ALTERNATIVE MASS TRANSPORTATION TECHNOLOGIES
TECHNICAL DATA

by

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Research Report 339-4
Improving Urban Mobility Through Application of High-Occupancy Vehicle Priority Treatments

Research Study Number 2-10-84-339

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16. Abstract

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This report documents data describing alternative mass transit systems. Considered in this document are high-occupancy vehicle facilities, heavy rail transit, light rail transit, and automated guideway transit. Data included address areas such as capital cost, operating cost, ridership, mode split, and transit operating characteristics. The data are intended to provide decision-makers with information that may be useful in comparing various transit technologies.

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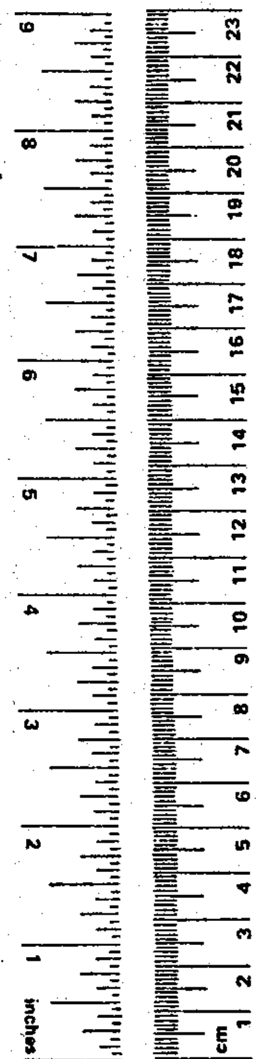
METRIC CONVERSION FACTORS

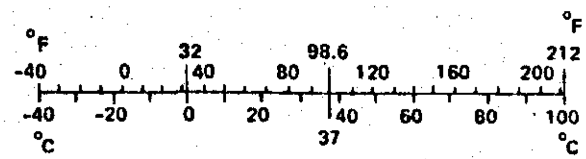
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
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)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
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)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

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

ABSTRACT

The State Department of Highways and Public Transportation has funded research in the area of high-occupancy vehicle (HOV) priority facilities for over a decade. Recently, major transit plans have been developed for the Dallas and Houston areas. Those plans considered, in addition to HOV facilities, various rail technologies. Similar analyses are now being initiated in the Austin area.

This report documents data describing alternative mass transit systems. Considered in this document are high-occupancy vehicle facilities, heavy rail transit, light rail transit, and automated guideway transit. Data included address areas such as capital cost, operating cost, ridership, mode split, and transit operating characteristics. The data are intended to provide decision-makers with information that may be useful in comparing various transit technologies.

Key Words: Mass Transit, Light Rail Transit, Heavy Rail Transit, Bus Rapid Transit, High-Occupancy Vehicle Facilities, Automated Guideway Transit

SUMMARY

This report presents data from existing and proposed transit systems. The data are intended to help define the advantages and disadvantages of alternative transit technologies. In particular, data associated with bus transitways, light rail transit systems, heavy rail transit systems, and automated guideway transit are presented. The data are intended to be of benefit to policy makers in assessing the role of transit and in comparing alternative transit technologies.

Much of the data presented is shown as averages. Due to the differences between systems, care must be exercised in interpreting aggregated data.

Roles of Urban Public Transit

As defined in this report, transit serves 3 primary roles. The first is referred to as public transportation. This form of transit primarily offers some level of mobility to those who otherwise would not be able to make the trip; it provides transportation to employment, shopping, medical facilities, etc., for those without access to auto transportation. This is the principal role transit has served in Texas for the past 2 decades; it serves a social-welfare function. This transit role is not specifically addressed in this report.

A second role is referred to as internal circulation. Within major activity centers, travel distances can become too long to be served only by walking. Some form of mechanized transport may be needed to help meet travel demands that exist within major activity centers. Limited data regarding this role are included in this report in the "Automated Guideway Transit" section.

The third major role is referred to as mass transportation. To support the intensity of development occurring in Texas cities, a high-capacity mass transportation system is essential. The primary intent of this role is to move large volumes of persons to major employment centers during peak commuter periods. In fulfilling this role, transit is serving an economic need. It is a role that can be served by transitways (i.e., high-occupancy vehicle facilities), heavy rail transit, or light rail transit. This mass transportation role is the primary topic of this report.

The Need For Mass Transportation

A relationship exists between transportation and the intensity of land use development. Once a city attains a certain size, a mass transportation system must be provided to supplement the street and highway network. Larger Texas cities have grown to a size that requires development of mass transit.

Congestion on the streets and highways serving the large employment centers is severe; these employment centers are projected to experience substantial growth. It is not possible, nor economically feasible, to serve that growth simply by more use of the private auto at 1.2 occupants per auto.

Transit use in large Texas cities, relative to other major North American cities, is relatively low (Table S-1). The percent of trips served by transit will need to essentially double, as will the number of transit trips per capita.

Table S-1. Comparison of Current Transit Usage in Texas Relative to Other North American Cities

Indicator of Transit Usage	Corresponding Value
Percent of Peak-Period Downtown Work Trips	
Served by Transit	
Average, 18 cities outside of Texas	51%
Average, 4 largest Texas cities	25
Annual Transit Trips Per Capita	
Average, 15 cities outside of Texas	85.1
Average, 3 largest Texas cities	38.8

Given that total population and employment are increasing, the absolute number of trips served by transit will need to increase by a factor of 3 to 4. For example, today in Houston some 11,000 persons enter downtown by transit in the peak-hour, and 16,000 persons enter downtown Dallas; both of those volumes will need to be in excess of 40,000 within the next 20 to 30 years.

In general, mass transportation will need to serve approximately 15% of total work trips in the large urban areas. More importantly, 30% to 50% of work trips to the large activity centers will need to be served by mass transportation.

Comparative Mass Transportation Data

This section summarizes some of the data presented in the main text. Due to site specific differences, considerable care must be used in drawing conclusions from aggregated data.

Capacity

Capacity for the line-haul portion of the transit trip is not a consideration in selection of transit technology for Texas. Long-range planning in both Houston and Dallas has identified a maximum peak-hour, peak-direction demand to be in the range of 12,000 persons per hour. All technologies being considered -- transitways, light rail transit, and heavy rail transit -- have demonstrated the capability to serve that level of demand.

In considering the capacity issue, it is essential to evaluate both the line-haul capacity and the collection-distribution capacity within the activity center. That is, while the demand in each corridor can be satisfied, accommodating demand within the activity center where several corridors converge will require careful planning and analysis. No universal conclusions can be drawn concerning capacity in the activity centers; site specific analyses will be required. While it is known that rail in subways can serve the function, the constraints of bus operations on downtown surface streets are not as well defined.

Capital Cost

Capital cost data for the technologies being considered are summarized in Table S-2.

Table S-2. Capital Cost Per Mile, Major Transit Projects

Technology	Cost Per Mile (millions of dollars)	
	Range	Non-Weighted Average
Bus Transitway (n=14)	$ 2.4 -$ 20.0	$ 8.1
Heavy Rail Transit (n=12)	$22.4 -$268.2	$98.8
Light Rail Transit (n=23)	$ 7.3 -$ 78.1	22.6[1]
Automated Guideway Transit		
People Mover (n=8)	$18.4 - $100.0	$48.9
Intermediate Capacity (n=3)	$34.7 - $ 45.6	$39.6

[1]Two systems have unusually high costs. Not considering those two costs, the non-weighted average (n=23) is $18.8 million per mile.

Source: Main text; Tables 24, 39, 47 and 51

The cost values shown above are, in general, an average of construction year dollars rather than current dollars; since all technologies have a similar mix of construction years, this would not appear to be a major problem in comparing the relative magnitude of costs. For schematic conceptual planning, the following might provide an estimate of expected current costs for new systems as opposed to extensions of existing systems. Again, site specific features can result in costs different from those shown below.

- Transitways $ 10 million per mile
- Heavy Rail Transit $100+ million per mile

- Light Rail Transit — $15-$25 million per mile
- Automated Guideway Transit
  - People Mover — $40-$75 million per mile
  - Intermediate Capacity — $40-$50 million per mile

As stated in Pushkarev (2), "Obviously any aggregate averages of this type have to be treated with caution; they cannot reflect the large variation in site specific construction conditions, including geology and groundwater, the method of construction, the amount of utility relocation, the need to underpin buildings, local labor relations and the prospect for administrative or other construction delays..."

Operating Cost

Operating cost for the technologies being considered are summarized in Table S-3.

Table S-3. Operating Cost (Cents Per passenger Mile), Major Transit Projects

Technology	Cost Per Passenger Mile (cents)	
	Range	Non-Weighted Average
Bus Transitway (n= 4)	5.5 - 15.4	9.9
Regular Route Bus Service (n=14)	16-50	27.7
Heavy Rail Transit (n=11)	13-32	19.6
Light Rail Transit (n=5)	6-50	18.8
Automated Guideway Transit		
People Mover (n=4)	19-44	29.8
Intermediate Capacity (n=1)	5	5

Source: Main text; Tables 26, 27, 39, 48, and 52.

One of the major variables influencing operating costs is labor. A summary of transit employees per 100,000 annual passengers is shown in Table S-4.

The data for buses is for the entire bus service. Data for bus transitways only are not available.

Given the extent and the range of the data reported in Tables S-3 and S-4, it appears that, at this level of analysis, all of the mass transit technologies have, in terms of cost per passenger mile, similar operating costs.

Table S-4. Employment Requirements of Alternative Transit Technologies

Technology	Employees/Million Annual Passengers	
	Range	Non-Weighted Average
Regular Route Bus Service (n=19)	14.4 - 45.8	26.9
Heavy Rail Transit (n=10)	11.2 - 44.4	26.9
Light Rail Transit (n=16)[1]	8.7 - 79.0	28.8
Automated Guideway Transit[2]		
People Mover (n=5)	1.1 - 40.0	19.3
Intermediate Capacity (n=1)	6.3	6.3

[1] Elimination of the Pittsburgh data reduces the average from 28.8 to 22.9. This is part of the reason why firm conclusions should not be drawn from this table; selective inclusion or exclusion of a limited number of data points can significantly change averages.

[2] Due to the limited data and the variation in the data, this should be viewed with extreme caution.

Source: Main text; Tables 36, 37, 46, and 50

System Characteristics

Table S-5 provides an overview of system characteristics. HOV technology tends to serve long-distance commute trips; thus, it has a longer trip length and a higher peaking factor. The lower rail peaking factor indicates these systems attract more off-peak utilization. Frequent rail station spacing is more attractive for serving shorter trips.

The line haul speed can be misleading. The rail speeds include station stops. The HOV speeds are line-haul operating speeds. To pick-up and distribute passengers, those buses will have to operate in mixed flow; this will typically occur at 10-15 mph outside downtown and 4-6 mph in the downtown.

Table S-5. System Characteristics of Alternative Mass Transit Technologies, Selected Systems

Technology/System	Line-Haul Speed (mph)[1]	Avg. Trip Length (miles)[2]	Ridership: Peak Hour (peak direction)	Ridership: Total Daily	Ridership: Peak Hr. as a % of Daily
High Occupancy Facilities					
El Monte, Los Angeles	50+	---	6,490	36,000	18%
Shirley Hwy., Virginia	50+	---	22,800	80,000	29
I-45 Contraflow, Houston	50+	9.6	5,500	16,600	33
Heavy Rail Transit, Avg.	32	7.5	---	---	13%
Manhattan, Lexington Ave.	18.3	7.0	35,700	250,000	14
Toronto, Yonge	20	3.5	22,900	200,000	12
Chicago, Dan Ryan	25	7.3	12,500	100,000	13
Light Rail Transit, Avg.	17	4.9	---	---	12%
Boston, Green Line	12	4.5	6,900	70,000	10
Pittsburgh, South Hills	14	7.0	3,800	25,000	15
Edmonton	22	3.5	2,100	20,000	12
Automated Guideway					
People Mover	13	0.8	---	---	--
Intermediate Capacity	22	6.4	---	---	--

[1]This is the speed on the transit guideway. For the rail systems this includes stops at stations. For the busways, distribution has to be made on city streets; outside the CBD this will occur at 10-15 mph; inside the CBD travel speed will be 4-6 mph.

[2]This is the trip length on the transit guideway. In some cases, the rail speeds and trip lengths are for the entire system, not just the line shown.

Source: Main text; Tables 15, 16, 17, 32, 35, 39, 42, 45, and 49.

Impact On Congestion

The principal role of mass transit in Texas is to accommodate growth without increasing existing congestion. While the contraflow lane moves over 8,000 persons in the peak period, the volume of traffic on the freeway lanes has not been affected. Similar data are beginning to develop for the Katy Transitway (Table 11).

Mass transportation should not be expected to "solve" the congestion problem.

Ridership Characteristics

All of the mass transit modes have demonstrated an ability to attract choice riders. If transit offers a reliable, fast, and cost competitive alternative, individuals will forego their auto to ride transit (Tables 29 and 40).

IMPLEMENTATION STATEMENT

Project 339 is oriented toward assisting the Department in the planning, implementation, and evaluation of priority treatment projects. As major Texas cities develop mass transportation plans, priority treatment is being considered as a possible alternative to rail for serving travel in at least some corridors. In comparing various transit technologies, a relevant data base is useful. The intent of this document is to present information that will be of value to decision-makers in assessing the advantages and disadvantages of the alternative transit technologies.

