even though the air and truck technologies do not possess scale economies (*13–15*).

Still others argue that even creating such route structures would not attract the suburb-to-suburb traveler. This is because transit is not as attractive as driving, so that those who have a choice will not choose transit unless there is a disincentive to drive. Driving disincentives, such as tolls or high parking charges, generally apply to the suburb-to-CBD or other CBD-related trips but not to suburb-to-suburb trips (*16,17*). Moreover, suburb-to-suburb travel generally involves transit disincentives in the form of site and street design that is hostile to pedestrians. This is because suburbs were built when the automobile was the dominant transportation mode. Poor pedestrian access reduces the likelihood of suburb-to-suburb transit travel even more (*4,18*).

The purpose of this research is to test the extent to which suburb-to-suburb commuter rail service is used where it is provided. Generally, such locations are few in number, because the planners of most commuter rail services, even the most recently inaugurated ones, conceived of them only in the traditional suburb-to-CBD role. They have not planned the lines to serve edge cities or to link together with other commuter lines or other types of transit service to form networks where extensive suburb-to-suburb travel opportunity is available to the traveler. Despite such oversight, almost all rail commuter lines inadvertently serve a small number of suburb-to-suburb markets. This is because they have trains that originate in the distant suburbs and then stop numerous times as they proceed into the CBD. The intermediate stops are intended to allow additional CBD-bound passengers to board, but they could be used by passengers wanting to go from one suburban station to another. The questions explored here are whether there is any demand between such stations, and to what extent the rail service taps whatever demand there is. If there is no demand, or if there is demand but rail service fails to penetrate it, there is no point in trying to reorganize existing commuter rail services or plan new ones to serve the suburb-to-suburb market. On the other hand, if there is demand that is penetrated, planners might be well advised to consider ways in which they can serve more such markets.

The focus of this experimental design is Southern California's Metrolink, a new commuter rail network recently established by the Southern California Regional Rail Authority (SCRRA). SCRRA purchased nearly 400 mi of tracks once owned by the Atchison, Topeka and Sante Fe Railway and the Southern Pacific Company. It subsequently entered into an agreement with the Union Pacific to use about 60 mi of additional line. It then had the lines rebuilt to accommodate peak-period commuter trains from suburban points on five lines to Los Angeles Union Station (Figure 1).

Metrolink provides a traditional suburb-to-CBD service. It is not designed to serve suburb-to-suburb markets (except in the case of the Riverside to Irvine line, which opened in November 1995 after this paper was written), and to emphasize speedy service for long-distance commuters to downtown Los Angeles, each of

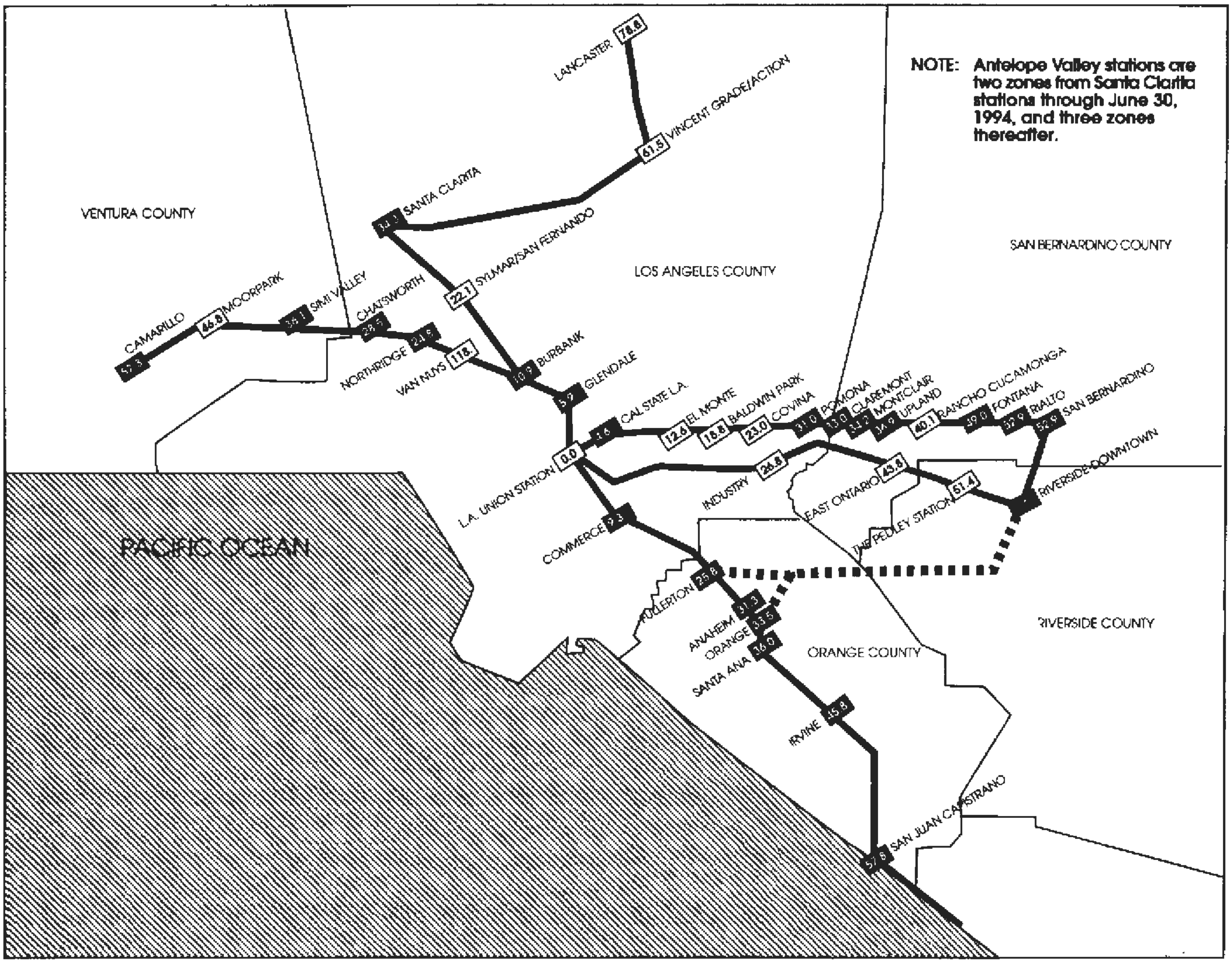

FIGURE 1 **Metrolink mileage map—distance from Los Angeles Union Station. Riverside is 58.7 mi from Union Station via the Union Pacific line. Riverside via Fullerton is 68.8 mi. (Information provided by Metrolink.)**

its lines has far fewer stations than is common for commuter operations. This makes the number of suburb-to-suburb station pairs that it inadvertently serves very few in number. Nevertheless, there are enough station-to-station pairs served to set up a quasi-experimental design to test the depth and penetration of suburb-to-suburb markets in comparison with suburb-to-CBD markets.

The two routes included in this study are those from Union Station to Riverside and Orange County. The original intent was to include the other three routes from Union Station, but complete origin-destination survey data were not available at that time. The additional data would have added to the strength of the study, because two of the routes included heavily used shuttle buses from two suburban stations to employment destinations within a 10-mi radius, inaugurated with Federal Emergency Management Agency funds in the wake of the January 1994 Northridge earthquake. A freeway competing with one of the two lines was closed for several months by the earthquake, but the freeway paralleling the other line remained open, enabling a test of how important shuttle bus service might be in attracting suburb-to-suburb riders. As it turned out, we could not obtain data for the two lines, so they were left out of the study.

Methodology

A quasi-experimental design was used to examine the size of various station-to-station markets and the degree to which Metrolink penetrated each of the markets. We used two categories of station type: suburb to suburb and suburb to CBD. For each type, we examined four distance categories: less than 11 mi, 11 to 20 mi, 21 to 30 mi, and greater than 30 mi. Two hypotheses were tested. One was that no significant difference existed in size or penetration of the two types of markets for a given distance category. The second was that as distance increased, market size decreased but market penetration increased for each type of station pair. The latter hypothesis reflects generally accepted distance-decay effects on the size of transit commuting markets (*19*), and it reflects the probability that commuter rail is not attractive for short-distance riding because of high initial fares and infrequent service. We did not control for other factors, such as fares or presence or absence of shuttle buses from suburban stations to nearby employment areas.

Two data sources, which we obtained with the assistance of Schiermeyer Associates, enabled us to estimate commuter market size for each station pair. Both were compiled by the Air Quality Management District (AQMD) in Southern California. One provides a listing of every company within the AQMD air shed area that has more than 50 employees. Each record for a company includes an identification code, address, ZIP code, and a count of the number of employees working in the company. The second AQMD data base records the number of employees residing in each ZIP code within the air basin. A worker listed in the second data base can be traced back to the first data base through a company identification code, making it possible to determine in which ZIP code areas an employee lives and works.

To measure the potential market size of each station pair, we drew 2-mi buffers around each station and then noted the ZIP codes that fell within each buffer. ZIP codes that had only a small portion extending into the 2-mi buffer were eliminated. ZIP code areas with a majority inside and only a portion outside the buffer were included. The decision to include or exclude ZIP codes lying both inside and outside the buffer zone depended largely on the size of the ZIP code area and the size of the portion lying within the buffer. Workers who both lived and worked in the ZIP codes so defined were considered potential rail commuters.

Two related criticisms have been made of this definition of potential. One is that the 2-mi radius is too conservative on the origin end of the trip. Most users gain access to the line by automobile, and whereas a majority of riders drive about 2 mi to board trains, some drive considerably further. This is particularly true at the suburban termini of the various Metrolink lines. The other criticism is that the buffer on the origin end of the trip should not be a fixed distance but should increase with trip length.

