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TRANSPORTATION
INSTITUTE

STATE DEPARTMENT
OF HIGHWAYS AND
PUBLIC TRANSPORTATIC

COOPERATIVE
RESEARCH

TRANSITWAY CONVERSION TO RAIL TRANSIT GUIDEWAYS

in cooperation with the
Department of Transportation
Federal Highway Administration

RESEARCH REPORT 425-2F (SUPPLEMENT)
STUDY 2-10-84-425
TRANSITWAYS

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16. Abstract

Transitways are defined as exclusive, physically separated, access controlled high-occupancy vehicle (HOV) priority treatment facilities which are typically located within existing freeway right(s)-of-way. Transitways are sometimes referred to as busways, HOV lanes or AVLs (authorized vehicle lanes).

This report was prepared for the Texas State Department of Highways and Public Transportation (SDHPT) to provide guidelines and standards for the planning and design of transitway facilities to allow subsequent conversion to rail transit guideways. It follows the general style and format of the SDHPT Manual for Planning, Designing and Operating Transitway Facilities in Texas. The Transitway Manual was prepared as an independent document to replace and consolidate existing SDHPT information on the design of high-occupancy vehicle facilities.

This report is divided into four primary technical divisions. These are: 1) Rail Transit Systems (an overview of technologies); 3) Rail Transit Design Guidelines; and, 4) Conversion of Transitways. Information presented within the Transitway Manual should promote uniformity of design and operational efficiency for transitway facilities in Texas. Information presented herein supplements the Manual and is intended to provide general design criteria and guidelines for converting a transitway from rubber-tired HOV operation to rail transit service. Considerations of both light rail transit (LRT) and heavy rail transit (HRT) vehicles are included within the report.

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Form DOT F 1700.7 (8-69)

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

LENGTH

Symbol	When You Know	Multiply by	To Find	Symbol
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km

AREA

Symbol	When You Know	Multiply by	To Find	Symbol
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha

MASS (weight)

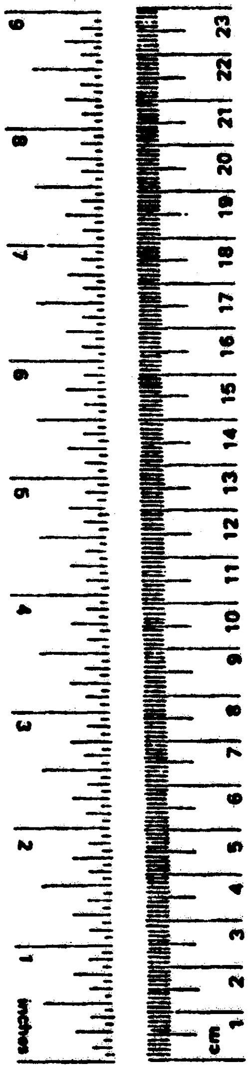
Symbol	When You Know	Multiply by	To Find	Symbol
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t

VOLUME

Symbol	When You Know	Multiply by	To Find	Symbol
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply by	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

LENGTH

Symbol	When You Know	Multiply by	To Find	Symbol
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi

AREA

Symbol	When You Know	Multiply by	To Find	Symbol
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	

MASS (weight)

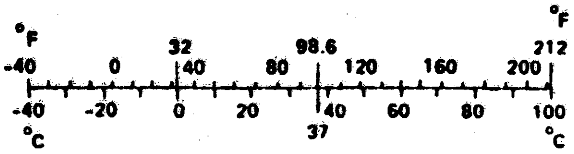
Symbol	When You Know	Multiply by	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	

VOLUME

Symbol	When You Know	Multiply by	To Find	Symbol
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply by	To Find	Symbol
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

TRANSITWAY CONVERSION TO RAIL TRANSIT GUIDEWAYS

Research Report 425-2F Supplement
Study Number 2-10-84-425

Prepared by

Richard L. Peterson
Robert W. Stokes
John M. Mounce

Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843

Sponsored by

Texas State Department of Highways and Public Transportation
U.S. Department of Transportation
Federal Highway Administration

August 1986

ABSTRACT

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KEY WORDS: Transitway, Rail Transit, Light Rail, Heavy Rail, Trackbed, Mass Transportation, Urban Transit, Priority Treatment, HOV Lane, System Planning, Rail Vehicle, Train, Busway Conversion.

IMPLEMENTATION STATEMENT

Study 2-10-84-425 is intended to assist the Texas State Department of Highways and Public Transportation (SDHPT) in the planning and implementation of transitways and related support facilities in the State. The information presented in this report should enhance the cost-effectiveness of future priority treatment projects. Planning, operational and design elements of urban rail transit systems are presented and compared to criteria set forth for transitway facilities in Texas. Certain urban travel corridors within Texas cities (i.e., Houston, Dallas, Fort Worth, Austin, San Antonio) may warrant higher capacity transit service than afforded by rubber-tired HOV priority treatments. As determined from this research, conversion of a transitway to rail transit is feasible and should be considered, where practical, for incorporation within the planning and design process. Results of this work should be useful and beneficial to SDHPT personnel, city planners, transit agencies and officials, private consultants, industry representatives and various professional/governmental organizations (i.e., TRB, ITE, AASHTO, AAR, FRA, UMTA, FHWA).

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the Texas State Department of Highways and Public Transportation. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

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TRANSITWAY CONVERSION TO RAIL TRANSIT GUIDEWAYS

1 INTRODUCTION

1.1 General

Exclusive, barrier protected facilities for priority treatment of high occupancy vehicles (buses, vans, carpools) are being planned, designed, and constructed within Texas freeway rights-of-way. The application of transitway facilities has been accepted as an effective and relatively inexpensive alternative for management of peak period congestion on urban freeways. Transitway systems are being implemented both statewide and nationally in major metropolitan areas.

However, transportation officials (1, 2) recognize that future travel demand and development potential in some urban corridors may require a higher capacity mode for person-movement (i.e., rail transit). With this in mind, several other states (3, 4, 5, 6) have mandated, by statue or policy, that transitway planning and design must consider and allow for the expansion or conversion to a rail transit system of some type. The needs for future urban mobility in the major cities of Texas warrant the same type of operational and design evaluation.

Where, in a corridor, agreement exists that projected demand for public transportation may reach levels in excess of the transitway capacity, one planning alternative is to provide for the conversion of the transitway to a higher capacity, fixed guideway transit mode. Although this document primarily concentrates on "rail transit", an appendix is provided on an alternative fixed guideway system for rubber-tired vehicles. To facilitate future conversion of a transitway to rail transit, the decisions to permit such conversion should be made initially in planning and designing the transitway. The design considerations made in developing a convertible transitway should attempt to minimize the initial investment in structures and other provisions which are governed by the future rail transit system. It is conceivable to develop a transitway design, with only minor adjustments, which would simplify and expedite future conversion to rail.

Conversion of a high occupancy vehicle (HOV) transitway to a rail transit system is not, however, simply a matter of reconstructing the transitway to put rails and related wayside equipment in place. Profound changes in the terminal and access connections of the transitway must take place. The rail operations, even those of the flexible light rail transit mode, cannot leave the transitway route and simply mix with the general traffic downtown or in the suburbs. Although the light rail mode can join other surface traffic as a trolley line, there are restrictions and controls on its placement and operations which are more complicated than for rubber tired HOV's. In the case of heavy rail transit, full grade separation must be afforded throughout the extent of revenue service operations due to the third-rail power supply. These features and limitations make conversion of any transitway to a rail transit system a larger undertaking than traditional highway planning and design. Such planned conversion may indeed be the proper solution for a selected design in a given corridor, but the plan should initially consider the full practicality of future conversion.

The principal impact considerations which must reflect the future rail mode, and which differ from those of a transitway, are:

(a) Horizontal and vertical alignment maxima and minima, including in particular, horizontal curvature, grades, and vertical curves.

(b) Load carrying capacity, deflection and harmonic characteristics of bridges and elevated structures.

(c) Load and vibration transmittal and resistance characteristics of grade slabs, retaining walls and abutments.

Other considerations of lesser impact relate to rates of superelevation, electrification and control system, spatial allowances, and direct anchorage of rails and power poles on transitway pavement slabs.

To effectively assess the impacts of transitway conversion, planners and designers must initially have a working knowledge of guidelines and criteria necessary for the implementation of both transitway and rail transit facilities. Previous Texas efforts (7) have addressed the former, while subsequent sections herein will discuss details of the latter.

1.2 Scope

This report provides an introduction to urban rail transit planning and design, and is intended for engineers already familiar with general highway planning and design principles. The intent is to assist the Texas State Department of Highways and Public Transportation (SDHPT) in evaluating transitway designs in terms of possible future conversion to rail transit systems. Throughout the report, an attempt is made to stress the unique aspects of rail transit engineering and present those elements of rail design which differ from highway and transitway design.

The materials presented herein are general in nature. The tables, graphs and illustrations are intended as aids in the design process and not as substitutes for accepted engineering techniques or standards established by the rail industry. Standard textbooks (8, 9, 10, 11, 12) and the numerous references cited in the text should be consulted during the advanced planning and design phases of project development.

1.3 Organization

In addition to this introductory section, the report is organized according to the following topic areas:

Section 2 - Rail Transit Systems. Section 2 presents an overview of current rail transit technologies in terms of basic definitions, characteristics, and the general application of each technology to urban travel needs.

Section 3 - Rail Transit System Planning and Operational Considerations. Section 3 outlines key physical and operating features of rail systems which should be taken into consideration in designing transitways which may evolve into rail facilities.

Section 4 - Rail Transit Design Guidelines. Section 4 is divided into two major subsections. Section 4.2 presents representative dimensions, performance, capacity, weight and electrical data for rail vehicle design. Design loading and trackway data are presented in Section 4.3. Trackbed design including track spacing, gauge and alignment are also included in this section.

Section 5 - Conversion of Transitway. The final section identifies principle design elements of rail transit systems which are compatible with or different than transitway design. Transitways may initially be designed and constructed to facilitate retrofitting of rail service. The process of converting an operational transitway to a rail transit system is also discussed.

Section 6 - References. The references section identifies numerious reports, design aides, publications and other secondary sources of rail transit information. Some 69 citations are listed and liberally referenced within the text of this report to facilitate the work of a designer or planner considering the details of transitway conversion.

2 RAIL TRANSIT SYSTEMS

2.1 General

Rail transit is one form of public transportation which utilizes a fixed-guideway throughout its length (13, 14). Depending upon the technology employed, and the final system design, rail transit may operate on exclusive right-of-way or in mixed-flow operation with other transportation modes. Some reasons for developing rail transit systems instead of alternative transit services or facilities (i.e., transitways) may involve the following (5, 13, 15):

- Internal distribution at activity centers, and aesthetics.
- Reduced labor requirements and potentially lower operating costs.
- Relatively short trip patterns within a travel corridor.
- Attractiveness of route certainty and simplified transferring of patrons.
- More favorable impacts upon the environment (i.e., air quality, noise).
- Enhancement of the downtown area or other major activity center(s).

Five types of rail transit technologies are used in the United States for the movement of people. These are commonly known as (13, 14, 16, 17, 18, 19):

- Light Rail Transit (LRT);
- Heavy Rail Transit (HRT), sometimes called Rapid Rail Transit or Metro;
- Commuter Rail Transit (CRT), sometimes called Regional Rail Transit;
- Automated Guideway Transit (AGT); and,
- High Speed Rail (HSR) Transportation for intercity passenger service.

The LRT, HRT and CRT systems are the most typical rail technologies employed within major urbanized areas; an overview of performance indicators for these three rail technologies is presented in Table 1. AGT systems are

Table 1: Overview of Rail Transit Performance Indicators (1983 Data)

Performance Indicators:	Rail System Type:		
	Light Rail Transit (LRT)	Heavy Rail Transit (HRT)	Commuter Rail Transit (CRT)
Revenue Vehicles			
Per Thousand Directional Miles	2,292	8,238	1,223
Revenue Vehicles in Max. Scheduled Service			
Per Thousand Directional Miles	1,193	6,254	1,156
Annual Vehicle Miles			
Per Vehicle in Max. Scheduled Service	34,057	55,328	37,855
Per Operator	15,982	45,327	37,346
Per Vehicle Hour (Miles Per Hour)	11	17	92
Per Directional Mile	40,620	346,006	43,775
Annual Vehicle Hours			
Per Vehicle in Max. Scheduled Service	3,098	3,202	412
Per Operator	1,454	2,623	406
Annual Vehicle Revenue Miles			
Per Vehicle in Max. Scheduled Service	33,948	54,407	34,955
Per Operator	15,931	44,573	34,485
Per Vehicle Revenue Hour (Miles Per Hour)	11	19	100
Per Directional Mile	40,490	340,248	40,422
Annual Vehicle Revenue Hours			
Per Vehicle in Max. Scheduled Service	3,012	2,798	349
Per Operator	1,413	2,292	344
Fuel Consumption (KWHS)			
Per Hundred Vehicle Miles	1,011	665	n/a
Per Hundred Passenger Miles	42	27	n/a
Per Hundred Capacity Miles	8	4	n/a
Total Operating Expenses ($$)			
Per Vehicle in Max. Scheduled Service	254,581	303,378	37,634
Per Vehicle Mile	8	6	1
Per Hundred Capacity Miles	6	3	1
Per Vehicle Hour	82	95	91
Per Vehicle Revenue Hour	84	108	108
Per Hundred Unlinked Pass. Trips	88	103	74
Per Employee	33,751	45,300	7,486
Per Operator Hour	60	115	18
Annual Passenger Miles			
Per Directional Mile (Thousands)	990	8,534	1,439
Per Revenue Vehicle (Thousands)	432	1,036	1,176
Per Vehicle Revenue Hour	276	488	3,565

Table 1: Overview of Rail Transit Performance Indicators (1983 Data) (Con't.)

Annual Unlinked Pass. Trips			
Per Directional Mile	346,812	1,840,296	58,606
Per Vehicle Mile	8	5	1
Per Employee (Thousands)	38	44	10
Per Vehicle Revenue Hour	97	105	145
Total Employees			
Per Revenue Vehicle (Total)	4	5	5
Per Vehicle in Max. Scheduled Service	8	7	5
Administrative Employees			
Per Ten Revenue Vehicles	6	7	6
Per Ten Vehicles in Max. Scheduled Service	12	9	7
Annual Vehicle Miles			
Per Dollar Vehicle Maintenance Expense	0.5	0.9	24
Per Road Call	1,155	5,722	n/a
Revenue Vehicles			
Per Maintenance Employee	0.5	0.4	0.4
Number of Collision Accidents			
Per Million Vehicle Miles	122.5	0.4	0.5
Per Million Passenger Miles	5.0	0.0	0.0
Total Number of Noncollision Accidents			
Per Million Vehicle Miles	51.7	6.9	6.5
Per Million Passenger Miles	2.1	0.3	0.2

Source: National Urban Mass Transportation Statistics, 1983 Section 15 Annual Report, Urban Mass Transportation Administration, Washington, DC, December 1984.

Note:

1. Performance Indicators, shown above, are derived statistics which provide "typical" measures useful for general comparisons.

2. The derived statistics are weighted averages based upon the number of reporting transit systems within a given category (i.e., LRT, HRT or CRT).

3. Performance indicators summarized in the table include directly operated or large contractor services; they do not include data from purchased transportation services for contacts using less than 50 vehicles.

used within major activity centers (e.g., airports, central business districts, amusement parks, universities) for relatively short, specialized internal trips. High speed rail (HSR) passenger service between urban areas is an emerging transit service which, if developed, could impact the urban areas and the local transportation system. The following subsections present the characteristics, a description, and some examples of each rail transit type. Emphasis is placed on LRT and HRT due to their widespread use and greater application potential within the family of rail transit services.

2.2 Light Rail Transit

Light rail transit (LRT) is an evolutionary development of streetcars toward more modern rapid rail systems. LRT vehicles may be referred to as streetcars or trolleys (20) in some locales. Modern LRT systems are an urban railway mode which can generally be defined by (16, 21):

- Predominately reserved, but not necessarily grade-separated, rights-of-way.
- Overhead electrical power distribution.
- Single or dual-directional rolling stock.
- Low or dual-level passenger loading platforms at stations or stops.
- Single vehicle operation during off-peak periods with multiple vehicle (train) operation during peak periods.

Light rail rapid transit (LRRT) is the highest form of LRT and is characterized by grade-separated rights-of-way (16). Due to the above flexibilities, which serve to decrease implementation costs, LRT has recently become the most popular form of new rail transit in U.S. cities (5, 22).

Table 2 summarizes selective design characteristic of 17 LRT systems in urban areas of the United States (23). Table 3 presents representative operational parameters for light rail transit (24).

Table 2. Design Characteristics of Urban Light Rail Transit Systems in the U.S.

Urban Area	Population of Service Area	Route Miles (Kilometers)	Number Stations or Stops	Rail Gage feet-inches (millimeters)	Rail Weight & Type (kg/m)	Electrification	Vehicle Suppliers	Remarks
Boston, MA	2.6 million	29.3 (47.2 km)	21	4'-8 1/2" (1435 mm)	n.a.	600v. dc, Catenary	Hawker Siddeley Boeing Vertol Kinki Sharyo	LRT comprises 42% of rail system milage.
Buffalo, NY	400,000	6.4 (10.3 km)	11	4'-8 1/4" (1429 mm)	n.a.	650v. dc, Overhead	Tokyu Car Corp.	Initial operation began October 1984.
Cleveland, OH	1.6 million	13.2 (21.2 km)	29	4'-8 1/2" (1435 mm)	90 ARA-B (45 kg/m)	600v. dc, Overhead	St. Louis Car Breda	LRT comprises 41% of rail system milage.
*Dallas, TX	1.4 million	160.3 (258.0 km)	98	n.a.	n.a.	n.a.	n.a.	LRT system approved by voter referendum August 1983.
Detroit, MI	1.2 million	15.0 (24.2 km)	n.a.	4'-8 1/2" (1435 mm)	n.a.	600v. dc	n.a.	In final design; plan approved by State Legislature in 1980 for funding, subject to local voter endorsement.
Ft. Worth, TX	400,000	1.0 (1.6 km)	n.a.	n.a.	n.a.	n.a.	Rebuilt PCC Cars	Privately owned system; free service provided by Tandy Corporation.
*Los Angeles, CA	7.6 million	131.7 (212.0 km)	17	4'-8 1/2" (1435 mm)	n.a.	750v. dc	n.a.	Service on first 29 km of line expected to start in 1990.
Newark, NJ	2.0 million	4.3 (6.9 km)	11	4'-8 1/2" (1435 mm)	100 ARA-B (50 kg/m)	600v. dc, Overhead	St. Louis Car	Max. gradient of 6%; min. curve radius of 12m; proposal for a 6 km extension of system.
New Orleans, LA	558,000	13.0 (21.0 km)	n.a.	5'-2 2/5" (1586 mm)	n.a.	600v. dc, Overhead	Perley Thomas Car Co.	The last remaining U.S. tram line to run traditional (1923) cars; a designated national monument.

Table 2. Design Characteristics of Urban Light Rail Transit Systems in the U.S. (con't)

Urban Area	Population of Service Area	Route Miles (Kilometers)	Number Stations or Stops	Rail Gage feet-inches (millimeters)	Rail Weight & Type (kg/m)	Electrification	Vehicle Suppliers	Remarks
Philadelphia, PA	4.0 million	98.2 (158.0 km)	n.a.	5'-2 1/4" (1581 mm)	100 ASCE (49.6 kg/m)	600v. dc, Overhead	Kawasaki	Max. gradient of 5%; min. curve radius 22.5 m; 12 lines with 286 cars.
Pittsburgh, PA	2.5 million	26.1 (42.0 km)	n.a.	5'-2 1/5" (1580 mm)	115 RE (57.5 kg/m)	600v. dc, Overhead	Siemens/Duewag Rebuilt PCC Cars	--------
*Portland, OR	400,000	14.9 (24.0 km)	25	4'-8 1/2" (1435 mm)	n.a.	750v. dc, Overhead	Bombardier	December 1984 delivery of 26 articulated tramcars; scheduled opening in July 1986; max. grade of 7%.
*Sacramento, CA	780,000	18.2 (29.3 km)	27	4'-8 1/2" (1435 mm)	n.a.	750v. dc, Overhead	Siemens/Duewag	Six-axle cars (26) scheduled for 1985 delivery.
San Diego, CA	900,000	15.9 (25.6 km)	18	4'-8 1/2" (1435 mm)	n.a.	600v. dc, Overhead	Siemens/Duewag	An additional 27.7 km extension in progress; initial opening in 1981.
San Francisco, CA	2.5 million	24.2 (39.0 km)	n.a.	4'-8 1/2" (1435 mm)	n.a.	600v. dc, Overhead	Boeing Vertol	Conventional tramway upgraded to LRT standards in 1981.
*San Jose, CA	1.3 million	19.9 (32.0 km)	34	4'-8 1/2" (1435 mm)	n.a.	n.a.	UTDC	Construction started in 1984 with revenue service scheduled for 1987; Canada's UTDC six-axle articulated cars scheduled for 1986 delivery.
Seattle, WA	1.3 million	1.6 (2.6 km)	7	4'-8 1/2" (1435 mm)	n.a.	600v. dc, Overhead	Duewag	Three tramcars acquired from Melbourne to serve the water front area as a tourist attraction; plans call for a 0.6 km extension with the addition of one or two more cars.

*Note: Systems under construction or authorized (systems only in the planning stage not included).

Source: Jane's Urban Transport Systems, 4th ed., Jane's Publishing Inc., NY, NY, 1985, pp 3-290.

Table 3. Operating Parameters for Light Rail Transit in the U.S. (1982 Data)

Parameter:	Range		Average:
	Minimum:	Maximum:	
Vehicle Operating Cost			
Per Total Hour	$ 40.	$ 224.	$ 94.
Per Revenue Hour	$ 40.	$ 224.	$ 94.
Per Revenue Mile	$ 3.	$ 15.	$ 7.
Per Employee	$27,287.	$54,224.	$40,795.
Personnel Per 1,000 Total Vehicle Hours			
All	1.08	4.14	2.42
Operators	0.35	1.63	0.87
Injury Accidents			
Per Million Car Miles	NA	NA	89.52
Per Million Passengers	NA	NA	10.85
Fatal Accidents			
Per Million Car Miles	NA	NA	0.31
Per Million Passengers	NA	NA	0.04

Source: Reference (24), pp. 18-21, 43

2.3 Heavy Rail Transit

Heavy rail transit (HRT) is sometimes referred to as rapid rail transit (RRT), conventional rail, subway, or metro (16). HRT is a system designed to move large numbers of passengers on relatively long trains over an exclusive, grade separated right-of-way. High-level station platforms and varying degrees of automation characterize HRT systems (13). Features typical of HRT include (16, 21):

- Dual guideways (tracks) located on fully grade-separated rights-of-way.
- Third-rail electric power distribution.
- Dual-directional vehicles operated in coupled (or "married") pairs.
- High-level passenger loading platforms at on-line stations.

Design characteristics of nine HRT systems in the United States are shown in Table 4 (23). Operating parameters representative of HRT systems are presented in Table 5 (24).

2.4 Commuter Rail Transit

Commuter rail transit (CRT), also known as suburban (21) or regional rail, is operated by public transit agencies or by private railroad companies along shared, multiple track rail rights-of-way. The use of existing railroad right-of-way for urban transit is a common practice with CRT services and is increasing in popularity (17). Most CRT systems operate over a number of railroad lines radiating from the central business district to suburban stations and are intended to serve the long distance, suburb-to-CBD commute trips (16). Characteristics of CRT include (16, 17, 21):

- Rolling stock dimensions and design compatible with mainline railroad standards.
- Trains typically propelled by diesel-electric locomotives.
- Track and right-of-way shared with intercity passenger service and/or freight train operation.

Table 4. Design Characteristics of Urban Rapid (Metro) Rail Transit Systems in the U.S.