DISCLAIMER

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LIGHT RAIL TRANSIT, TECHNOLOGY

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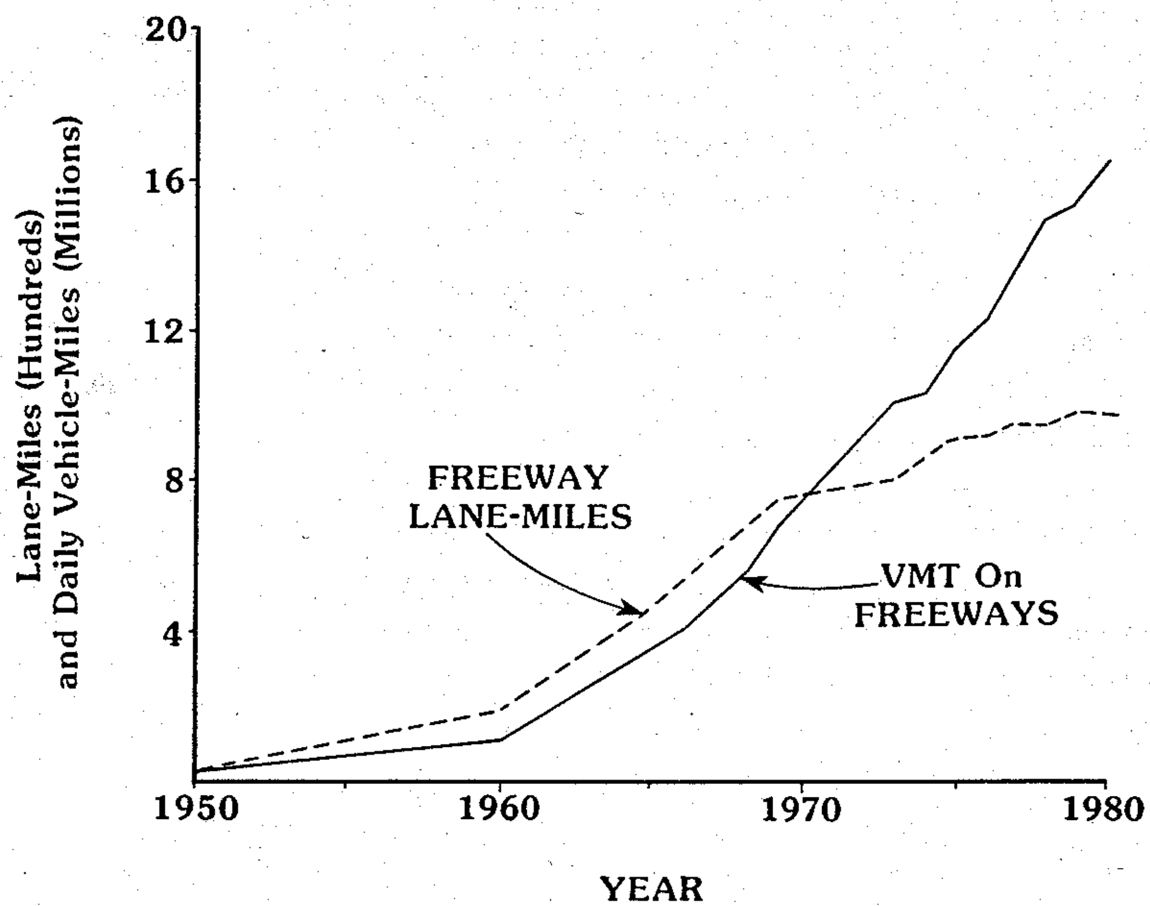
INTRODUCTION

Texas cities developed during the "age of the automobile". For the most part, a system of urban highways was provided in advance of development, and the true advantages of an auto-oriented transportation system were realized.

Even in the most congested of Texas cities -- Houston -- the auto oriented system provided excellent mobility until at least 1970; daily vehicle miles of travel per lane mile of freeway remained below 8500 (Figure 1).



Source: "Restoring Mobility in Houston, Texas, A Technical Paper", Prepared by Texas Section, Institute of Transportation Engineers, 1984.

Figure 1. Relationship Between Freeway Vehicle-Miles of Travel and Lane miles of Freeway, City of Houston

This highway system was well received by the public and provided the mobility necessary to allow two things to happen: 1) the residents of major Texas cities were able to choose a lifestyle centered around single-family dwelling units on individual lots; and 2) the transportation mobility existed to encourage and support the massive migration to the sunbelt along with its related economic benefits.

However, around 1970, two things began to happen. First, for a variety of reasons, the rate at which new highways were constructed was greatly curtailed. In Houston, a freeway system (lane miles) that was expanded by 300% in the 1960's was expanded by only 25% in the 1970's (Table 1). At the same time, with the migration to the sunbelt, massive increases in transportation demand resulted (Table 2). The effect was that cities that enjoyed excellent mobility in 1970 were highly congested by 1980. And, while Houston may be the most congested city, other Texas cities are not that far "behind" Houston in terms of congestion (Figure 2).

During this time period, public transportation in Texas was relatively insignificant. In 1976, fewer than 450 buses operated in Dallas and in Houston (1). Other major cities, such as Los Angeles, were operating in the range of 2000 buses.

In order for the major urban areas to continue to grow and receive the benefits of that economic growth and to provide an acceptable quality of life for urban Texans, new approaches for maintaining mobility need to be pursued; those measures at least partly involve expansion of the role served by public transportation.

Table 1. Trends in Travel Demand and Freeway Facilities, City of Houston

Year	Annual Average Population (1000)	Annual Average Vehicles (1000)	Freeway Travel in VMT Per Day[1] (1000)	Freeway Capacity (Lane-Miles)	Daily VMT Per Freeway Lane-Mile (1000)
1950	596[2]	240	201	24	8.4
1955	692[2]	375	620	100	6.2
1960	938[2]	480	1,044	187	5.6
1965	1,084	625	3,425	456	7.5
1970	1,240	777	7,320	761	9.6
1975	1,440	1,000	11,366	898	12.7
1980	1,604	1,272	16,308	959	17.0
Percent Increase Per Year					
1960-70	2.8	4.9	19.6	15.1	5.5
1970-80	2.6	5.1	8.4	2.4	5.9

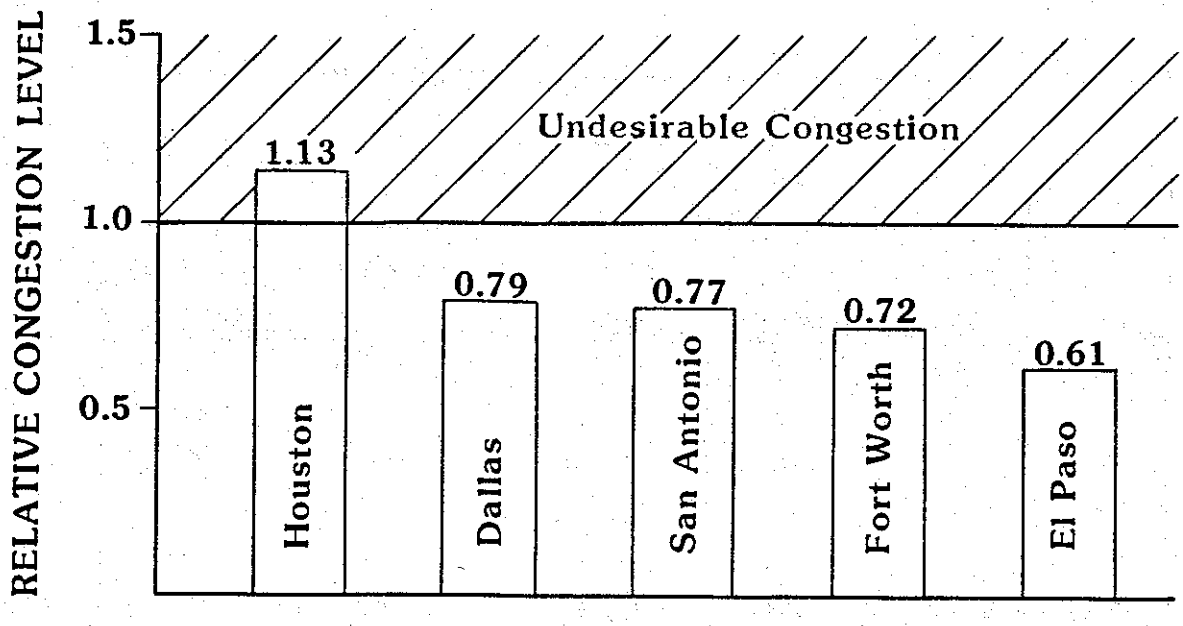
[1]VMT-Vehicle Miles of Travel

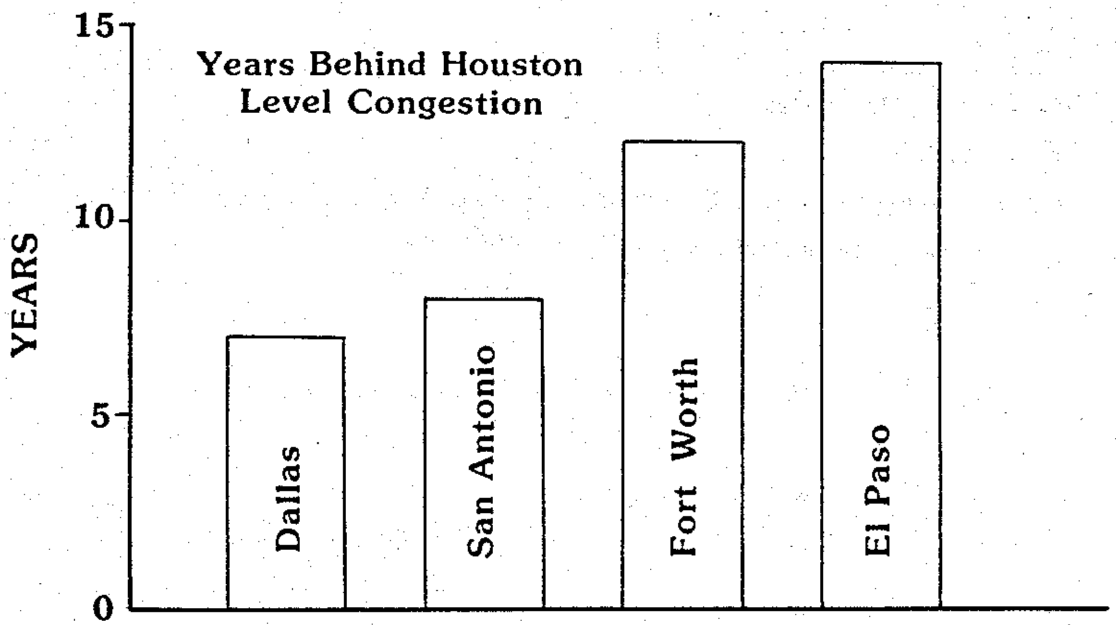
[2] As of April 1

Source: "Estimates of Relative Mobility In Major Texas Cities," Research Report 323-1F, Texas Transportation Institute, 1982.

Table 2. Growth in Factors Impacting Transportation, Harris and Dallas Counties, 1970-1980

Factor	% Increase, 1970-1980	
	Harris Co.	Dallas Co.
Population	+ 37%	+17%
Vehicle Registration	+ 80%	+45%
Vehicle-Miles of Travel	+ 75%	+75%





Source: "Estimates of Relative Mobility In Major Texas Cities," Research Report 323-1F, Texas Transportation Institute, 1982.

Figure 2. Relative Congestion Levels in Major Texas Cities, 1980

Purpose of this Report

Several major Texas cities are currently pursuing major mass transportation plans. Project 339 has always been oriented toward assisting the Department in planning, implementing, and evaluating high-occupancy vehicle (HOV) lanes. These lanes are now being viewed as one alternative approach for providing mass transportation and, increasingly, are being compared to various rail transit technologies.

It is the intent of this report to present unbiased data describing existing and planned transit technology. The thrust of Project 339 and its predecessor (Project 205) has been HOV lanes; as a result, much of the data in this report pertains to HOV lanes. However, relevant data pertaining to the need for mass transportation, light rail transit, heavy rail transit, and automated guideway transit are also presented.

THE ROLES OF URBAN PUBLIC TRANSPORTATION

While there is overlap between roles, in urban areas transit serves three different roles. Depending upon the role being served, the transit technology and operating strategy employed can vary considerably. As defined in this report, the three principal roles are mass transportation, internal circulation, and public transportation.

Mass Transportation

Transportation and intensity of land use are interrelated. The type(s) of transportation system available influences how large an urban area can grow; this relationship is quantified in a subsequent section of this report.

To support the intense development associated with large urban areas, a high-capacity mass transportation system is essential. The primary intent of this mass transportation role is to move large volumes of persons to major employment centers during peak commuter periods. In fulfilling this role, transit is serving an economic need.

It is this mass transportation role that is primarily addressed in this report.

Internal Circulation

Within major activity centers (e.g. large downtown areas, airports, universities, amusement parks, etc.), travel distances can become too long to be served only by walking. Some form of mechanized transport may be needed to meet the travel demands that exist within these activity centers. Various types of transit technology -- often referred to as people movers or automated guideway transit (AGT) -- are used to serve this transit role, which is referred to in this report as internal circulation. In some instances, the mass transportation system ties directly into the internal circulation system.

Limited data are included in this report describing the internal circulation function. Also included in this category is data pertaining to the "so called" intermediate capacity transit systems (ICTS).

Public Transportation

In all urban areas there is a segment of the population that does not, or cannot, meet travel needs through use of the private automobile. Included in this group are the very young, the elderly, handicapped persons, and individuals who do not have an auto available for their trip. A transit system can offer these individuals a basic level of mobility. This form of transit primarily fulfills a social need. It is referred to as public transportation.

Characteristics of the types of persons and trips commonly served by transit systems providing primarily public transportation (at the time of the surveys) is shown in Table 3.

This is the only role that has, historically, been served by transit in Texas. As a result, to many Texans, this is the only role that comes to mind when transit is discussed.

However, this role is not addressed in this report. Public transportation largely serves a social-welfare function, and how much (if any) of this service is provided is essentially a policy decision.

This report concentrates on the economic role served by mass transportation. For major Texas cities, this mass transportation role is relatively new.

Table 3. Characteristics of Public Transportation Patrons

Characteristic[1]	Houston	San Antonio	Waco	Wichita Falls
Riders Per Day, Thousands	67	75	1.6	1.6
% Daily Users	75	76	69	69
Family Income Level				
% less than $3000	32	32	--	--
% less than $4000	--	--	50	53
% less than $6000	67	71	90	82
% Riders from families that do not own a car	45	44	54	56
% Riders with no car available for that trip	80	84	89	--
Sex of Rider				
% Male	28	29	30	27
% Female	72	71	70	73
Age of Riders, years				
% Under 16	3	6	--	12
% 17-65	92	88	--	73
% Over 65	5	6	--	15

[1]These surveys were performed in the early 1970's. At that time, the type of transit service provided by these systems was all essentially public transportation.

Source: Transit studies conducted in the various cities.

THE NEED FOR MASS TRANSPORTATION IN TEXAS

The mass transportation role -- as defined in the previous section of this report -- can be served by several alternative transit technologies. In this report, primary consideration is given to the advantages and disadvantages associated with using high-occupancy vehicle lanes, light rail transit, or heavy rail transit to serve the mass transportation role; all of these are alternative mass transportation technologies.