The criticisms have merit, but they affect our study design only in one area. We likely overestimate the distance-decay effect on the absolute size of markets, which is to say that we underestimate the size of potential markets, particularly for longer trips. In other areas the biases noted in the criticism are not severe, because our interest is in comparisons between market sizes and penetrations rather than in absolute sizes and penetrations. To the extent that we underestimate each station pair market by defining the origin-station buffer too restrictively, we do so equally for suburb-to-suburb and suburb-to-CBD categories of a given distance category.

The definition of potential has another bias toward underestimation of the size of the potential market. The bias results from including only workers in firms with 50 or more employees. This is unavoidable, given the only data source from which we could determine potential easily. It is likely, however, that a significant part of the work force is employed in firms with 49 or fewer employees, and their inclusion would increase the size of the potential rail rider pool. This point must be kept in mind when interpreting the results pertaining to potential. However, there is no reason to expect that this bias would act differently for suburb-to-suburb or suburb-to-CBD categories or for different distance categories.

Finally, the failure to consider nonworkers as potential rail riders also underestimates the size of potential rail demand. This again stems from the data source available to us. Whereas it could be a problem in analyzing some commuter rail operations, it was not a problem in analyzing Metrolink. Given that Metrolink was designed only with workers in downtown Los Angeles in mind and that at the time of the survey it did not offer much service other than weekday peak-period runs into Los Angeles in the morning and return trips in the evening, this bias likely did not affect results. It could affect analysis of a more fully developed commuter rail service that offered bidirectional midday, evening, and weekend services.

To examine market penetration of each station-to-station pair, we noted the actual number of passengers using Metrolink between each station pair and divided this by the potential riders, calling the resulting ratio the achieved potential ratio (APR). For example, if a station pair captures only 9 riders per day but its potential ridership is 483 riders per day, the APR is 0.018633. This shows that Metrolink is only capturing about 2 percent of the potential riders between the two stations in question.

The actual number of passengers came from an on-board passenger survey conducted by Metrolink in May 1994. Riders were asked to complete a questionnaire regarding their travel patterns and preferences of Metrolink services. The survey specifically had respondents note their origin and destination stations. Because the survey is a sample of the total ridership, the true ridership for Metrolink was greater than this study represents.

Because of the biases in estimating potential ridership noted earlier, the APRs could be greater than one. This posed no difficulty so long as APRs for station pair and

TABLE 1 Cross Classification of Demand Potential

Distance Category (miles)	Station-Pair Category					
	Suburb-CBD			Suburb-Suburb		
	Per Pair	# of Pairs	Total	Per Pair	# of Pairs	Total
0-10	574	2	1,148	659	22	14,498
11-20	0	0	0	70	10	700
21-30	50	4	200	19	14	266
31+	50	16	800	5	8	40
Average for All Distance Categories	97	22	2,134	287	54	15,498

distance classifications had similar biases. As discussed earlier, we believe they did.

The APRs thus calculated were then cross-classified by station pair type and by distance categories for hypothesis testing. We tested the effect of station pair type and distance on APRs. We also tested the effect of the interaction between station pair type and distance on APRs (*20*).

In cases where the potential ridership estimate is very small, even moderate amounts of reported patronage will result in extremely high APRs. For example, we estimated potential ridership for the station pair Industry to Union Station on the Riverside line as only 10 but the survey reports actual ridership of 278. This produces an APR of 27.8. Such a high APR is explained in this case by the fact that the Industry Station has very few residential areas within the 2-mi radius, so those persons using it are likely to be coming from outside that area and are not found in potential ridership capture.

This example is the most extreme in the study; however, there are other cases with very high APR values resulting from small estimates of potential ridership. Such outliers may skew the results. To ensure an accurate analysis, it is desirable to examine the data with the outliers, as well as to examine a data set that excludes extreme values. We analyzed the data both ways. In the data set without outliers all station pairs with a potential ridership lower than 25 persons are removed. This eliminated most of the extreme APR values, while maintaining most potential ridership and somewhat more than half of the station pairs.

RESULTS

The results are presented in two parts. We first examine differences in potential ridership between each of the categories. We then examine differences in the degree to which Metrolink penetrates potential ridership in each category. In the examination of market penetration, we use both the original data sets and data sets with outliers removed.

Potential Ridership

The cross classification of potential ridership by station pair category and by distance is given in Table 1 for the original data set. Table 1 indicates potential for the average suburb-to-suburb station pair as about three times greater than that for suburb-to-CBD. In addition, there are more than twice as many suburb-suburb pairs as suburb-CBD pairs. Together, these two points explain why the suburb-suburb category has much more potential (15,498) than the suburb-CBD category (2,134).

The traffic potential in the two station-type categories is distributed very differently over the distance categories. Most of the suburb-to-suburb and almost none of the suburb-to-CBD potential is in the short-distance categories. This is accounted for by the large number of suburb-to-suburb (22) and the small number of suburb-to-CBD (2) observations in the distance category 0 to 10 mi. There are no suburb-to-CBD observations in the distance category 21 to 30 mi. The paucity of observations in the suburb-to-CBD shorter-distance categories reflects Metrolink's orientation to the longer-distance commute. The final system plan has few stations within 30 mi of the CBD, and some of those that are planned were not yet opened at the time of the survey.

In the distance category 21 to 30 mi, the potentials of the two station-type categories are about evenly matched, each having a potential in the range of 200 to 300 passengers. The average station pair in the suburb-to-suburb category has only about 40 percent of the po-

TABLE 2 Cross Classification of Demand Potential for Purged Data Set

Distance Category (miles)	Station-Pair Category					
	Suburb-CBD			Suburb-Suburb		
	Per Pair	# of Pairs	Total	Per Pair	# of Pairs	Total
0-10	574	2	1,148	659	22	1,430
11-20	0	0	0	112	6	672
21-30	95	2	190	46	4	184
31+	92	8	736	31	1	31
Average for All Distance Categories	173	12	2,076	466	33	15,378

TABLE 3 Cross Classification of APRs for Original Data Set

Distance Category (miles)	Station-Pair Category (mean value of APR in each category)		
	Suburb-CBD	Suburb-Suburb	Average over station types
0-10	.01 (2)	.07 (22)	.07 (24)
11-20	.00 (0)	.37 (10)	.04 (10)
21-30	7.80 (4)	2.22 (14)	3.46 (18)
31+	2.90 (16)	3.95 (8)	3.25 (24)
Average over all distances:	3.53 (22)	1.30 (54)	1.96 (76)

Note: Numbers in parentheses are number of observations in each category.

tential of the average suburb-to-CBD station, but there are 2.5 times as many suburb-to-suburb station pairs in this category.

In the category greater than 30 mi the suburb-to-CBD station type has the most potential at 794 passengers compared with 43 potential passengers in the suburb-to-suburb category. The average suburb-to-CBD station has about 10 times the potential of the average suburb-to-suburb station, and there are twice as many of them. The strength of the suburb-to-CBD station category in the longest distance classification again reflects Metrolink policy.

For both suburb-to-suburb and suburb-to-CBD categories Table 1 clearly shows a distance-decay effect. It is strongest for the suburb-to-suburb station category. As trips become longer, potential falls off. This effect is as expected, but because of the data biases already discussed, the effect probably is overstated, particularly for the suburb-to-CBD stations pairs.

The conclusions reached about the distribution of potential demand from Table 1 are strengthened by an examination of Table 2. The generalization can be made that for the suburb-to-suburb station category most demand is in the shorter distances. A very strong distance-decay effect is shown, which likely would remain after biases inherent in the data were corrected. On the other hand, for the suburb-to-CBD station category there is less of a distance-decay effect, which falls off completely in the two longest distance categories. If biases inherent in the data were corrected, this might be reversed.

Market Penetration

Two tables indicate market penetration. Table 3 gives the distribution of market penetration over station-type and distance categories for the original data set. Table 4 does the same for the purged data set, from which observations having fewer than 25 trips were removed. As discussed earlier, this was done to reduce volatility in the APR ratio, which can occur when the denominator (po-

TABLE 4 Cross Classification of APRs for Purged Data Set

Distance Category (miles)	Station-Pair Category (mean value of APR in each category)		
	Suburb-CBD	Suburb-Suburb	Average over Station Types
0-10	0.01 (2)	0.08 (22)	0.07 (24)
11-20	0.00 (0)	0.11 (6)	0.11 (6)
21-30	0.71 (2)	0.64 (4)	0.65 (5)
31+	3.07 (8)	1.13 (1)	2.85 (9)
Average over Distance Categories:	2.30 (12)	0.19 (33)	0.72 (44)

Note: numbers in parentheses are number of observations in each category.

TABLE 5 Summary of Computed *F* Statistics

	Original Data Set	Refined Data Set
Due Distance	32.61	74.88
Due Location	50.68	379.81
Distance/Location Interaction	30.7	210.76

Note: All values are significant at the one percent level.

tential trips) is small. Table 3 indicates negligible market penetration for the suburb-to-CBD category in the two shortest distance categories, but surprisingly large penetration in the longest two. The suburb-to-suburb category shows small penetration (0.07) in the shortest category, but given the large potential in this category (14,322 trips), more than 1,003 trips actually occur in it. As distance increases, the penetration of the suburb-to-suburb category also increases to surprisingly large levels, but potential declines.