Urban Area	Population of Service Area	Route Miles (Kilometers)	Number Stations	Rail Gage feet-inches (millimeters)	Rail Weight & Type (kg/m)	Electrification	Vehicle Suppliers	Remarks
Atlanta, GA	1.3 million	24.9 (40 km)	25	4'-8 1/2" (1435 mm)	119 RE (52.12 kg/m)	750v. dc, Third Rail	Franco-Belge C. Itoh/Hitachi	First line opened in 1979; max. gradient 3%; min. radius of 230 m.
Baltimore, MD	800,000	8.0 (12.8 km)	9	4'-8 1/2" (1435 mm)	115 RE (57.5 kg/m)	700v. dc, Third Rail	Budd	Metro line opened in late 1983; max. gradient 4%.
*Boston, MA	2.6 million	40.0 (64.3 km)	62	4'-8 1/2" (1435 mm)	80 ASCE 90 ARA-B 136 RE	600v. dc, Third Rail and Catenary	Pullman Standard Hawker Siddeley UTDC	Metro comprises 58% of rail system mileage.
*Cleveland, OH	1.6 million	19.0 (30.6 km)	18	4'-8 1/2" (1435 mm)	90 ARA-A (45 kg/m)	600v. dc, Overhead	St. Louis Car Pullman	Metro comprises 59% of rail system mileage.
Miami, FL	1.7 million	15.5 (25 km)	15	4'-8 1/2" (1435 mm)	n.a.	700v. dc, Third Rail	Budd	Initial section opened in 1984.
*Newark, NJ	2.0 million	13.8 (22.2 km)	13	4'-8 1/2" (1435 mm)	120 #/yd (60 kg/m)	650v. dc, Third Rail	St. Louis Car Hawker Siddeley Kawasaki	Metro operated by PATH to/from New York; max. gradient 4.8%; min. curve radius 27.4 m.
*Philadelphia, PA	4.0 million	24.0 (38.7 km)	62	4'-8 1/2" (1435 mm)	100 #/yd (49.6 kg/m)	625v. dc, Third Rail	Budd Kawasaki	Max. gradient 5%; min. curve radius 32 m.
*San Francisco, CA	2.5 million	71.5 (115 km)	34	5'-6" (1676 mm)	n.a.	1000v. dc, Third Rail	Rohr Industries	Max. gradient 4%; min. curve radius 120 m.
Washington, DC	3.0 million	60.1 (96.7 km)	60	4'-8 1/2" (1435 mm)	105 #/yd (52.16 kg/m)	750v. dc, Third Rail	Rohr Industries Breda	Max. gradient 4%, min. curve radius 198 m.

*Note: Urban areas with both Metro Rail and Light Rail Systems.

Source: Jane's Urban Transport Systems, 4th ed., Jane's Publishing Inc., NY, NY, 1985, pp. 3-290.

Table 5. Operating Parameters for Heavy Rail Transit in the U.S.

Parameter:	Range		Average:
	Minimum:	Maximum:	
Vehicle Operating Cost			
Per Total Hour	$ 77.	$ 114.	$ 94.
Per Revenue Hour	$ 80.	$ 114.	$ 98.
Per Revenue Mile	$ 3.	$ 6.	$ 5.
Per Employee	$30,979.	$61,015.	$43,610.
Personnel Per 1,000 Total Vehicle Hours			
All	1.85	2.62	2.19
Operators	0.21	1.01	0.42
Injury Accidents			
Per Million Car Miles	NA	NA	4.72
Per Million Passengers	NA	NA	1.26
Fatal Accidents			
Per Million Car Miles	NA	NA	0.12
Per Million Passengers	NA	NA	0.03

Source: Reference (24), pp. 11-14, 41

Note: Cost and Labor Data for 1982; Accident Data for 1983.

- Passenger boarding/alighting is predominately from low-level station platforms.
- Central city stations are frequently combined with intercity (AMTRAK) rail and other urban transit services.

Although most CRT systems utilize diesel-electric locomotives for propulsion, some routes in the United States systems (Chicago, New York, Philadelphia and Washington, D.C.) (16) and, more commonly, systems in other countries (25,26, 27) use an overhead power supply for electric locomotives. Examples of CRT are found in the following urban areas (16, 17, 28):

Boston
Chicago
Detroit
Dover (DE)
Los Angeles
New York
Newark
Philadelphia
Pittsburgh
San Diego
San Francisco
San Jose
Washington, D.C.

2.5 Automated Guideway Transit

Automated guideway transit (AGT), also known as light guideway transit or peoplemover, is designed to move small groups of passengers in small automated vehicles without an on-board attendant (13). Compared to other fixed guideway transit modes, AGT is relatively new with only limited, specialized applications to date (16). Characteristics of AGT systems are generally defined by (16, 29):

- A class of transportation in which driveless vehicles are operated on fixed guideways along exclusive rights-of-way.
- All vehicle functions (e.g., speed, braking, station stops, doors, headways) are fully automated and continuously monitored from a remote location.
- Stations may be either on-line or off-line and provide high-level passenger platforms.

- Full automation allows short headways throughout the day with no additional labor cost.
- Trains can be easily placed into or taken out of service in response to prevailing conditions.
- The fully automated and futuristic image are attractive to the public.
- Alignment geometry (i.e., radii, gradients, cross-sectional profiles) and axle loadings are similar to other rail transit systems.

AGT systems are designed to serve specialized, medium-capacity transit lines and, in a sense, may compete with the light rail transit market (29). Currently, 18 AGT systems are in operation in the United States with five additional systems under construction in Jacksonville, Orlando, Las Vegas, Tampa and Chicago (16). The characteristics of operational AGT systems are presented in Table 6.

2.6 High Speed Rail Transit

High speed rail (HSR) transit is an emerging passenger service intended for intercity travel between major urban areas located between 200 to 300 miles apart (19, 27, 30, 31). The definition of HSR varies and depends upon the responsible agency (i.e., AMTRAK) and upon the technology under consideration. AMTRAK defines HSR in the 80 to 120 mph range whereas others (19, 31) are considering rail technologies in the 150 to 300 mph range. The Federal Railroad Administration (FRA) prescribes track standards, based upon varying passenger train speeds, up to a maximum of 110 mph. The FRA design criteria for six classes of railroad track are presented in Table 7 (32). HSR systems exceeding 110 mph maximum speeds are in the planning stages and, as of yet, do not have prescribed FRA track standards (19). If HSR systems are implemented between major urban areas, comprehensive and coordinated planning must be undertaken by all involved state and local agencies due to the potential impacts upon the other transit modes within the affected urban areas.

Table 6. Characteristics of Selected Automated Guideway Transit Systems

System/Location:	System Configuration:	Guideway Location:	Guideway Length (miles):	Number of Stations:	Number of Vehicles:	Vehicle Capacity:	Year Opened:
Airtrans - Dallas-Fort Worth Airport Arlington, Texas	single-lane multi-loops	elevated/ at-grade	12.80	14	52	40	1974
Atlanta Hartsfield Int'l Airport Atlanta, GA	dual-lane shuttle with by-pass	underground	2.09	10	17	40	1980
Busch Gardens (Recreation Center) Williamsburg, Va	single-lane loop	elevated/ at-grade	1.33	2	1 (2-car train)	192	1975
Detroit Downtown Peoplemover Detroit, MI	single-lane CBD collection and distribution	elevated	2.92	13	13	NA	1986
Disney World (Amusement Park) Orlando, FL	single-lane loop	elevated	0.87	1	30 (5-car train)	20	1975
Duke University Medical Center Durham, NC	double-lane & single-lane shuttle	elevated/ at-grade/ underground	0.34	3	4	22	1980
Fairlane Town (Shopping) Center Dearborn, MI	single-lane shuttle with by-pass	elevated	0.49	2	2	24	1976
Houston Intercontinental Airport Houston, Texas	single-lane loop	underground	1.48	9	6 (3 car train)	36	1981
King's Dominion Amusement Park Doswell, VA	single-lane loop	elevated/ at-grade	2.06	1	6 (9-car train)	96	1975

Table 6. Characteristics of Selected Automated Guideway Transit Systems (con't)

Miami International Airport Miami, FL	dual-lane shuttle	elevated	0.26	2	2 (3-car train)	297	1980
Miami (Downtown) Metromover Miami, FL	dual-lane loop	elevated	1.90	10	12	147	1985
Miami Zoo Miami, FL	single-lane loop	elevated/ at-grade	1.97	4	3 (10-car train)	149	1982
Minnesota Zoological Garden Apple Valley, MN	single-lane loop	elevated/ at-grade	1.25	1	3 (6-car train)	94	1979
Morgantown People Mover System WV Univ., Morgantown, WV	dual-lane shuttle with off line stations	elevated/ at-grade	4.30	5	73	20	1975
Orlando International Airport Orlando, FL	2 dual-lane shuttles	elevated	0.74	4	4 (2-car train)	200	1981
Pearlridge Shopping Center Aiea, HI	single-lane shuttle	elevated	0.23	2	1 (4-car train)	64	1977
Seattle-Tacoma Int'l Airport Seattle, WA	2 single-lane loops with shuttle connection	underground	1.71	6	24	102	1973
Tampa International Airport Tampa, FL	4 dual-lane shuttles	elevated	0.68	8	8	100	1971

Source: Reference (16), pp. 92-93.

Table 7. Railroad Track Standards

FRA Track Type:	Maximum Passenger Train Speeds	Tangent Track Gage		Curve Track Gage		Maximum Alignment Deviation		Inspection Frequency[3]
		Minimum	Maximum	Minimum	Maximum	Tangent Track[1]	Curved Track[2]	
Class 1	15 mph	4'-8"	4'-9.75"	4'-8"	4'-9.75"	5.00"	5.00"	Twice Weekly
Class 2	30 mph	4'-8"	4'-9.50"	4'-8"	4'-9.75"	3.00"	3.00"	Twice Weekly
Class 3	60 mph	4'-8"	4'-9.50"	4'-8"	4'-9.75"	1.75"	1.75"	Twice Weekly
Class 4	80 mph	4'-8"	4'-9.25"	4'-8"	4'-9.50"	1.50"	1.50"	Twice Weekly
Class 5	90 mph	4'-8"	4'-9.00"	4'-8"	4'-9.50"	0.75"	0.625"	Twice Weekly
Class 6	110 mph	4'-8"	4'-8.75"	4'-8"	4'-9.00"	0.50"	0.375"	Twice Weekly

Notes: [1] The deviation of the mid-offset from a 62-foot line on the gage side and point (5/8" below top) of the railhead.

[2] The deviation of the mid-ordinate from a 62-foot cord from the gage point (5/8" below top) of the railhead on the outside rail.

[3] Twice weekly inspections required for Class 1, 2, and 3 track that carries passenger trains (otherwise, only weekly inspections required). At least one calender day between inspections required for twice weekly frequency.

Source: The Track Cyclopedia, 9th ed., Simmons Boardman Publishing Corporation, Omaha, Nebraska, 1978, pp. S31-1 to S31-10.

3 RAIL TRANSIT SYSTEM PLANNING AND OPERATIONAL CONSIDERATIONS

3.1 General

Numerous factors interact in the planning analysis and design process for new or expanded rail transit service. Emphasis in the following sections is given to light rail and heavy rail transit system development; however, many of the planning considerations and design elements can be applied to the other system types (i.e., commuter rail, high speed rail). Planning, design and operational elements of light and heavy rail are similar when considering exclusive, grade-separated rights-of-way common to freeway transitways.

The operating characteristics of any rail transit system are a function of the service policies, physical constraints, and vehicle performance capabilities. This section presents factors, data and relationships that are major determinants of a rail system's performance. Basic considerations which influence design decisions are included and cover such topics as route planning, scheduling and control, system capacity, train headways, and operating profiles for different vehicle capabilities on varying alignments.

System performance is determined by planning and design criteria which are influenced, to a large degree, by service philosophies, policy decisions and future expansion needs. The criteria for planning and designing of new rail transit systems must evolve from policy determinations on the type, extent, frequency, duration and nature of the desired transit service (24, 28, 33). These determinations should be agreed to by all involved agencies early in the planning/design process.

Physical and operational limitations are imposed upon a rail system that uses, or attempts to use, railroad rights-of-way (17) and/or highway rights-of-way (19). These limitations may be acceptable in terms of the transit service policies; however, the implications of such limitations should be recognized and clearly understood by the policy makers (33).

System goals, performance objectives and achievement measures depend to a large extent, upon the perceptions of system purpose and the external environment in which it exists. Regional transportation needs vary in form and magnitude. The elements of a multimodal, regionwide transportation system perform different functions and satisfy different needs. A single criterion or set of criteria (18, 24, 28) can not satisfactorily be defined to measure and compare performance of all transportation modes or all elements within a given mode. In the case of a transit system, the high-capacity line haul, feeder, and distribution elements are interdependent; performance measures of one element or function should not be optimized without regard to the total system performance (33).

3.2 Vehicle Operating Profile

The performance capabilities of a particular vehicle determine the time required to serve transit patrons along a given rail line. Figure 1 illustrates the basic relationships that govern the running time between stations: 1) acceleration; 2) deceleration; and, 3) dwell time. Vehicle performance and passenger comfort considerations determine the maximum acceleration and deceleration rates while operating policies and passenger loads set the length of station dwell time (19).

Acceleration and deceleration rates are limited by the wheel-rail adhesion and are influenced by safety considerations, the traction motor, and power demand and consumption. Braking capabilities are usually based on stopping with a crush load of passengers on a level tangent track. Modern transit vehicles typically employ a three-level braking system: 1) electro-dynamic; 2) friction disc; and, 3) magnetic track brakes (33). Figure 2 presents a series of curves for the acceleration of different rail vehicles while Figure 3 shows the braking profiles. Both figures are for level tangent track conditions and show the distances required for starting and stopping based upon a range of top (maximum) speeds.

Horizontal and vertical alignment of the track can have pronounced effects on vehicle acceleration, deceleration and speed-distance

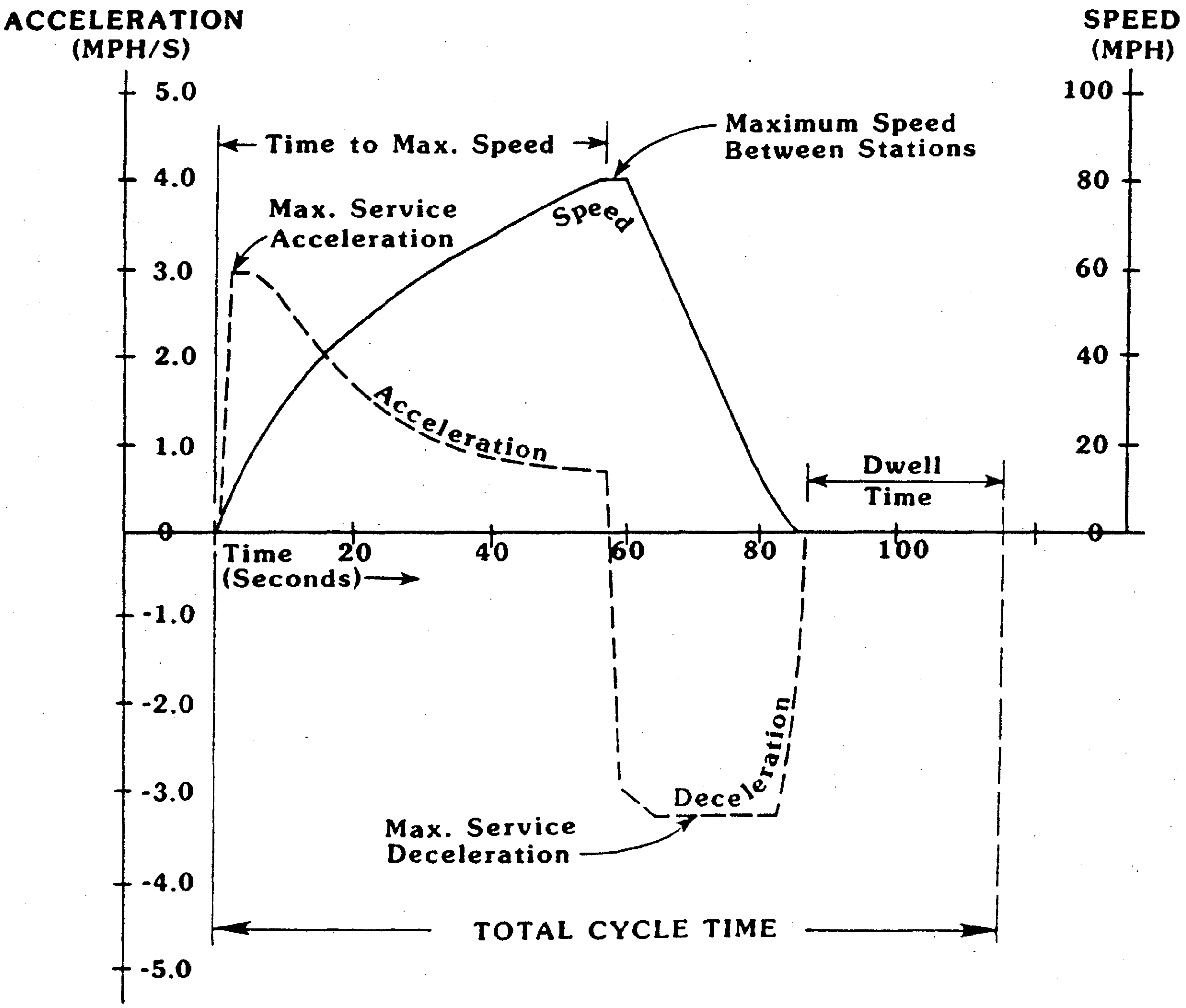
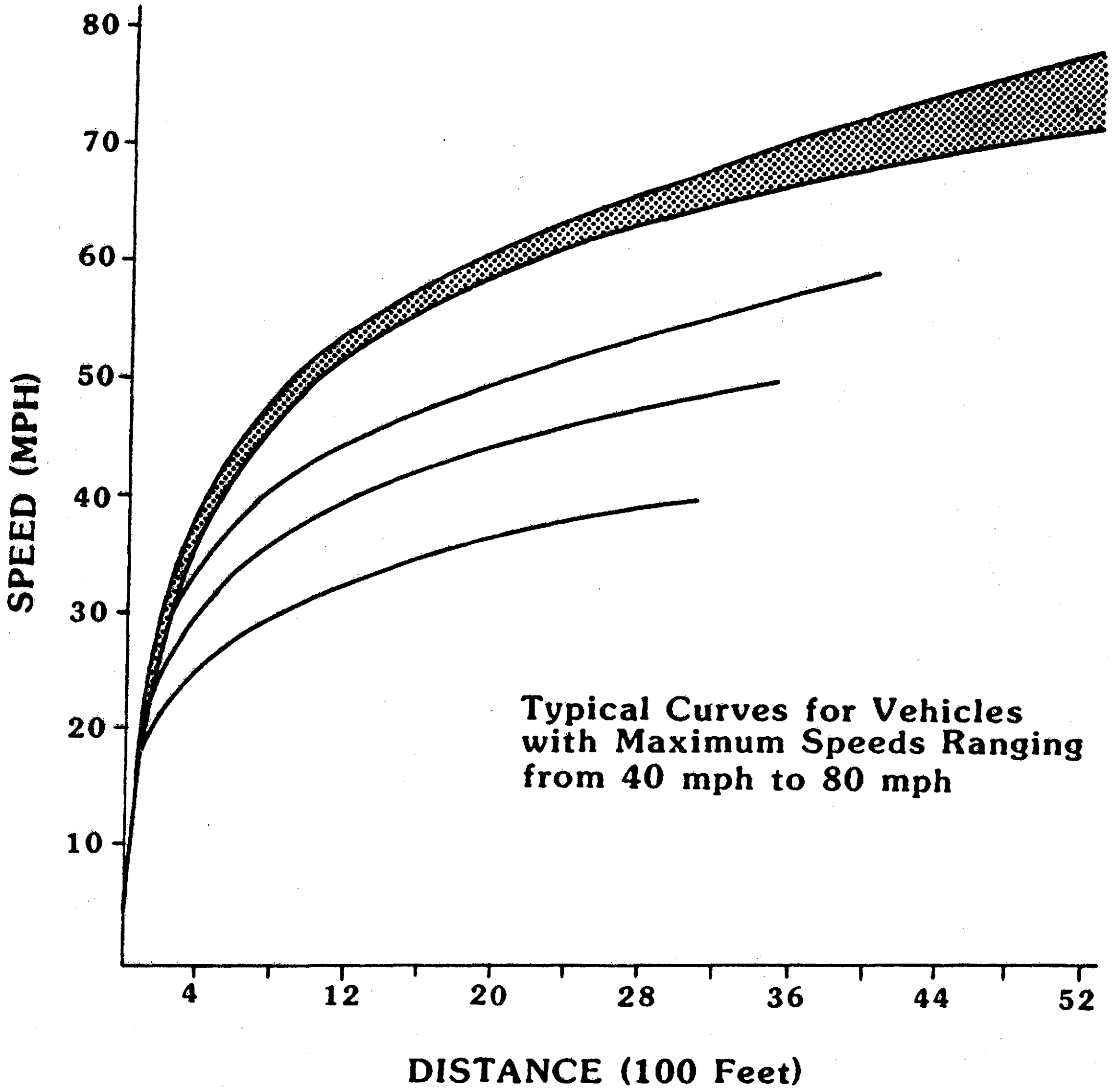


Figure 1. Vehicle Operation Profile Between Transit Stations

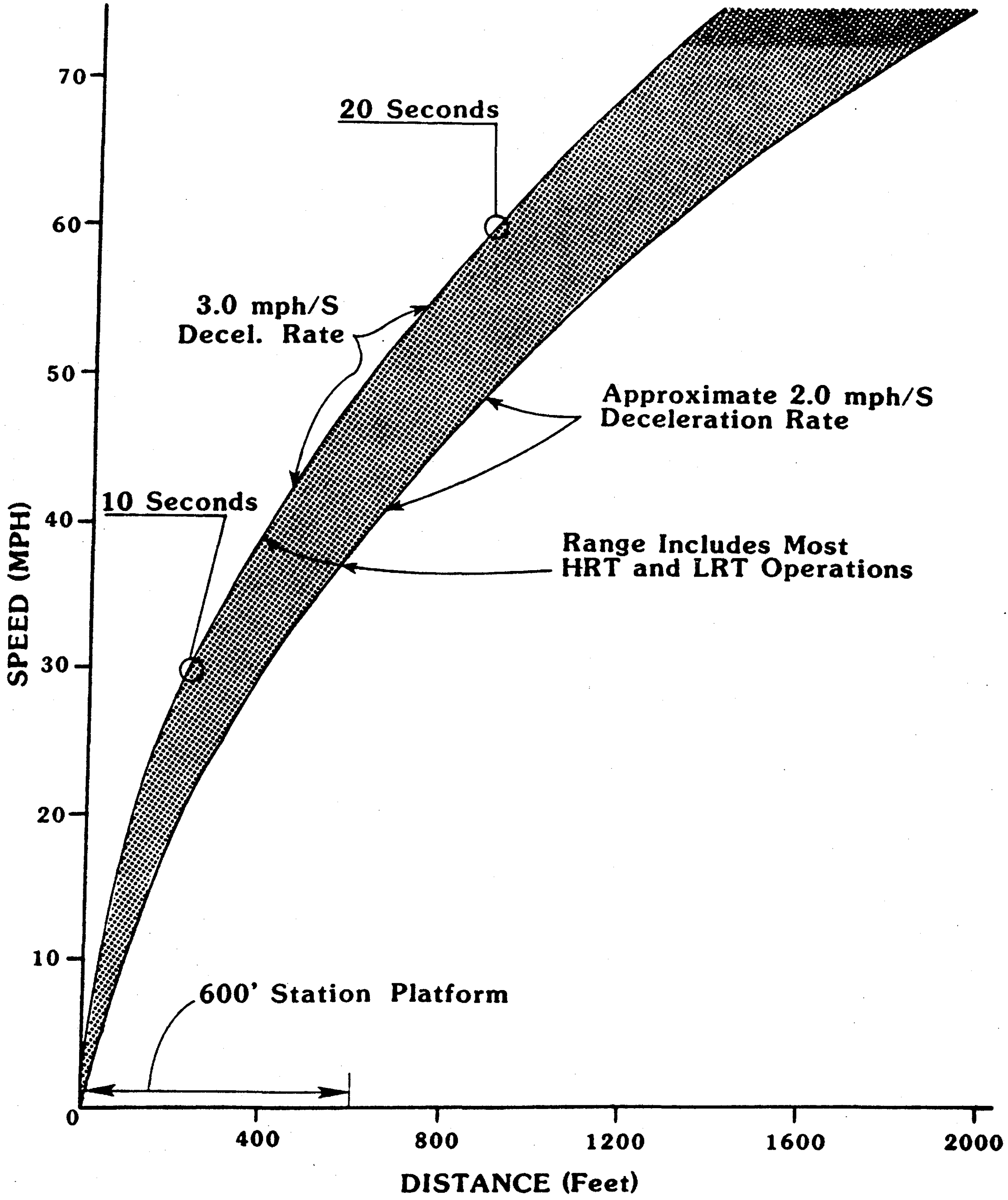
Source: Ref. (33), p. 3-9.27



Note: Acceleration curves representative of HRT and LRT vehicle on level tangent track.