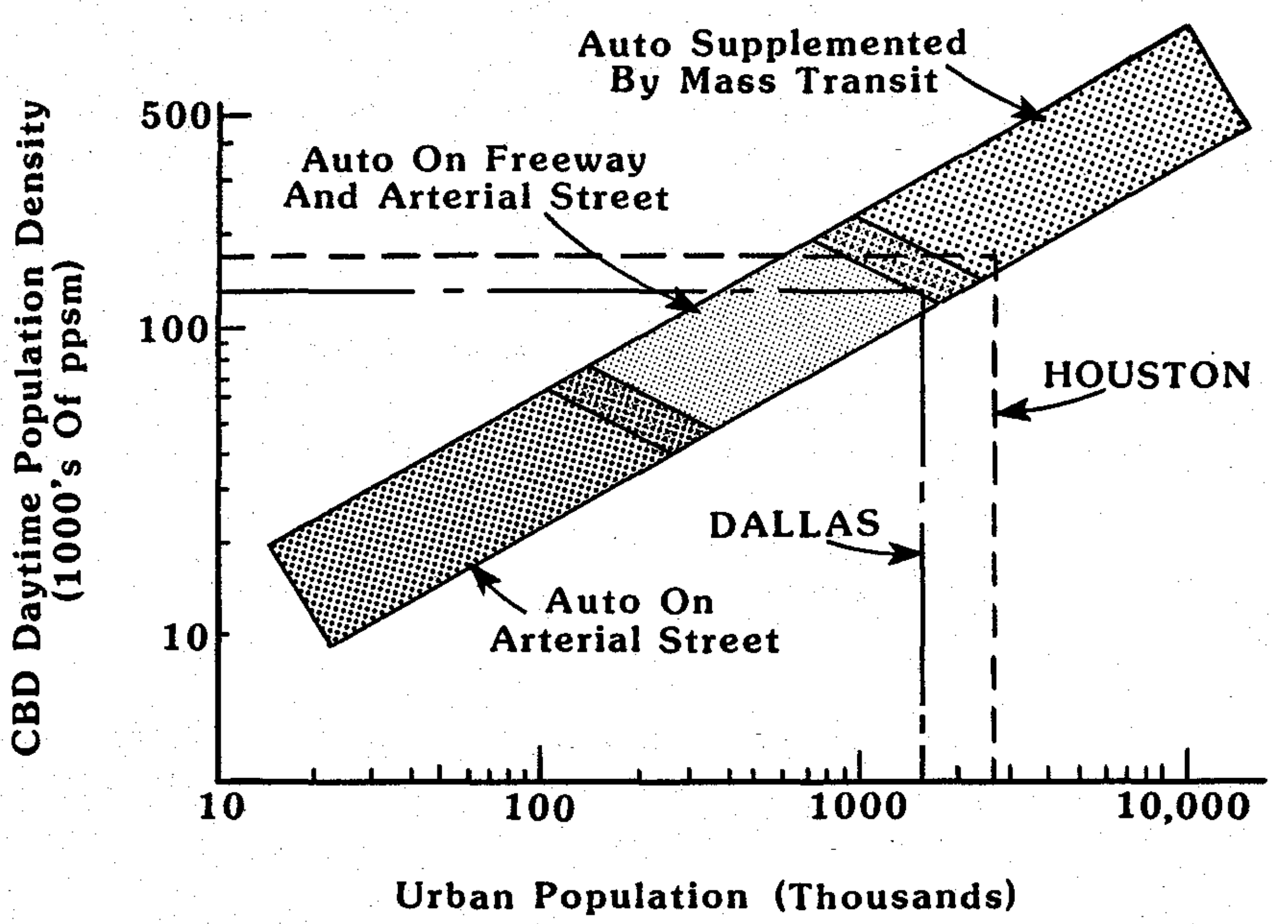
Also, it should be emphasized that, while this report concentrates on the need to develop mass transportation in Texas, mass transportation is only one tool that must be used to maintain and restore mobility in Texas cities. Continued street and highway construction is also essential.

The Transportation/Land Use Relationship

As indicated in the previous section, a relationship exists between transportation and land use. Urban areas can only grow to certain sizes depending upon the type of transportation system available.

Theoretical research, confirmed by observation of transportation in major cities, has quantified the transportation/land use relationship (Figure 3). That figure suggests that, with an excellent urban arterial street system, a city can grow to a population of about 250,000. If an extensive freeway system is superimposed over the arterial street system, the resulting transportation system can support an urban population of up to 2,000,000. To support a larger development, a high capacity mass transportation system is required to move large volumes of persons to major employment centers during peak commuter periods. As defined in the previous section of this report, this is the transit role referred to as mass transportation.

Just as it is necessary to begin to develop a freeway system once a city reaches a certain size, it is necessary to develop a mass transportation system once that city reaches a certain larger size.



Source: "The Influence of Transportation On The Intensity of CBD Development", Compendium of Technical Papers, TexITE Annual Meeting, 1973

Figure 3. The Relationship Between Transportation and Land Use

In reviewing Figure 3, two points should be made. First, both Houston and Dallas have attained sizes that mandate that a mass transportation system be developed. Second, neither Houston nor Dallas has an ideal arterial and freeway system; that simply re-emphasizes the need for a mass transportation system.

The relative extent of the freeway system in major Texas cities is shown in Table 4. In terms of limited access highway miles per million residents, of the 20 largest metropolitan areas, only New York City, Los Angeles, and Chicago have fewer miles than Houston. Dallas has 80% more miles per resident than Houston.

Table 4 Extent of Limited Access Highway Development in Major Urban Areas

Metropolitan Complex	Land Area (mi^2)	Population	Limited Access Divided Highway Miles			Limited Access Divided Highway Density	
			Interstate	State & Local	Total	Miles per 100 sq mi	Miles per million pop
1. New York	2500	13,987,900	215	585	800	32.0	57.2
2. Los Angeles/Long Beach	2100	9,409,227	270	260	530	25.2	56.3
3. Chicago	1750	7,745,109	225	165	390	22.3	50.4
4. Philadelphia	2750	5,548,789	205	285	490	18.1	88.3
5. Detroit	2500	4,617,510	245	160	405	16.2	87.7
6. San Fran./Oak/San Jose	1900	4,547,792	180	190	370	19.5	81.4
7. Boston	2050	3,751,645	155	185	340	16.6	90.6
8. Washington, D.C.	2200	3,060,240	175	120	295	13.4	96.4
9. Dallas/Fort Worth	2400	2,974,878	285	160	445	18.5	149.6
10. Houston	2400	2,905,350	150	80	230	9.6	79.2
11. Miami	1100	2,640,022	55	130	185	16.8	70.1
12. Cleveland	1750	2,559,048	225	115	340	19.4	132.9
13. Saint Louis	2250	2,355,276	210	30	240	10.8	102.8
14. Pittsburgh	2450	2,263,894	120	160	280	11.4	123.7
15. Baltimore	1700	2,174,023	160	75	235	13.8	108.1
16. Minneapolis	2300	2,114,256	180	55	235	10.2	111.2
17. Seattle	2400	2,092,408	130	120	250	13.2	119.5
18. Atlanta	2400	2,029,618	265	55	320	13.3	157.7
19. San Diego	1350	1,861,846	150	60	210	15.6	112.8
20. Denver	2400	1,619,921	140	60	200	8.3	123.5
AVERAGE	2105	4,012,938	187	153	340	16.2	84.7

Source: "Limited-Access Divided Highways in America's Twenty Largest Metropolitan Complexes," West Houston Association, 1983.

Downtown Trips Served By Transit

In most cities, mass transportation primarily serves trips to and from the central business district (CBD). Transit is most effective at serving trips to densely developed activity centers, and the CBD is generally the most intensely developed (employment per square mile) activity center in an urban area. As a result, one measure of the extent of mass transportation in an urban area is the percentage of downtown trips served by transit.

Percent of Peak Period Trips to Downtown by Transit

In most urban areas in the United States, transit serves fewer than 5% of total urban person trips. However, for certain types of trips at certain times of day (i.e., peak-period work trips), mass transportation serves large volumes of urban commuters. Table 5 summarizes data for several North American cities; the data in that table show that the average major city outside of Texas has 51% of peak-period CBD trips served by transit; in Texas, that average is 25%.

Transit plans being developed for major Texas cities generally call for serving 40% to 50% of downtown work trips by transit. These percentages are certainly "in line" with the values shown in Table 5. They also represent nearly doubling the percentage of trips currently served by transit.

Table 5. Percent of Peak-Period Downtown Work Trips Served by Mass Transportation, Selected North American Cities

City	% of Trips	City	% of Trips
Atlanta	40%	New York City	80%
Boston	49	Ottawa	70
Chicago	81	Philadelphia	64
Cleveland	50	Pittsburgh	65
		Portland, Ore.	45
Dallas	30	San Antonio	27
Denver	30	Seattle	50
Detroit	35	Toronto	80
Fort Worth	7		
Houston	18	Vancouver, B.C.	40
Los Angeles	39	Washington, D.C.	38
Miami	14		
Milwaukee	25		
Average, all cities outside of Texas		51%	
Average, Texas cities		25%	

Downtown Cordon Counts

Most major cities conduct downtown cordon counts. Those counts are useful in understanding travel patterns. A summary of cordon count data for selected cities is shown in Table 6. That table also reflects the current dependence on auto travel in Texas cities.

Table 6. Peak-Hour Person Travel Into Selected Downtown Areas by Mode

Urban Area	Arrival Mode				
	Auto & Vanpool	Transit		Other	Total
		Bus	Rail[1]		
Boston (1982)	55,030 (45%)	11,384 (9%)	48,754 (40%)	6,600 (6%)	121,828 (100%)
Chicago (1982)	23,985 (15%)	27,150 (18%)	97,622 (63%)	6,420 (4%)	155,177 (100%)
Dallas (1983)[2]	36,900 (69%)	16,400 (31%)	0	---	53,300 (100%)
Fort Worth (1983)[2]	20,700 (93%)	1,600 (7%)	0	---	22,300 (100%)
Houston (1980)	49,000 (82%)	11,000 (18%)	0	---	66,000 (100%)
Los Angeles (1980)	47,716 (54%)	34,358 (39%)	0	6,303 (7%)	88,381 (100%)
Miami (1985)	22,000 (76%)	5,000 (17%)	2000 (7%)	---	29,000 (100%)
San Antonio (1979)	15,455 (73%)	5,794 (27%)	0	---	21,249 (100%)

[1]All forms of rail, including commuter rail.

[2]Estimated from peak 2-hour data.

Source: Downtown cordon counts for respective cities.

As indicated previously, the percentage of downtown trips served by transit in Texas cities may need to double. However, given the growth that is occurring in Texas cities, the absolute volume of persons using transit for the downtown trip may need to increase by a factor of 3 to 4 for this to occur (Table 7). Virtually all of the growth in travel to the downtown will need to be accommodated by transit. For example, while approximately 16,000 persons currently enter downtown Dallas by transit in the peak hour (Table 6), if the projected growth occurs in the downtown area and if DART achieves its desired mode split, some 40,000 to 50,000 persons will use transit to travel to downtown Dallas; this is similar to the Houston volume (Table 7).

Table 7. Estimated 1980 and 1995 Peak-Hour Person Trips to Downtown Houston, By Mode

Arrival Mode	Year	
	1980[1]	1995[2]
Auto	45,000 (75%)	48,000 (48%)
Vanpool	4,000 (7%)	12,000 (12%)
Transit	11,000 (18%)	40,000 (40%)
Total	60,000 (100%)	100,000 (100%)

[1]1980 Cordon count with TTI estimate of vanpooling.

[2]TTI estimate.

Annual Transit Trips Per Capita

Tables 5-7 all reflect downtown travel and illustrate that, in relation to other major cities, transit is serving a relatively small percentage of downtown trips in Texas. Not surprisingly, total annual transit trips per capita are also relatively low for Texas cities in relation to other cities (Table 8). Again, the national numbers are twice the Texas numbers.

It is also of interest to note that, while in Texas it will be necessary to greatly increase the number and percentage of persons using transit, between 1970 and 1980 the number of workers using transit in major Texas cities showed little change. However, many cities in the southwest and west did experience significance increases in persons using transit (Table 9). In evaluating the numbers in Table 9, it might be noted that the Houston regional transit plan calls for serving 14% of total regional work trips by transit in the year 2000; that value appears to be a reasonable goal.

Table 8. Annual Transit Trips Per Capita, Selected North American Cities, 1983

City	Urbanized Area Population[1]	Unlinked Passenger Trips (System Total)	Annual Transit Trips Per Capita
Atlanta	1,613,357	124,787,000	77.4
Boston	2,678,473	253,055,149	94.5
Chicago (CTA)	6,779,799	624,713,727	92.2
Cleveland	1,752,424	85,709,771	48.9
Dallas	904,000	35,810,000	39.6
Denver	1,352,070	48,249,949	35.7
Houston	1,956,000	67,000,000	34.2
Los Angeles (SCRTD)	9,479,436	415,865,888	43.9
Miami	1,608,159	64,299,727	40.0
Milwaukee	1,207,008	76,574,249	63.4
New York City (NYCTA)	15,590,274	2,067,485,945	132.6
Ottawa	717,978	111,518,192	155.6
Philadelphia (SEPTA)	4,112,933	355,989,764	86.6
Pittsburgh	1,810,038	90,286,439	49.9
San Antonio	785,000	33,433,000	42.6
Seattle	1,391,535	79,682,642	57.3
Toronto	2,998,947	649,936,512	216.8
Vancouver, B.C.	1,269,183	104,474,624	82.3
Average, all cities outside of Texas			85.1
Average, Texas cities			38.8

[1]In many instances the urban area population is not the same as the service area population. As a result, the trips per capita measure is subject to error in the table.

Source: American Public Transportation Association, "1984 Operating Report". Texas population data from "Texas Transit Statistics" published by the Texas Department of Highways and Public Transportation, with additional population data provided by Metropolitan Transit Authority of Harris County.

Table 9. Work Trips Served by Transit, Selected U.S. Cities

City	Percent of Total Workers Using Public Transportation		Percent Change In Total Number of Workers Using Transit
	1970	1980	1970-1980
Atlanta	8.4%	7.6%	+30.4%
Boston	19.7	15.6	- 8.7
Chicago	23.3	18.0	-12.6
Cleveland	13.4	10.6	-18.9
Dallas-Fort Worth	5.1	3.4	+ 1.4
Denver	4.4	6.1	+129.2
Detroit	7.9	3.7	-49.0
Houston	5.4	3.0	+ 2.4
Los Angeles - Long Beach	5.6	7.0	+52.5
Milwaukee	12.0	7.7	-26.2
New York City	52.5	45.1	-17.2
Philadelphia	20.7	14.0	-28.1
Pittsburgh	14.6	11.5	-14.9
San Antonio	5.6	4.6	+11.6
Seattle	7.1	9.6	+94.4
Washington, D.C.	16.3	15.5	+18.5
United States Total[1]	9.0	6.4	- 7.3
Average, all cities outside Texas[2]	15.8	13.2	+11.5
Average, all Texas cities	5.4	3.7	+ 5.1

[1]Includes numerous cities not shown in table.

[2]Includes only cities shown in table.

Source: U.S. Bureau of the Census, 1980 Census of Population, Summary Tape File 3.

Transit Volumes to be Served In Texas

When mass transportation is discussed, people frequently think of the passenger volumes served in New York and feel a need exists for an extremely high-capacity transit system. In reality, the volumes to be served in Texas cities are not unusually high.

Three North American cities -- New York, Toronto, and Montreal -- have high peak-hour volumes. The 28 rapid transit tracks entering these three downtowns in 1976 averaged 21,500 persons per track per hour; this is in contrast to 6,500 per track entering the downtowns of Chicago, Philadelphia, Boston, San Francisco and Newark. Three tracks into Washington, D.C. in 1980 averaged 11,000 peak-hour entrants, while the tracks into Atlanta averaged just over 4,000 patrons per hour (2).