Table 4 also strengthens the conclusion reached in Table 3 that as distances increase, so does market penetration. This trend is evident for both categories of station type, but it is particularly pronounced for the suburb-to-CBD category. The large APR for the longest distance category probably reflects users from distant locations making long drives to the terminal stations to access the trains. It is clear from these results that the pattern of potential and the degree to which it is tapped are different for suburb-to-suburb trips than for suburb-to-CBD trips. Both categories display distance-decay characteristics, but distance decay is stronger for suburb-to-suburb trips. Both categories indicate higher market penetration with distance, but the degree of market penetration increases more for suburb-to-CBD trips. These conclusions are confirmed in an analysis of variance in APRs, the measure of market penetration, as given in Table 5 for both data sets. Table 5 indicates that station-type category, distance category, and the interaction of the two categories all are highly significant in explaining market penetration. If one switches from a suburb-to-suburb station pair to a suburb-to-CBD pair for a given distance category, market penetration increases. If one switches from a shorter distance category to a longer distance category for a given station type, market penetration increases. The interaction effect confirms that market penetration rises more rapidly for the suburb-to-CBD category with increasing distance. These results cause us to reject the hypothesis that commuter rail can tap suburb-to-suburb markets to the same extent they can tap suburb-to-CBD markets. The results also cause us to accept the distance-decay hypothesis on market potential as well as the hypothesis that market penetration is easier with longer distance.

Having come to these conclusions, we still are impressed by the extent to which there is a latent suburb-to-suburb market for commuter rail even for a system whose planners did not lay out its routes and stations to serve it. We equally are impressed by the degree to which trains penetrate the suburb-to-suburb market. For stations less than 10 mi apart the latent market is in many instances large; what is surprising is that Metrolink with its peak-hour-only trains and high initial fares gets about 7 percent of it. It appears plausible that more frequent service and fares oriented to short-distance riders might get more passengers on board in the outer suburban areas where most of the seats are empty.

There also is significant potential from distant suburban points to large suburban employment centers, such as Fullerton, Santa Ana, and Commerce, with an average APR of 1.13 on suburb-to-suburb commutes greater than or equal to 31 mi. Metrolink taps about 60 percent of such potential. This observation suggests that planners should consider locating suburban stations not only to facilitate access to and from the homes of commuters but also to facilitate access to and from major employment centers in the suburbs. Doing so in conjunction with employer-provided shuttle vans or local transit could increase ridership significantly.

There obviously are implications for how the polycentric region could be served by commuter rail. One is that traditional CBDs probably should remain the focus of service into the foreseeable future. However, rail lines serving traditional CBDs also should attempt to serve major suburban employment centers near tracks. This would require stations as near as possible to the centers with train service coordinated with local transit or employer-provided shuttles.

Despite our inability to get data that would have allowed us to examine the emergency-funded shuttle buses on two other lines, we were able to examine survey questionnaires to get a sense of shuttle bus importance, which appears to be considerable. The Metrolink survey data provided a breakdown of the stations providing such services. We found that up to 30 percent of departing passengers at suburban stations used shuttle bus service. The largest percentages were at the Fullerton and Anaheim stations. This may be due to the proximity of these stations to major employers for that area. The California State University at Fullerton lies just at the 2-mi buffer for the Fullerton station and is a major employer in the area. Anaheim Station lies within 2 mi of Disneyland. Further expansion of shuttle bus service at suburban stations could increase the ridership traveling to those destinations.

In addition to having shuttle buses, regional trains and regional buses should be operated as networks to create large numbers of suburb-to-suburb station pairs, many of which have significant destinations associated with them. Even with the two Metrolink lines that we examined and their very sparse station spacing, the number of suburb-to-suburb station pairs is considerably larger than the number of suburb-to-CBD pairs. A lower market penetration of individual suburb-to-suburb station pairs could more than be made up for by planners systematically creating large numbers of them. This suggests that systems serving polycentric areas could acquire additional lines to those focused on the CBD to better serve suburb-to-suburb commuters.

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Accounting for Multimodal System Performance in Benefit-Cost Analysis of Transit Investment

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Benefit-cost analysis, in the conventional planning and modeling paradigm, estimates benefits from transit rail investment as the consumer surplus (willingness-to-pay) from forecast trips. New studies indicate that this paradigm, as currently implemented, fails to capture a wide array of benefits, namely improved multimodal system performance in congested corridors, transit-oriented development benefits, and cross-sectoral resource savings. The economic theory predicting improved multimodal performance in congested corridors when the transit mode is improved is developed, the empirical evidence supporting that theory is described, and a method for refining the practice of benefit-cost analysis to account for the benefit of improved multimodal performance is proposed. In urban corridors served by highways and a high-capacity transit mode, peak travel times and the modal split of trips will, in general, be influenced by highway capacity, relative prices, and individual preferences. However, in congested urban corridors door-to-door journey times are observed to be nearly equal across modes, converging toward the journey time by the high-capacity transit mode. The convergence of travel times is predicted from microeconomic theory. Empirical evidence from a recent study of 14 urban corridors in the United States supports this theoretical finding. It is further found that reducing transit headways contributes to the modal convergence of travel times. The principal policy implication of these findings is that improving the peak-hour performance of the high-capacity transit mode will also yield peak-hour performance improvements on the highway mode. The convergence of travel times across modes would not, in general, be the outcome predicted by the conventional models that forecast modal splits and transit ridership, which, in turn, form the basis for the analysis of benefits from transit investment. The multimodal effect of transit investment, as evidenced by the convergence of journey times, should be explicitly accounted for in the analysis of benefits. This can be accomplished through the calibration of estimated modal constants so that the assignment of trips to the urban transportation network yields nearly equal door-to-door journey times in the relevant market segments.

The current practice of benefit-cost analysis as applied to transit investments follows the conventional planning paradigm. Total demand is forecast as trips between zones; forecast trips are allocated to modes by means of a modal choice model; and, typically, the benefits from the proposed transit investment are estimated as the willingness-to-pay for the trips taken plus the benefits of reduced congestion on the highways. Recent studies conducted for the Federal Transit Administration's Office of Policy (publication forthcoming) have identified three areas in which this model fails to capture the full array of benefits from transit investment.

First, there remains the issue of the interaction between transportation investment and land use. The planning paradigm described was used to justify numerous road projects by assuming, for instance, that an outlying area would be developed. Under this assumption build and no-build scenarios were compared and road projects were shown to display strong benefits. Of course, it was often doubtful that development in the outlying area would have occurred in the absence of the road project. Furthermore, the conventional paradigm does not adequately address the issues of whether the planned road actually contributed to net new development or whether the development was preferable to other development alternatives. In contrast to highways, the benefit-cost analysis of transit rail investments does not account for the transit-oriented development that would legitimately be associated with a "build" scenario. A refinement of methods is under way that incorporates interactive land use and transit development scenarios, hedonic pricing methods for valuing development alternatives, and stated preference methods that seek to indirectly gauge the benefits of transit-oriented development.

The second area of benefits not captured by benefit-cost analysis is cross-sectoral resource savings. The absence of transit will restrict the mobility of some users and may require an increase in resource use for medical and social services. Studies demonstrating these benefits have been conducted in the United Kingdom, and methods for incorporating them into benefit-cost analysis are being developed.

Finally, conventional benefit-cost analysis does not account for the multimodal interrelationships that are observed in congested urban corridors. Mogridge (*1*) has shown that in congested urban corridors, door-to-door journey times are nearly equal and tend to converge to the journey time of the high-capacity transit mode. New evidence confirming this finding has been documented in recent and ongoing studies in the United States (see Table 1).

Triple Convergence or Travel Time Convergence?

Downs (*3*) discusses as a principle of traffic analysis the notion of "triple convergence," whereby peak-hour traffic speeds converge spatially (across the road network) in time and across modes. Under the triple convergence principle, an improvement in peak-hour travel conditions on high-capacity roadways "will immediately elicit a triple convergence response, which will soon restore congestion during peak periods, although those periods may now be shorter." The prospects for improving transportation performance through transit investment are no less gloomy. Downs states that a new fixed-rail public transit system should initially reduce peak-period traffic congestion, but "as soon as drivers realize that expressways now permit faster travel, many will converge . . . onto those expressways during peak periods."

However, in congested urban corridors the observed convergence of peak-hour, door-to-door journey times—by the highway and high-capacity transit modes—suggests that a different dynamic is at work. If the travel time convergence dynamic were in effect, it is anticipated that a carefully chosen fixed-rail investment would indeed yield an improvement in journey times by highway. In general, the convergence of journey times to the journey time by the transit mode implies that a change in the performance of transit will result in a change in the performance of highways.

The phenomenon of travel time convergence to the transit journey time has profound policy implications for the planning and allocation of funds for transportation in metropolitan areas. Furthermore, it enables the application of benefit-cost analysis methods to alternatives across different modes (i.e., highway and transit projects are more readily comparable insofar as the cross-modal

TABLE 1 Door-to-Door Travel Times for Peak Journeys (*2*)

Corridor	Auto Mode (Minutes)	High-Capacity Mode (Minutes)
New York Queens-Manhattan	63.9	64.4
San Francisco Bay Bridge	72.3	73.1
Philadelphia Schuylkill Expressway	48.4	52.5
Chicago - Midway	54.2	60.6
Chicago - O'Hare	53.9	59.3
Pittsburgh Parkway East	38.1	42.5
Princeton - New York	113.4	104.9
Washington - I-270	71.9	67.4

impacts can be compared where the conditions for trip time convergence are found to exist).

Modal Explorers

What explains the phenomenon of travel time convergence? One claim is that a dynamic relationship exists that parallels that of a multilane highway: speeds across lanes tend to be equal because some drivers are "explorers" who seek out the faster-moving lane, thus driving the system to an equilibrium speed shared by all lanes. By the same token, in congested urban corridors some travelers and commuters are explorers. They are not committed through circumstance or strong preference to either mode and they behave as occasional mode switchers. If the transit mode has a high-speed, line-haul segment, the door-to-door journey time by this mode will be relatively stable, and small shifts in ridership will not significantly affect the journey time by the transit mode. On the other hand, under congested conditions even a 0.5 percent increase in highway traffic volume in the peak period can have a major impact on journey times. Because the journey time by transit is stable and determined by the speed of the high-capacity mode, transit "paces" the performance of the urban transportation system in the congested corridor. The modal explorers, like exploring drivers on the multilane highway, serve to bring about an equilibrium speed across modes as they seek travel time advantages across modes.