Figure 2. Typical Speed-Distance Curves for Heavy and Light Rail Vehicle Accelerations

Source: Ref. (33), p. 3-9.17



Note: Deceleration curves typical of HRT and LRT vehicle on level tangent track.

Figure 3. Typical Speed-Distance Curves for Heavy and Light Rail Vehicle Decelerations

Source: Ref. (33), p. 3-9.18

relationships. The braking distance for a typical heavy or light rail vehicle on a minus 5% grade is slightly more than twice the distance required on a plus 5% grade as shown in Figure 4. The effects of plus and minus grades on the acceleration capabilities of two representative vehicles, having top speeds of 50 mph and 80 mph, are shown in Figure 5. As illustrated for the 80 mph vehicle, some 4500 feet would be required to reach 55 mph on a plus 4% grade while only a 1000 feet would be required to reach the same speed on a minus 4% grade (33). In this example, the 55 mph speed on a 4% up-grade represents the limit of vehicle performance; the vehicle capabilities are in "balance" with the grade and no further acceleration would occur (33). Horizontal alignment also affects the operating profile along a given track. The horizontal curvature and superelevation considerations are presented within the track design information (Section 4.3).

3.3 System Capacity

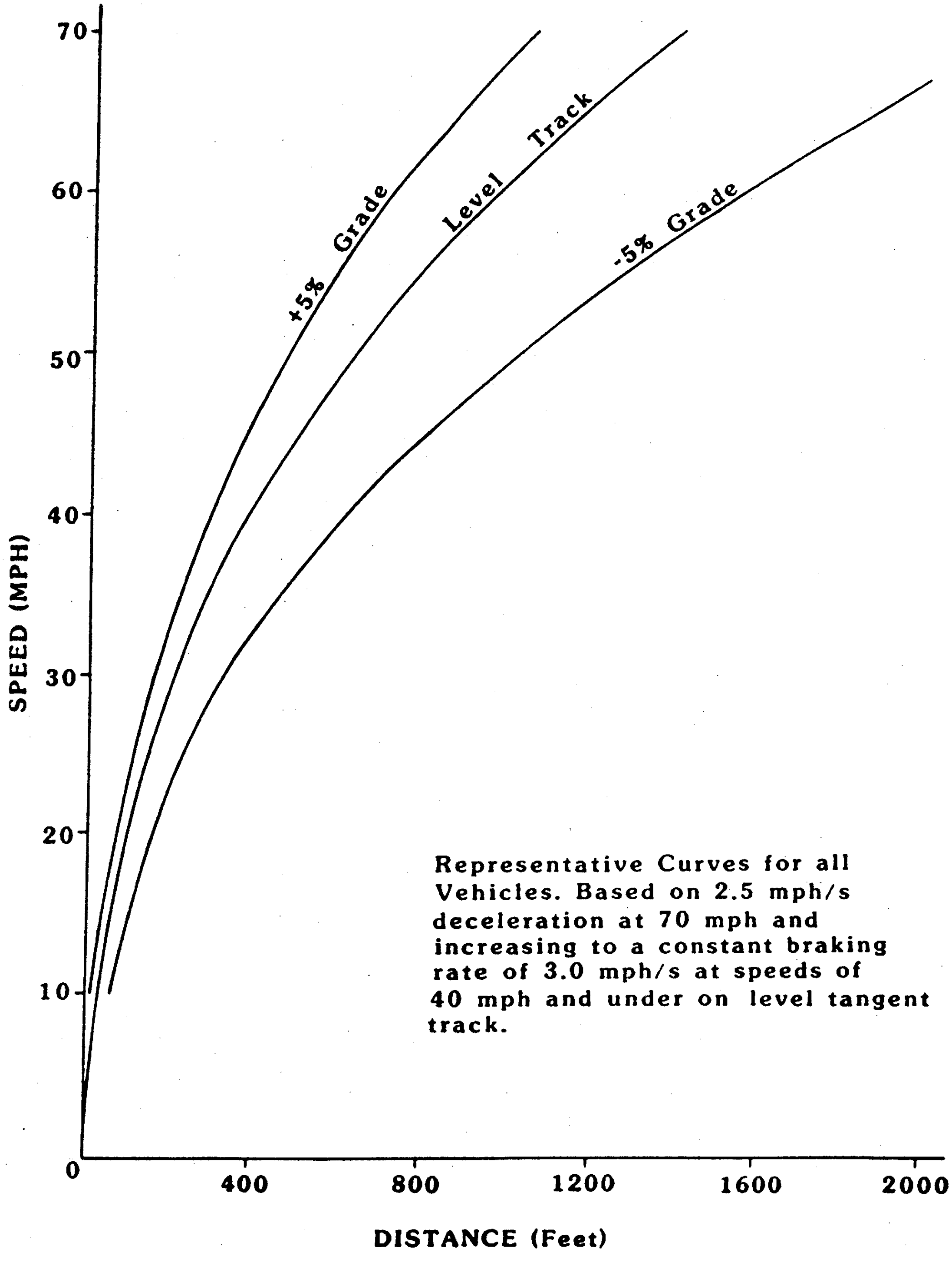
The passenger carrying capacity of rail transit is defined as the maximum number of people that can be moved past a given point per unit of time per track. Capacity may be computed by (33):

$$C = \frac{3600 \quad P}{H}$$

Where:
C = Capacity in passenger per hour
P = Number of passengers per train
H = Headway in seconds

Line capacity of a rail transit system is a complex function involving not simply train headways but the following elements (33):

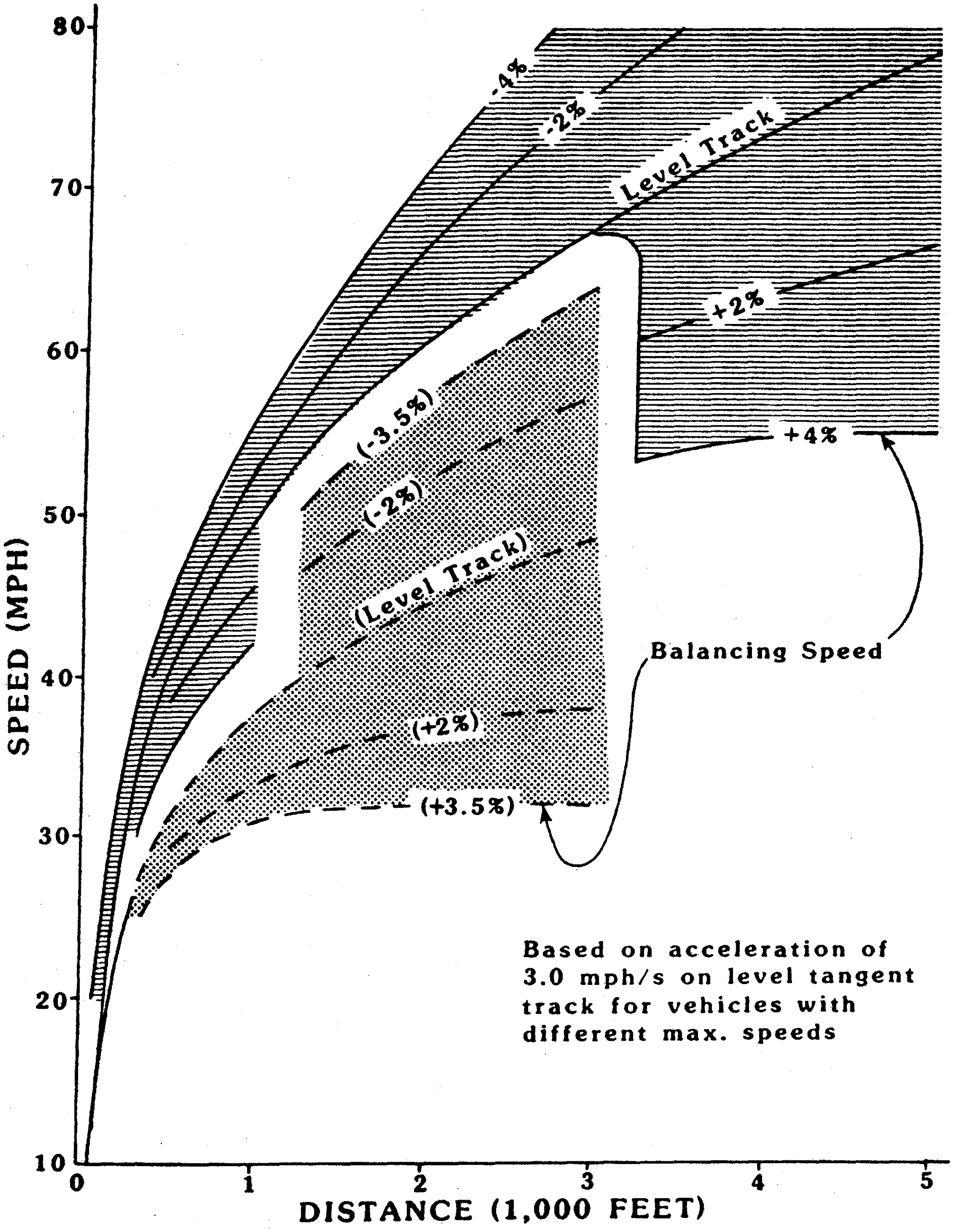
- Vehicle size
- Passengers per vehicle (seated and standing)
- Number of vehicles per train
- Train speed



Representative Curves for all Vehicles. Based on 2.5 mph/s deceleration at 70 mph and increasing to a constant braking rate of 3.0 mph/s at speeds of 40 mph and under on level tangent track.

Figure 4. Effect of Grades on Speed-Distance Relationships for Vehicle Deceleration

Source: Ref. (33), p. 3-9.20



Note: Two representative rail transit vehicles are shown; one vehicle with a maximum speed of 80 mph (upper right) and one vehicle with a maximum speed of 50 mph (center) on level track.

Figure 5. Effect of Grades on Speed-Distance Relationships for Vehicle Acceleration

Source: Ref. (33), p. 3-9.19

- Track curvature and grades
- Acceleration and deceleration rates
- Braking distance
- Frequency of station stops
- Station dwell time
- Right-of-way restrictions
- System reaction time

Similar to highway capacity, maximum rail capacity occurs at a moderate, critical speed. For a given line, the critical speed permits minimum headway and maximum capacity for any given train length; critical speed increases with the length of the train. If speed exceeds the critical value, headways will increase and capacity will decrease. To illustrate, the theoretical critical speed is 40 mph with a 23 second headway for a 500 foot long train running on grade-separated track with no station stops. If a 20 second station stop was provided, critical speed would drop to 25 mph and the headway would increase to 48 seconds (33).

The following equation, based on constant headway, may be used to estimate the approximate number of vehicles needed for a route (line) operation during the peak hour (33):

$$N = \frac{60nTL}{VH}$$

Where:
N = Number of cars required for peak hour
n = Number of cars per train
T = Number of tracks operated at the same headway
L = Length of line in miles
V = Average speed (mph)
H = Headway in minutes

Additional cars need to be provided to account for the idle trains at terminal areas and for the number of "spares" held in reserve at the yard(s).

Headway is defined as the interval of time between successive trains measured from the front end of the first to the front end of the second as they pass a given point. Minimum achievable headways depend upon vehicle speed, braking rates, degree of safety, system response time, train length, station dwell time and right-of-way influences. Station stops are frequently the controlling factor of minimum headways. Station time includes braking, dwell, and acceleration times. The distance (or time) between trains must provide not only for braking distance but also distance for reaction time of the following train and the response time of the signal (control) system. A safety factor of 35% is added to the worst condition for stopping distance within the system (33).

3.4 Stations

3.4.1 General

Passenger facilities are important to any rail transit system and may range in complexity from a "platform" in the street, a simple shelter, up to a regional multimodal transportation center. Despite the facility's relative complexity or function, stations share certain design principles and a common purpose of facilitating passenger access to the transit service. Station design and construction must comply with applicable municipal, county, state and federal regulations, operating policies, and building codes (34). Some general characteristics and station design criteria are presented in this section.

For any type of station, considerable discretion can be exercised when matching appearance, function and amenities to a given site and to the transit operation for providing patron safety, comfort and convenience. Smooth and comfortable transition from mode to mode within an urban network is essential to an integrated transportation system (35). Given the nature of heavy rail transit, stations are completely separated in pedestrian and vehicle functions. Conversely, pedestrian and vehicle flows are not necessarily separated at light rail stations. However, if light rail operates on exclusive rights-of-way, the light rail stations may be very similar in design and function to heavy rail stations.

3.4.2 Location and Frequency

Station frequency involves the balancing of service area access with desirable line-haul operating speed. If trains load to maximum capacity in an outlying residential area with all patrons destined to the central business district (CBD), intermediate station stops are unnecessary; through express or skip-stop service may be more appropriate. Frequent stops in the CBD and other major activity centers minimize passenger concentrations and congestion; the passenger load is discharged (or picked up) in a relatively small area which calls for short interval station spacing.

Station intervals in residential areas are influenced by transit feeder routes, passenger demands, transfer facilities (i.e., park-and-ride lots), as well as safety and security considerations. Light rail transit systems typically have more stops and shorter station intervals (0.2 to 0.4 miles) that do heavy rail systems (0.4 to 1.4 mile intervals) (33). However, these "typical" intervals are based upon system-wide facilities and do not reflect the desirability of more frequent stations in the CBD and residential areas with fewer stations on line-haul, express routes. The express line-haul operation within a retrofitted freeway transitway may necessitate station intervals of several miles in length for either light or heavy rail transit.

3.4.3 Design Considerations

Station facilities are intended to accommodate all passenger types (i.e., young, elderly, physically disabled) in a safe (36), convenient, comfortable and efficient manner. The facility design is a function of the following variables (33):

- Train frequency;
- Type of service;
- Station intervals;
- Climate;
- Method of fare collection; and,
- Compatibility with surrounding area.

Architectural concepts can influence security and patron safety. Stations should provide good visibility to improve security of employees and passengers (36). In addition, the design must consider maintenance activity and cost. Cleaning and repair work of windows, floors, lighting, utilities and equipment under both pedestrian and train traffic will be required; station design should facilitate these activities.

Pedestrian circulation and flow patterns should, as much as possible, be simple, obvious and comfortable. Consideration of the following are important in achieving good pedestrian orientation and circulation (33):

- Avoid unnecessary turns and dead ends.
- Avoid bottlenecks by providing adequate space.
- Generally provide for right-hand flow pattern.
- Avoid cross circulation at fare collection areas and decision points.
- Where feasible, provide separate entrances and exits for the station.
- Locate passageways, stairways, escalators, etc. to encourage balanced train loading and unloading.
- Provide escalators whenever vertical change exceeds 12 feet up, or 24 feet down.
- Provide required ramps, elevators and facilities for the disabled.
- Provide adequate space on platforms for peak crowds (desirably 8 square feet per patron).

The station platform area is a key design element for any rail transit system. Platform size is a function of peak passenger volume, train length, vehicle design, required clearances and pedestrian circulation or flow. Platform length between end railings range from 100 to 300 feet for light rail systems and from 300 to 700 feet for heavy rail systems (33). Light rail systems employ either low-level or high-level platforms. Low-level platforms in the range of 6 to 22 inches require the patron to step-up into the vehicle or to use a suitable handicapped lift. High-level platforms, in the range to 34 to 39 inches, improve vehicle accessibility and provide for faster loading/unloading of passengers. Heavy rail platforms are typically at the vehicle floor height or 1 inch below and range from 39 to 42 inches above the top of rail (33).

Each station site is unique and, if properly designed, provides an efficient link between the rail transit system and other surface transportation modes. This may involve bus platforms, park-and-ride and/or kiss-and-ride facilities, pedestrian access provisions, and special considerations for the elderly and disabled. Fare collection procedures are also a primary determinate of station layout and design. Fare control equipment should be positioned to provide simple, rapid ingress and egress of patrons and includes such items as: 1) fare vending machines; 2) deficit fare collectors; 3) transfer validating machines; 4) agent booths; 5) agent-controlled turnstiles; 6) ticket-operated gates; 7) coin-operated turnstiles; and, 8) exit turnstiles or gates (33).

3.4.4 Parking

Integrated park-and-ride facilities must be a part of station location and design. Coordinated architectural-engineering planning for parking facilities requires consultation with all involved public and private interests and with law enforcement, fire protection and building officials (33, 34). All-day parking, hourly parking, and preferential parking for the disabled and for carpools, vanpools, bicycles, motorcycles and subcompacts should be considered. Priority for station access, in terms of distance from the platform, should be provided in the following order:

1. Disabled or handicapped;
2. Buses;
3. Kiss-and-ride patrons and taxies;
4. Bicycles and motorcycles;
5. Paid hourly (metered) parking;
6. Priority vehicle parking (carpools, vanpools);
7. Other priority vehicles (subcompacts);
8. Long-term, non-priority parking; and
9. Free parking.

Parking facilities intended to support a transit system should follow accepted practices (34) including geometric design of access points and internal circulation, parking space layout, pavements, traffic control devices, lighting and landscaping.

3.5 Service Concepts

3.5.1 Route Planning

A rail transit system may be visualized as a series of independent lines or as a much more complex, integrated network. The "single line (zone) concept" appears appropriate for a high-volume, well defined radial travel corridor. This scheduling concept should improve running time and schedule dependability and also provide benefits through simplifying fares, reducing equipment requirements and utilizing train crews more effectively (33).

The "network concept" is more applicable to a higher density area with a regular (grid) street pattern. In the concept, the patron is offered a wide variety of destinations via a single route or by transferring between routes. A 0.5-mile grid utilizing a combination of transit modes (i.e., commuter rail, light rail, bus) could, with close scheduling, theoretically offer service between any two locations with no more than one transfer and minimal travel time (33).

A third approach in routing and service provision is quickly gaining popularity and is known as the "timed-tranfer concept". Successfully used in U.S. and Canadian cities, this approach reduces transfer waiting times and improves regional mobility. Radial transit routes are connected by crosstown routes at the timed-transfer centers in a cobweb type of pattern. Limiting the number of nodes or transfer centers and the length of routes along with controlling the scheduling are key elements of successful operation (33).

3.5.2 Scheduling and Control

The physical nature of the route and vehicle or train operating characteristics determine the running time. The overall round-trip time includes the running time, dwell time at stations, and any layover or turn-around time at the route ends. Service frequency (headways) during peak demand periods is usually based upon the number of passengers at the maximum load point. Headways during off-peak periods (mid-day or night) are frequently a policy determination of the system. Control systems (8, 37, 38) are important design elements in maintaining schedules and headways safely and effectively (33).

4 RAIL TRANSIT DESIGN GUIDELINES

4.1 General

A need was perceived in the early 1970's by the Urban Mass Transportation Administration (UMTA) to develop a successor to the Presidential Conference Committee (PCC) car while decreasing the unit cost of new light rail vehicles (39). Through a cooperative effort involving UMTA, vehicle manufacturers, consultants, equipment supplies and transit agencies, this need was translated into the "Standard Light Rail Vehicle (SLRV) Specification" (40). The Specification, published in October 1972, was first used in November 1972 by the Massachusetts Bay Transportation Authority (MBTA) and the San Francisco Municipal Railway (SFMR or MUNI) Improvement Corporation in a joint bid advertisement for 230 new light rail cars (39). Subsequent work by McGean, et. al. (41), sponsored by UMTA in 1979, identified 20 areas of the SLRV Specification which could be relaxed or modified in order to realize further vehicle cost reductions.

The SLRV specification guidelines (39, 40, 41) along with vehicle procurement criteria developed by others (25, 33, 42, 43 , 44 , 45, 46, 47, 48, 49, 50) provide the general framework for this section. Typical vehicles and design values contained herein are appropriate for preliminary studies and evaluations. Final system design, however, should use specific data (51) on dimensions, weights and operating characteristics of the selected vehicles for a particular transit system (33).

4.2 Rail Vehicle Design Guidelines

4.2.1 General

The dimensions and characteristics outlined herein are intended to aid in preliminary studies and evaluation (33). Information presented is representative of vehicles currently in operation and generally available from manufactures. As advances are made in rail system development, the given dimensions and characteristics should be reviewed and revised as necessary (44). Table 8 presents vehicle features and typical values which provide a basis for the discussions in the following subsections.

4.2.2 Physical Characteristics

Dimensions - Vehicle dimensions vary between manufactures and for different systems (51). Figure 6 shows two examples of light rail vehicles while Figure 7 presents two types of heavy rail vehicles (33). The data shown in Table 8 is not all inclusive. For example, a group of double-articulated light rail vehicles 80 to 90 feet long have been omitted. These cars are less than 8 feet wide, have less passenger capacity and only appear suitable for special limited situations (33).

Width selection is primarily influenced by external clearances and cost, balanced with the desire for interior spaciousness and passenger comfort. Axle and wheel positions are rigidly fixed to truck assemblies which have center pivots. Truck spacing is from pivot point to pivot point while the wheel base is the distance between axles on the truck. Unarticulated vehicles are supported on two trucks while articulated vehicles employ a third, unmotorized truck under the center joint (33).

The 11.5 foot height from rail to roof shown for the light rail vehicle allows for a pantograph in the locked down position. The operating pantograph height is normally 15 to 20 feet above tracklevel and must be considered for vertical clearance requirements. Floor height is important in station platform design and may be influenced by clearance requirements for chopper control, air conditioning, braking components, etc. which are normally placed beneath the car floor (33). Again, it is extremely important for the designer to obtain and use specific data for the vehicle intended for the particular transit system.