Estimates of peak-hour transit volumes in major corridors in Houston are shown in Table 10. These year 2000 estimates are roughly half of existing volumes in Montreal, Toronto, and New York City. The highest estimated transit volume in the Dallas area, projected to occur in the North Central corridor, in roughly equivalent to that projected for the Houston Westpark corridor.

The projected Dallas data are not greatly different from the Houston data in Table 10. In the North Central Expressway corridor -- the highest volume Dallas corridor -- the maximum peak hour volume (2 directions) is 15,000.

Table 10. Morning Peak Hour, Peak-Direction Maximum Transit Load, Houston, Year 2000

Corridor/Facility	Maximum Passenger Volume
I-45 North	9,000
Eastex	7,000
East End	2,000
Gulf, I-45 South	6,500
TSU/U of H/SH 35	4,000
South/Southwest	6,000
Southwest Freeway	5,500
Westpark	12,000
Katy	11,500
US 290	4,000
Ft. Worth and Denver RR	9,000

Source: Metropolitan Transit Authority of Harris County, Regional Transit Plan, Background Briefing Material, Fall, 1984.

As is shown subsequently, the magnitude of the volumes in Table 10 is a critical consideration. All of the mass transportation modes considered in this report have the demonstrated capacity to serve the volumes shown in Table 10; as a result, capacity does not become an issue in selecting between the alternative transit technologies discussed in this report.

Impact of Mass Transportation on Freeway Congestion

An argument frequently made for mass transportation is that it will reduce corridor traffic congestion. In rapidly growing urban areas, such as Texas, this is not likely to be true.

Freeway traffic volumes are typically growing at 4% to 6% per year. In addition, in the congested corridors, a substantial latent traffic demand exists; that is travel demand that would occur were it not suppressed by the presence of intense traffic congestion.

As a result, in actuality, it is probable that, for each person attracted from highway travel to mass transportation, another will be attracted to highway travel. This has been the experience with the contraflow lane on I-45N in Houston. While that contraflow lane serves over 5000 peak-hour person trips -- the equivalent of two freeway lanes -- congestion in the mixed flow lanes has not changed (Table 11). Similar data are being shown for the Katy Freeway transitway in Houston.

Table 11. **Peak-Period (7-9 a.m.), Peak Direction Travel On I-45N at Link Road, Houston**

Year	Auto Volume, Vehicles	Contraflow Volume, Persons[1]
1978 (pre-contraflow)	12,724	0
1979	13,492	4,400
1984	13,104	8,000
[1]2.5 hour volume (6-8:30)		

Source: "Evaluation of the First Year of Operation, I-45 Contraflow Lane, Houston", Research Report 205-9, Texas Transportation Institute, 1981, and Texas Transportation Institute traffic counts.

Consequently, the benefit of the mass transportation system is, primarily, to move more persons during peak periods without increasing the level of congestion. Thus, more regional economic growth can be supported at existing levels of congestion.

It may be found that the mass transportation system may slightly reduce the duration of the peak period. However, studies to date in Texas have not confirmed that the duration of the peak has been shortened; mass transportation should not be expected to reduce the intensity of congestion that is occurring in a corridor, nor should it be anticipated that the duration of congestion will noticeably change.

Concluding Observations

In the major urban areas in Texas, it will be essential to continue to construct new streets and highways. The year 2000 transit plan for Houston indicates that, of total 24-hour trips, 4% will be served by transit (3).

Nevertheless, in the larger cities, it is critical to develop mass transportation systems oriented toward moving large volumes of commuters to major employment centers during peak periods. Houston and Dallas are projecting that, by the year 2000, transit will serve 14% of total work trips; for trips to major employment centers, between 30% and 50% of the trips will be served by transit (3). In order for the major Texas cities to be able to provide the mobility required for additional growth to occur, it is imperative that effective mass transportation systems be developed.

In general, the percent of total trips served by transit in the major cities will need to approximately double, as will transit trips per capita. Given the growth that is occurring in total areawide travel, this will result in the absolute number of trips served by transit increasing by a factor of 3 to 4. From 1970 to 1980, the total number of workers using transit in the major Texas cities remained essentially unchanged. However, there are indications that transit travel can increase substantially, as it did between 1970 and 1980 in cities such as Atlanta, Denver, Los Angeles, Seattle, and Washington, D.C. (refer to Table 9). Also, from 1980 to 1985, transit trips in Houston have increased from approximately 45 million to 67 million.

To sustain and support the type of development that is occurring in the larger Texas cities, a much larger volume of trips will need to be served by mass transportation.

HIGH-OCCUPANCY VEHICLE LANE TECHNOLOGY

This technology is referred to by a variety of names, including HOV lanes, authorized vehicle lanes (AVL's), busways, and transitways. Many of these facilities are developed within freeway rights-of-way; techniques include separate busway facilities, concurrent flow lanes, contraflow lanes, and priority entry ramps. These techniques are described in other sources (4,5), and a detailed description of the techniques is not included in this report. In essence, to implement these priority techniques the manner in which a freeway facility is designed or operated is altered to provide priority treatment for high-occupancy vehicles (buses, vanpools, carpools); the priority treatment offers a travel time reduction to HOV occupants relative to other freeway traffic. These projects tend to be "successful" when 1 minute of travel time savings is provided per mile of priority lane (6), and where a minimum time savings of 5 minutes is realized by the HOV's. To accomplish this, it is important to provide 50+ mph operation on the HOV lane. Total lane volumes must be controlled to assure this.

Recently, attention has also been focused on transitway facilities developed in separate rights-of-way. The data presented in this section apply to all types of priority lanes, both within and outside of freeway rights-of-way.

General Advantages and Disadvantages

A brief overview of some of the major advantages and disadvantages associated with the priority high-occupancy vehicle lanes is presented in this section. Much of this information is expanded upon subsequently in this report. The advantages and disadvantages are generally in comparison to a rail technology.

Advantages

Implementation Cost. These facilities often represent the least costly fixed transitway facility.

Implementation Time. These facilities can be planned, designed and constructed in a 3 to 8 year time frame. The construction involves well-known highway construction technology, a technology possessed by numerous firms in Texas.

Staged Opening. Transitways can be opened relatively easily as each section is completed. The entire facility does not need to be finished before benefits can be realized.

Limited Risk. The facilities are relatively inexpensive to construct. If the transitway is not sufficiently utilized, it can be converted to other useful functions such as additional mixed-flow lanes or emergency shoulders.

Cost Effectiveness. Evaluation of transitways on congested highways in Dallas and Houston has shown that the benefit/cost ratios for such projects are frequently in excess of 6.

Multi-Agency Funding. Transitways are eligible for local, state, and federal funding from both highway and transit agencies.

Multiple User Groups. In addition to transit vehicles, vanpools and carpools can also utilize the transitway, thereby increasing potential total person movement.

Labor Disputes. During transit strikes, vanpools and carpools can continue to use the transitway, transporting approximately 75% of the person movement that occurred on the facility prior to the strike.

Operating Costs. Bus operating cost (cents per passenger mile) on transitways are significantly lower than for local bus service. Also, the transitway operating costs (cents per passenger mile) are comparable to rail operating costs. No direct subsidy is required for the vanpool and carpool users of these facilities.

Operating Speed. Transit service on transitways is often express and non-stop. As a result, the line-haul travel speeds are extremely high. The systems in Houston are intended to operate at 50+ mph.

Park-and-Ride Lot Locations. Lots and bus transfer facilities can be located remote from the transitway on relatively inexpensive land without requiring a transfer at the line-haul transitway.

Flexibility. The vehicles using the transitway can use the existing street system for the collection/distribution function.

Disadvantages

Activity Center Distribution. Attempting to serve large volumes of buses on the downtown street system will pose problems. The extent of these problems is a function of the street layout, intersection levels-of-service, and sidewalk width. Also, operating speeds will be low in the downtown area.

Types of Trips Served. Transitways are typically oriented toward serving the long-distance urban commute trip; transitways typically do not have the frequent station spacing often associated with rail lines.

Location of Freeway Transitways. While locating high-occupancy vehicle lanes in the freeway reduces right-of-way costs and speeds implementation, that location also forces additional vehicular travel onto the already congested freeway corridors and the arterials serving those corridors. The median location of many transitways is not conducive to serving walk-in travel.

Construction Disruption. Users of the mixed-flow lanes are impacted by the freeway-oriented HOV construction. Desirably, needed freeway improvements will be made at the same time.

Potential Labor Savings. With current operations, transitways compare favorably with rail systems in terms of operating cost per passenger mile. Much of the operating cost is labor. A better potential appears to exist for rail (i.e., driverless vehicles) to reduce current labor costs in the long run.

Minimize Transfers. To the extent feasible, it is desirable to minimize transfers. If some rail is developed to serve travel into the major activity centers, patrons using buses on transitways may be forced to transfer from bus to rail to complete their trip. This decreases the attractiveness of transit.

Environmental. In some highly sensitive areas, the noise and air quality concerns associated with bus transit may pose significant problems.

Theoretical Transitway Capacity

Considerable disagreement exists over the capacity of a transitway. Frequently, low capacity is cited as a reason for selecting rail over transitways.

The available data suggest that line-haul capacity is not an issue; transitways have more than sufficient capacity to serve the volumes being estimated for corridors in Texas (refer to Table 10).

Capacity of a Freeway Lane

The capacity of a single lane transitway is at least somewhat related to the capacity of a single freeway lane; the capacity of a freeway lane is generally considered to be 2000 passenger car equivalents per hour (7). This is confirmed by observation of volumes on Houston freeways (Table 12). At that volume, the freeway operates at 30 to 35 mph.

Table 12 Observed Volumes on Houston Freeways

Freeway	Date and Time	Hourly Volume	Volume Per Lane
Katy Freeway, WB at Wirt	12/22/80, 3-4 p.m.	6437	2146
Katy Freeway, EB at Bunker Hill	6/14/83, 6-7 a.m.	5360	1787
W. Loop, SB at Buffalo Bayou	4/15/80, 7-8 a.m.	9273	1855
W. Loop, NB at Buffalo Bayou	7/27/83, 2-3 p.m.	7391	1848
S.W. Freeway, NB at Kirby	7/26/83, 5-6 p.m.	7388	1847

Source: Texas Transportation Institute traffic counts.

Theoretical Capacity of a Transitway Lane

Estimates of theoretical transitway capacity are shown in Table 13.

While the capacities shown in Table 13 vary considerably, all are well in excess of the demand volumes shown in Table 10. It is important to realize that most of the Table 13 volumes are for the line-haul section of the transitway; in planning, it is important to also consider the capacity of the collection and distribution system as well as the stations that interface with the line-haul sections to assure that the capacities are in-line with each other. Otherwise, the high line-haul capacity can become meaningless. The capacity of the collection-distribution system and stations is addressed subsequently in this report.

Existing Bus Volumes on Transitways

Table 13 shows theoretical capacity. Bus utilization on existing facilities is shown in Table 14. As shown subsequently, carpool volumes also use several of the facilities shown in Table 14.

Table 13. Typical Theoretical Bus Volumes

Facility or Source	Buses Per Hour	Headway (Seconds)	Average Bus Stop Spacing (Feet)	Average Bus Speed (mph)	Equivalent Passengers Per Hour[1]
G.M. Proving Grounds: Uninterrupted Flow (8) (Initial Studies)	1450[2]	2.5	No Stops	33	72,500
Highway Capacity Manual (7), 1965					
Freeway - Level of Service D	940	3.8	No Stops	33	47,000
Level of Service C	690	5.2	No Stops	40-60	34,500
G.M. Proving Grounds: 6-Bus Platoons, 30-sec On-Line Stops (8)	400	9.0	Variable	15	20,000
Estimates from El Monte Busway (9)	800	4.5	No Stops	50	40,000-43,750

[1]Equivalent passenger volume assumes 50 passengers per bus.

[2]Subsequent studies have reported bus volumes of 900 to 1,000 vehicles per lane per hour, these are consistent with reported flows.

Note: Carpools also use several of these facilities, refers to Tables 15 and 16.

With the exception of the Lincoln tunnel operation, all the projects in Table 14 are well below the capacity estimates shown in Table 13. The operators of the Lincoln Tunnel believe they can handle up to 1000 buses/hour. This contraflow lane is narrow and has relatively poor geometrics, both horizontal and vertical.

Existing Carpool Volumes on Transitways

One of the advantages of transitways is that, in addition to the bus volumes served (Table 14), some of these facilities also serve carpools and vanpools. There is some "overlap" between modes; that is, if carpools were not allowed to use transitways, some of the carpool patrons would use transit. Data from the El Monte Busway (9) suggest that as many as 25% of carpoolers may have been drawn from transit. Nevertheless, given the large percentage of total transitway person movement served by vanpools and carpools (Table 15), permitting these vehicles to use the transitway does increase total person movement.

Table 14 Existing Peak-Direction, Peak-Hour Bus Volumes on HOV Lanes

Location	Type of HOV Treatment	Peak-Hour Volume Per Lane	
		Persons	Buses
Lincoln Tunnel, New York City	Contraflow	30,000	600
Long Island Expressway, New York City	Contraflow	7,000	150
Gowanas Expressway, New York City	Contraflow	5,800	130
Brooklyn-Queens Expressway, New York City	Concurrent Flow	5,100	140
Shirley Highway, Washington D.C.[1]	Exclusive Lanes	12,000	200
I-66, Washington, D.C.	2-lane, 2-way	2,800	80
El Monte Busway, Los Angeles	Exclusive Lanes	3,400	75
PatWay, Pittsburgh	2-Lane, 2-way	5,000	60
I-45N, Houston	Exclusive Lane	3,300	66
Katy Transitway, Houston	Exclusive Lane	1,100	22
8-Lane Freeway (for comparison)	4 Lanes/Direction	9,000	-0-

[1]The Shirley Highway is a 2-lane reversible facility. The volume shown is a 2-lane volume.

Note: Carpools also use several of these facilities, refer to Tables 15 and 16.

Source: Data provided or estimated by operating agencies.

As shown in Table 15, between 21% and 88% of total person movement is served by carpools or vanpools. On I-66 in Virginia (10) lowering the carpool definition from 4+ to 3+ increased person movement by approximately 48%. Even though carpooling does draw some patronage from buses to carpools, in all instances where the volume of vehicles allowed to use an HOV lane has been increased, total person movement has also increased. These data are summarized in Table 16.