Travel Time Equilibrium and Modal Choice

Whereas travel time represents a dominant component of the cost of trips, the generally accepted models of modal choice and the assignment of trips to networks would not predict travel times to be equal. Rather, the theory behind current practice anticipates modal choice by individuals to be driven by income, car ownership, money price differentials, and modal preferences that account for nonmoney factors like convenience, seamless travel, and so forth. The persistence of equal, or nearly equal, travel times across modes in congested corridors suggests that current theory fails to correctly capture modal interrelationships in a multimodal system.

The following model presents the economic theory for consumer behavior under congestion and develops the conditions under which door-to-door trip time by highway converges to the trip time by the high-capacity transit mode. It further demonstrates how congestion promotes the modal explorer behavior. Empirical evidence supporting the convergence of trip times to the high-capacity mode in congested corridors is presented. In the concluding section of this paper a proposed modification to the practice of the benefit-cost analysis of transit rail investment is discussed to account for this multimodal effect.

Theoretical Structure

The theory presented here follows the standard model from public economics of utility maximization under a budget constraint with an external effect. Consider an individual who derives utility from consuming z units per week of a basket of commodities. To generate the income required to purchase the consumption good, the individual must take x trips per week (say, five inbound and five outbound) from a residential area to a central business district. The individual derives disutility, however, from the amount of time spent traveling. Whereas disutility may be derived differently from different types of travel time (i.e., driving, riding, walking, waiting in congestion, etc.), for simplicity the individual is assumed to be indifferent between travel times of different types. The individual can choose to travel by one of two modes, highway or high-capacity transit, each of which has a money price associated with the trip.

If there are I individuals, the utility maximization problem of the ith individual is expressed as follows:

$$\max u^i(z, t) \text{ such that } x_1^i p_1 + x_2^i p_2 + z \le y^i \quad (1)$$

where t represents time spent commuting and x_1^i and x_2^i are the number of trips taken by the highway and the transit modes, respectively. The prices P_1 and P_2 are the money cost of a trip by each mode. y^i is the individual's income. The price of the consumption good z is 1.

The utility function is assumed to be continuous and twice differentiable, having the following properties:

$$u_z^i > 0 \qquad u_{zz}^i < 0 \qquad u_t^i < 0 \qquad u_{tt}^i < 0 \quad (2)$$

The conditions on z are the regular strong concavity conditions for consumption goods. Time spent traveling is a "bad," which the individuals would be willing to pay to avoid. Concavity with respect to t implies an increasing marginal disutility—the more time spent traveling, the greater the disutility from additional travel time.

The individual must allocate his total number of trips among the two modes:

$$x^i = x_1^i + x_2^i \quad (3)$$

The trip time by the highway mode is an increasing function of the number of trips taken by all travelers:

$$t_1 = d + a\left(\frac{X_1}{v - X_1}\right)^b \tag{4}$$

where

$X_1 = \sum_{i=1}^{I} x_1^i$, the total number of trips by all travelers via the highway mode;
d = uncongested, "free-flow" travel time;
v = capacity constraint of the highways (the upper bound on the number of trips that could be taken by highway, which would result in gridlock and an infinite trip time); and
a, b = structural parameters reflecting the speed-volume relationship of the highway network.

The high-capacity transit mode is assumed to be completely unaffected by additional trips, and the trip time is a fixed value:

$$t_2 = c \tag{5}$$

The transit mode is assumed to be a high-speed mode, where the line-haul segment of a journey is rapid relative to, say, the expressway segment of a highway journey, thus compensating for slower speeds accessing the high-capacity mode including walk and wait times.

Equation 5 expresses the absence of an external effect from additional riders on the high-capacity mode. Of course, crowding on transit results in some riders standing and other inconveniences. However, the key operational assumption is that travel times on the high-speed mode are unaffected by changing volumes of passengers, which corresponds to the actual scheduling practice in rail transit systems.

Time spent commuting is given by the sum of trips weighted by the average time per trip. The ith commuter's total travel time is given by

$$t^i = x_1^i t_1 + x_2^i t_2 \tag{6}$$

The total trip time by the individual can be expressed as a function of the number of highway trips by substituting Equations 4 and 5 into Equation 6:

$$t^i(x_1^i) = x^i c + (d - c) + a\left(\frac{X_1}{v - X_1}\right)^b \cdot x_1^i \tag{7}$$

The first-order conditions of utility maximization are given by

$$P_1 - P_2 = \frac{u_{x_1}^i}{u_z^i} = \frac{u_t^i}{u_z^i} \cdot \frac{\partial t^i}{\partial x_1^i} \tag{8}$$

where

$$\frac{\partial t^i}{\partial x_1^i} = (d - c) + a\left(\frac{X_1}{v - X_1}\right)^b \cdot \left[1 + \frac{x_1^i \cdot b \cdot v}{(v - X_1) \cdot X_1}\right]$$
$$= t_1 - t_2 + \left(\frac{abv}{v - X_1}\right) \cdot \left(\frac{x_1^i}{X_1}\right) \cdot \left(\frac{X_1}{v - X_1}\right)^b \tag{9}$$

Some individuals will maximize utility by choosing all trips by one mode or another. However, some individuals will find their optimum allocation of trips by a mix of trips on both modes. These are "casual" switchers—that is, their circumstances or preferences do not lock them into a particular mode—and they correspond to the modal explorers discussed earlier. Equation 9 can be rearranged to give

$$\left[(P_1 - P_2) \cdot \frac{u_z^i}{u_t^i}\right] - \left[\left(\frac{abv}{v - X_1}\right)\left(\frac{x_1^i}{X_1}\right)\left(\frac{X_1}{v - X_1}\right)^b\right] = t_1 - t_2 \tag{10}$$

or the condition under which door-to-door journey times across modes will be equal is given by

$$\left[(P_1 - P_2) \cdot \frac{u_z^i}{u_t^i}\right] = \left[\left(\frac{abv}{v - X_1}\right)\left(\frac{x_1^i}{X_1}\right)\left(\frac{X_1}{v - X_1}\right)^b\right] \tag{11}$$

Equation 11 indicates what combinations of prices, congestion, personal preferences, and highway speed-flow relationship will result in equal travel times. However, under the assumptions described earlier—especially the assumption of a growing marginal disutility with respect to travel time—it can readily be shown that with sufficient levels of congestion both the left-and right-hand sides of Equation 11 approach zero.

What happens under congested conditions? The left-hand side tends to zero because of the growing marginal disutility from increased travel time (also, the left-hand side approaches zero with increasing income—the individual becomes indifferent to the price differential as trip cost consumes a smaller portion of income). The theory also implies that congestion pricing will be less effective as congestion becomes more severe. It can be readily shown that if u_t^i is not bounded, then for any combination of prices and capacity equation parameters and for any small value $\varepsilon > 0$, there is a level of congestion (number of total trips) sufficiently large such that

$$\left| t_1 - t_2 \right| < \varepsilon \tag{12}$$

Empirical Evidence

Equations 10 and 11 tell us that if congestion is severe enough, journey times will tend to equal the journey time by the transit mode under the assumption of growing marginal disutility. This assumption can be tested empirically by estimating the relationships between travel time differentials, congestion, and additional factors.

Source of Data

In an ongoing study for the Federal Transit Administration, door-to-door travel time tests were conducted on 14 urban corridors. The testing was conducted between February and June 1995. The corridors were selected on the basis of criteria that included congestion, population density, the existence of mature dedicated-guideway transit systems, and public transportation headways. The 14 corridors where data was collected are given in Table 2. The corridors span a range of moderate to high congestion. In each corridor random routes of origins and destinations were selected. Survey crews conducted peak-hour trips on the different modes under comparable conditions.

More than 1,000 trips were recorded, and some of the average results are reported in Table 1. Of the trips taken, 495 pairs of comparable automobile/transit trips were observed. Congestion data for the metropolitan areas in which each of the corridors was located were taken from the recent TRB study on urban congestion (4). The metropolitan planning organizations in each corridor provided information on transit headways.

Analysis of Data

A regression analysis of time differentials was conducted. The absolute value of the travel time difference, automobile versus transit, was regressed against the metropolitan area congestion index and the transit mode headway (minutes). The results are presented in Table 3. The two explanatory factors, congestion and headway, do little to explain the variation between each of the 495 trip pairs. This is not surprising, since these variables have no variation within the corridor and transit mode. However, we observe that the coefficient for congestion is negative whereas that of headway is positive, and both coefficients are significant at the 99 percent level. This means that travel time differentials diminish with growing congestion and increase as transit headways increase.