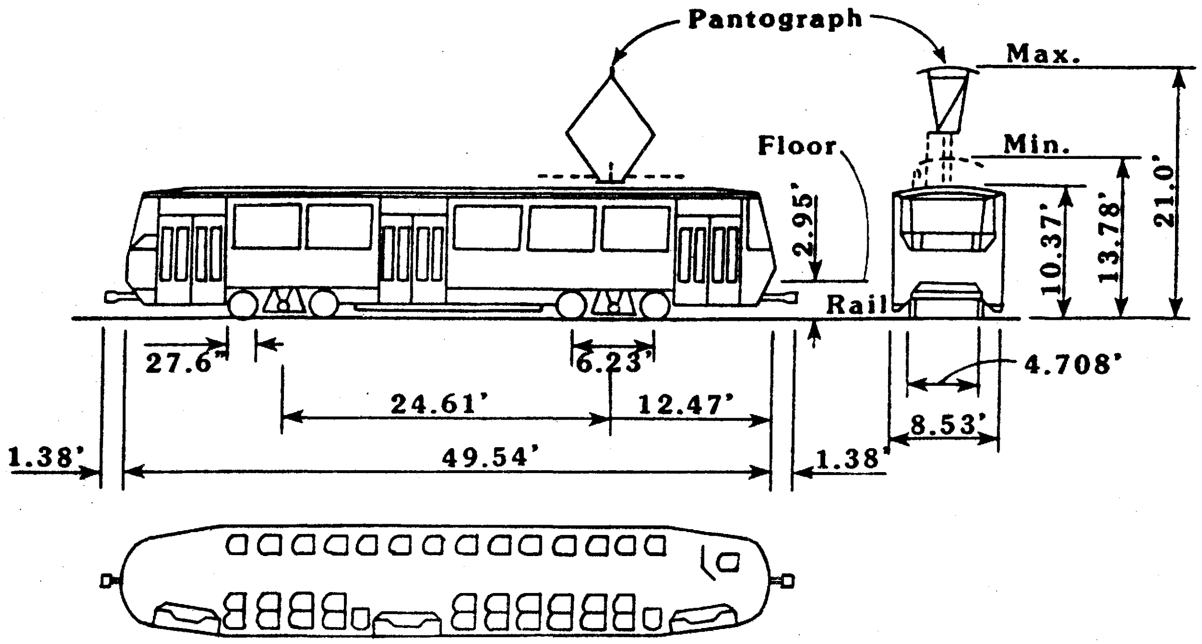
Weight - Suspension and propulsion equipment contribute a large amount to the vehicle weight. The values shown for empty vehicle weights are based upon typical unit weights of 95 to 110 pounds per square foot of vehicle;

Table 8. Typical Light and Heavy Rail Vehicle Characteristics

Characteristic:	Heavy Rail Vehicles:		Light Rail Vehicle:	
	50-ft. Class	70 to 75-ft Class	50-ft Class	70 to 75-ft Class
Dimensions -				
Length Over Couplers	50 ft	75 ft	51 ft	73 ft
Body Length	48.5 ft	73.5 ft	49 ft	71 ft
Body Width	9.33 ft	10.33 ft	8.67 ft	8.67 ft
Truck Spacing	33.5 ft	52.5 ft	24 ft	23.0 ft
End Overhang	7.5 ft	10.5 ft	12.5 ft	12.5 ft
Wheel Base	6.5 ft	7.5 ft	6.0 ft	6.0 ft
Wheel Diameter	28 inches	30 inches	26 inches	26 inches
Height (Rail to Roof)	11.75 ft	11.75 ft	11.5 ft	11.5 ft
Height (Rail to Floor)	44 inches	44 inches	34 inches	34 inches
Height (Rail to Pantograph)	NA	NA	15 ft	15 ft
Performance -				
Maximum Speed	70 mph	75 mph	50 mph	50 mph
Accel/Decel Rates	3.0 mph/sec	3.0 mph/sec	3.0 mph/sec	3.0 mph/sec
Emergency Decel Rate	3.4 mph/sec	3.4 mph/sec	6.7 mph/sec	6.7 mph/sec
Min. Horiz. Turn Radius	90 ft	300 ft	45 ft	45 ft
Min. Vert. Curve Radius	900 ft	2,000 ft	900 ft	500 ft
Maximum Grade	± 4%	± 4%	+ 6%,-8%	+ 6%,-8%
Capacity -				
Number of Seats	50	72	38	52
Standees (Design)	52	111	90	83
Standees (Crush)	100	150	135	160
Total (Crush)	150	222	173	212
Weight -				
Vehicle (Empty)	50,000 lb	72,000 lb	42,000 lb	65,000 lb
Passengers (Crush)	23,000 lb	33,000 lb	26,000 lb	32,000 lb
Vehicle (Gross)	73,000 lb	105,000 lb	68,000 lb	97,000 lb
Electrical -				
Line Voltage	750 VDC	750 VDC	750 VDC	750 VDC
Power Collection	Third-Rail	Third-Rail	Overhead	Overhead
Motor Controls	SSC	SSC	SSC	SSC

NOTES: 1. The 70 to 75-ft Class light rail vehicle is articulated.
2. Standee Design allows 2.7 sq. ft. per person.
3. Standee Crush allows 1.4 sq. ft per person.
4. "SSC" Motor Controls are Solid State Chopper.

Source: Ref (33), p. 3-2.24 and Ref (45), p.3-11, p. 3-28.



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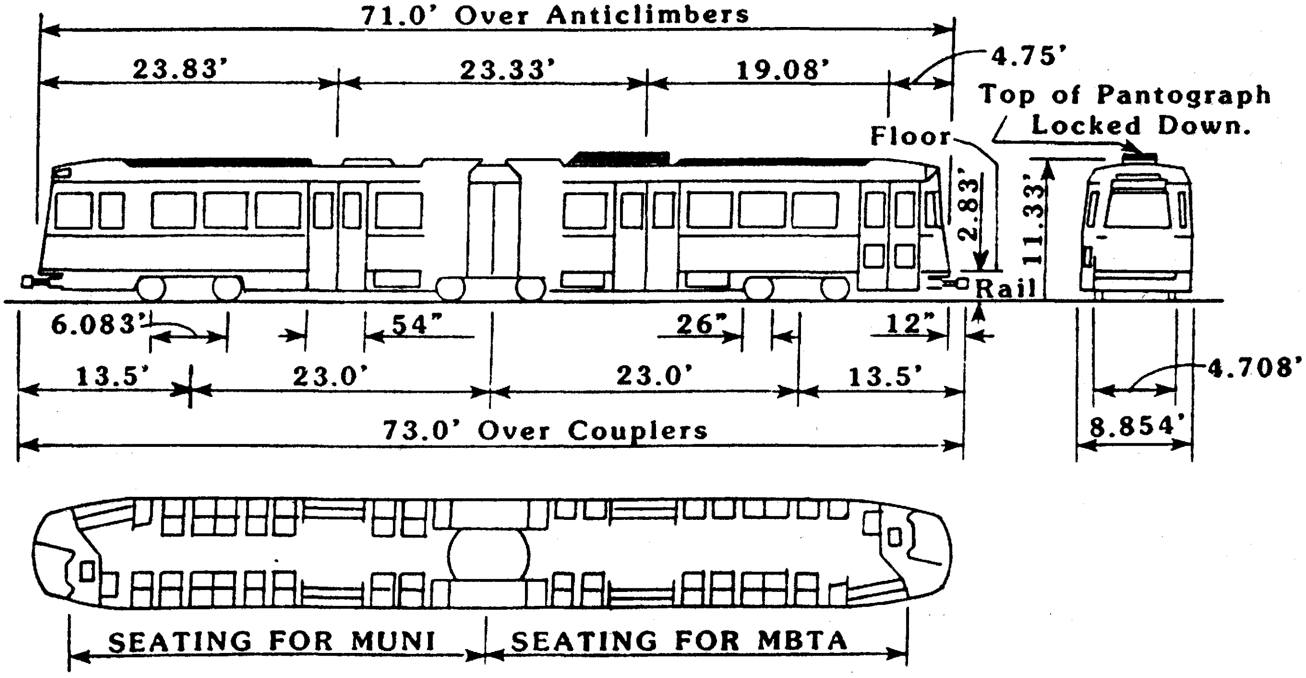

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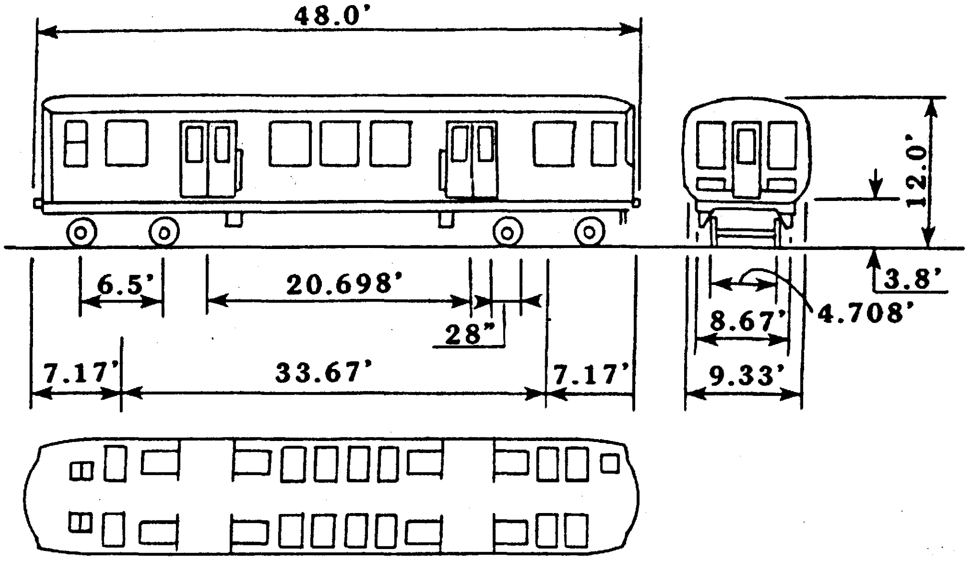
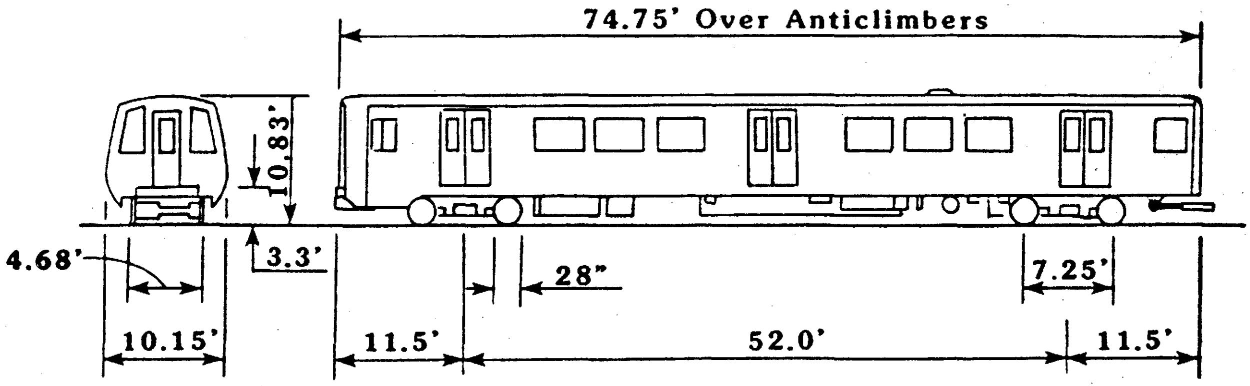
Figure 6. Two Examples of Light Rail Vehicles Dimension

Source: Ref. (33), p. A-4 (3)



CHICAGO BOEING-VERTOL METROCAR



WASHINGTON (ROHR) METRO

Figure 7. Two Examples of Heavy Rail Vehicle Dimensions

Source: Ref. (33), p. A-5 (3)

unit values vary depending upon fabrication material and auxiliary equipment. The passenger weights typically range from 135 to 175 pounds per person; an average weight of 150 pounds per passenger is recommended (33).

The gross vehicle weights in combination with addition design loads (discussed in Section 4.3.3) are used in preliminary design of structures and track systems for the vehicle axle loadings (33).

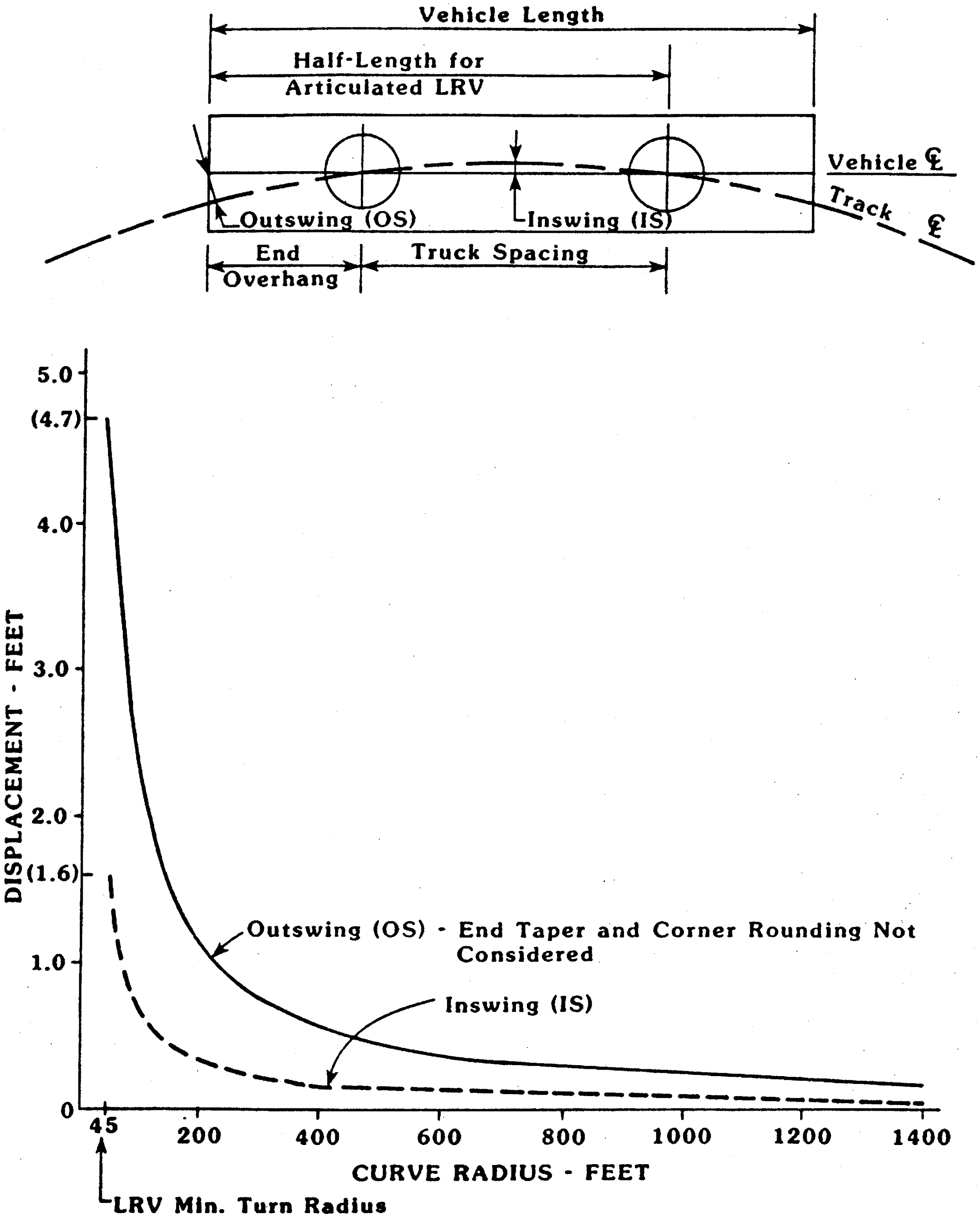
Considerable variation in actual vehicle weight may exist. For an articulated, six-axle vehicle, crush loaded weight may approach 128,000 (45) to 130,000 (44) pounds. Depending upon axle and truck spacings, the worst case loading condition per axle may be 25,000 pounds (44).

4.2.3 Operating Characteristics

Performance - The acceleration/deceleration rates (shown in Table 8) are typical for passenger comfort and, for planning purposes, can be used in preliminary design. Modern rail vehicles are capable of the maximum speeds shown in the table and even more; however, track geometry and operational constraints frequently limit the running speed (33).

Vehicle design characteristics (i.e., truck spacing) govern minimum radii for track curvature. Usually, trains of coupled vehicles have the same turning characteristics as the basic unit comprised of a single vehicle or a married pair. Maximum vertical up-grades are limited by vehicle power, desired performance and wheel-rail traction. Braking capability, influenced by train length and loading, is the principle consideration for down-grades (33).

Figure 8 shows typical vehicle displacement for rail vehicles on curves having 45 to 1400 feet radii. The "inswing" and "outswing" are based upon the vehicle dimensions shown previously in Table 8 (33). Vehicle displacement and impact upon track space are disucssed further in Section 4.3.4 under trackbed design.



Note: Plotted values based upon LRT vehicle classes and dimension shown previously in Table 8.

Figure 8. Typical Rail Vehicle Displacement on Horizontal Curves

Source: Ref. (33), p. 4-3.18

Capacity - Vehicle capacity may be expressed in three ways: 1) design capacity; 2) crush capacity; and, 3) seated capacity. Design capacity is the number of seats plus the number of standees to be accommodated under system operating policies. The crush capacity is the number of seats plus the maximum allowable number of standees; crush capacity results in the maximum gross vehicle weight and should be used in system design calculations. Wide variation exists in the number of seats that can be provided on any given vehicle, depending upon arrangement and door configuration/ placement. Seat numbers, relative to the values shown in Table 8, may vary +10% for heavy rail and +25% for light rail vehicles (33).

4.3 Rail Guideway Design Guidelines

4.3.1 General

This section sets forth basic design criteria for right-of-way, vehicle loads and clearances, trackwork and trackways, and track alignment. The criteria are based on current practices (52) and on proposed standards (33) for new system development. All criteria presented herein are based on the standard U.S. rail gauge of 4 feet-8 1/2 inches (1435mm). All track structures must be designed for the vehicle load and forces plus any system element loads such as electrification, signalization, and communication equipment (6, 53, 54).

4.3.2 Right-of-Way Requirements

The broad spectrum of rights-of-way that are normally used by light rail transit distinguishes it from heavy rail. Typically, rail transit rights-of-way have been classified into three categories (33):

- Category A - exclusive, fully controlled with grade separation of vehicular and pedestrian traffic (all heavy rail systems and some portions of light rail systems).

- Category B - semi-exclusive, partially controlled rights-of-way separated from other traffic except at-grade crossings (typical of light rail systems).

- Category C - a non-exclusive, shared right-of-way condition (typical of street cars, trolley buses and other buses operating in mixed-flow with automobiles).

Light rail transit systems are characteristically of Category B operation but may employ segments of all three categories. Where Category A rights-of-way are used, light rail transit operation is essentially the same, in terms of vehicle speed and service, as heavy rail operation.

The use of existing rights-of-way for implementation of rail transit is attractive when cost, acquisition time and community disruption are considered (33). Utilization of abandoned railroad right-of-way may be the least costly alternative for rail transit. The sharing of lightly used freight trackage, however, poses institutional, jurisdictional and operational problems (17, 33, 55).

Considerable interest has been expressed in combining rail transit with existing freeways; however, the advantage of such joint use is significantly diminished if the trackbed can not be constructed at essentially the same elevation (or profile) as the freeway alignment (19, 30, 33). A double-trackbed light rail installation requires an absolute minimum of 3 feet of lateral clearance plus twice the width of the transit vehicle; if the light rail vehicle were assumed to be 8 feet wide, the absolute minimum clear width (on a tangent segment of track) would be 19 feet. This width, however, does not provide allowance for the following elements (33):

- Parallel walkways;
- Barriers and shoulders;
- Passenger islands, platforms, shelters or structures;
- Stairways, escalators and elevators;
- Bridge supports and other freeway structures;

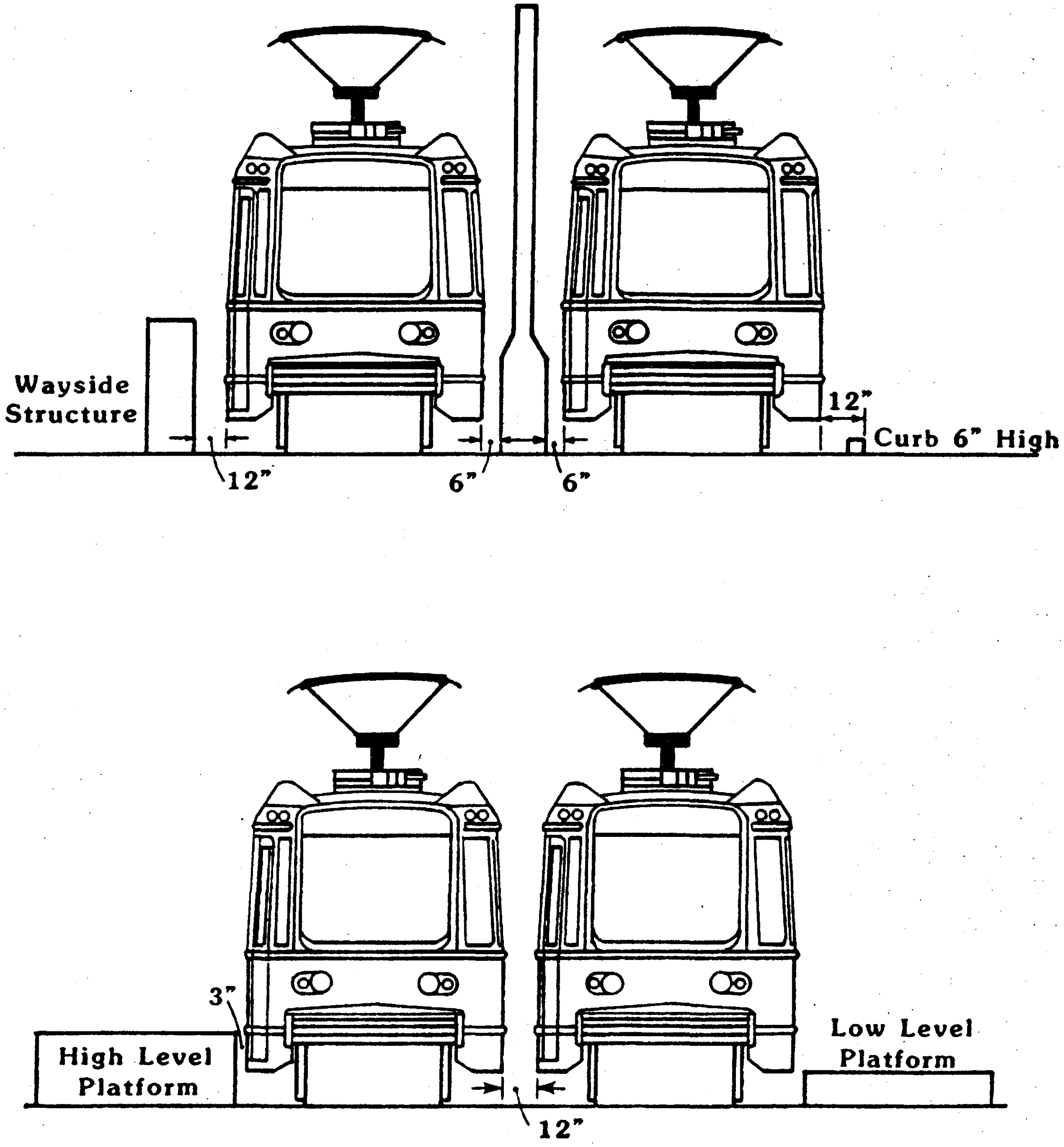
- Transit vehicle overhang on curves; and/or,
- Spiral offsets to circular freeway curvature.

These elements tend to be cumulative and serve to increase the lateral clear width necessary to accommodate a double-track rail transit system. If walkways (2 feet in width) were provided on both sides of the track, a clear width of some 21 to 25 feet for light rail and 25 to 28 feet for heavy rail would be required (33).

When utilizing existing travel corridors for rail transit, other factors such as the following must be considered (17, 19, 30, 33):

- Accessibility for construction and maintenance;
- Accessibility for users;
- Compatibility of joint usage; and,
- Alternative utilization of right-of-way

The right-of-way must provide sufficient space to construct, maintain, operate and protect all aspects of the system. During construction, work areas require temporary barricades and/or fencing to protect pedestrians and vehicles. Category A rights-of-way are designed to prohibit access by non-transit vehicles and pedestrians except at access points (i.e., stations, parking areas). Temporary easements may be required for rail system construction; the need will be determined by construction sequencing, topography, drainage, utilities, service roads, structures, slide slopes and/or retaining walls, adjacent properties, and the ultimate system design (33). The ultimate design may accommodate either single or double-track operation, with or without on-line stations. The required right-of-way envelope will be established by the design vehicle and defined by the vertical and horizontal planes. Figure 9 illustrates the minimum lateral clearances, based upon design vehicle width, for typical light rail system conditions. Table 9 presents lateral clearance dimensions for use in assessing the adequacy of right-of-way.



Note: Low level platform may extend beneath a LRT vehicle provided the minimum horizontal and vertical clearances for the given vehicle are maintained.