Table 15. Estimated Carpool and Vanpool Utilization of HOV Lanes

Facility and Time Period	Bus Passengers		Vanpool and Carpool Passengers		Total Passengers
	No.	%	No.	%	
Houston, I-45N Contraflow (buses and vanpools)					
6-8:30 a.m.	5,100	63%	3,000	37%	8,100
Houston, Katy Transitway (buses and vanpools)					
6-9:00 a.m.	2,000	69%	900	31%	2,900
Shirley Highway, Wash. D.C. (buses and 4+ carpools)					
7-8:00 a.m.	11,800	52%	11,000	48%	22,800
6-9:30 a.m.	23,700	55%	19,700	45%	43,400
El Monte Busway, Los Angeles (buses and 3+ carpools)					
6-10:00 a.m.	8,470	54%	7,330	46%	15,800
peak-hour	3,450	53%	3,040	47%	6,490
I-66, Wash., DC (buses and 3+ carpools)					
a.m. peak hour	2,600	29%	6,500[1]	71%	9,100
I-95 Miami Concurrent Flow					
a.m. peak hour	640	23%	2,200[1]	77%	2,840
U.S. 101 Marin County					
a.m. peak hour	3,700	79%	980	21%	4,680
Santa Monica, Los Angeles					
peak period	3,810	20%	15,289	80%	19,099
Banfield, I-80, Portland (buses and 2+ carpools)					
a.m. peak hour	300	12%	2,100	88%	2,400
Average, non-weighted	---	46%	---	54%	---

[1]Includes illegal vehicles (i.e., less than 3 persons/vehicle) in the priority lanes

Source: Texas Transportation Institute Surveys.

Table 16. Estimated Impact of Increasing the Volume of Vehicles Eligible to Use a High-Occupancy Vehicle Facility

Project Time Period Type of HOV	Vehicles Allowed in HOV Lane		HOV Vehicle Volume			HOV Person Volume			Violation Rate		HOV Speed (MPH)	
	Before (date)	After (date)	Before	After	% Chg.	Before	After	% Chg.	Before	After	Before	After
Banfield, I-80 Portland, Ore. (WB, A.M. Peak Hour)	Buses 3+ (1975)	Buses 2+ (1979)										
Bus			16	16		300	300					
Carpool			200	900		550	2100					
TOTAL			216	916	324%	850	2400	182%	18%-22%	6%-10%	48	50
I-95, Miami (Peak Hour)	Buses 3+ (1976)	Buses 2+ (1977)										
Bus			20	20		600	640					
Carpool			915	1100		1900	2200					
TOTAL			935	1120	20%	2500	2840	14%	63%	36%	50-55	50-55
Route 101, Concurrent San Francisco (SB, A.M. Peak Hour)	Bus Only (1974)	Buses 3+ (1976)										
Bus			94	97		3600	3700					
Carpool			—	288		—	979					
TOTAL			94	385	310%	3600	4679	30%	1%-3%	6%-18%	46	46
Garden State Pkwy. New Jersey (peak hour)	3+ (1980)	2+ (1981)										
Carpool			320	900	181%	870	1800	106%	10%-35%	6%-18%	58	56
El Monte, Los Angeles (WB, 6-10 AM)	Buses Only (1973)	Buses 3+ (1977)										
Bus			160	160		5200	5200					
Carpool			—	1200		—	4000					
TOTAL			160	1380	763%	5200	9200	77%	0%	10%	55	55
I-66, Virginia (AM, Peak Hour)	Buses 4+ (1982)	Buses 3+ (1984)										
Bus			70	79		2240	2600					
Carpool			900	1900		3900	6500					
TOTAL			970	1979	104%	6140	9100	48%	10%	10%	52	51
Shirley Hwy., Virginia (EB, 6-9:30 AM)	Buses Only (1970)	Buses 4+ (1973)										
Bus			310	350		13500	15700					
Carpool			—	1100		—	4500					
TOTAL			310	1450	367%	13500	20200	50%	0%	10%	NA	NA

Note: Some of the data, as presented in this table, are not available. In those cases, the estimates shown were made by combining data from several sources. Thus, some numbers shown are TTI estimates.

In assessing carpool utilization, it is important to maintain total vehicular flow at a level (perhaps less than 1200 vph/lane) that can be served at a high speed. High carpool volumes are beginning to lower the level-of-service provided on both the Shirley Highway and the El Monte Busway. This is a major concern in considering potential carpool utilization. It should be noted that, for all the projects listed in Table 16, adding new vehicles to the lane did not impact level-of-service. Had level-of-service been impacted, person movement may have been adversely impacted.

Daily Transitway Volumes

Most of the ridership values presented have been peak-hour or peak period. Daily ridership for selected facilities is shown in Table 17.

Table 17. Estimated Daily Ridership on Selected Transitway Facilities

Facility and Hours of Operation	Daily Passengers
I-45N, Houston, 5 hr./day (2.5/peak)	16,600
Katy Freeway, Houston, 6 hr./day (3/peak)	5,700
Shirley Highway, Washington, D.C., 20 hr/day	80,000
I-66, Washington, D.C., 4 hr./day (2/peak)	28,000
El Monte Busway, 24-hr., both directions	36,000
PatWay, Pittsburgh, 24-hr., both directions	49,000
Lincoln Tunnel, 3 hr. (7-10 a.m.)	50,000

Source: Texas Transportation Institute Surveys

Growth Trends in HOV Volumes

Once a transitway is implemented, most individuals need to make a mode shift to be able to use the facility. As a result, ridership does not develop immediately but rather, continues to grow for a period of several years. Figures 4-6 show growth trends on selected transitway projects. It is also evident from those figures that permitting carpools to use transitways has increased total person movement, confirming data shown in Table 16.

More detailed growth rates for the projects shown in Figures 4-6 are summarized in Table 18.

Table 18. Estimated Annual Growth Rates in Utilization of Selected Transitway Projects

Year	Shirley Highway 6-9:30 a.m.		El Monte Busway 6-10 a.m.		I-45N Contraflow both 2.5 hr. peak periods	
	Volume	% Increase	Volume	% Increase	Volume	% Increase
1970	4,500	----				
1971	9,000	+100%				
1972	12,000	+ 33%				
1973	13,500	+ 12%	1,700	---		
1974	20,000[1]	+ 48%	3,500	+105%		
1975	24,000	+ 20%	4,600	+ 31%		
1976	29,000	+ 21%	8,000[1]	+ 74%		
1977	34,000	+ 17%	9,200	+ 15%		
1978	37,000	+ 9%	10,000	+ 9%		
1979	43,000	+ 16%	13,000	+ 30%	4,324	---
1980	43,500	+ 1%	13,700	+ 5%	9,746	+125%
1981	43,500	0%	14,700	+ 7%	14,808	+ 52%
1982	41,900(est)	- 4%	13,100	(11%)	14,870	+ 1%
1983	40,300	- 4%	14,500	+11%	15,890	+ 7%
1984	NA	---	15,900	+10%	16,640	+ 5%
Average, non-weighted		21%		26%		38%
Average, 1st 5 years		43%		47%		38%

[1]Carpools introduced onto project.

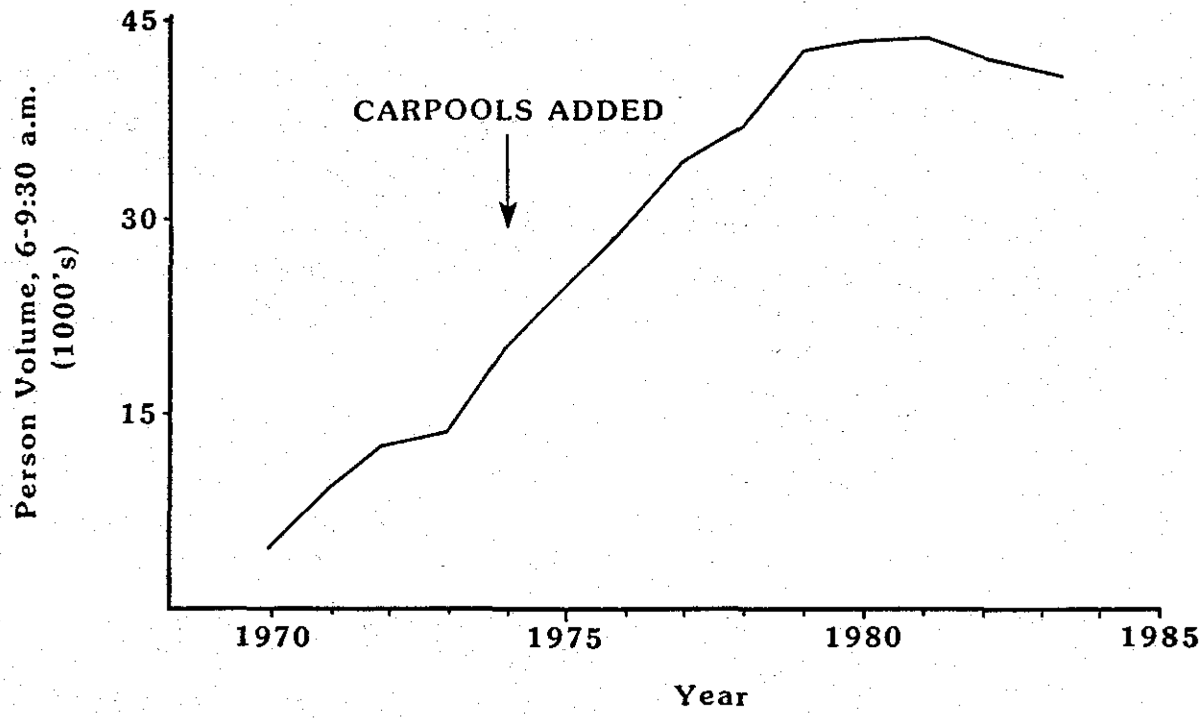


Figure 4. Shirley Highway, Virginia, Trends in Utilization

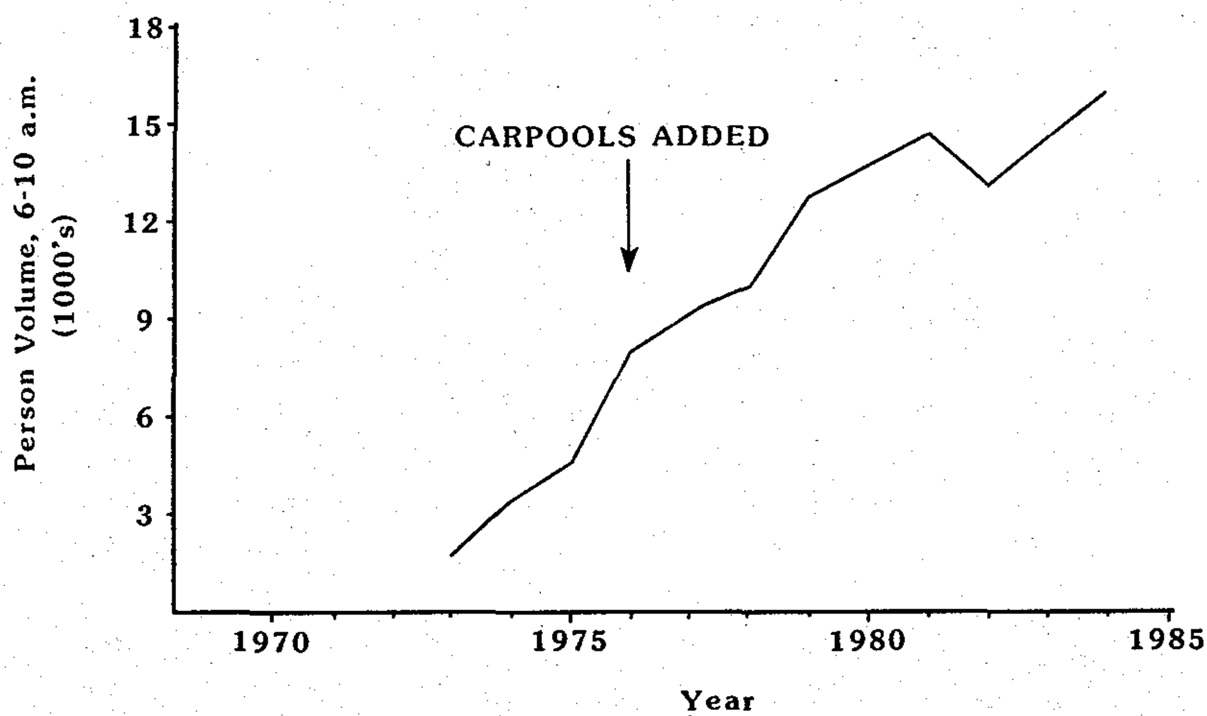


Figure 5. El Monte Busway, Los Angeles, Trends in Utilization

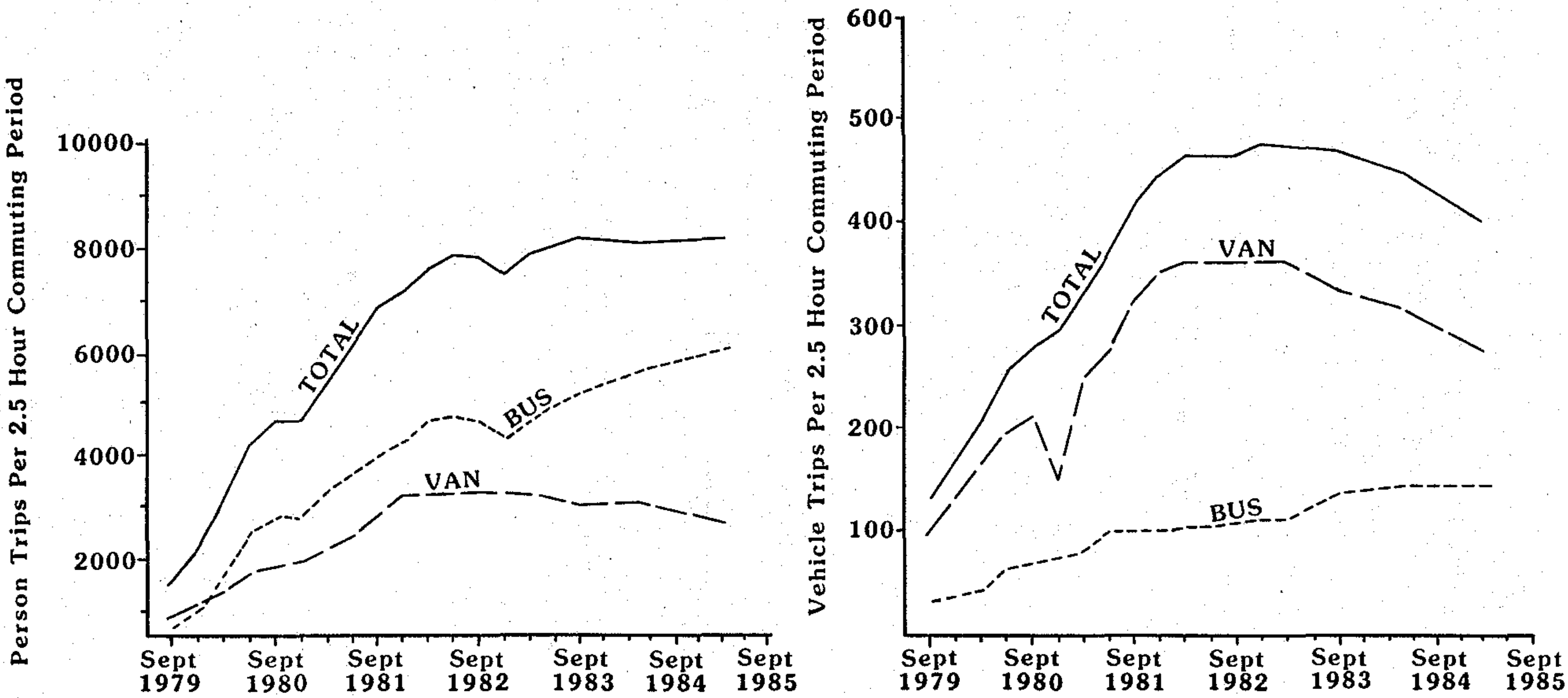


Figure 6. I-45N Contraflow Lane, Houston, Trends in Utilization

It appears that, for successful projects, ridership can be expected to increase by over 100% during the first year of operation. Significant additional increases will continue to occur after that first year; for the first 5 years, average annual increases of 40% to 50% might be expected.