Undoubtedly there are additional factors that contribute to the explanation of travel time differentials, some of them location specific and others associated with price and other variables. However, we find that the evi-

TABLE 2 Corridors Studied

Corridor	Modes
Boston - Mass Pike	Auto, Commuter Rail
Boston - Southeast Expressway	Auto, Heavy Rail
Chicago - Midway	Auto, Heavy Rail
Chicago - O'Hare	Auto, Heavy Rail, Commuter Rail
Cleveland - Brook Park	Auto, Heavy Rail
Philadelphia Schuylkill - Bryn Mawr	Auto, Commuter Rail
Philadelphia Schuylkill - Upper Merion	Auto, Commuter Rail
Philadelphia - Wilmington	Auto, Commuter Rail
Pittsburgh - Parkway East	Auto, Express Bus
Princeton - New York	Auto, Commuter Rail
San Francisco - Bay Bridge	Auto, Commuter Rail
San Francisco - Geary	Auto, Express Bus
Washington - I-66	Auto, Heavy Rail, HOV
Washington - I-270	Auto, Heavy Rail

TABLE 3 Regression Results

Dependent Variable: Absolute Value of Trip Time Difference (Auto - Transit)	
Variable	**Coefficient (t-values)**
Constant	21.51 (5.54)
Congestion Index	-4.743 (-2.61)
Headway	0.2703 (4.07)
All coefficients are significant at the one percent level	
Summary Statistics	
Number of Observations	495
R^2	0.051
Mean Dependent Variable	15.63
F-Statistic	13.18

dence supports the theory that in congested urban corridors the growing marginal disutility from time spent traveling causes door-to-door journey times to converge to the journey time by the high-capacity transit mode. Furthermore, the data indicate that reducing transit headways (which, in general, will contribute to shorter trip times by transit) will also contribute to a reduction in the time differentials between modes.

Implications for the Benefit-Cost Analysis of Transit Investments

The preceding analysis indicates that the observation of equal or nearly equal travel times across modes is consistent with consumer theory and may be observed under a wide range of circumstances with high levels of congestion. Congestion, if severe enough, will drive a multimodal transportation system toward convergent travel times. The further empirical study of congested corridors will reveal which combination of underlying factors (economic, demographic, spatial-locational, etc.) are most closely associated with the condition of travel time convergence. Travel time convergence in congested urban corridors and the factors promoting that convergence should be crucial elements in the development of transportation policies, especially in an environment of budgetary constraint with congestion pricing a rarity.

The benefit-cost analysis of transit investment examines the demand for trips and derives consumer surplus estimates based on the schedule of demand. The non-transit trips are mostly assigned to the highway network, and cost savings from reduced congestion are estimated. Trips are allocated between modes using a modal choice algorithm that does not take into account the dynamic interaction between the modes. When the allocated trips are assigned to the highway network, even under highly congested conditions, forecast journey times will likely be highly divergent.

As a first step toward refining the benefit-cost analysis of transit investment with a view to accounting for the phenomenon of convergence in congested corridors, the analyst should examine whether the modal split will yield journey times consistent with the convergence dynamic after trips are assigned to the urban transportation network. If convergence is likely to occur in the corridor under analysis, there is strong theoretical and empirical justification for calibrating the modal constants in the modal choice model such that the assignment of traffic yields nearly equal journey times.

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Operational Level-of-Service Index Model for Rail Rapid Transit

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In planning a new transit system or considering alternatives to improve services of an existing transit system, it is essential to consider both the system capacity and the levels of service. However, the concept of transit level of service, unlike that of highways, is not well established. Although the level of service is directly related to capacity, their relationship is poorly understood. A level-of-service index model is described that attempts to establish levels of service for rail rapid transit on the basis of vehicle load factors and headways. The model clearly demonstrates the relationship between level of service and system capacity. It may be used as the basis for developing practical tools for assisting transit agencies to plan a new system or for rail rapid transit operators to better manage train operation, including, for instance, selection of optimal operating schemes and assurance of service quality. The proposed model also makes it possible to compare the levels of service offered by different rail rapid transit systems on a common basis, and it may be used to develop a standard service guideline, which may be adopted by local transit agencies with modifications to reflect local conditions.

As urban congestion in U.S. cities continues to worsen and the need for air pollution reductions becomes more urgent, guideway transit systems are likely to play a larger role in public transit. Guideway transit ridership has been steadily increasing in the past several years (*1*). At the same time, transit funding has become more uncertain, limiting the ability of transit agencies to increase system capacity or expand or improve services. Service quality is, however, important for the success of public transit systems since they must compete with automobiles, which offer excellent flexibility, comfort, and convenience. To maintain the trend of increasing demand for guideway transit and to invest wisely for transit service improvements, one of the important questions that needs to be answered is how resources should be managed to provide the best possible service for a system with a given capacity.

A system's capacity is affected by many factors, including vehicle capacity, vehicle load factor (defined as the ratio of the number of passengers on board to the number of seats), number of vehicles operated per train, headway, and so forth. Some of these variables, such as vehicle load factors and headway, directly affect passenger comfort and convenience and thus the level of service. A relationship therefore exists between the system capacity and the levels of service.

Levels of service are a set of qualitative and quantitative measures describing the conditions under which transit operates and those that are perceived by passengers. Presently, levels of service for transit are not defined. For highways the emphasis has been on moving vehicles, so levels of service are defined on the basis of vehicle densities. However, transit is concerned with moving not vehicles but mainly people. Transit levels of service may include such considerations as the coverage of major residential areas and activity centers, comfort, speed, and service reliability. For instance, convenient schedules, comfortable vehicles, and frequent, fast, and reliable service contribute to the level of service. Many of the factors describing transit levels of service are determined by the technical capability of the transit equipment, whereas others depend on the operating policies of the transit agency, which specify service frequencies and allowable passenger loading.

Just as it is for highway design and operations, level of service is an important concept for transit because it is useful in transit service planning and may be used partly as a measure of service quality. For instance, qnestions such as how many passengers can be transported per unit of time at a specific level of service, how many transit vehicles are needed to provide a specific level of service and rate of passenger flow, and how many passengers can be transported with a given vehicle fleet at the designed level of service are often asked. These questions can be answered more easily if the relationship between rapid transit capacity and level of service is understood and clearly defined, which, unfortunately, is not the case.

There is much operational experience, and many analyses of rail transit capacity have been conducted. For instance, the Board of Supervising Engineers for Chicago Traction analyzed street railway capacity in 1912 and passenger dwell times by door width in 1916 (*2*). Lang and Soberman derived rapid transit track capacity formulas in 1964 (*3*). More recent studies by Homberger (*4*), Pushkarev et al. (*5*), Vuchic et al. (*6*), and Vuchic (*7*) addressed rail transit capacity theory and practices further. A Transit Cooperative Research Program project on rapid transit capacity is also being conducted (*8*). In contrast, there have been limited studies on transit levels of service. The concept of level of service has been rarely used in rail transit operations, or, if used, it has been used rather arbitrarily and its scope has been limited. Whereas the *Highway Capacity Manual* (*9*) addressed transit capacity and levels of service, it mainly emphasized bus transit, and the information related to rail transit is minimal.

This paper presents results from a study of the relationship between level of service and transit capacity for rail rapid transit. In particular, a level-of-service index model is described that is used to study the relationship between capacity and level of service. The purpose is to define levels of service more systematically for rail rapid transit to provide a basis for the development of practical tools that will allow transit agencies to carry out better service planning and operations, making rail rapid transit systems more cost-effective. In the remainder of this paper, the concept of transit level of service is discussed, and a level-of-service index model for rail rapid transit is described. Its use in understanding level of service, its relationship to system capacity, and its applications are discussed. Finally, conclusions are drawn and suggestions for future research are provided.

Transit Levels of Service

Meyer and Miller (*10*) give the following definition of level of service:

> Level-of-service is a qualitative measure of the effects of a number of factors (e.g., speed, travel time, traffic interruptions, safety, comfort, operating costs, volume-to-capacity ratios) on the performance of a facility. These qualitative measures have been grouped into different levels to represent different facility or service conditions.

Various factors affecting transit level of service from a passenger's viewpoint have been identified (*8,9,11–15*), which cover several different aspects of service quality. The following are some of the factors:

- Coverage of major residential areas and activity centers;
- Transportation capacity;
- Directness of service;
- System accessibility (walking distance, feeder buses or a background network of bus lines, ample parking facilities, simple transferring, and handicap accessibility);
- Service period (days of service and service span);
- Service frequency (headway);
- Convenient schedules;
- Journey speed;
- Comfort (acceleration and jerk of the vehicle, the number and arrangement of seats, space for standing passengers);
- Cleanliness;
- Service reliability (i.e., on-time performance);
- Total amount of service (for example, as measured by vehicle miles);
- Total travel time;
- In-vehicle time;
- Out-of-vehicle time;
- Walk time;
- Wait time;
- Transfer time;
- Number of transfers;
- Availability of information (schedule, facilities, amenities);
- Character of the information (e.g., clear and adequate signage);
- Safety and security of passengers, both actual and perceived; and
- Fares.

TABLE 1 Levels of Service and Loading Criteria for Bus and Rail Transit

Peak-Hour LOS		50-seat, 340-sq ft Bus (HCM 1985) Approximate Passengers/Seat	Approximate Square Meters[a] per Passenger	Urban Rail (HCM 1985) Approximate Passengers/Seat	Approximate Square Meters per Passenger
A		0.00 to 0.50	1.22 or more	0.00 to 0.65	1.43 or more
B		0.51 to 0.75	1.21 to 0.79	0.66 to 1.00	1.41 to 0.93
C		0.76 to 1.00	0.78 to 0.60	1.01 to 1.50	0.92 to 0.62
D		1.01 to 1.25	0.59 to 0.48	1.51 to 2.00	0.61 to 0.47
E	E-1	1.26 to 1.50	0.47 to 0.40	2.01 to 2.50	0.46 to 0.37
	E-2[b]			2.51 to 3.00	0.36 to 0.31
F[c]		1.51 to 1.60	<0.40	3.01 to 3.80	0.30 to 0.24

[a] 1 square meter = 10.75 square feet
[b] maximum schedule load for urban rail
[c] crush load

Some of these variables may be measured, whereas others are difficult to analyze or quantify. In addition, it is extremely difficult, if not impossible, to combine all these variables to arrive at a single level of service indicator. For rapid transit systems that have fixed guideways, route coverage cannot be easily changed once construction is completed. Service quality is mostly dependent on the practices of the transit operators. These practices may be examined, in part, by looking at the service standards adopted by the transit operators. According to Zhao et al. (*15*), these service standards vary greatly in their comprehensiveness. However, service span, policy headway, and vehicle load factors are commonly included in service standards.