Figure 9. Minimum Lateral Clearances for Various Light Rail Transit Conditions

Source: Ref. (33), p. A-11 (9)

Table 9. Minimum Right-of-Way Widths for Light Rail Transit Vehicles

Vehicle Width:	Single Track:	Double Track:
7'-0"	9'-0"	17'-0"
7'-4"	9'-4"	17'-8"
7'-8"	9'-8"	18'-4"
8'-0"	10'-0"	19'-0"
8'-4	10'-4"	19'-8"
8'-8"	10'-8"	20'-4"
9'-0"	11'-0"	21'-0"

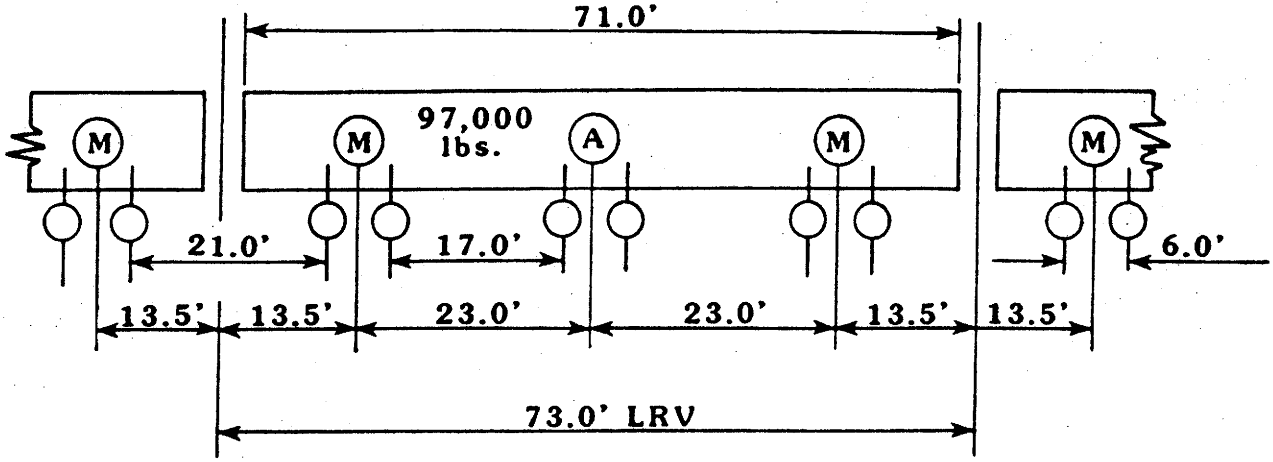
Notes:

1. Minimum widths shown are for tangent track sections without superelevation.
2. All minimum widths provide for 12 inches of lateral clearance between rail vehicle(s) and structures; for double track, clearances also provide 12 inches between vehicles.
3. Vehicle widths, ranging from 7 feet to 9 feet in 4 inch increments, are intended to represent the variety of designs available.
4. Additional width will be required for poles, barriers, stations, spirals and/or curves.

4.3.3 Design Loads

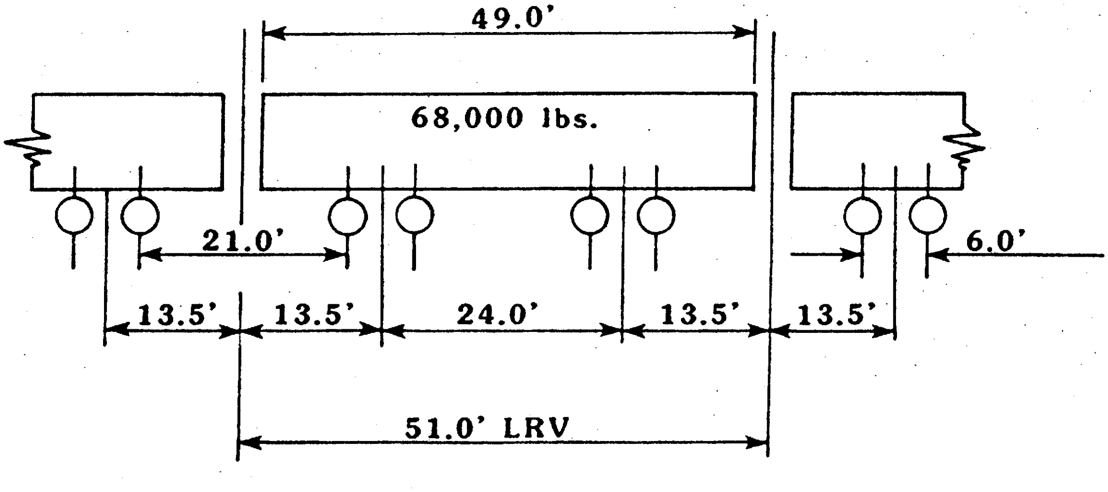
Axle and Wheel - All transit structures are designed to sustain the maximum dead loads (DL), live loads (LL), and any other loads which might be encountered (i.e, erection loads occurring during construction). Vehicles or trains are placed on one or more tracks to produce maximum stress conditions for structural design. Figure 10 shows axle loads and spacings for the design vehicles previously defined (Section 4.2.2). The designer must determine or verify the vehicle type, spacing and arrangement producing the most critical conditions for axial, bending, shearing and torsional stresses, deflections, and stability (6).

For rail mountings placed directly on the pavement slab (56, 57) wheel loads may be assumed (33) to be uniformly distributed over 3 feet of rail longitudinally and a transverse width of 14 inches centered on rail as shown in Table 10.



DESIGN LOADS: Vehicle (Empty)-------65,000lbs.
Passengers ----------32,000lbs.
Total Vehicle Load --97,000lbs.

AXLE LOADS: Motorized Trucks Ⓜ---18,350lbs.
Center Truck (Artic. Joint) Ⓐ--11,800lbs.



DESIGN LOADS: Vehicle (Empty)------ 42,000lbs.
Passengers ------------ 26,000lbs.
Total Vehicle Load--- 68,000lbs.

AXLE LOADS (All Axles)-----------------17,000lbs.

Figure 10. Axle Loads for Standard Light Rail Vehicles

Source: Ref. (33), p. 4-2.5

Table 10. Distribution of Wheel Loads

Rail Placement:	Assumed Distances	
	Longitudinally	Traverse
On Slab	3 feet	14 inches
On Open Deck	4 feet or 3 ties	No
On Ballasted Deck	3 feet plus[1]	Tie length plus[2]

Note: 1. Plus twice ballast depth below tie and twice effective depth of slab (not to exceed axle spacing).

2. Plus ballast depth below tie (not to exceed base width of ballast).

On open deck structures, wheel loads are distributed longitudinally over three ties or 4 feet of rail (33).

On ballasted decks, wheel loads may be assumed (33) as uniformly distributed over 3 feet of rail longitudinally plus twice the depth of ballast under the tie plus twice the effective depth of the slab; however, the sum may not exceed the axle spacing. The axle loads are distributed normal (transverse) to the track for the length of the tie plus the depth of ballast under the tie; however, the sum may not exceed the total width (base) of the ballast.

Impact - A vehicle-guideway interaction analysis (58, 59, 60, 61) is recommended for any given system. However, in the absence of such detailed analysis, an impact factor (I) of 30% of the wheel load may be applied vertically to each track (maximum of two tracks for a multiple track structure) (33). Both vertical impact force and transverse horizontal impact force shall be applied to all superstructures, including steel or concrete support columns, steel towers and legs of rigid frames (6).

Centrifugal - Centrifugal force (CF) accounts for curve geometry and design speed. A percentage of total vehicle load is computed as follows and is applied 5 feet above the top of the low rail on all tracks (33):

$$CF = 6.8755 \frac{V^2}{R}$$

Where:

CF = Centrifugal Force (%)

V = Velocity (mph)

R = Curve Radius (feet)

Rolling - A rolling force (RF) is applied on all tracks. The RF is 10% of the total vehicle load per track. It is applied downward on one rail and upward on the other rail for all tracks present (33).

Longitudinal - A longitudinal braking or tractive force equal to 15% of the total vehicle load per track is applied 5 feet above the rail on all tracks. In applying longitudinal force (LF), consideration is given to combinations of acceleration and deceleration forces where multiple tracks exist (6, 33).

Wind - In addition to wind loading specified for the structure by AASHTO (34, 52, 62) a wind load (WL) on the train is applied. A transverse horizontal wind load of 300 pounds per linear foot of train is applied simultaneously with a longitudinal horizontal load of 75 pounds per linear foot of train. The transverse WL is applied as a concentrated load at the axle locations in the plane 7 feet above the top of the low rail and normal to the track. (The horizontal force component is concentrated at the rail with direct wheel-flange contact). The longitudinal WL is applied to the rails and superstructure as a uniformly distributed load over the length of the train in a horizontal plane at the top of the low rail (33).

Other - Service walks and their immediate supports should be designed for a live load of 85 pounds per square foot of walkway area. Except for bridge structures and pedestrian bridges, all members supporting 50 square feet of walkway, or more, should be designed for a live load of 60 pounds per square foot of walkway area (6). Safety railings shall be designed to withstand a horizontal force of 50 pounds per lineal foot, inward or outward, applied at the top of the railing and perpendicular to the plane of the railing (6).

Provision shall be made for loads due to rotating ventilation equipment. Structures supporting fan dampers or by-pass dampers should be designed for a uniform pressure, in either direction, of 40 psf over the surface area of the damper (6).

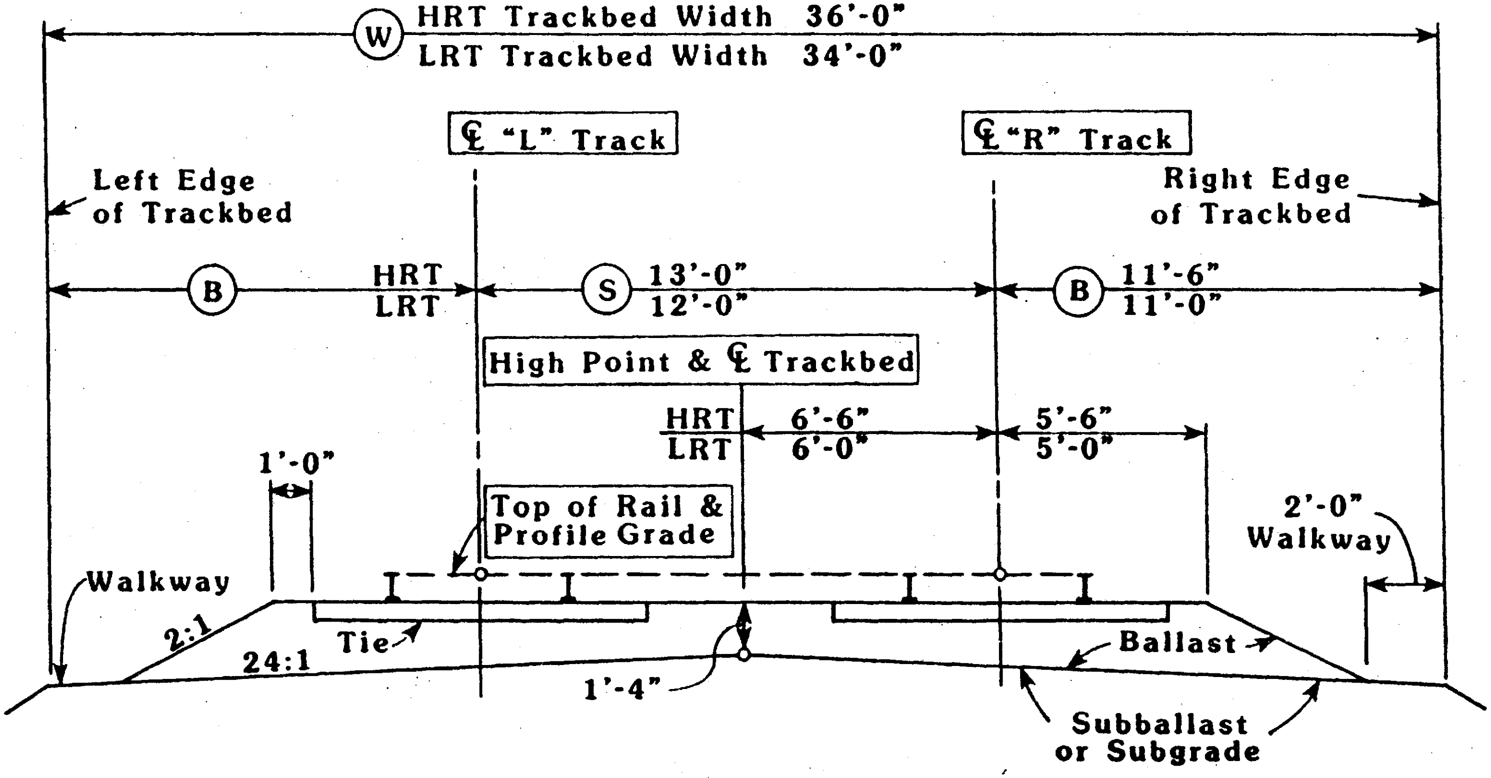
4.3.4 Trackbed Design

The trackbed is defined (33) as the finished surface of the subballast or subgrade between the outside edges of the shoulders. Trackbed width is influenced by:

- Track spacing (centerline-to-centerline);
- Track gauge;
- Superelevation;
- Depth of tie, slab or beam supporting the rails;
- Distance from track centerline to top of ballast slope;
- Ballast side slope;
- Walkway requirements; and,
- Tie length.

Figures 11, 12 and 13 illustrate typical cross sections and dimensions for transit trackbed. Figure 11 shows a tangent section while Figure 12 presents a typical superelevated section. Figure 13 illustrates a retained trackbed on an embankment section. All figures are for a double track design using U.S. standard track gauge (4 ft. - 8 1/2") and a centerline track spacing of 13 feet for heavy rail transit and 12 feet for light rail transit (33).

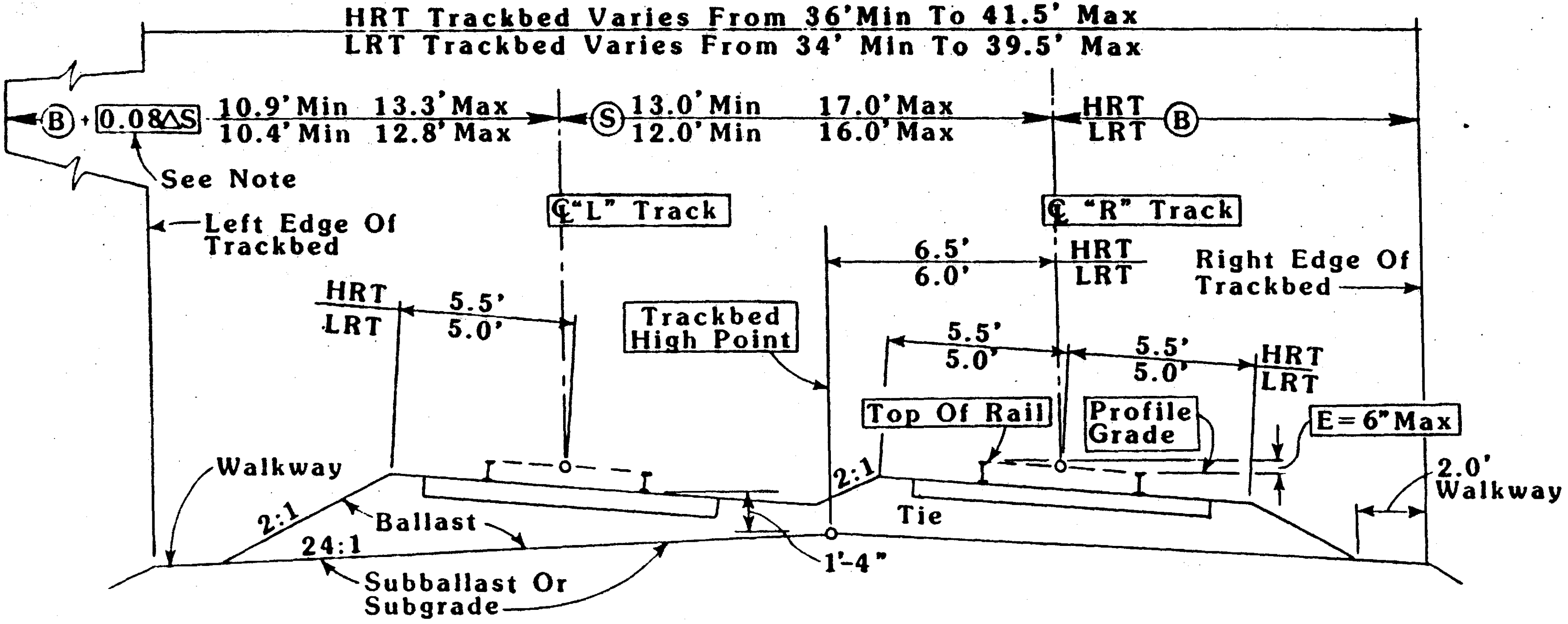
Track Spacing - A 14 foot, centerline-to-centerline, distance is the most commonly specified minimum separation for railroad and transit facilities in the United States (33). However, for preliminary design, track



Note: Dimension "B" should allow for tie replacement as needed, a 2:1 ballast slope to sub-grade, and a service walkway.

Figure 11. Trackbed Cross-Section of a Typical Tangent Segment

Source: Ref. (33), 4-5.10

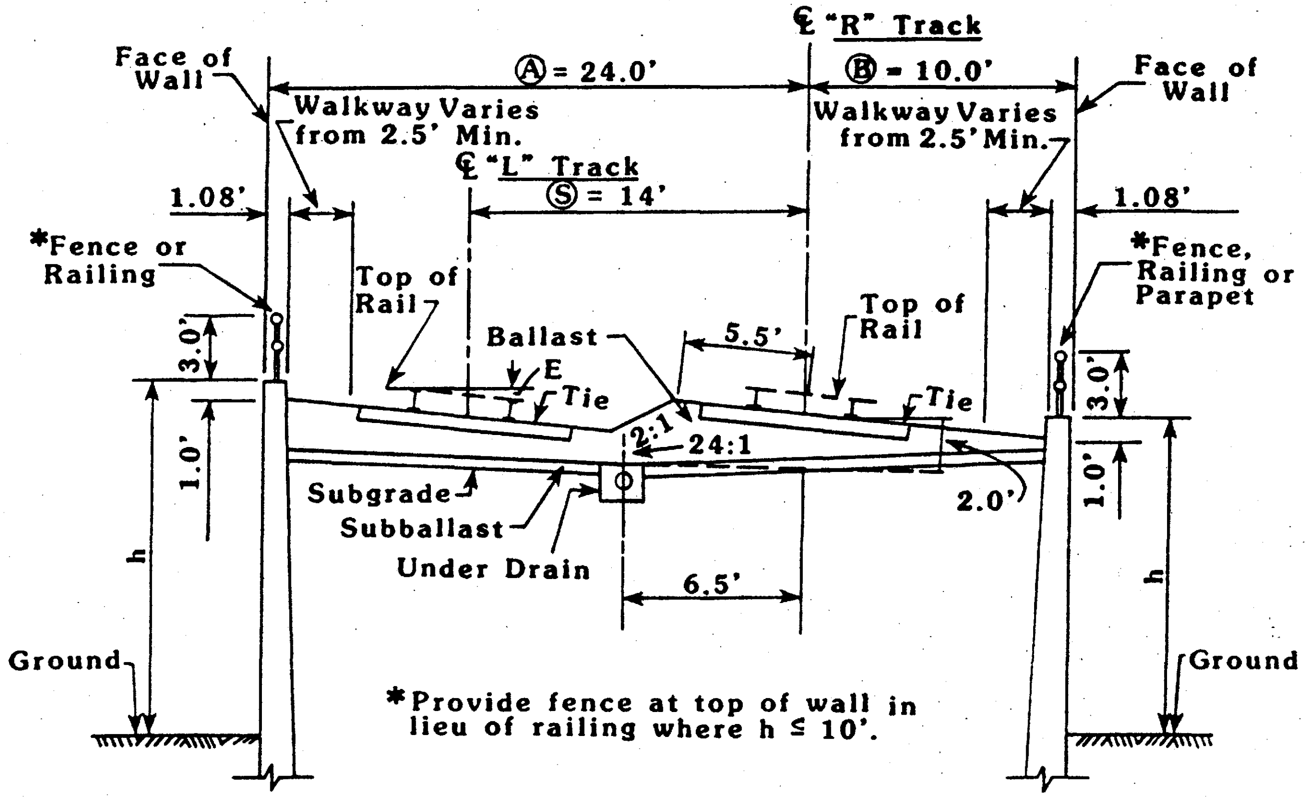


NOTE: When S is increased, left edge of trackbed moves out from ℄ "L" a distance equal to 0.08ΔS, where ΔS equals the increment of widening in feet or meters above minimum S distance shown.

SYSTEM	DIMENSION Ⓑ ADJUSTMENT FOR CURVES WITH A RADIUS OF 755' OR MORE	
	ON OUTSIDE OF CURVE Ⓑ EQUALS	ON INSIDE OF CURVE Ⓑ EQUALS
	FEET	FEET
HRT	11.5 + 0.3E	11.5 - 0.1E
LRT	11.0 + 0.3E	11.0 - 0.1E
Where: E= Actual Super	INCHES	INCHES

Figure 12. Trackbed Cross-Section of a Typical Superelevated Segment

Source: Ref. (33), p. 4-5.11



NOTES:1–Ⓐ & Ⓑ Dimensions Shown Are Appropriate for Right or Left Curves With "R" Track Radius of 755' or More When:

- **Ⓢ = 14'**
- **E = 6" Max. Superelevation**
- **Ties are 9' Long.**

2–Ⓐ,Ⓑ or Ⓢ Should Allow for Tie Replacement as Needed.

Figure 13. Trackbed Cross-Section of a Typical Retained Embankment Segment

Source: Ref. (33), p. 4-5.12

spacing for heavy and light rail transit may be assumed as shown in Table 11 for tangent track and for curves greater than 500 foot radius. When curve radii fall below 500 feet, clearance envelopes are affected by vehicle displacement and the track spacing must be adjusted as suggested in Table 12 (33).

Table 11. **Centerline-to-Centerline Track Spacing for Tangents and Curves Greater Than 500 Feet Radius**

Track Location:	Heavy Rail Transit:	Light Rail Transit:
Surface	13.0'	12.0'
Aerial	13.0	12.0
Cut and Cover	16.0	14.0
Tunnel	30.0	30.0

Source: Ref. (33), p. 4-5.8

Table 12. **Incremental Increase in Centerline-to-Centerline Track Spacing for Curves Less Than 500 Feet Radius**

Curve Radius:	Required Increase:
400'	0.2'
300'	0.5'
200'	1.0'
100'	2.0'
50'	4.0'

Source: Ref. (33), p. 4-5.8

Track Gauge - Most rail transit systems in the United States employ a "standard gauge" of 4 feet- 8 1/2 inches. Track gauge is the distance between the inner sides of the rail heads measured 5/8 inch below the tops of rails. Most transit systems require that the tangent track gauge (4'-8 1/2") be increased in 1/4 inch increments as curvature becomes more severe (33).

Horizontal Alignment - Horizontal alignment of mainline track consists of tangents joined to circular curves by spiral transitions; spiral curves are generally not used in yards or service areas (33). Compound circular curves can be used; however, transition spirals between such curves must be introduced under certain conditions (6). Curvature and superelevation relate to design speed and to the performance characteristics (61, 63) of the transit vehicle.

Tangent length is often (33) specified as an absolute minimum of 75 feet or 100 feet; a preferred minimum is 200 feet. An acceptable minimum is determined by (33):

$L = 3V$

Where:

L = Minimum tangent length (feet); and,

V = Design speed through tangent section (mph).

It is desirable to extend tangent alignment 75 feet in both directions beyond station platforms.

Circular curves, defined by the arc definition, are specified by their radii. Desirable minimum radius for mainline track is 1000 feet for heavy rail transit and for light rail transit approaching heavy rail performance. The absolute minimum frequently specified (33) for yard and secondary track ranges from 250 to 350 feet; however, light rail transit may employ radii of 40 to 50 feet for low speed operation (6). The desirable minimum length of a circular curve may be determined from (33):

$L = 3V$

Where:

L = Minimum curve length (feet); and

V = Design speed through curve (mph).

Tracks are placed on concentric curves for multiple track designs.