Mode Split

Mode split, defined as the percentage of total trips between an origin and a destination served by transit, is greatly impacted by the provision of priority treatment. Data collected in Houston suggest that mode split increases by 120% through provision of priority treatment (Table 19).

Table 19. Bus Mode Split For Downtown Trips at Park-and-Ride Lots With and Without Transitways, Houston

Park-and-Ride Lot/Priority Treatment	Percent of Travel by Bus
North Shepherd (with priority treatment)	33%
Addicks (without priority treatment)	15%

Note: Mode split is defined as the percent of park-and-ride lot market area population working in downtown that uses the park-and-ride service.

Source: "Effectiveness of Transit Operations in Texas Cities", Technical Report 1077-1F, Texas Transportation Institute, 1984.

The absolute mode splits served by transitways are significant; transitways have demonstrated the capability to serve the mode splits referred to previously in this report that are associated with the long-range transit planning in Texas (Table 20).

Table 20. Mode Splits Associated With Selected Transitway Projects

Project	Mode Split	
I-45N Contraflow, Houston		
Bus	33%	
Vanpool	19	
TOTAL		52%
El Monte Busway, Los Angeles		
Bus	25	
Carpool	20	
TOTAL		45%

Note: Mode split as defined in Table 19. For I-45N, these are trips from the park-and-ride market areas to downtown. For El Monte, these are trips from the east end of the busway to downtown.

Source: TTI surveys and data provided by Southern California Rapid Transit District.

Bus Service on Downtown Streets

A drawback of the busway concept is, while it works well in each individual corridor, the transit vehicles operating in all the corridors converge on the downtown. Whether or not the bus volume can be handled satisfactorily in the downtown is a function of several factors, including the bus volume, the downtown street and sidewalk system, and the volume/capacity relationship at the critical intersections.

The volume of buses entering major downtown areas is estimated in Table 21. Also, while line-haul speeds are high on transitways, the distribution inside the activity center will typically occur at 4 to 6 mph.

Table 21. Estimated Peak-Hour Bus Volumes Entering Major Downtown Areas

City	Peak-Hour Bus Volume
Chicago	855
Dallas	591
Fort Worth	120
Houston	400
Los Angeles	700
New York City (Manhattan)	5000
Pittsburgh	700-800[1]
San Antonio	212
Seattle	500

[1] In addition, approximately 100 light rail transit vehicles enter and operate at street level.

Table 22 summarizes bus volumes served on major downtown streets. As a "rule of thumb", the capacity of a reserved downtown street lane appears to be in the range of 100 buses per hour. According to data in reference 8, peak-hour bus volumes of 90-120 can be expected; headways will be 30 to 40 seconds for a bus stop every 500 feet on average with a resulting bus speed 5-10 mph.

The all busway plan for Houston is estimated to bring 1000-1200 buses into the downtown during the peak hour. This is, with the exception of Manhattan, greater than any of the values shown in Table 21.

Table 22. Peak-Hour Bus Volumes Served on Specific Downtown Street Facilities

City	Facility	Buses/Hr./Lane
Chicago	State Street Mall[1]	a.m. 130 SB 155 NB
	Michigan Avenue (mixed-flow)	100
	Contraflow Lanes	60-70
Dallas	In mixed flow[2]	120
Houston	Main (2 directions)[2]	107
	Louisiana[2]	100
	Travis[2]	84
Minneapolis	Nicollet Mall	60
New York City	Madison Avenue (2 curb lanes)	220/hr./2 lanes
	5th Avenue (1 curb lane + mixed-flow)	200/hr./2 lanes
	2nd Avenue contraflow	100-120
Portland	Portland Mall[3]	a.m., 158 5th Ave., 175 6th Ave.
		p.m., 167 5th Ave., 142 6th Ave.
San Antonio	Downtown contraflow	28

[1]This is a 2-lane mall (1 lane each direction) with 3 lanes at intersections.

[2]These are volumes per street rather than per lane.

[3]The mall consists of 2, 3-lane streets (2 lanes on each street for buses).

Bus Transit Center Volumes

One means of serving relatively high bus volumes is to bring the buses into a terminal. This reduces the demand for curb space and street lanes. The operating capacity of selected bus terminals is shown in Table 23. The high volume served at the Lincoln Tunnel (Table 14) is made possible in part by the high-capacity bus terminal serving that facility.

Table 23. Buses Served Per Bus Berth, Selected Bus Transfer Facilities

Bus Terminal, City	Peak-Hour Buses	Buses/Berth/Hour
Port Authority, New York[1]	730	4.0
George Washington Bridge, New York	108	2.5
Transbay, San Francisco	350	9.5
Denver Mall, Denver	---	15.0
Dixie, Cincinnati	48	8.0
Wilson Subway, Toronto	136	7.6
McKeesport, Pittsburgh	30	4.3
Lockwood, Houston (est.)	95	6.8

[1]Includes intercity buses.

Source: "Lockwood Transit Center, Conceptual Planning and Design," Texas Transportation Institute, March 1983.

Capital Costs

Capital costs are difficult to estimate since it is not always possible to tell precisely what is included in the cost values. Table 24 summarizes available cost data. The qualifying statement regarding capital cost comparisons presented in the "Summary" should also be recognized in interpreting these values.

In reviewing the cost numbers, it must be realized that additional buses are required, bus maintenance facility expansion is needed, and support facilities (park-and-ride lots, bus transfer facilities) must be developed. The following might be used as guidelines for total cost per corridor.

• 50 buses at $140,000	$ 7,000,000
• 6000 park-and-ride spaces (5 lots at $5M/lot)	$25,000,000
• 1 bus transfer facility	$ 4,000,000
• 1/2 bus operating facility	$10,000,000
TOTAL	$46,000,000

Table 24. Estimated Cost of Exclusive HOV Facilities

Location	Distance (miles)	Estimated Cost (millions of dollars)	Cost/Mile (millions)
Houston			
Katy Fwy., Phase 1[1]	5	$ 12	$ 2.4
Katy Fwy., Phases 1-3	11	40	3.6
North Fwy., Phases 1-4[2]	17.6	75	4.3
Gulf Fwy., Phases 1-3[3]	15	80	5.3
Northwest[4]	13.8	100	7.2
Southwest[5]	10	110	11.0
Ottawa[6]	18.6	250	13.4
Pittsburgh			
South Patway[7]	4.5	27	6.0
East Patway[8]	6.8	113	16.6
Baltimore (proposed)[9]	12.7	127	10.0
Shirley Highway (1970)[10]	11	43	3.9
Proposed Extension	19	98	5.2
El Monte (1973)[11]	11	56	5.1
Proposed Extension[12]	1	20	20.0
AVERAGE (non-weighted)	-----	----	$ 8.1

[1] 1-lane reversible in freeway median, 1-grade separated access point.

[2] 1-lane reversible in freeway median, 4 grade-separated access points, 1 bus transfer center, 2 park-and-ride lots, 2 vanpool staging areas.

[3] 1-lane reversible in freeway median, 4 grade-separated access points, 1 bus transfer center, 2 park-and-ride lots, 2 vanpool staging areas.

[4] 1-lane reversible in freeway median, 5 grade-separated access points,2 park-and-ride lots.

[5] 2-lane, 1- or 2-way in freeway median, 6-grade separated access points, 2 park-and-ride lots.

[6] 2-lane, 2 direction on exclusive right-of-way, includes 26 stations.

[7] 2-lane, 2 direction on exclusive right-of-way.

[8] 2-lane, 2 direction on exclusive right-of-way, includes $7.5 million for R.O.W., 1/2 of construction cost to relocate RR.

[9] 2-lane, 2 direction on exclusive right-of-way, includes $28M for vehicles.

[10] 2-lane, 1 direction in freeway median.

[11] 2-lane, 2 direction in freeway median, includes costs to relocate RR, construct 3 passenger stations, and build or modify numerous highway, pedestrian and RR structures.

[12] A fully grade separated section extending into downtown Los Angeles

Note: In general, costs are shown in construction year dollars. No attempt has been made to express all costs in current dollars.

Assuming that an average corridor might be 15 miles in length, the cost per mile for support facilities would be roughly $3 million.

Multi-Agency Funding

An advantage of the transitway concept is that it can be funded by a variety of agencies. Table 25 summarizes funding for the Houston transitway system.

Table 25. Proposed Funding by Agency of Transitways In Houston

Transitway	Cost by Agency (millions of dollars)			
	METRO	UMTA	SDHPT/ FHWA	TOTAL
Katy (11 miles)	$ 25	$ 12	$ 3	$ 40
North (18 miles)	14	55	6	75
Gulf (15 miles)	3	0	77	80
Southwest (10 miles)	44[1]	55	11	110
Northwest (14 miles)	39[1]	50	11	100
TOTAL	$125 (31%)	$172 (42%)	$108 (27%)	$450

Note: In all cases, the State Department of Highways and Public Transportation is making the freeway median right-of-way available. That could be valued at as much as $200 million.

[1]Included in this $83 million is $39 million in UMTA Section 9 money.

Operating Cost

Operating cost for regular route bus transit systems is in the general range of 25 cents to 30 cents per passenger mile (Table 26). The cost per passenger-mile for bus transitway operations is roughly half that cost (Table 27). However, the extent and reliability of the data reported in Table 27 are less than desirable. "1984 APTA Operating statistics" show, for the

Table 26. Estimated 1982 Operating Cost Per Passenger Mile, Regular Route Transit Service

City	Cents Per Passenger Mile
Atlanta	24 cents
Chicago	28
Dallas	50
New York City	30
Baltimore	23
Los Angeles	22
Pittsburgh	27
San Antonio	29
Miami	25
Washington, D.C.	31
San Diego	19
San Francisco	16
Philadelphia	38
New Orleans	26
Range	16-50 cents
Non-Weighted Average	27.7 cents

Source: 1982 APTA Operating Statistics

Table 27. Estimated Operating Cost Per Passenger Mile, Bus Transit on HOV Lanes

City	Cents Per Passenger Mile
Houston contraflow lane	
contract carriers	15.4 cents
METRO buses	8.9
Los Angeles, El Monte	
Busway SCRTD	5.5
San Francisco, Golden Gate	
Bridge Golden Gate Transit	9.7
Range	5.5 - 15.4 cents
Non-Weighted Average	9.9 cents

Source: Metropolitan Transit Authority of Harris County survey.

entire Golden Gate Transit operation, an operating cost of 18 cents per passenger mile.

Cost Effectiveness

As part of the planning process in Texas, Texas Transportation Institute has used computer simulation to estimate the benefit/cost ratios for proposed transitway projects. The methodology used results in a conservative estimate of the benefit/cost ratio. These estimates are summarized in Table 28.

User Characteristics

The persons using buses on transitways are educated, white-collar Texans (Table 29).

In another question, contraflow riders were asked how important the presence of the priority lane was in their decision to use transit. Responses are summarized in Table 30. This further corroborates the mode split increase associated with HOV lanes referred to previously in this report.

Table 28. Estimated Benefit/Cost Ratios for Proposed Transitway Projects In Texas

City, Freeway, and Improvement	Benefit/Cost Ratio
Houston	
Southwest Freeway (W. Bellfort to Spur 527)	
1-lane reversible	11.7
2-lane reversible	7.5
3-lane, 2 direction	5.4
Eastex Freeway	
1-lane reversible	6.8
2-lane reversible	4.1
West Loop (US 290 to Fournace)	
1-lane reversible	13.7
2-lane, 2 direction	7.2
Katy Freeway (SH 6 to Washington)	
1-lane reversible	10.3
Dallas	
East R.L. Thornton	
1-lane reversible	3.3
Stemmons	
1-lane reversible	5.4
2-lane, 2 direction	6.8
North Central Expressway	
1-lane reversible	10.0
2-lane reversible	8.0
LBJ	
2-lane, 2 direction	6.1

Note: Benefits are travel time savings to transit and highway users, reduced fuel consumption, and reduced transit operating cost. 20-year analysis period, 10% discount rate, $7/hour value of time, $1.20 per gallon of fuel, and $50/hour for bus operations.

Source: FREQ computer simulation model using input values from the Highway Economic Evaluation Model. Texas Transportation Institute.

Table 29. Characteristics of Persons Using Buses on the I-45N Contraflow Lane, Houston

Characteristic	Report 205-25[1]	Report 1077-1F[2]
Age (years)		
50th percentile	31	33
85th percentile	45	43
Sex (percent)		
Male	45%	43%
Female	55%	57%
Last Year of School Completed		
50th percentile	15	--
85th percentile	16	--
Occupation (percent)		
Clerical	35%	37%
Managerial	19%	16%
Professional	40%	41%
Other	6%	6%
Previous Mode of Travel (percent)		
Drove Self	49%	45%
Carpool/Vanpool	21%	22%
Regular Route Bus	5%	4%
Did not make trip	23%	26%
Other	2%	3%
Save Time Using park-and-Ride (percent)		
Yes	74%	87%
No	19%	9%
No Change	7%	4%
Save Money Using Park-and-Ride (percent)		
Yes	89%	88%
No	7%	7%
No Change	3%	4%
Not Sure	1%	1%

[1]"Houston Park-and-Ride Facilities, An Analysis of Survey Data", Research Report 205-15, Texas Transportation Institute, 1981.

[2]"Effectiveness of Transit Operations in Texas Cities," Technical Report 1077-1F, Texas Transportation Institute, 1984.

Table 30. Importance of the Contraflow Lane to North Freeway Park-and-Ride Users

Question	North Freeway CFL Lots
In deciding to use park-and-ride, how important was the availability of the CFL?	(n=1139)
Not important	1%
Not a major factor	4
Very Important	95
Would you use park-and-ride if the CFL did not exist?	(n=1140)
Yes	24%
No	33
Not sure	43

Source: "Effectiveness of Transit Operations in Texas Cities," Technical Report 1077-1F, Texas Transportation Institute, 1984.