Of all the level-of-service factors, vehicle loading or load factor may be the one most often used in service standards. The value of the load factor varies from agency to agency and depends on the number of seats, the floor area available to the passengers, anticipated average trip lengths, acceptable comfort level in terms of space per passenger, available operating funds, travel demand, and even political considerations. For instance, the largest number of seats and smallest number of standees should occur on the longer suburban bus routes or on commuter rail routes where a higher level of comfort is essential. Table 1 compares the levels of service defined on the basis of vehicle loading for bus transit and for urban rail transit (*9*). Level of Service A (LOS A) indicates the best level of facility performance, whereas LOS F indicates the worst.

Table 1 indicates that the recommended load factor for a standard bus with a normal scheduled load is between 1.26 and 1.50 passengers per seat with an average of 4.3 to 5.1 ft^2/passenger. Suggested load factors for urban rail transit vehicles are higher than those for bus transit. LOS D allows up to two passengers per seat and a minimum per passenger space of 5.0 ft^2. It is consistent with the use of 5.4 ft^2/passenger, suggested by Pushkarev et al. (*5*) as a realistic passenger capacity for rapid transit lines. (The suggested loading criteria for rail transit are not specifically for rail rapid transit.)

Level-of-Service Index Model for Rail Rapid Transit

Whereas load factors mainly affect the comfort of passengers, they do not reflect overall service quality because other important variables are not considered. Other variables that may be controlled by rail rapid transit operators and have a direct bearing on system capacity are headway, travel speed, acceleration and jerk rates, the number and arrangement of seats, and service reliability. For rail rapid transit, the maximum vehicle speed operated is commonly about 80.5 km/hr (50 mph), whereas the actual journey speed is influenced by dwell times, station spacing, and track geometry, the latter two of which cannot be modified without major reconstruction. The acceleration and jerk rates are also rather standard. It appears that headway is the other most important controllable variable with a direct bearing on both level of service and system capacity. From a capacity perspective, headway refers to the number of trains (vehicles) operated per hour, which is one of the two variables that determine the system passenger capacity. From a passenger perspective, headway is related to the out-of-vehicle waiting time. The shorter the headway, the higher the level of service. On the basis of these considerations and for simplicity, we presently combine load factor and headway to derive an index of the level of service for rail rapid transit.

Construction of the Model

Many possible function forms may be used to construct the model. Our choice of a circle function has been mainly influenced by consideration of the relative importance of load factor and headway. According to a survey conducted among rail rapid transit professionals, these two variables were ranked as equally important (*15*). Because of the lack of evidence indicating otherwise, it has been decided that the function chosen will reflect equal contributions from both variables to the level-of-service index. This requirement is satisfied by the circular function because of its symmetry.

To use a circle equation requires that the two variables, headway and load factor, have the same value domain. This is not the case, since the value of load factor may range from 0.0 to 3.0, whereas that of headway may range from 3.0 to 30 min under normal operating conditions for most rail rapid transit systems. To satisfy the requirement that the two variables have the same value domain, headway domain must be mapped into the same range as the load factor domain. A linear mapping, however, does not reflect the fact that passengers are more sensitive to the same headway change in shorter headways than in longer ones. For instance, passengers are more sensitive to a headway change from 5 to 10 min than from 30 to 35 min. Therefore, a logarithmic scale of headway is used in the model to reflect the greater sensitivity of the level-of-service index to headway changes in shorter headways. The level-of-service index model has the following form:

$$I_{LOS} = \text{sqrt}\{L^2 + [\ln(\alpha + \beta H)]^2\} = \text{sqrt}(L^2 + H_e^2) \quad (1)$$

where

I_{LOS} = level-of-service index,
L = load factor,
H = headway (min),
H_e = $\ln(\alpha + \beta H)$ is the equivalent logarithmic headway (min), and
α, β = parameters used to map the domain of headway into that of load factor.

The model may be considered as an extension of the level of service definition based solely on load factor as suggested in the *Highway Capacity Manual* (*9*) by adding a modifying term that accounts for the contribution from the headway.

The two parameters α and β allow H_e to be adjusted so that appropriate headway values may be chosen to correspond to different levels of service. The values of α and β may be selected such that (*a*) H_e has the same value range as L and (*b*) H^A, the headway that corresponds to the highest level of service (LOS A), will give the limiting H_e^A for LOS A using Equation 1, whereas H^F, the headway corresponding to the lowest level of service (LOS F), will give the limiting H_e^F for LOS F. For example, if load factor L is 0.5 at LOS A and 3.0 at LOS F, assuming $H_e^A = 0.5$ for LOS A and $H_e^F = 3.0$ for LOS F, one has

$$\ln(\alpha + \beta * H^A) = 0.5$$
$$\ln(\alpha + \beta * H^F) = 3.0$$

or

$$\beta = (e^{3.0} - e^{0.5})/(H^F - H^A) \quad (2)$$
$$\alpha = e^{0.5} - \beta H^A \quad (3)$$

Using Equations 2 and 3, if $H^A = 2.0$ min and $H^F = 30.0$ min are chosen, we have

$$\alpha = 0.3318 \quad (4)$$
$$\beta = 0.6585 \quad (5)$$

Rail Rapid Transit Levels of Service Based on the Model

On the basis of the definition of levels of service given in the 1985 *Highway Capacity Manual* and using I_{LOS}

TABLE 2 Suggested Rail Rapid Transit Levels of Service

Rail Transit Level-of-Service	Index Values
A	0.00 - 0.50
B	0.51 - 1.00
C	1.01 - 1.50
D	1.51 - 2.00
E	2.01 - 3.00
F[a]	3.01 or more

[a] crush load

TABLE 3 Theoretical and Operated Minimum Headways of Rapid Rail Systems

City	System	Operated Minimum Headway (Minutes)	Theoretical Minimum Headway (Minutes)
San Francisco	BART	3:00	2:30
Vancouver	BCRTC	1:35	1:30
Chicago	CTA	2:45	N/A
Cleveland	GCRTA	6:00	2:00
Los Angeles	LACMTA	6:00	3:00
Atlanta	MARTA	8:00	1:30
Boston	MBTA	3:30	3:00
Miami	MDTA	6:00	3:00
Baltimore	MTA	6:00	1:30
New York	NYCTA	2:00	2:00
Philadelphia	PATCO	2:00	1:30
NY - NJ	PATH	3:00	1:30
Philadelphia	SEPTA	3:00	3:00
New York	SIRTOA	2:00	2:00
Toronto	TTC	2:27	2:00
Washington DC	WMATA	2:00	1:30
Average		3:40	2:06

defined in Equation 1 in place of load factor, a definition of levels of service that considers both load factor and headway is suggested in Table 2. There are three minor modifications. One is that we have changed the value of the load factor for LOS A from 0.65 to 0.50 for convenience. The second is that the upper limit of the load factor for LOS F is ignored since LOS F should not be used for service planning, and the lower limit is adequate to reflect the operating condition. The last modification is that for simplicity we did not subdivide LOS E into LOS E-1 and LOS E-2.

To apply the model, the headway values corresponding to LOS A and LOS F must take into account current operating conditions and future operating plans. To provide an understanding of current practices, Table 3 gives the theoretical and operated minimum headways for rail rapid transit systems in North America. Ten of the systems have theoretical minimum headways less than or equal to 2 min. The average theoretical minimum headway of the 15 systems is 2 min 6 sec, whereas the minimum operated headway is often 3 to 3.5 min. The trend of future train control based on moving block technology is likely to make the current theoretical headway practical in rail operations. On the basis of these data, a 2-min headway, or $H^A = 2$ min, is recommended for LOS A. Considering the widely used service standard on off-peak headway, which is between 20 and 30 min and falls into the range of LOS E, a 30-min headway or $H^F = 30$ min is suggested for LOS F. The values for α and β for $H^A = 2$ min and $H^F = 30$ min were obtained in Equations 4 and 5, which give the level-of-service index model as follows:

$$I_{LOS} = \mathrm{sqrt}\{L^2 + [\ln(0.3318 + 0.6585H)]^2\} \qquad (6)$$

To illustrate the contribution of the headway to I_{LOS}, the level-of-service index, Table 4 gives the level-of-service indexes for different headways when load fac-

TABLE 4 Headway Influence on Level-of-Service Index (L = 1.0)

Headway (minutes)	2	5	10	15	20
Levels of service index	1.12	1.47	1.91	2.22	2.45
Levels of service	C	C	D	E	E

tor is held constant at 1. 0. It is observed that the headway has strong influence on level-of-service indexes and that a long headway effectively lowers the level of service.

Figure 1 shows the level-of-service index model. The arcs are level-of-service index contour lines representing the various levels of service. Each point in the chart refers to a particular operating condition or a level of service determined by the load factor and the headway. In other words, given a load factor and headway, the corresponding level of service may be easily determined. In Figure 1, the operating conditions during peak hours and the corresponding LOS ranges are illustrated for the systems operated by the Metropolitan Atlanta Rapid Transit Authority, the Metro-Dade Transit Agency, and the Greater Cleveland Regional Transit Authority on the basis of data obtained from their respective service standards, planning guidelines, or service policy (*16–18*). The off-peak operating conditions and the corresponding level of service ranges are shown in Figure 2. It may be seen that, according to this model, the peak-hour services for all three systems are planned on the basis of LOS D and E, and the off-peak-hour services are based on levels of service between D and E, which is reasonable and expected.