Superelevation is the vertical difference between the high (outside) rail and the low (inside) rail and is composed of:

$E = A + U$

Where:

E = Total superelevation required for equilibrium;

A = Actual superelevation to be constructed; and,

U = Unbalanced superelevation (difference between E and A).

Unbalanced superelevation for a transit system should desirably be 3 inches or less (6); 4.5 inches is considered the maximum unbalanced superelevation (33). The actual superelevation to be constructed may be determined from (33):

$$A = 3.775 \frac{V^2}{R} - U$$

Where:

A = Actual superelevation (inches);

V = Design speed (mph);

R = Radius of curve (feet); and

U = Unbalanced superelevation (inches).

If unbalanced superelevation (U) is set equal to zero, the actual superelevation (A) is the equilibrium superelevation for a given design speed. Calculated values are normally (6) rounded to the nearest one-quarter inch; if the calculated value is 1/2 inch or less, no actual superelevation need be provided (33). Actual superelevation (A) is normally added, or removed, linearly throughout the spiral transition curve by raising the outside rail and maintaining the profile of the inside rail (33).

Spiral transitions between tangents and curves on mainline track have an absolute minimum length of 100 feet. The greater length of the following two equations is used for spirals over 100 feet long (33):

$LS = 50A$, or
$LS = 1.22\ (U)\ (V)$
Where:
LS = Length of spiral (feet);
A = Actual superelevation (inches);
U = Unbalanced superelevation (inches); and,
V = Design speed (mph).

Spirals are omitted (6) where the length of spiral (LS) divided by the radius of circular curve (R) is less than 0.01 and the superelevation (A) is attained (or removed) throughout equal lengths of tangent and curve (33). In the case of compound circular curves, the length of the spiral transition is determined by the greater value of (33):

$LS = 50\ (AB-AA)$, or
$LS = 1.22\ (UB-US)V$
Where:
LS = Length of spiral (feet);
AB = Actual superelevation of second curve;
AA = Actual superelevation of first curve;
UB = Unbalanced superelevation of second curve;
UA = Unbalanced superelevation of first curve; and,
V = Design speed (mph).

If conditions prohibit use of the minimum tangent length between reversing curves, transition spirals may meet at the point of reverse curvature and superelevation accommodated as shown in Figure 14. This situation, however, is undesirable and should be avoided if possible (33).

Vertical Alignment - Profile grade represents the elevation of the low rail. All grade changes are connected by parabolic vertical curves. Vertical alignment for light rail transit will generally conform to street profiles within the limits of vehicle performance capabilities.

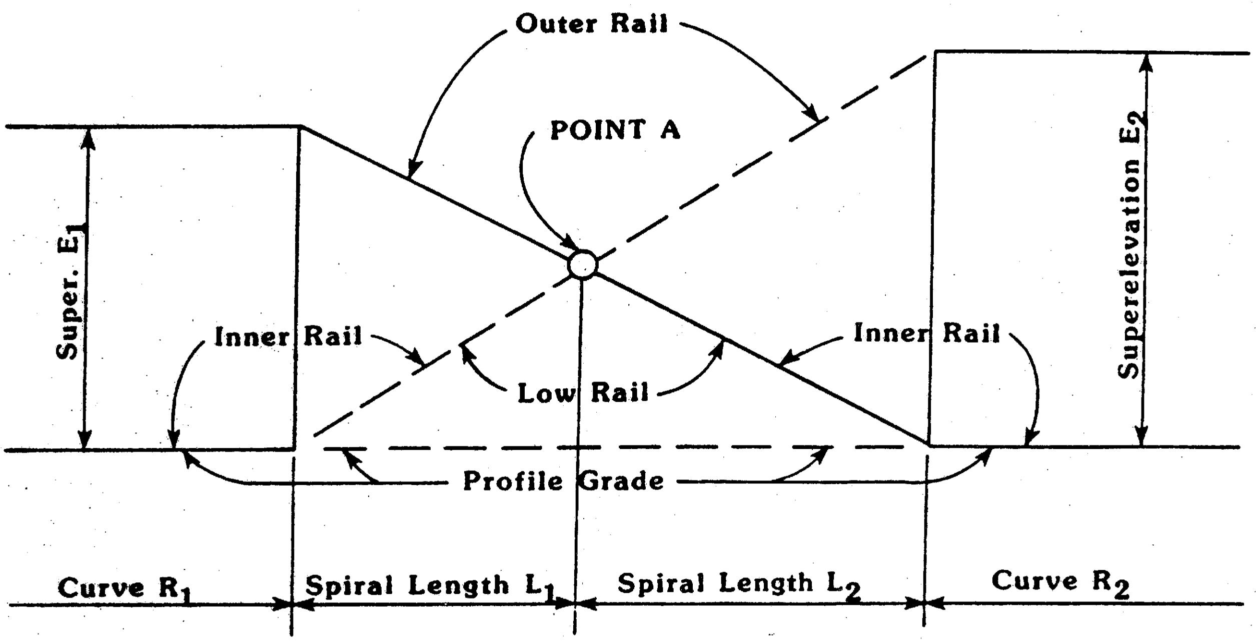


Figure 14. Superelevation Transitions On Spirals Between Reverse Curves

Source: Ref. (33), p. 4-6.14

A minimum grade of 0.25 percent should be maintained on aerial structures and for underground construction to provide drainage; zero percent grade is acceptable for at-grade construction and/or station areas if drainage can be accommodated (33).

The desirable maximum grades for light rail transit are plus 6 percent and minus 8 percent. However, higher grades (i.e., plus 8 percent and minus 10 percent) can be accommodated based upon system requirements and vehicle performance (6, 33).

The minimum length of constant profile grade between vertical curves on mainline track is often (33) determined by:

$L = 3V$

Where:

L = Minimum length of grade (feet); and,

V = Design speed (mph).

The absolute minimum length of mainline vertical curves (crests or sags) is typically 100 feet with the preferred minimum being 200 feet (33). Length of mainline vertical curves above the minimum may be computed by the following (33):

$$L = 100\ (G1-G2)$$

Where:

L = Length of vertical curve (feet);

G1 = Profile grade entering curve (percent);

G2 = Profile grade leaving curve (percent); and,

(G1-G2) = Algebraic difference in profile grades (percent).

Where vertical and horizontal curves are combined and unbalanced superelevation (U) exceeds 1 inch, the length of vertical curve should be doubled; the above equation then becomes (33): $L = 200\ (G1-G2)$. Some transit systems do not establish minimum vertical curve lengths for yard and secondary tracks; however, suggested minimum length for use off of the mainline are included in Table 13 for reference (33).

Table 13. Minimum Vertical Curve Lengths for Rail Transit

Algebraic Grade Difference (G1-G2):	*Minimum Vertical Curve Length (feet)		
	Yards and Secondary Track	L=100 (G1-G2)	L=200 (G1-G2)
12%	na	1200	2400
11%	na	1100	2200
10%	na	1000	2000
9%	na	900	1800
8%	na	800	1600
7%	160	700	1400
6%	140	600	1200
5%	120	500	1000
4%	100	400	800
3%	80	300	600
2%	60	200	400
1%	40	100	200

*NOTE: Except for yard and secondary track, 200 feet is the preferred minimum length. As a general guide, the L=200 (G1-G2) equation should be used wherever possible for mainline track design.

Source: Ref (33), p. 4-7.6

For aesthetic reasons, both sag and crest vertical curves should be as long as possible especially when connecting long constant-grade mainline profiles. Also, the tops of rails and edges of aerial structures should be checked to avoid a "roller-coaster" appearance; profiles plotted to an exaggerated scale can assist in this analysis (33). Short horizontal curves should be avoided at sags and crests. Preferably, vertical control points should lie either completely inside or completely outside of horizontal control points.

5 CONVERSION OF TRANSITWAYS

5.1 General

The following factors are essential in planning and design decisions regarding the conversion of a transitway, which initially accommodates rubber-tired high-occupancy vehicles, to a rail car transit system:

- Transitway geometric features;
- Vehicle operating and performance characteristics;
- Station location, size, and frequency; and,
- Operations during conversion (converting existing transitway to rail facility).

Planning guidelines and design criteria specific to transitway geometric features are available from various sources (4, 34, 64, 65) and were presented and discussed in detail for Texas in previous work (7). The following sections address desirable standards for transitways which may be converted to rail transit facilities.

5.2 Design Guidelines

5.2.1 Design Vehicles

Rail vehicle considerations deemed critical to transitway design are size and configuration, performance capabilities, and power and steering systems (7). Vehicle design characteristics that influence transitway design for rail convertibility are:

- Vehicle height, width, length, and weight;
- Number and location of doors; and,
- Maximum number of vehicles per train.

The geometric design of a transitway must also be compatible with the performance capabilities of the most restrictive vehicle or technology that will use it. The following items are critical to the overall design:

- Maximum grade at operating speeds;
- Maximum grades for entry and exit speeds; and,
- Turning radii versus speed.

Rail transit vehicles receive their power and steering from the track guideway. All special requirements for vehicle power and steering systems inherent for a given rail technology should be related to each transitway design. Specifically, light rail transit utilizes overhead electrification which generally necessitates a minimum height clearance of 15.5 feet (see Section 4.2.2).

Table 14 summarizes rail vehicle considerations in comparison to other types of transitway high occupancy vehicles.

Table 14. Transitway Design Vehicles

Design Vehicle (Type)	Height (Ft)	Width (Ft)	Length (Ft)	Weight (Lb)
Passenger Car	4.25	7.00	19.00	2-3,500
Commuter Van	6.50	7.50	25.00	3-5,500
Single Unit Bus	13.50	8.50	40.00	37,000
Articulated Bus	10.50	8.50	60.00	53,000
Light Rail Transit*	15.00	8.67	50.00	68,000
Heavy Rail Transit*	11.75	9.33	50.00	73,000

*50-ft. class (see Table 8 for typical rail vehicle characteristics)

Source: Ref. (<u>33</u>, <u>45</u>, <u>66</u>)

5.2.2 Level-of-Service

The capacity of a transitway lane has an upper limit which is governed by the headway, or spacing, of the high occupancy vehicles (HOV's) authorized for facility use and the occupancy of each vehicle. The headway as a minimum time interval (giving maximum HOV capacity) is governed by operating speed and by the practical aspects of merging HOV movements at entry points to the ends of the transitway. In general, the practical capacity of a transitway lane accommodating bus, vanpools and carpools is in the range of 9,000 to 12,000 persons per hour (45).

Rail transit systems can serve a higher patron flow rate when a transitway lane is replaced by a track-system. A light rail transit system can provide a capacity of 18,000 to 24,000 persons per hour (11). This capacity, as discussed in Sections 3.2 and 3.3, is governed by a minimum headway, train performance and capacity, station frequency, and ROW dedication (i.e. exclusive versus shared). A heavy rail transit track can provide a capacity of 30,000 to 50,000 persons per hour, governed as well by minimum headway and train operations (5, 11, 33).

5.2.3 Design Speed

Desirably, design speeds on transitway mainlane(s) should be 50 to 60 mph, for incentive utilization by buses, vans, and carpools. For future consideration of rail transit conversion, design speeds should be desirably 70 mph for heavy rail and 50 mph for light rail. Corresponding sight distance, alignment, and other geometric controls should satisfy these criteria.

5.2.4 Cross Sections

Transitway cross sections may be termed either narrow (single lane) or wide (multiple lane) inclusive of travel lanes plus lateral clearances. Desirable total pavement width to accommodate rail conversion depends upon track configuration (single or bi-directional), type of rail transit (LRT or

HRT), and transitional operations (maintenance of rubber-tired HOV use during conversion). Each of these factors must be taken into consideration for potential rail conversion. However, as presented in Section 4.3.2, a transitway pavement width of 21 to 25 feet is sufficient for dual track LRT while 25 to 28 feet is adequate for dual track HRT operation. To facilitate conversion while maintaining HOV service, a cross sectional width of 28 to 34 feet for LRT and 38 to 44 feet for HRT is desirable (45).

5.2.5 Alignment

Transitway alignment should conform to AASHTO (66) practice. The passenger car is the critical design vehicle for establishing stopping sight distance relative to design speed. Rail transit vehicles exhibit a substantially higher eye height which, in combination with the wayside control signals, reduces the calculated stopping distance. Provision for future rail conversion does not preclude the passenger car as the critical vehicle for this design criterion.

Horizontal curvature criteria is dependent upon the combined factors of design speed, side friction, and superelevation in balance against inertia forces. For rail transit, a desirable minimum radius of mainline curvature is 1,000 feet as discussed in Section 4.3.4, Trackbed Design.

5.2.6 Gradients

Gradients on transitways should be reflective of the capabilities of the vehicles utilizing the facility. Whereas a 6% maximum grade was recommended for buses on transitways, rail transit vehicles operate more efficiently with a 4% maximum grade (see Section 3.2). A 0.35% minimum longitudinal grade is recommended due to the need to provide adequate drainage of the transitway surface and prevent long periods of water retention (ponding). Likewise, minimum grades of 0.25% are required for drainage purposes on rail transit alignment (see Section 4.3.4).

The maximum length of grade (in concert with percent of grade) should consider the power capabilities of the designated rail transit design vehicle. Operations should be optimized by avoiding excessively long grades. It is also desirable to provide flatter grades of sufficient length at starting and stopping locations (i.e., stations).

5.2.7 Clearances

Vertical clearances on transitways must be sufficient to accommodate rubber-tired authorized vehicles (buses, vans, cars) and, if intended for conversion, potential rail transit vehicles. Clearances for existing rail systems vary from 14.0 feet for third-rail facilities up to 21.0 feet for overhead contact (catenary). Generally, a vertical clearance of 15.5 feet, including a 6 inch allowance for possible future resurfacing, will provide adequate space required for future rail conversion.

Lateral clearances on HOV transitways must account for possible vehicle breakdowns and shoulder space to pass stalled vehicles. However, with rail transit systems, a minimum lateral clearance of 2.0 feet is acceptable as a safety margin to adjacent fixed obstructions (see Section 4.3).

5.2.8 Stations

Stations for transitway or rail transit share design principles and a common purpose to facilitate passenger access to line-haul operations (4). If a transitway is intended for future conversion to rail operation, close attention should be given to initial station location and design. Several considerations influence the design of a station. These are identified in the five following subtopics (67).

Configuration - The function and configuration of a station varies with its location along the transitway as follows:

- Terminal station (at end of transitway);

- Intermediate station (along a transitway);
- Transfer station (at the intersection of two transitways); and
- Remote station (for system monitoring, control and operations).

Passenger Facilities - It is assumed that all stations, regardless of mode, will include a park-and-ride lot. It is also assumed that certain amenities (benches, telephones, litter bins, and possibly vending machines and restrooms) will be considered for all stations. However, the need for fare collection systems (turnstiles, ticket machines, change machines, etc.) and dual level structures (to reach loading platforms) will depend upon the mode.

Control and Communications Facilities - Provisions should be made for equipment required to control rail transit vehicles on that section of guideway assigned to the station control unit. The station control unit also must be tied into the communication network serving the guideway and the central control. Close attention to the control and communications aspects of future train service is necessary in providing transitway convertability; these aspects (68, 69) are significantly different for rail transit than for rubber-tired (driver-controlled) vehicles as discussed in Section 3 of this report.

Power System Facilities - It is assumed that power substations required for rail transit systems will be housed in the stations whenever feasible. All stations should also include adequate equipment room space for the machinery needed to operate the station.

Transit Vehicle Facilities - Platform lengths, switching requirements, and safety measures will vary, depending upon the transit mode using the station. It is assumed the higher capacity HRT systems will require platforms from 300 to 750 feet long while LRT platforms will be in the range of 100 to 300 feet long. Buses will load at a transit shelter in the park-and-ride lot as discussed in Section 3.4.

5.2.9 Wheel Loads

Axle spacing, vehicle weight and load distributions for rail transit are significantly different from rubber-tired HOV design. Section 4.3.3 discussed the design loadings which should be considered for rail transit conversion. It is extremely important to determine the specific rail vehicle dimensions, weights and axle configurations intended for a given system. Optional equipment included in the vehicle procurement specifications, such as for the Dallas Area Rapid Transit (DART) Authority (51), can significantly impact the design loadings. Given the dynamic interactions of the rail vehicles with the fixed guideway (track) under varying geometric configurations, it is recommended (51) that an interactive commuter analysis for rail loadings and track design (53, 54) be performed. This analysis may result in structual design requirements of some 50% greater (67) for rail vehicles than for other transitway vehicles.

5.2.10 Summary

Table 15 presents a summary comparison of "desirable" rail-HOV transitway design criteria. The dimensions and weight of the design vehicle determine the required geometric design parameters. Similarly, the required system capacity and desired level-of-service will (or should) dictate the optimum technology or design vehicle. The design values presented in Table 15 provide a general comparison of the light rail transit (LRT) technology with typical HOV transitway vehicle (i.e., bus, van, car) requirements. Conversion of a transitway to a rail system will also necessitate special consideration of mode change facilities (stations), the communication/control system, and the power supply and distribution system.

Table 15. Summary Comparison of Rail-HOV Transitway Design Criteria

Criteria (Desirable)	Facility	
	Rail Transit (light)	HOV Transitway (bus, van, car)
Design Speed (mph)	50	60
Cross-Section		
Narrow (ft)	28-34	28.0
Wide (ft)	38-44	38.0
Alignment		
Stopping Distance (ft)	275	525
Horizontal Curvature (ft)	1000	1350
Superelevation (ft/ft)	----	0.06
Gradients		
Maximum (%)	4	6
Minimum (%)	0.25	0.35
Length (ft)	----	1250
Clearance		
Vertical (ft)	15.5	16.5
Lateral (ft)	2.0	8.00

5.3 Implementation

5.3.1 General

An advantage of initially building and operating a transitway, then later converting to rail transit is the likely lessened of the original investment in fixed facilities --- costs which must be augmented in the future when the conversion to rail takes place. If there is a measure of certainty on the part of the transportation system planners that such conversion will be needed, analysis of the alternative initial investments should be made regarding the deferred installation of rails.

5.3.2 Facility Conversion

Physical transitway limitations (narrow vs. wide) along with construction and safety requirements will determine the evolutionary conversion path from a rubber-tired vehicle facility to a rail transit facility. Figure 15 illustrates a three phase conversion from an elevated, 44 foot wide transitway to rail. The three phase conversion path, developed for maintaining basic transit service (i.e., bus) during construction, is described as follows (4, 7):

Phase A

1. Terminate carpool, and possibly vanpool, use. (This determination must be made in light of existing conditions for a given facility; certain situations may permit continued use by carpools and vanpools).
2. Continue peak period bus service; off-peak service provided in mixed-flow freeway lanes.
3. Construct during off-peak hours a one direction rail facility and necessary electrification with passing track.
4. Continue peak period bus operation during "shakedown" testing of the rail mode.

Phase B

1. Begin bi-directional rail operation on single track.
2. Terminate bus service on transitway.

Phase C

1. Complete rail system construction.
2. Initiate full bi-directional, double track rail operation.

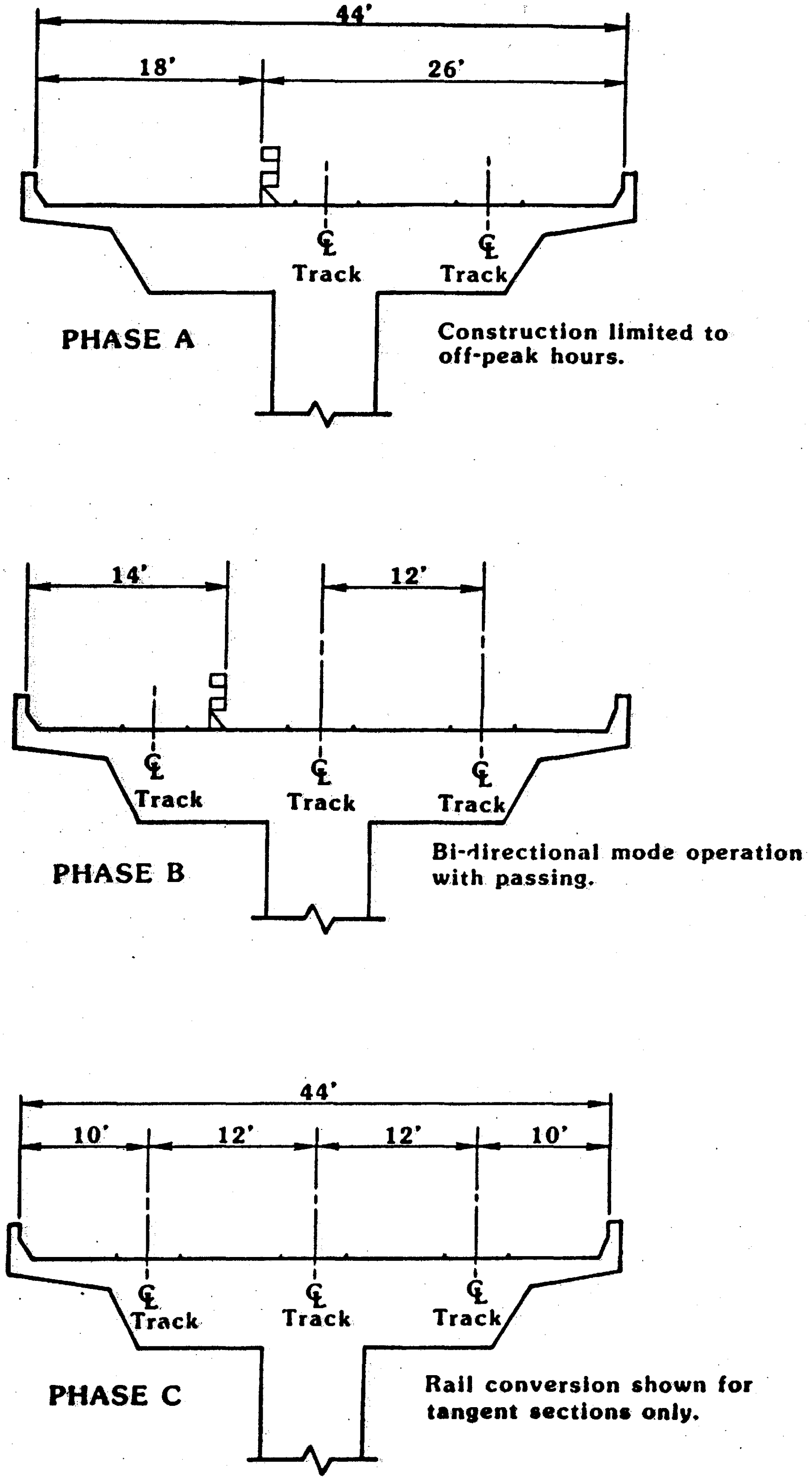


Figure 15. Three Phase Conversion of Wide Transitway to Rail

Source: Ref. (4,7)

Figure 16 indicates the evolutionary path from transitway to rail transit operation for an at-grade, 28 foot narrow transitway. As in the wide transitway, continued transit service during conversion is considered necessary for ultimate success of the operation. The conversion path is similar to that previously given for wide transitway conversion (4, 7).

5.3.3 Transition Operations

One critical issue, relative to transitway conversion to rail transit, is maintenance of service operations during the transitional period of construction. Figures 18 to 21 illustrate a staged sequence of operations during conversion of a wide transitway for use by buses, vans, and carpools to a fixed rail system (45). Figure 17 depicts transitway cross section dimensions prior to conversion.

Under Stage I (Figure 18), transitway operations are shifted to one side of the transitway and confined to two travel lanes without allowance for passing a stalled vehicle. A temporary concrete barrier is installed to initially separate construction operations from HOV movements. The operating lanes are separated by a row of flexible lane dividers spaced far enough apart to permit crossing of the line to pass a stalled vehicle. The provision affords use of the transitway lanes for work site access and for the movement of materials and equipment during low traffic periods. Under Stage I, a single track is completely installed including electrification equipment.

Under Stage II (Figure 19), energizing and testing of the rail line and the new rail vehicles takes place. Therefore, a critical need is to isolate the rail line from the HOV operations by a continuous fence along the traffic barrier. Where the transitway is at-grade, such fencing must be added to both sides. This is critical since rail line testing and operational training goes on in close proximity to the traveling public. As an option, the transitway could be used only for one-way, reversible, peak direction operation. Non-peak direction buses may be diverted to the freeway or surface streets during this stage.