Land Use Impact

There is also reason to believe that the presence of the contraflow lane in Houston has had an impact on both where people choose to live and work. The data shown in Table 31 represent surveys of park-and-ride lots served by the contraflow (CFL) lane and surveys of park-and-ride lots not served by the contraflow lane. It is apparent that the presence of both park-and-ride and priority treatment (in this case, contraflow) influence decisions regarding where to live and work.

Automated Busways

In recent years, attention has been given to a new concept, automated busways. These systems are intended to take advantage of certain

Table 31. Changes in Job and Residential Locations Since Park-and-Ride Lot Opened, With and Without Priority Freeway Lanes

Question	North Freeway CFL Lots	Katy & SW Freeway Non CFL Lots	Total Sample
Have you changed job locations since Park-and-Ride (or P&R and CFL) opened?	(n=1118)	(n=558)	(n=1676)
Yes	41%	27%	36%
No	59	73	64
If "yes", did the availability of Park-and-Ride (or P&R and CFL) influence decision?	(n= 445)	(n=147)	(n= 592)
Yes	51%	40%	48%
No	49	60	52
Have you changed residential locations since Park-and-Ride (or P&R and CFL) opened?	(n=1122)	(n= 563)	(n=1685)
Yes	55%	54%	55%
No	45	46	45
If "yes", did the availability of Park-and-Ride (or P&R and CFL) influence decision?	(n= 603)	(n= 303)	(n= 906)
Yes	57%	50%	54%
No	43	50	46

Note: CFL means contraflow. The North Freeway Park-and-Ride lots are served by the priority contraflow lane. No priority treatment was available on either the Katy or Southwest Freeway at the time of the survey.

Source: "Effectiveness of Transit Operations in Texas Cities", Technical Report 1077-1F, Texas Transportation Institute, 1984.

characteristics of bus and rail. The specially designed vehicles can be operated on city streets for circulation purposes under driver control. The vehicles can also operate on a guideway without driver control. Thus, transfers are minimized while the rail benefits of guideway operation (station spacing, environmental) are also realized. Buses could also operate in light rail transit tunnels.

The technology has been developed in West Germany by Daimler-Benz. A 4,200 foot test track opened in Essex, Germany in 1980; this was the first bus guidance system for passenger operation. Two other small, mainly experimental automated busways have opened in Wittenbergstrable (1983) and Furth (1984).

The systems can be either mechanically or electronically operated. With the mechancial system (Essen and Wittenbergstrable), the buses use special curbs to "feel" their way along the guideway. With the electronic system (Furth) steering is accomplished by a hydraulic actuator linked to an electronic control system. The course of the bus is marked by cables buried in the surface. Antennae located below the bus are used to measure deviation from the path.

With this O-Bahn system, no shoulders are provided; in the event of a breakdown, the next bus pushes the stalled bus. On-line stations are used, and capacity is estimated at 93 buses per hour.

<u>Adelaide, South Australia</u>

The first non experimental system is currently under construction in Adelaide. It will be 7.3 miles in length and will cost $86 million, or $11.8 million per mile. Vehicles on the guideway will travel at speeds of 60 mph. An alternative light rail transit system was estimated to cost $140 million, or 63% more.

THE CASE FOR RAIL TRANSIT

The previous section of this report dealt primarily with bus transitways. The advantages and disadvantages of transitways, as documented in the previous section, are, in effect, the advantages and disadvantages of transitways as compared to rail transit.

Rail transit is being given strong consideration for development in major Texas cities. Much of the remainder of this report deals with rail transit. Set forth in this section are six possible reasons for selecting rail transit technology as opposed to transitway technology. The validity of each of these reasons will vary from city-to-city and, in some cases, from corridor-to-corridor.

Potential Reasons For Selecting Rail Transit

In the opinion of the author, the following reasons might be used to justify development of rail as opposed to bus transitways.

The Urban Image

While this reason is not frequently expressed, the "image" and "statement" made by a rail system appear to be positively viewed. A feeling seems to exist that, if Washington, Baltimore, Atlanta, Miami, San Francisco, etc., have rail transit, it must provide the desired image for a dynamic, growing urban area.

It is further argued that development of this type of transit system results in favorable features that are difficult to measure and quantify. An analogy might be that, while the City of Dallas probably could have constructed a city hall at a lower cost that would effectively have housed the city departments, a decision was made to spend additional funds to construct an extremely attractive and well landscaped structure that made a "positive statement" concerning the City of Dallas. Similarly, rail transit provides an image and provides an energy-efficient, relatively non polluting form of transportation.

Distribution Within the Activity Center

Transitways in all major corridors will generally function quite well within the corridor itself. However, all the corridors combined will result in extremely high bus volumes in the downtown area during peak hours. Analyses in Houston suggest that as many as 1000 to 1200 buses might be operating on the city streets during the peak hour.

Whether a downtown can support this volume of buses is primarily a function of the street layout and width, volume/capacity ratios at major intersections, allocation and control of curb space, and sidewalk width. Obviously, these features vary considerably between cities and, in some cases, may preclude at-grade operation of high bus volumes on city streets.

Strictly from the standpoint of internal distribution, air quality, noise, and aesthetics within the activity center, rail in subway has to be considered superior to buses operating on city streets. It is reasonable to assume that, if large volumes of buses are to be served on city streets, some relatively expensive improvements to that street system will be required.

Potential for Lower Future Operating Costs

It is frequently argued that rail systems have lower operating costs and require fewer employees. Data presented in this report refute these contentions based on current operating data.

Future technology advancements may have more of an impact on rail operations than on bus operations. Effective techniques may be developed for operating trains without on-board operators. If so, rail labor requirements can be reduced and operating costs lowered. While automated busway systems are also being developed, that technology does not appear to be as advanced as rail technology.

Since labor represents approximately 70% of transit operating costs, the possibility of significant reductions in labor requirements is an important concern in selecting the long-range transit technology.

Trip Patterns Served

Transitways are ideal for serving long-distance, peak-period urban commute trips to major activity centers. As shown in Figure 7, that type of service is ideal for trip patterns in several Texas corridors. Figure 7 also depicts one reason why North Central is considered to be a good candidate rail corridor.

Rail operations, with more frequent station spacing, can be better suited for serving relatively short trips. This arrangement should also be more effective at serving the transit demand that exists during off-peak periods.

The trade-off is that express buses on transitways operate at 50+ mph on the line-haul portion of the trip. As shown subsequently in this report, as rail station spacing decreases, rail operating speeds also become relatively slow; thus, by effectively serving short trips, the attractiveness of serving long-distance trips is decreased.

As a result, the characteristics of trip patterns in a particular corridor will help to identify an appropriate transit technology.

Minimize Transfers

To effectively serve the polynucleated Texas city with transit, some transferring will be essential. However, transfers are not a desirable feature of transit systems.

As a result, if rail is developed for any of the reasons stated in this section, some extension of the rail system may be helpful in minimizing the need for transfers and, thereby, making the transit system more attractive for the user.

Environment

In some highly sensitive corridors, the more favorable air and noise impacts of rail may help justify selection of that form of transit.

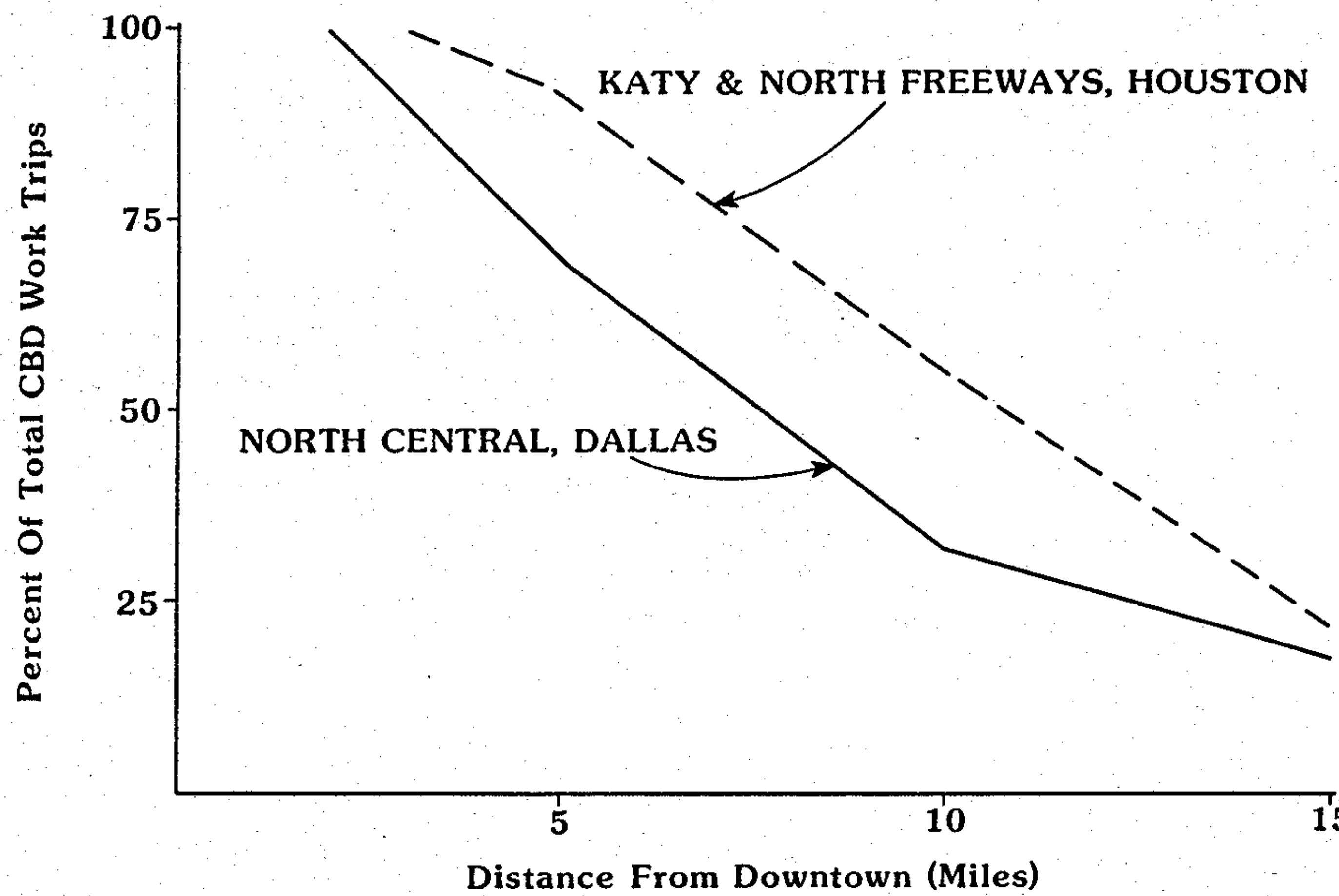


Figure 7. Percent of CBD Work Trips on the Freeway at Various Distances from Downtown, Selected Freeways

HEAVY RAIL TRANSIT TECHNOLOGY

Heavy rail transit, often referred to as rail rapid transit or conventional rapid transit, has been operating in the United States since the late 1890's. It is typically characterized by a fully grade-separated dual track transit guideway with a "third rail" power supply, high-level stations, and frequent, high-capacity train service. Several systems (e.g., New York CTA, Philadelphia SEPTA, Boston MBTA, and Chicago CTA) were principally developed in the late 1800's and early 1900's. A system was initiated in Toronto in 1954 and in Montreal in 1966. Systems were begun in San Francisco, Washington, D.C., and Atlanta in the 1970's; systems were initiated in Baltimore and Miami in the 1980's.

General Advantages and Disadvantages

The advantages and disadvantages of HOV lanes, as presented previously, were relative to a rail system. The preceding section of this report documents potential reasons for selecting rail transit.

Heavy rail transit offers a fully grade-separated transit guideway. It is capable of moving large volumes of persons and effectively distributing them at the major employment centers.

Capacity Considerations and Existing Volumes

Rail transit routinely moves more persons than the projected demand for any transit corridor in Texas (refer to Table 10). In major heavy rail transit corridors, approximately 25,000 seats per hour are provided by the service. Actual ridership is generally higher since as many as two-thirds of total passengers may be standees.

Table 32 summarizes peak-hour service on selected rail lines in major North American cities. On one line in New York City, 28 trains move over 53,000 persons in the peak hour. In general, 20% to 30% of the inbound daily ridership is served in the peak hour (10% to 15% of total daily ridership).

Heavy Rail Transit System Characteristics

Characteristics such as rail miles by system, percent of trips with at least one downtown trip end, average speed, and employees per passenger are presented for selected North American transit properties.

Rail Miles By System

Table 33 presents the extent of selected rail systems. Considerable variation exists in factors such as miles of track per capita and ridership per mile of track.

Downtown Orientation

Heavy rail transit is most effective at serving large volumes of travel to the downtown. For all systems summarized in Table 34, over 60% of total trips had at least one trip end in the downtown. On average, 75% of the trips have at least one trip end in the downtown area.

Reverse commuting is minimal. Peak-hour directional splits of between 80% and 95% have existed for lines in the Washington, D.C. system.

Average Speed

While commonly referred to as rail rapid transit, average speeds (excluding layovers) are almost always less than 35 mph (Table 35). The term rapid was applied in relation to alternative travel modes in the late 1800's and early 1900's.

Since trains typically stop at all stations, average speed is a direct function of station spacing. Figure 8 illustrates this relationship.