Calibrated Load Factors for Different Vehicle Configurations

Whereas load factors give a reasonable measure of passenger comfort and are taken into account in the proposed model, they do not always represent the same comfort level for passengers because of differences in rail rapid transit vehicle configurations. Because the number

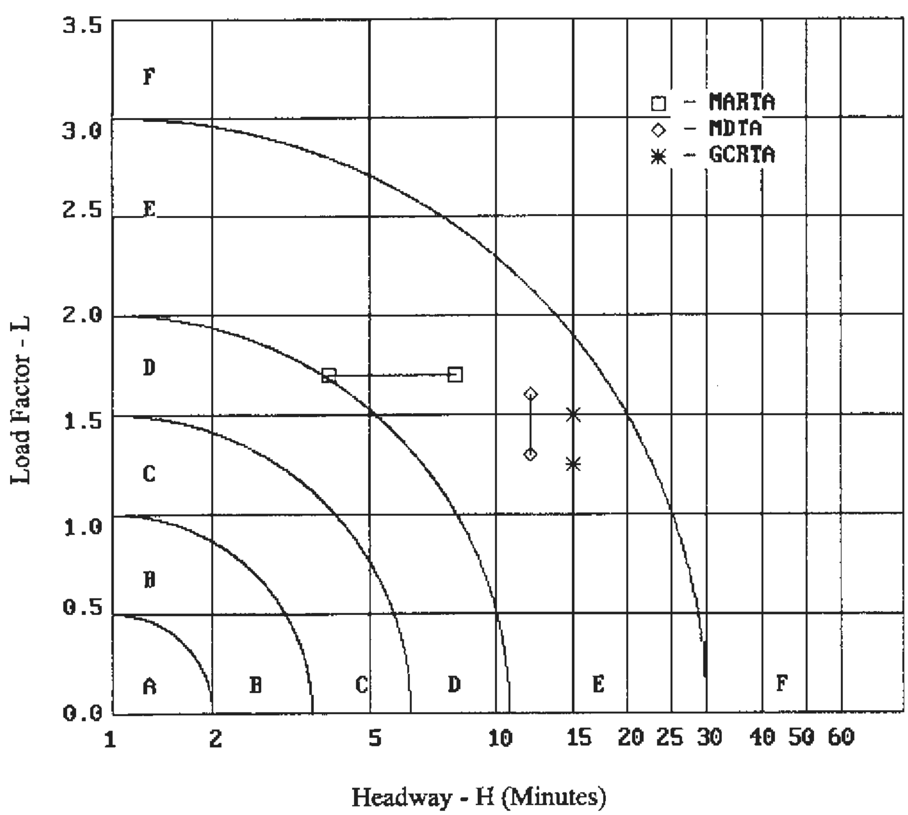

FIGURE 1 Peak-hour level-of-service ranges for three transit agencies.

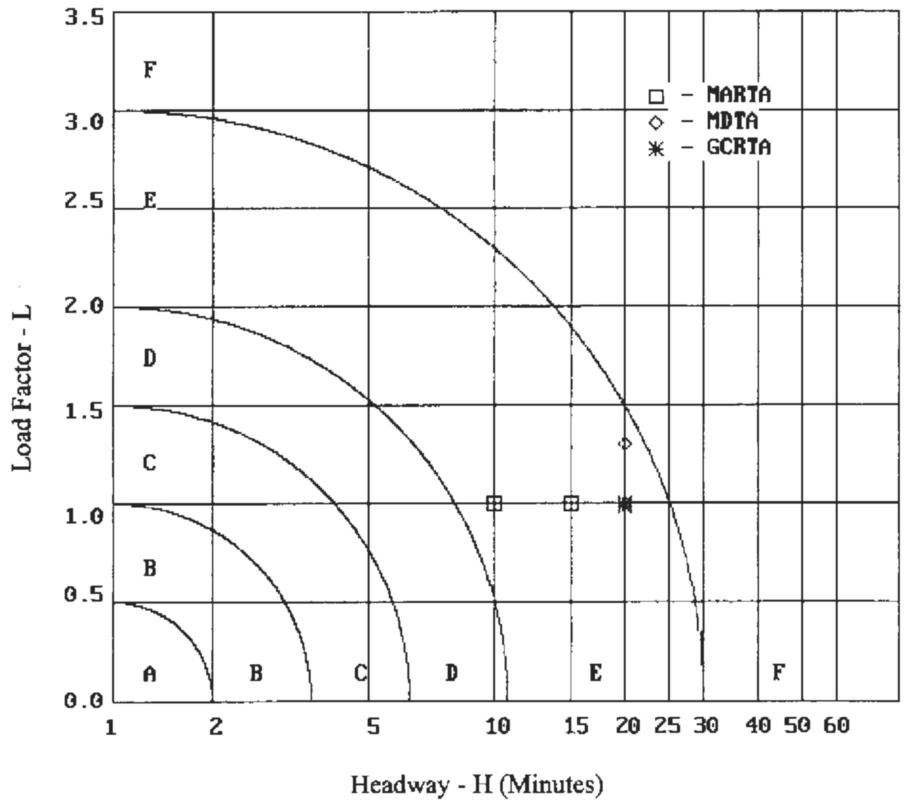

FIGURE 2 Off-peak level-of-service ranges for three transit agencies.

of seats often changes from one vehicle to another, the same load factor may have different meanings for different vehicles in terms of space per standing passenger. Inconsistent load factors for different vehicles is not a problem for the proposed model if the numbers of seats for all the vehicles are the same or similar. However, when differences in vehicle configurations cannot be ignored, using the same model for service planning within a transit property or for performance comparisons among transit properties will be misleading. It is necessary to use a refined or calibrated load factor to make the level-of-service index independent of the vehicle configuration.

For illustration, Table 5 gives load factors and the approximate space per standing passenger in square meters. The correlation is established by estimating space per standing passenger on the basis of the vehicles' dimensions, number of seats, and scheduled and crush capacities (*19*) and the typical space requirements for seated and standing passengers for urban rail transit as recommended in the 1985 *Highway Capacity Manual* (Table 12-7). Note that space per standing passenger is meaningful only when the load factor is greater than 1.0.

To use the proposed model, the desired space per standing passenger under the operational condition being considered needs to be determined first. The corresponding load factor may then be determined from Table 5 or a similar table. If the value of the space per standing passenger falls within a range in Table 5, the load factor may be calculated by using linear interpolation. The level of service may easily be determined with a known head-

TABLE 5 Space per Standee and Corresponding Load Factors

Approximate Square Meters[a] Per Standing Passenger	Load Factor
-	0.00 to 0.50
-	0.51 to 1.00
0.93 or more	1.01 to 1.50
0.47 to 0.93	1.51 to 2.00
0.27 to 0.47	2.01 to 2.50
0.22 to 0.27	2.51 to 3.00
< 0.22	3.01 or more

[a] 1 square meter = 10.75 square feet

way and space per standing passenger. When the load factor is greater than 1.0, and especially when it is greater than 1.5, it is recommended that space per standing passenger be used instead of load factor to calculate the level-of-service index.

Figures 3 and 4 show the planned peak levels of service for the New York City Transit Authority using the uncalibrated and calibrated load factors, respectively. In Figure 3, significant inconsistencies in the level of service for the three types of car are apparent. Figure 4, with space per standing passenger given along the vertical axis on the right side of the graph and calibrated load factors applied, shows consistent levels of service for all three types of car.

Relationship Between Level of Service and Capacity

Service planning and design need to consider not only the level of service but also transit capacity, since the desired level of service must be realized under the constraints of system capacity. The passenger capacity in the peak direction during peak hours may be estimated using the 1985 *Highway Capacity Manual* Formulas 12-5a and 12-6:

$$\text{Passengers/hour} = (\text{trains/hour}) \times (\text{cars/train}) \times (\text{seats/car}) \times (\text{passengers/seat}) \quad (7)$$

Let T_c be the number of cars per train (or train consist) and C_s be the number of seats per vehicle. Since trains/hour = 60/headway, Equation 7 may be rewritten as

$$\text{Passengers/hour} = 60/H \times T_c \times C_s \times L \quad (8)$$

where H and L are headway and load factor, respectively.

For the fleet of a given rail rapid transit system, the train consist and vehicle seating capacity are known, and the system capacity is therefore determined uniquely by the headway and load factor. This means that each point in the chart for the level-of-service index model also corresponds to a certain passenger capacity. As a result, a relationship between system capacity and level of service may be established, which is demonstrated by contour lines originating from the L axis in Figure 5.

As an example, consider the Metrorail system in Miami. Given that the vehicle seating capacity $C_s = 76$ and that, during peak hours, the headway is between 6 and 12 min, the load factor is between 1.3 and 1.6 (*17*), and the train consist $T_c = 6$, Figure 5 shows that the system offers a passenger capacity of between 2,964 and 7,296 ppdph.