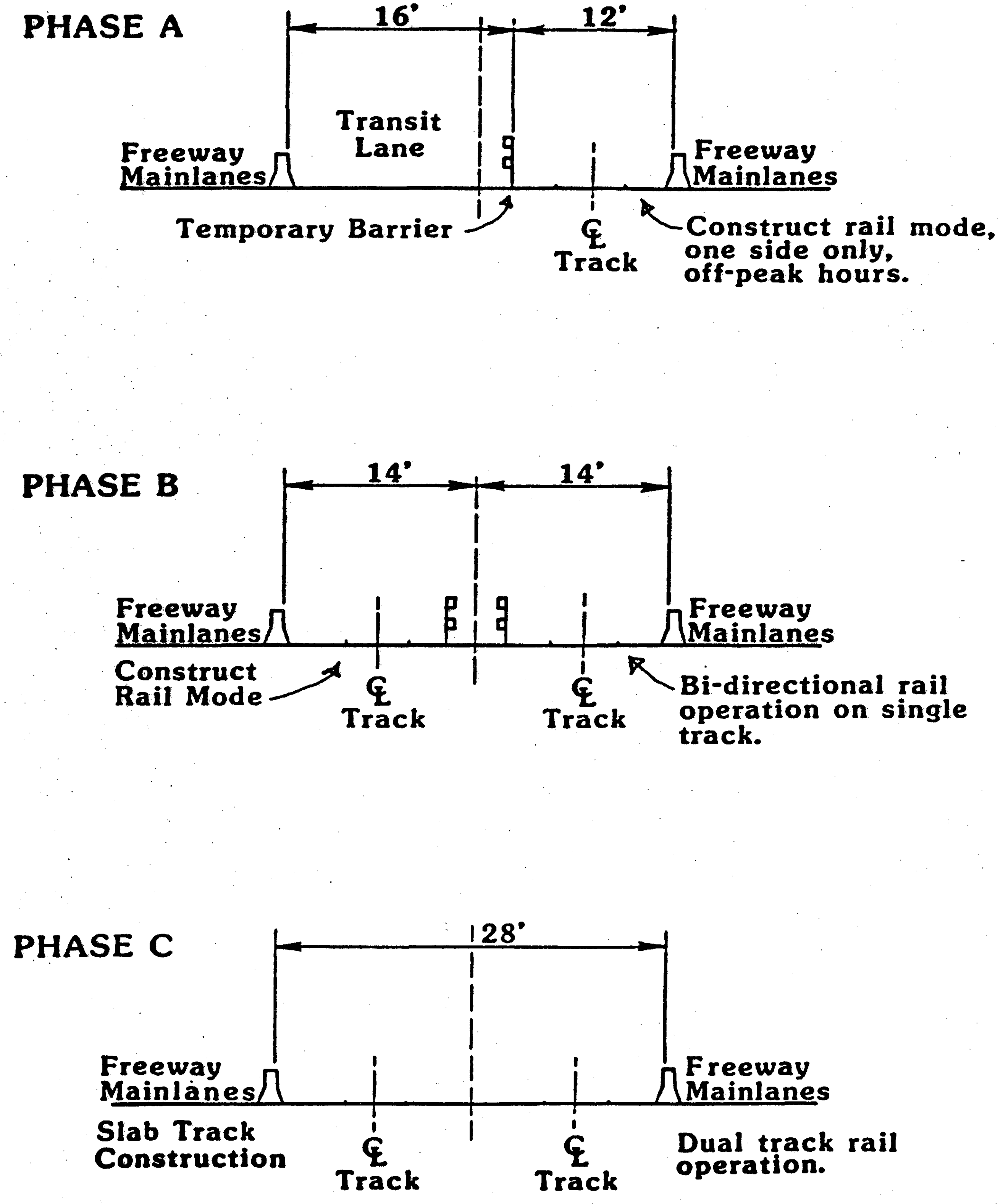


Figure 16. Three Phase Conversion of Narrow Transitway to Rail

Source: Ref (4, 7)

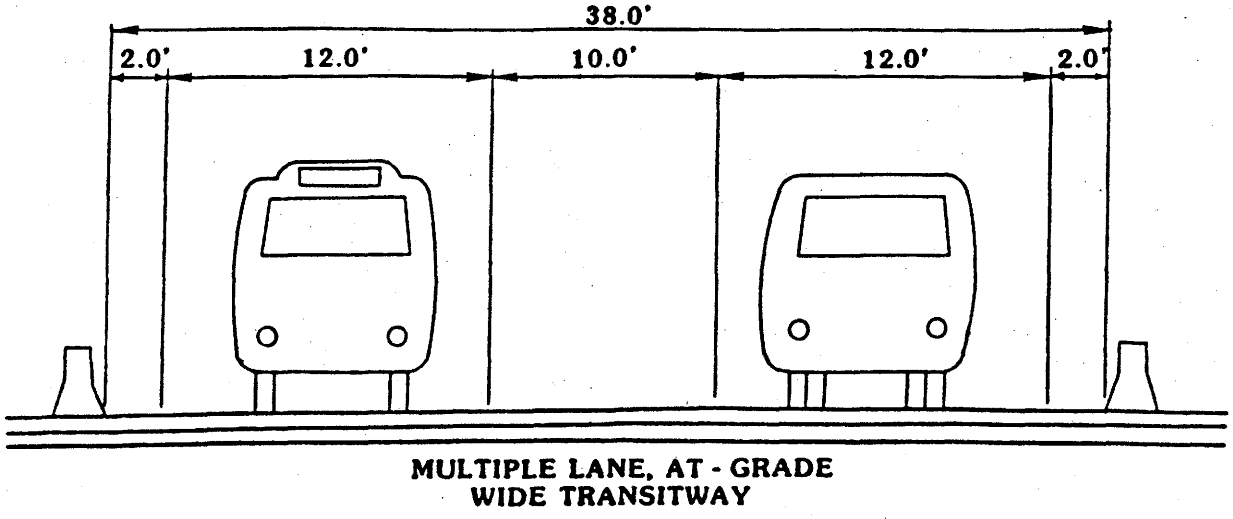


Figure 17. Typical Cross Section of Wide Transitway Prior to Rail Conversion

Source: Ref. (45).

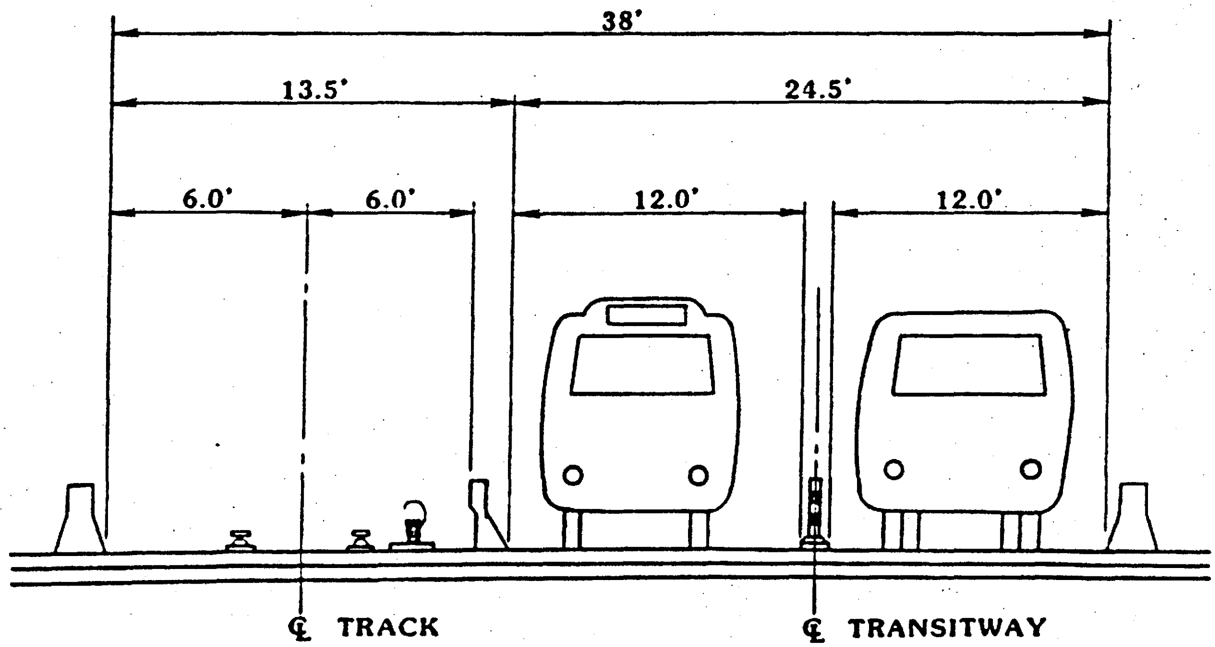


Figure 18. Stage I Conversion--Single Track Construction

Source: Ref. (45).

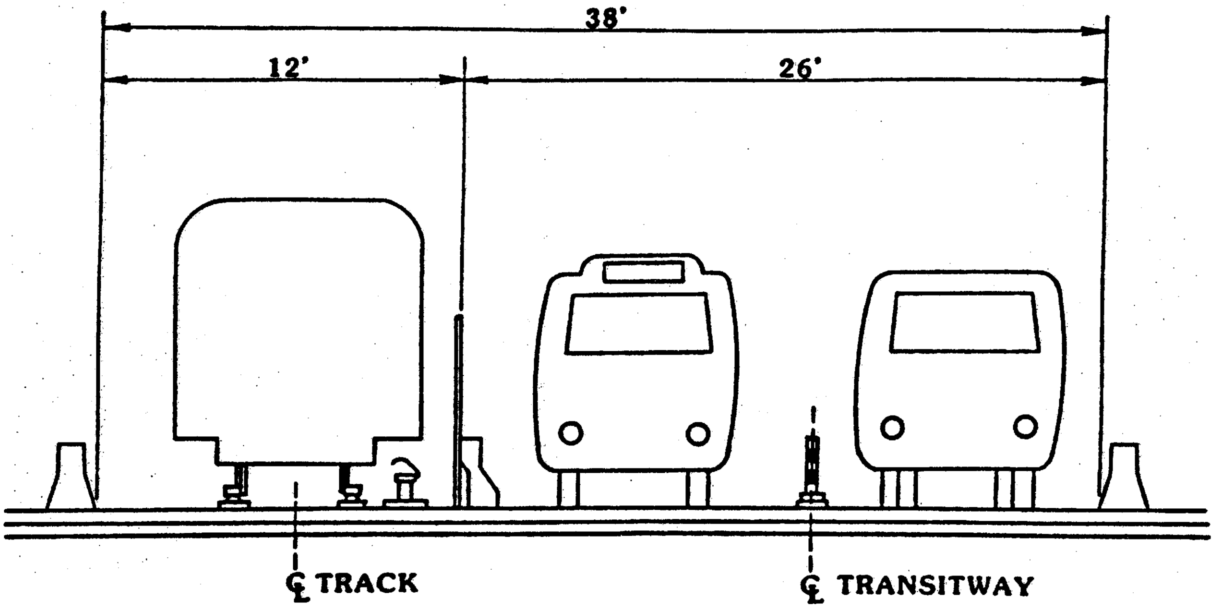


Figure 19. Stage II Conversion -- Rail Line Test Period
Source: Ref. (45).

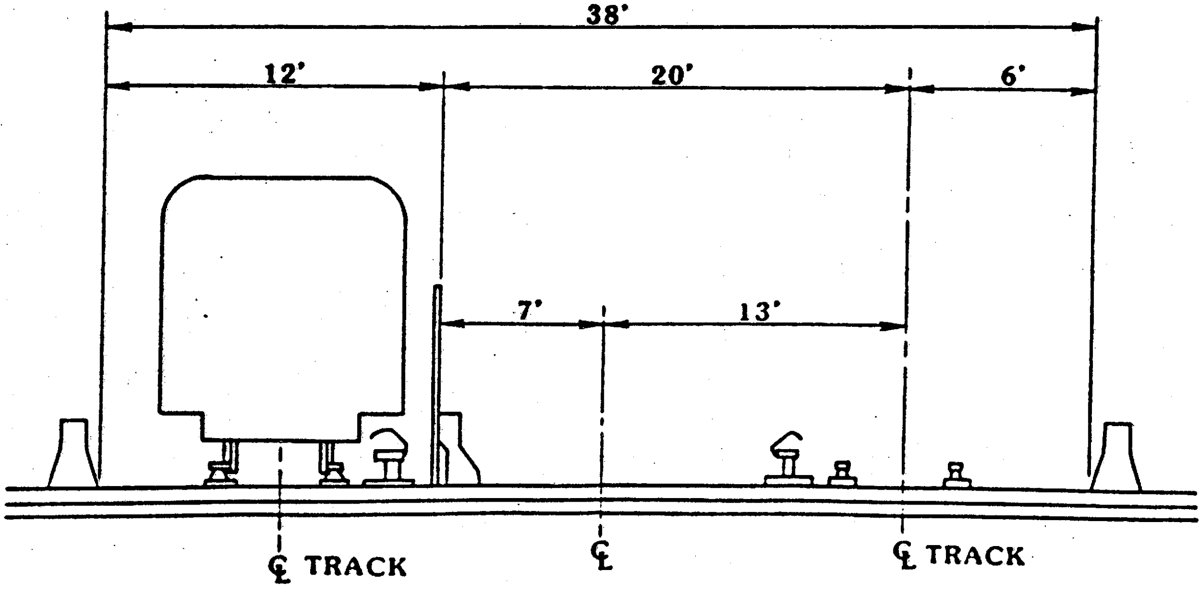


Figure 20. Stage III Conversion -- Single Rail Line Operation
Source: Ref. (45).

The changeover from HOV operations to rail is based on initially handling transitway patrons on a single track, with train operations in two directions, made possible by passing sidings located at about one-mile intervals and, desirably, at stations. It is likely that other bus operations along freeways or urban arterials will be needed to augment the single-track rail line. This will be a period of significant revisions to the bus system in any case, due to the need to match the differing characteristics of the transit network, including the new rail mode.

Under Stage III (Figure 20), the rail line takes over the transitway traffic, while the second track is constructed where the HOV operations have ceased. Once testing of the second track is completed, the temporary fencing and barriers are removed. Full revenue service on two-tracks commences and the conversion is complete (Figure 21). Quicker and less costly conversion is possible where the rail mode is light rail transit (Figure 22). If the conversion was to the light rail mode, matters would be simplified by not having the "hot" contact rail to contend with. Also, the light rail vehicles are narrower, allowing more clearance between transitway operations and rail line testing.

5.3.4 Impacts

The level of mobility provided by the urban transportation system greatly impacts the urban area's economy and its ability to compete in the state, national and international market place. An effective urban transportation system is composed of many discrete elements, modes and facilities which function collectively in the movement of people and goods to provide a balance between travel demand and travel supply measured by mobility. Transportation managers and officials attempt to maximize the level of mobility in concert with community goals and fiscal constraints in a cost-effective manner.

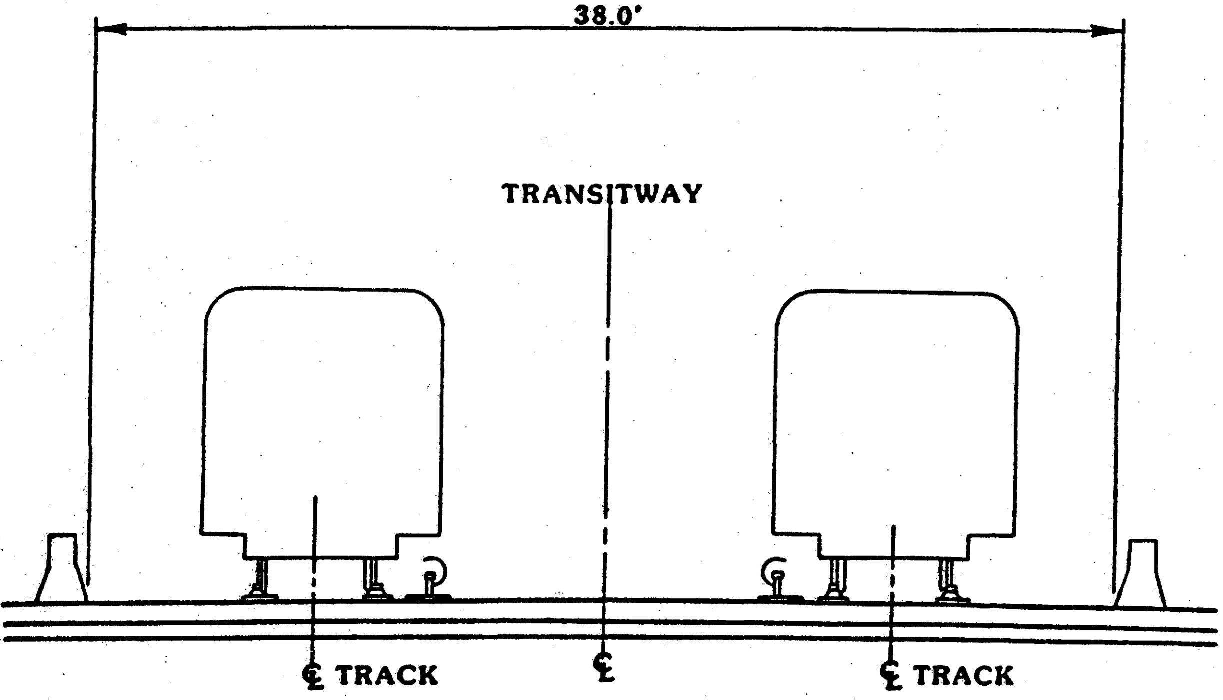


Figure 21. Stage III Conversion -- Dual Track Rail Transit Operation

Source: Ref. (45).

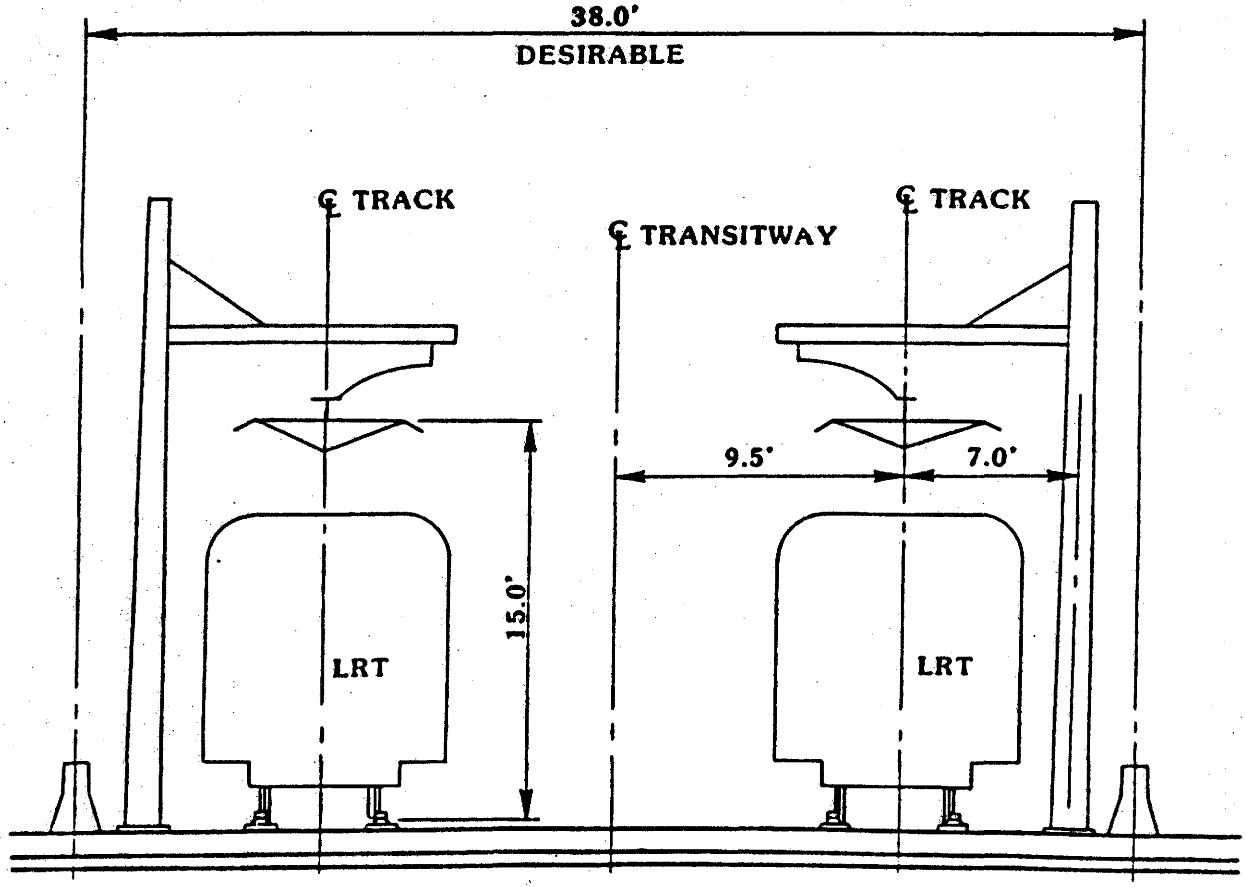


Figure 22. Full Conversion of Transitway to Light Rail Transit Service

Source: Ref. (45).

By definition, cost-effectiveness is a two component term which is used to assess the impacts or relative merits of proposed transportation improvements, modifications and/or services. The impacts of converting a HOV transitway to rail transit must be evaluated in terms of initial and long-term costs and benefits to the system users (present and future) and to the general public or community. Bay (69) suggests that lack of clarity and consistency in definitions, measurements, and methodology has characterized the cost-effectiveness evaluations associated with rail transit services; he recommends three things to reduce the ambiquities:

1. Transit cannot be examined in isolation, but only as part of the total transportation system for any community--costs and effects must be broadened to include the highway and automobile part of the system. However, this broadening should not try to include social, environmental, and economic costs and effects in a rigorous way. (Such factors can be examined in a subjective, judgmental manner, but should be separate from the quantitative analysis of the transportation system).

2. To do a better job of understanding the total costs and effects of alternative transportation systems. (Broader, long-term research is badly needed).

3. In the shorter term, the UMTA cost-effectiveness criteria represent a good start toward greater consistency although they lack the broad base that research might provide. However, the UMTA cost-effectiveness criteria should be modified to permit inclusion of related marginal highway cost impacts in a manner consistent with the treatment of marginal transit cost impacts.

Through the normal planning and design process, "costs" of transitway conversion can be estimated and determined with relative certainty. In order to determine "effectiveness", however, one must first determine the desired effects to be achieved in light of community goals and objectives. Bay (69) suggest the following categories of transit system goals to consider in quantifying rail service effectiveness:

1. Ridership Goals

   - total
   - route, guideway and/or segment
   - peak hour, daily and/or annual

2. Corridor Capacity Increase

3. Reduce Travel Time

   - systemwide
   - a particular corridor
   - set of corridors

4. Increasing Connectivity or Accessibility by Transit

   - work trips
   - all trips
   - other trip purposes

5. Reducing Environmental Impacts

6. Economic Development or Redevelopment

7. Solving Political Problems

   - relocating or redistributing wealth
   - greater social equity
   - equalizing services
   - addressing tax inequities

8. Reducing Total Transportation Costs

6 REFERENCES

1. "AASHTO Report: A Study on Future Directions of Public Transportation in the United States", American Association of State Highway and Transportation Officials, Washington, D.C., February 1985.

2. Bowsher, Charles A., "20 Years of Federal Mass Transit Assistance: How Has Mass Transit Changed", GAO/RCED-85-61, General Accounting Office, Gaithersburg, Maryland, September 1985.

3. Highway Design Manual, California Department of Transportation, Sacramento, California, As Revised 1985.

4. "Report on Design Criteria for Busways", Orange County Transit District, Cooperative Agreement No. 3607, California Department of Transportation, Sacramento, California, April 1982.

5. Christiansen, Dennis L., Alternative Mass Transportation Technologies - Technical Data, Report No. 339-4, Texas Transportation Institute, College Station, Texas, July 1985.

6. Manual of Design Criteria: Stage 1 Light Rail Transit System, Project No. UMTA-PA-03-0095, Port Authority of Allegheny County, Pittsburgh, Pennsylvania, December 1980.

7. Mounce, John M. and Stokes, Robert W., Manual For Planning, Designing, and Operating Transitway Facilities in Texas, Study No. 2-8-10-84-425, Texas Transportation Institute, September 1985.

8. Phillips, Jr., Edmund J., Railroad Operations and Railway Signaling, Simmons-Boardman Publishing Corporation, Omaha, Nebraska, 1942.

9. Armstrong, John H., The Railroad - What It Is, What It Does, Simmons-Boardman Publishing Corporation, Omaha, Nebraska, 1982.

10. Gray, George E. and Hoel, Lester A., Public Transportation: Planning, Operations, and Management, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1979.

11. Vuchic, Vukan R., Urban Public Transportation: Systems and Technology, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1981.

12. Levinson, Herbert S., Adams, C.L. and Hoey, W.F., Bus Use of Highways: Planning and Design Guidelines, NCHRP Report 155, Transportation Research Board, Washington, D.C., 1975.

13. Pushkarev, Boris S., Zupan, J.M. and Cumella, R.S., Urban Rail In America: An Exploration of Criteria for Fixed-Guideway Transit, Indiana University Press, Bloomington, Indiana, 1982.

14. Lea, Elliot, McGean, et. al., Dallas Fixed Guideway Rapid Transit Mode Analysis, Final Report, City of Dallas, Dallas, Texas, March 1983.

15. Howard, J.A., et al., Strategies to Implement Benefit-Sharing for Fixed-Transit Facilities, NCTRP Report 12, Transportation Research Board, Washington, D.C., July 1985.

16. Bullard, Diane L. and Nungesser, Lisa G., "Texas Public Transit Reference Manual", Report 1082-1F, Texas Transportation Institute, College Station, Texas, November 1985.

17. Peterson, Richard L., Porterfield, C.J. and Petersen, H.C., Feasibility of Utilizing Existing Railroad Rights-of-Way for Transit Corridors in Urban Areas, Report No. 1074-1F, Texas Transportation Institute, College Station, Texas, May 1984.

18. Pushkarev, Boris and Zupan, Jeffrey, Urban Rail In America: An Exploration of Criteria for Fixed-Guideway Transit, Report No. UMTA-NY-06-0061-80-1, Urban Mass Transportation Administration, Washington, D.C., November 1980.

19. Peterson, Richard L, et. al., Use of Existing Highway Right-of-Way for High Speed Rail Transportation, Report No. 418-1F, Texas Transportation Institute, College Station, Texas, February 1985.

20. "The Trolley Bus: Where It Is and Where It Is Going", Special Report 200, Transportation Research Board, Washington, D.C., 1983.

21. "Transit Fact Book - 1985", American Public Transit Association, Washington, D.C., May 1985.

22. Norley, K.T., Light Rail Application and Design, NTIS Report No. PB81-124620, South Australia Director-General of Transport, Adelaide, Australia, December 1979.

23. Jane's Urban Transport Systems, 4th ed., Jane's Publishing Incorporated, New York, New York, 1985.

24. Reno, Arlee T. and Bixby, Ronald H., Characteristics of Urban Transportation Systems, Report No. UMTA-MA-06-0173-85-1, Urban Mass Transportation Administration, Washington, D.C., October 1985.

25. Harris, Ken, World Electric Locomotives, Jane's Publishing Incorporated, New York, New York, 1981.

26. Association of American Railroads, The Car and Locomotive Cyclopedia of American Practices, Simmons-Boardman Publishing Corporation, Omaha, Nebraska, 1980.

27. Jane's World Railways, 1985 - 1986, 27th ed., Jane's Publishing Incorporated, New York, New York, 1985.

28. Lyons, William M., National Urban Mass Transportation Statistics, FY 1983 Section 15 Annual Report, Report No. UMTA-MA-06-0107-85-1, Urban Mass Transportation Administration, Washington, D.C., December 1984.

29. Stanger, Richard M. and Vuchic, V.R., "Automated Guided Transit Versus Conventional Rail", No. 120, TR News, Transportation Research Board, Washington, D.C., September/October 1985, pp. 9-13.

30. Petersen, H.C., et al., "Comparison of Freeway and Railroad Rights-of-Way for High-Speed Trains in the Texas Triangle", Transportation Research Record 1023, Transportation Research Board, Washington, D.C., 1985, pp. 24-30.

31. Peterson, Richard L., "High-Speed Rail Passenger Transportation for the Texas Triangle", ITE Journal, Vol. 55, No. 9, Institute of Transportation Engineers, Washington, D.C., September 1985.

32. Association of American Railroads, The Track Cyclopedia, 9th ed., Simmons-Boardman Publishing Corporation, Omaha, Nebraska, 1978.

33. Hintzman, K.W., et. al., Rail Transit Criteria for System Review and Preliminary Design, Report No. UMTA/CA/PD-78/1, Division of Mass Transportation, California Department of Transportation, Sacramento, California, December 1979.

34. "Guide for the Design of High Occupancy Vehicle and Public Transfer Facilities", American Association of State Highway and Transportation Officials, Washington, D.C., 1983.

35. Hoel, Lester A. and Roszner, Ervin JS., Transit Station Planning and Design: State of the Art, Transportation Research Institute, Carnegie-Mellon University, Pittsburgh, Pennsylvania, April 1976.

36. Mauri, Ronald A., Cooney, N.A. and Prowe, G.J., Transit Security: A Description of Problems and Countermeasures, Report No. UMTA-MA-06-0152-84-2, Urban Mass Transportation Administration, Washington, D.C., October 1984.

37. "Electromagnetic Compatibility Improves Reliability and Safety", No. 120, TR News, Transportation Research Board, Washington, D.C., September/October 1985, pp. 14-15.

38. Sagar, Navin S., Detection of Low-Current Short Circuits, NCTRP Report 7, Transportation Research Board, Washington, D.C., December 1984.

39. Standard Light Rail Vehicle Specification - Project Final Report, Report No. UMTA-MA-06-0015-73-1, Urban Mass Transportation Administration, Washington, D.C., February 1973.

40. Standard Light Rail Vehicle Specification - Technical Section, Report No. UMTA-MA-06-0015-72-4, Urban Mass Transportation Administration, Washington, D.C., October 1972.

41. McGean, T.J., et al., Cost Savings Potential of Modifications to the Standard Light Rail Vehicle Specifications, Report No. UMTA-MA-06-0025-79-11, Urban Mass Transportation Administration, Washington, D.C., February 1979.

42. "Light Rail Transit: Planning, Design, and Implementation", Special Report 195, Transportation Research Board, Washington, D.C., 1982.

43. Elms, C., et. al., Light Rail Car Specification Guide, Report No. UMTA-MA-06-0025-81-4, Urban Mass Transportation Administration, Washington, D.C., December 1981.

44. Parsons Brinckerhoff Quade and Douglas, Inc., et. al., "Technical Analysis and Technology Assessment: Design Criteria Manual", Working Paper No. 6, Regional Transportation District, Denver, Colorado, October 1985.

45. Bovay Engineers, Inc./Parsons Brinckerhoff, Uniform Design Standards Manual, Metropolitan Transit Authority of Harris County, Houston, Texas, July 1981.

46. Diamant, E.S., et. al., Light Rail Transit: State of the Art Review, Report No. DOT-UT-50009, Urban Mass Transportation Administration, Washington, D.C., Spring 1976.

47. Alan M. Voorhees and Associates, Inc., Metro for Buffalo: Transit Alternatives for the Buffalo-Amherst Corridor, Project UMTA-NY-09-0017, Niagara Frontier Transportation Authority, Buffalo, New York, June 1976.

48. Banfield Light Rail Project Information Book, Tri-County Metropolitan Transportation District of Oregon, Portland, Oregon, November 1980.

49. Banfield Light Rail Project: Pre-Design Summary Report, Tri-Country Metropolitan Transportation District of Oregon, Portland, Oregon, October 1980.

50. State-of-the-Art of Primary Transit System Technology, Technical Report No. 24, Southeastern Wisconsin Regional Planning Commission, Waukesha, Wisconsin, February 1981.

51. Rapid Transit Cars, Technical Specification (Draft for Industry Review), Dallas Area Rapid Transit (DART), Dallas, Texas, November 1985.

52. Standard Specifications for Highway Bridges, 13th ed., American Association of State Highway and Transportation Officials, Washington, D.C., 1983.

53. Meacham, H.C., Prause, R.H. and Waddell, J., Assessment of Design Tools and Criteria for Urban Rail Track Structures, Volume II, At-Grade Slab Track, Report No. UMTA-MA-06-0025-74-4, Urban Mass Transportation Administration, Washington, D.C., April 1974.

54. Prause, Robert H., et al., Assessment of Design Tools and Criteria for Urban Rail Track Structures, Volume I, At-Grade Tie-Ballast Track, Report No. UMTA-MA-06-0025-74-3, Urban Mass Transportation Administration, Washington, D.C., April 1974.

55. Lipinski, Martin E., Hurley, J.W., and Beck, R.F., "Analysis of Urban Rail Service Alternatives", Transportation Research Record 1023, Transportation Research Board, Washington, D.C., 1985, pp. 31-37.

56. Hanna, Amir N., Technical and Economic Study of At-Grade Concrete Slab Track for Urban Rail Transit Systems, Report No. UMTA-MA-06-0100-81-4, Urban Mass Transportation Administration, Washington, D.C., August 1981.

57. Transportation Systems Center, Proceedings: Direct Fixation Fastener Workshop, Report No. UMTA-MA-06-0153-85-3, Urban Mass Transportation Administration, Washington, D.C., June 1985.

58. Longi, Mohammad, S., "Innovations in Track Structures on Long Island Rail Road - Rational Design Criteria, and Performance", Paper at 62nd Annual Meeting, Transportation Research Board, Washington, D.C., January 1983.

59. Cunney, Edward G. and Yang, Ta-Lun, U.S. Transit Track Restraining Rail: Volume I, Study of Requirements and Practices, Report No. UMTA-MA-06-0100-81-6, Urban Mass Transportation Administration, Washington D.C., December 1981.

60. Cunney, Edward G., and Yang, Ta-Lun, U.S. Transit Track Restraining Rail: Volume II, Guidelines, Report No. UMTA-MA-06-0100-81-7, Urban Mass Transportation Administration, Washington, D.C., December 1981.

61. Saurenman, Hugh J., Nelson, J.T. and Wilson, G.P., Handbook of Urban Rail Noise and Vibration Control, Report No. UMTA-MA-06-0099-82-1, Urban Mass Transportation Administration, Washington, D.C., February 1982.

62. "AASHTO Interim Guide for Design of Pavement Structures", American Association of State Highway and Transportation Officials, Washington, D.C., 1972, Revised 1981.

63. Rickley, E.J. and Brien, M.J., Noise Test-Resilient Wheels, Massachusetts Bay Transportation Authority, Green Line, Report No. UMTA-MA-06-0099-82-4, Urban Mass Transportation Administration, Washington, D.C., November 1982.

64. General Criteria for Transitway Design: Milwaukee County Transitway, Barton-Aschman Associates, Inc., Chicago, Illinois, December 1968.

65. Transitway Design Manual, Regional Municipality of Ottawa - Carleton, Ottawa, Canada, Revised 1982.

66. American Association of State Highway and Transportation Officials, A Policy on Geometric Design of Highways and Streets, Washington, D.C., 1984.

67. Texas Transportation Institute, Evolutionary Transitways: A Concept Evaluation, Final Report, North Central Texas Council of Governments, Arlington, Texas, November 1977.

68. Armstrong, John, "ATCS: The Chips are Down", Railway Age, Vol. 187, No.3 Simmons-Boardman Publishing Corporation, New York, New York, March 1986, pp. 57-59.

69. Light Rail Transit: System Design for Cost - Effectiveness, State-of-the-Art Report 2, Transportation Research Board, Washington, D.C. 1985.

APPENDIX A

Fixed Guideway System For Rubber-Tired Vehicles

Introduction

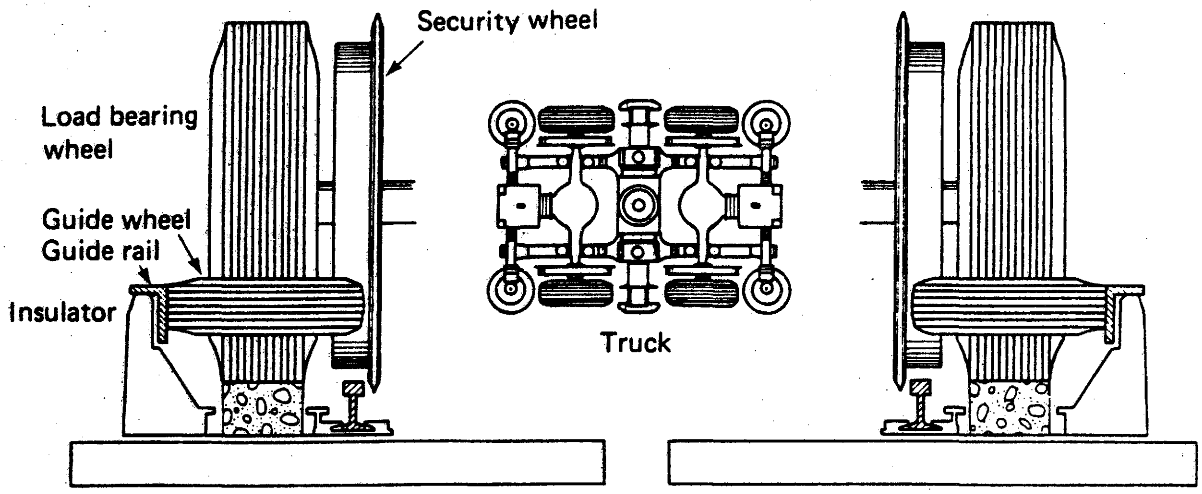
One advantage of a bus/HOV transitway over the conventional car/freeway facility is its increased person movement capacity while still maintaining the flexibility of the rubber-tired mode of transportation. Once transitway conversion to rail is accomplished, the rubber-tired flexibility of operation is lost; passengers must change travel modes at least once to reach their final destination. An alternative fixed guideway system with higher capacity and rubber-tired operational flexibility should be considered in transitway conversion. This appendix provides some planning and design factors for a higher capacity fixed guideway system (than a bus/HOV transitway) to accommodate rubber-tired vehicles.

Rubber-Tired Rapid Transit (RTRT)

Several cities utilize rapid transit systems with rubber-tired vehicles instead of conventional steel wheels on rails. Examples of RTRT systems can be found in Paris, Montreal, Mexico City, Santiago, Lyon and Marseille (11). The first RTRT system was developed between 1951 and 1956 for the Paris Metro. This type of system is a marginal member of the family of rail transit modes; they utilize rubber-tied cars on the same basic body/truck configuration as rail cars as shown in Figures A-1 and A-2 (11). RTRT technology has several features that should be evaluated and compared when considering conventional rail systems (11):

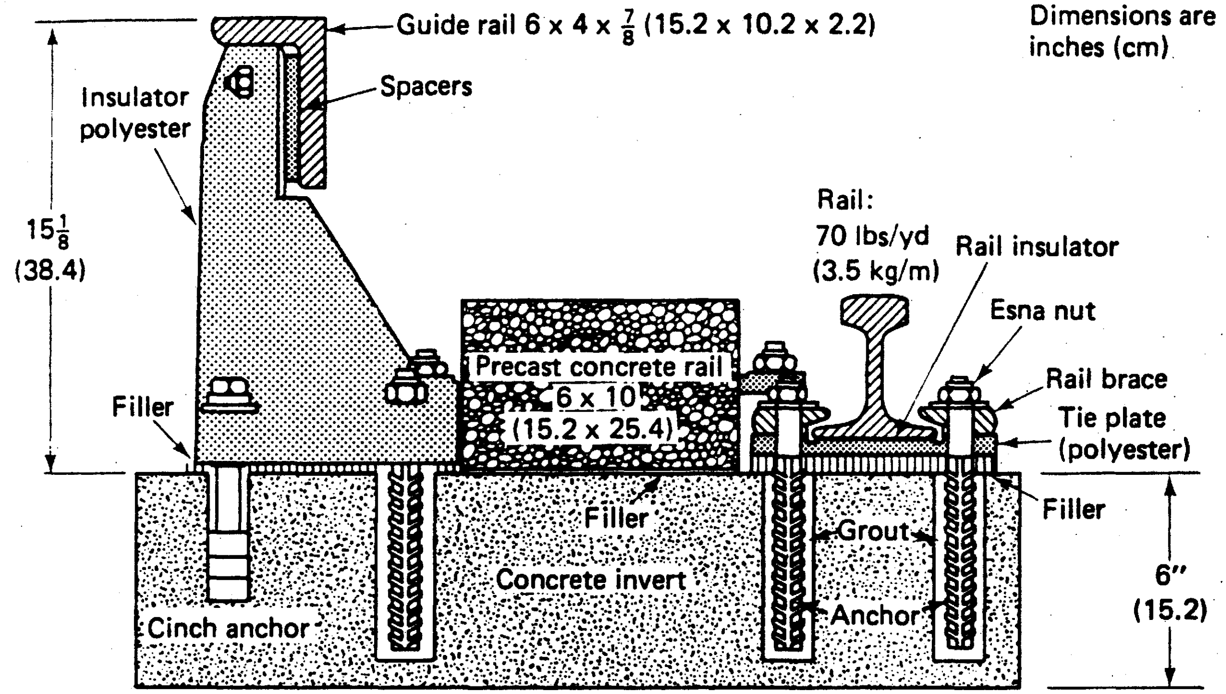
1. Adhesion is greater on a dry guideway with rubber-tired vehicles.
    - ability to negotiate steeper grades
    - higher acceleration capacity
    - sensitive to wet, snow and ice conditions
2. Noise is lower than old rail equipment but similar to modern HRT systems.

3. Weight of RTRT vehicles comparable to conventional rail vehicles.
4. Energy consumption considerably greater than HRT trains.
5. Heat produced by rubber-tired trains can be excessive.
6. Fire danger due to large amounts of flammable (rubber) material.
7. Costs of operation due to energy consumption and complexibility of vehicles and guideway are higher than conventional rail.

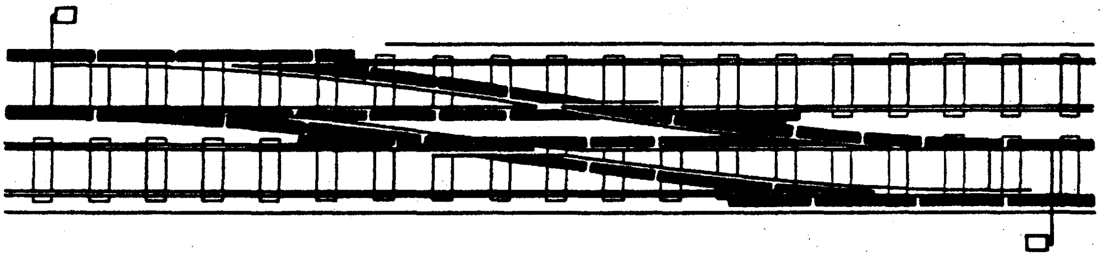


Source: Ref (11), p. 407

Figure A-1. Truck and Wheels of Rubber-Tired Rapid Transit (RTRT) Vehicle



(a) Details of one set of rails



(b) Crossover

Source: Ref (11), p. 408

Figure A-2. Illustration of Rubber-Tired Rapid Transit (RTRT) Track

Fixed Guideways for Buses (The O-Bahn System)

General

The "O-Bahn" system, developed by the Federal Republic of Germany, consists of conventional diesel buses equipped with an extendable/rectractable guidance mechanism to operate on special guideways or on regular streets in mixed-flow. O-Bahn combines the advantages of lower cost, flexible bus operation in low-density areas with the higher capacity and narrower right-of-way advantages of a fixed-guideway system.

System Description

The vehicle's retractable guidance mechanism consists of special arms with small horizontal solid rubber rollers that (when extended) are positioned in front of the front axle and contact the guidance rail; the steering function is performed by the mechanism while the bus is on the fixed guideway.

The guideway consists of two horizontal concrete running rails against which the rollers run and receive horizontal guidance for the vehicle. The guideway must be constructed to extremely precise horizontal and vertical alignment criteria due to the sensitivity of riding comfort. The O-Bahn combines highway and guided technology and provides a level of transit service between buses on transitway and a light rail transit (LRT) system.

Compared to driver steered transportation modes, fixed guideway systems have the following major advantages/disadvantages:

- Advantages
    1. Ability to use larger vehicles that have greater capacity and a more comfortable ride;
    2. Ability to operate trains, resulting in much higher line capacity and lower unit operating costs (greater driver productivity);

3. Possibility of using electric traction with associated advantages (performance, cleanliness, less noise, no exhaust, safety, etc.);
4. Narrower right-of-way requirement; and,
5. Greater safety due to positive guidance and (possibly) fail-safe signaling.

- Disadvantages

  1. Requires a higher capital investment;
  2. Less compatible with other traffic in street operation;
  3. Difficult (if not impossible) to reroute or detour; and,
  4. Vehicles cannot pass unless off-line stations are provided.

The German O-Bahn designers have developed several features to improve performance or to reduce the mentioned short comings. An articulated vehicle with diesel and electric propulsion has been developed to allow switching between the two propulsion types. To provide expandability to a train operation, a bidirectional, four-axle double-articulated vehicle, with guidance on all axles, has been developed; however, this design lacks the ability to operate on both streets and on a fixed guideway.

The O-Bahn system compared to buses operating on a bus/HOV transitway has the following advantages and disadvantages:

- Advantages
  1. Narrower right-of-way required for operation;
  2. Greater safety with full lateral control; and,
  3. Somewhat better riding quality.

- Disadvantages
  1. Higher capital investment required;
  2. More complicated and precision guideway required;
  3. More complex vehicles with the retractable guidance mechanism;
  4. Lower capacity since overtaking/passing is not possible;
  5. Stations must be off-line which increases cost; and,

6. Lower system reliability since a stalled vehicle cannot be passed.

The O-Bahn system compared to a light rail transit (LRT) system has the following advantages and disadvantages:

- Advantages
    1. Requires fewer transfers;
    2. Requires a somewhat lower capital investment; and,
    3. Involves considerably less complex technology for new lines.

- Disadvantages
    1. Has a much lower capacity;
    2. More labor intensive;
    3. Requires higher operating expenditures for large passenger volumes/demands;
    4. Has lower performance characteristics due to diesel traction;
    5. Less spacious vehicles and a less comfortable ride;
    6. More negative environmental impacts (noise, exhaust, and aesthetics);
    7. Lower reliability; and,
    8. Generally not appropriate for tunnel operation.

Table A-1 summarizes the major features of buses on transitways, the O-Bahn fixed guideway system, and light rail transit (LRT) as compared to regular bus service operating on surface streets in mixed flow traffic.

Table A-1. **Semirapid Transit Modes (Transitway Bus, O-Bahn, and Light Rail Transit) Compared with Regular Buses on City Streets**

Item	Transitway Bus	O-Bahn	Light Rail Transit
System and operation			
Capacity	+	0	++
Right-of-way width	0	+	+
Dynamic performance	0	0	+
Permanence of right-of-way exclusivity	+	++	++
Tunnel operation ability	0	+	++
Safety	+	++	++
Need for new technology	0	-	--
Level of service			
Need to transfer	0	0	--
Reliability of service	++	+	++
Comfort (seats, riding)	+	+	++
Costs			
Investment cost	-	-(-)	--
Operating cost	+	+	++
Impacts			
Image, land use impacts	0	+	++
Noise	0	0	+
Exhaust	0	0	++

Note: "--" very much inferior, "-" inferior, "0" no difference
"+" superior, "++" very much superior

Source: Vuchic, V.R., Transportation Research Record 1011, Transportation Research Board, Washington, DC, pp 8-15.