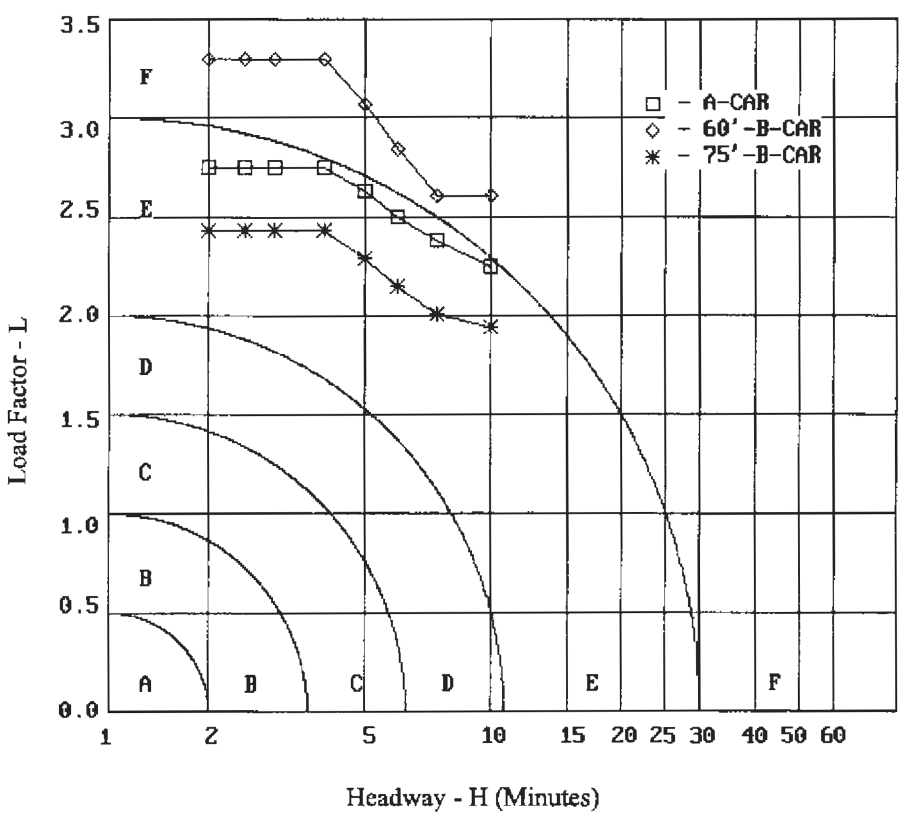

FIGURE 3 Planned peak-hour levels of service for NYCTA based on uncalibrated load factor.

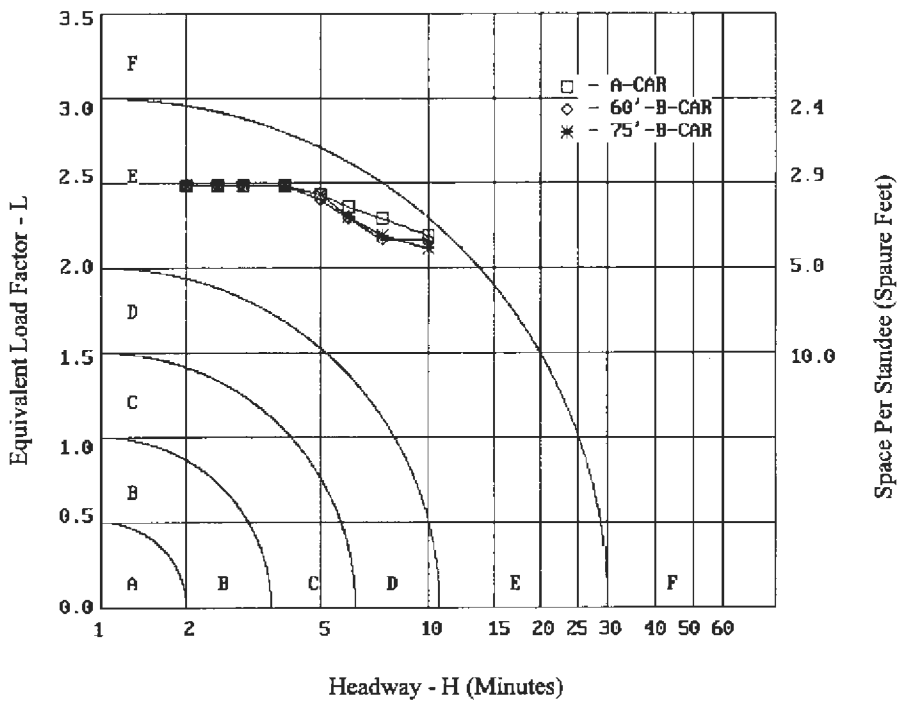

FIGURE 4 Planned peak-hour levels of service for NYCTA based on space per standee.

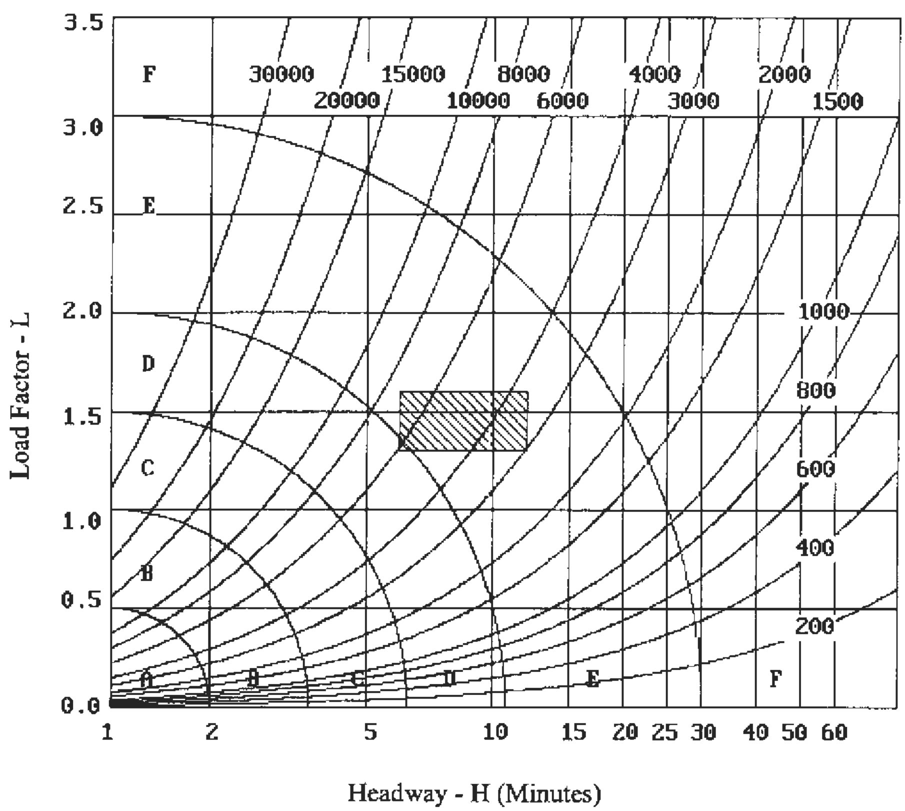

FIGURE 5 Relationship between level of service and system capacity.

Whereas line capacity is expressed in terms of an hourly passenger flow rate, in reality the passenger volume is not evenly distributed over time. For instance, there is normally a short period during peak hours that may last about 20 min during which the passenger volume will be much higher than the average during peak hours. Therefore, when planning for transit services for that period, the line capacity should be computed on the basis of the actual short-term passenger volume and the length of the period. In other words, if the average passenger volume in 1 hr during the peak period is 10,000, but during a 20-min period the volume is 3,800, the line capacity used for planning the service for the 20-min period should be 11,400. For this reason, many transit operators divide peak hours into periods of 0.5 hr or even less and design the services for each of them on the basis of demand.

Figure 5 may be conveniently used to plan the service on the basis of demand and to provide the basis for determining an operating schedule. Given the train consist, vehicle seating capacity, and the demand, the latter being predicted or observed, a passenger capacity contour line may be found from the chart that meets the given demand. By choosing a reasonable value range for the load factor on the basis of the service standards, the needed headways may be easily found from the chart. There will exist many combinations of load factors and headways that will meet the demand. The decision concerning the actual load factor and headway to be used may be made by considering the levels of service that they offer and the associated operating costs.

Conclusions

In this paper a level-of-service index model based on two important operational variables, load factor and headway, was described, and levels of service for rail rapid transit using the level-of-service index were suggested. The model is simple, has clear meanings in terms of system operations, and may be used to relate system capacity to level of service via the two variables. Testing the model with service data from several transit agencies has produced reasonable results. The model is useful because it allows an understanding of the concept of level of service and its relationship to rail rapid transit capacity. It may be further improved for use as the basis for developing practical tools to assist planners in determining the required facilities for a new system or an expansion or in designing optimal operating schemes while maintaining the desired level of service. From a performance perspective, the proposed model may be used to measure, in part, service quality and allow the levels of service offered by various rail rapid transit systems to be compared on a common basis.

This research is an initial attempt to understand rail rapid transit level of service and its relationship to capacity. Many issues remain unaddressed. Because of the many facets of service quality and level of service, more research is needed to further study the possible definitions of levels of service and practical measurements for ensuring service quality. More variables must be considered. To understand service quality from a customer perspective, a survey of transit users should be carried out. This is being accomplished through the Transit Cooperative Research Program. Levels of service may also be studied from a facility point of view (i.e., track capacity and its unitization for a given type of track environment, similar to highway levels of service being defined on the basis of vehicle densities). Another possible extension of the model is to incorporate a cost-benefit analysis that illustrates the cost implications and effect of a proposed service change on the level of service.

Aside from technical issues concerning system capacity and level of service, political decisions and inadequate funding also affect the ability of transit operators to increase or even maintain the system capacity or to improve services. For instance, Metropolitan Atlanta Regional Transit Authority has reported overcrowding on trains during the peak hours, but no services will be added because of budgetary constraints. Metro-Dade Transit Agency has also recently reduced the active fleet size in response to a shortage of operating funds. Because operating funds will likely continue to decline, transit services may be seriously affected both in quantity and in quality, making better service planning and design more important. On the other hand, the ability to measure level of service and the associated cost using tools such as the proposed method will allow transit agencies to influence the political decisions regarding transit service more effectively.

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FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
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ITE	Institute of Transportation Engineers
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