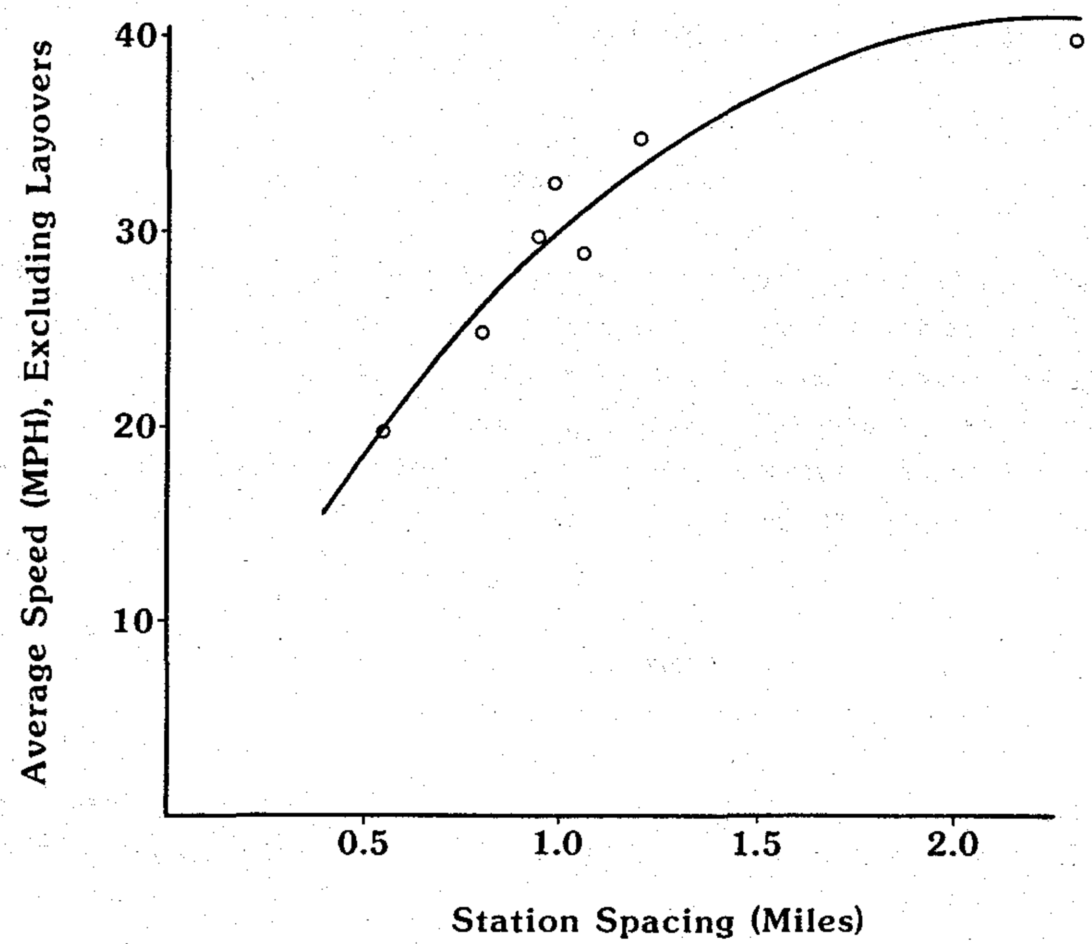


Figure 8. Relationship Between Average Speed (Excluding Layovers) and Average Station Spacing, Selected North American Heavy Rail Systems.

Employees Per Passenger

Since one train operator can transport many more persons than can a bus driver, rail transit is often assumed to be less labor intensive. That, in turn, is used as an argument that rail operating costs are lower.

This level of analysis overlooks the fact that rail systems require personnel for several other functions, such as security, maintenance of track and way, and station attendants. As a result, per passenger transported, regular route bus service and rail transit require a comparable number of employees. These data are summarized in Tables 36 and 37.

Capital Costs

Capital costs are difficult to estimate since it is not always possible to identify what is included in the cost values. Heavy rail transit, with fully grade separated and protected right-of-way, is the most capital intensive transit technology. Table 38 summarizes available capital cost data for rail transit systems. Again, in reviewing the capital cost, the qualifying comments presented in the "Summary" should be recognized.

Operating Cost

Operating cost per passenger mile for selected North American heavy rail transit systems is summarized in Table 39. These costs are commonly in the range of 16 cents to 17 cents.

User Characteristics

Patrons of heavy rail systems tend to be choice riders. They tend to be educated, with relatively high incomes, and use the rail transit system for the work trip (Table 40).

Land Use Impact

It is commonly argued that rail transit represents a means of influencing land use and attracting growth. The validity of this argument has not been satisfactorily resolved. Pushkarev (2) provides a good summary of the land use impact arguments, and the following are excerpted from his report.

> "A fixed guideway can do little to change the growth prospects of an urban area; it can do more as a catalyst for land use controls and urban design improvements;"
>
> "Empirical studies of the impact of transportation improvements on land value vary widely in quality. One of the more rigorous studies (which contains an analysis of the voluminous literature) indicates that land values in Washington do indeed rise with proximity to Metrorail stations, and are also influenced by the opening date of stations. However, factors unrelated to rail transit--those having to do with population composition and the character of the sites -- have a much larger impact on property values than transit access. Several studies of the Lindenwold line show a substantial increase in property values -- up to a $3,000 difference in sales price per single family house for each dollar of travel savings per day.
>
> Increased land values are reflected in intensified development. At the suburban end of the line, intensified residential development has been documented on the Lindenwold line and on the South Shore extension in Boston. The effect of BART on residential development has been much more limited. To what extent suburban rail extensions may reallocate residential development away from central cities is a question that has not been answered conclusively. Offsetting forces are at work which may make this effect negligible.

The most pronounced impact of new rapid transit lines could be expected in downtown areas, where the improvement in access is concentrated, and amplified by non-linear agglomeration effects. In Toronto, the increment of growth along the original Yonge Street subway, compared to growth in the rest of the city, was enough to produce more than $5 million in annual property taxes, compared to about $4 million in annual carrying charges for the bonds issued for construction. In Washington, ongoing or committed private development in various ways related to Metrorail has been put at about $3 billion since 1976. Figures of this nature abound, but it is virtually impossible to prove to what degree such development is in fact related to the transit improvement, how much of it would have occurred anyway, and how much of it would have occurred elsewhere."

Table 49. Automated Guideway Transit, System Size and Estimated Average System Travel Speed

System, Year	Line Miles	No. of Stations	Avg. Trip Length (miles)	Avg. Speed (mph)	
				Incl. Layover	Excl. Layover
People Movers					
Dallas (Airtrans), 1977	6.4	28	1.4	10.0	---
Seattle-Tacoma, 1977	0.85	6	0.36	8.2	9.2
Tampa, 1977	0.7	8	0.17	6.8	8.8
Morgantown, 1977	2.1	3	1.62	9.7	16.5
Fairlane, Mich,. 1977	0.5	2	0.47	9.7	17.8
ICTS					
Lille, France (MATRA)	8.5	18	6.4	----	22.0
Toronto (Scarborough)	4.3	5	---	----	----
Vancouver, B.C.	13.5	15	---	----	----
Range	---	---	0.17 - 6.4	6.8 - 10.0	8.8 - 22.0
Avg., Non-Weighted	---	---	1.8	8.9	14.9

Source: Reference 2 and "VAL The 1983-84 Record of Experience", presented at the International Conference on Automated People Movers, March 1985.

Table 50. Automated Guideway Transit, Employees Per Passenger (1977 data)

System, Year	Line Miles	Annual Passengers (millions)	Employees	Employees Per Million Passengers
People Movers				
Dallas (Airtrans)	6.4	6.1	160	26.1
Seattle-Tacoma	0.85	10.1	24	2.4
Tampa	0.7	14.5	16	1.1
Morgantown	2.1	1.9	51	26.7
Fairlane, Mich.	0.5	0.25	10	40.0
ICTS				
Lille, France (MATRA) 1985	8.5	28.0	175	6.25
Range	---	-----	---	1.1 - 40.0
Avg., Non-Weighted	---	-----	---	17.1

Source: Reference 2 and "VAL The 1983-84 Record of Experience", presented at the International Conference on Automated People Movers, March 1985.

Table 51. Automated Guideway Transit, Estimated Capital Costs

System	Line Miles	Capital Cost ($ millions)	Capital Cost Per Mile ($ millions)
People Movers			
Miami			
Initial System	1.9	$145	$ 76.3
Planned Extension	2.1	210	100.0
Detroit	2.9	210	72.4
Jacksonville (planned)	0.7	29	41.4
Houston (planned)	4.5	112	24.9
Tampa[1]	0.7	13	18.4
Seattle-Tacoma[1]	0.9	32	37.4
Morgantown[1]	2.1	42	20.4
ICTS			
Vancouver, B.C.	13.5	615	45.6
Toronto (Scarborough)	4.3	149	34.7
Lille, France (MATRA)	8.5	328	38.6
Range	----	---	$18.4 - $100.0
Avg., Non-Weighted	----	---	$46.4

[1] 1977 Cost from Reference 2.

Sources: Reference 2, "Urban Experience with AGT in North America" and "VAL The 1983-84 Record of Service" presented at the International Conference on Automated People Movers, March 1985, and data provided by systems.

Table 52. Automated Guideway Transit, Estimated Operating Cost Per Passenger and Per Passenger Mile

System	Annual Operating Cost ($ millions)	Annual Ridership		Operating Cost (dollars)	
		Passengers (millions)	Passenger Miles (millions)	Per Passenger	Per Passenger
People Movers					
Dallas (Airtrans), 1977	$3.0	6.1	8.6	$0.49	$0.35
Seattle-Tacoma, 1977	0.75	10.1	3.6	0.07	0.21
Tampa, 1977	0.48	14.5	2.5	0.03	0.19
Morgantown, 1977	1.37	1.9	3.1	0.72	0.44
(1984)	2.5	---	---	----	----
Fairlane, Mich. (1977)	0.4	0.25	0.12	1.60	3.33
ICTS					
Lille, France (MATRA), 1985	8.4	28.0	180.0	0.29	0.05
Range [1]	---	----	-----	$0.03-$0.72	$0.05-$0.44
Avg., Non-Weighted[1]	---	----	-----	$0.32	$0.25

[1]Excludes Fairlane data.

Source: Reference 2 and "VAL The 1983-84 Record of Experience", presented at the International Conference on Automated People Movers, March 1985.

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Table 32. Heavy Rail Transit, Peak-Hour Patronage on Selected Rail Lines (8 a.m. - 9 a.m., inbound to CBD)

System, Line Year	Peak-Hour Inbound		8-9 a.m. as a % of all day inbound	
	Trains	Passengers	Cars	Passengers
Manhattan, 1976				
N IRT, Lexington Ave, Express	23	35,700	9.9%	28.5%
E IND Queens	28	53,330	10.5	33.9
N IRT Broadway, Express	19	27,290	8.5	24.6
TOTAL/Avg., NYCTA	352	433,040	10.0	29.5
Toronto, 1976				
N Yonge-University	30	22,900	9.0	22.6
E Danforth	22	22,700	7.4	25.2
W Bloor	22	21,500	7.5	22.4
N Spadina (1980)	25	10,427	---	----
Montreal, 1976				
N Line 2, Rue Berri	23	28,230	9.2	28.8
E Line 1 Blde Mais.	17	19,110	7.3	27.3
TOTAL/Avg., Montreal	70	65,586	8.2	27.2
Chicago, 1976				
SW Dan Ryan	17	12,498	11.8	24.5
NW W-NW	22	10,213	12.2	25.5
TOTAL/Avg., Chicago	121	52,816	10.6	20.5
Philadelphia, 1976				
N SEPTA Broad	23	10,600	12.6	17.3
TOTAL/Avg., Philadelphia	169	43,900	12.6	20.5
Boston, 1976				
S Red Line	22	8,651	10.2	22.9
TOTAL/Avg., Boston	137	43,061	9.0	26.4
San Francisco, BART, 1977				
E Transitway Tube	11	8,016	11.7	27.8
W Mission Street	10	6,510	10.1	34.5
Cleveland, 1976				
E Joint Tract	9	4,100	11.0	24.0
W Airport	14	5,413	12.9	24.0
Washington, 1980				
W Blue Line	20	13,000	8.4	25.0
N Red Line	12	12,000	8.8	25.2
E Blue Line	20	8,000	8.4	27.0
Atlanta, 1980				
East Line	6	4,250	7.7	21.2
West Line	6	3,725	7.7	21.9

Source: Reference 2

Table 33. Heavy Rail Transit, Extent of Systems

System	Route Miles (1980)	Urban Population 1980 (millions)	Annual Ridership (millions)	Directional Miles of Track[1]	Miles of Track Per Million Population	Millions of Riders Per Mile of Track
Atlanta	12	1.6	39.9	46.8	29.2	2.8
Baltimore (1985)	8	1.8	11.4	---	---	---
Boston	33	2.7	124.9	106.0	39.3	1.17
Chicago	90	6.8	149.8	205.6	30.2	0.73
Cleveland	19	1.8	6.8	41.0	3.8	0.17
Miami (1985)	20.5	2.6	5.1	---	7.9	---
Montreal	24	2.8	164.2	58.0	20.7	2.83
New York City (CTA, PATH, SIRT)	258	15.6	1005.3	685.5	43.9	1.47
Lindenwold	15	4.1	10.7	30.5	7.4	0.35
SEPTA	24	4.1	98.3	70.4	17.2	5.72
TOTAL		4.1	109.0	100.9	24.6	1.08
San Francisco (BART)	71	3.2	57.7	184.2	57.6	0.31
Toronto	34	3.0	243.1	95.0	31.7	2.56
RANGE		---	---	---	3.8-57.6	0.17-5.72
AVG., Non-Weighted	--	---	---	---	27.8	1.75

[1]Definition. The total miles of R.O.W. over which rail vehicles travel while in revenue service. If vehicles travel in both directions on a 2-way track, both sides of the track are included. A one mile segment of rail over which trains operate on tracks in both directions is reported as 2 miles of directional track.

Source: "APTA 1984 Operating Statistics", Reference 2.

Table 34. Heavy Rail Transit, Estimated Percent of Trips with at Least One Trip End in the Downtown

System, Year	% Origins in CBD	% Destinations in CBD	% With One Trip End in CBD
New York City, 1974	41	41	82
Chicago, 1972	36	36	72
Philadelphia,			
Lindenwold, 1976	43	43	87
SEPTA, 1975	35	35	70
Boston, 1973	42	42	84
San Francisco, 1977	40	40	79
Toronto, 1976	36	36	72
Cleveland, 1976	35	35	70
Atlanta, 1980	--	--	75
Miami, 1985	--	--	61
Washington, D.C., 1984	--	--	68
RANGE	32% - 43%	32% - 43%	61% - 86%
AVG., Non-Weighted	38%	38%	75%

Source: Reference 2, 11, 12 and supplemental data provided by Miami and Washington, D.C.

Table 35. Heavy Rail Transit, Estimated Average System Travel Speed

System, Year	Avg. Speed (mph)		No. of Stations	Distance Between
	incl. layover	excl. layover		Stops (mi)
New York CTA, 1976	18.3	---	439	---
Toronto, 1976	20.4	---	49	0.54
Chicago, 1976	19.9	24.6	142	0.81
San Francisco, 1977	33.6	40.0	34	2.30
Washington, D.C., 1980	20.7	30.0	37	0.94
Philadelphia				
SEPTA, 1976	17.5	---	53	0.4
PATCO, 1976	28.0	34.8	13	1.18
Boston, 1976	15.6	---	43	0.78
Baltimore, 1984	---	---	9	0.90
Atlanta, 1980	24.5	33.7	13	0.98
Miami, 1985	---	---	20	1.00
Cleveland, 1976	22.8	29.0	18	1.13
RANGE	15.6-33.6	24.6-40.0	---	0.40-2.30
AVG., Non-Weighted	22.1	32.0	---	0.91

Source: Reference 2 and "State of the Art of Primary Transit System Technology" by SEWRPC, 1981.

Table 36. Heavy Rail Transit, Employees Per Passenger

System	Annual Rail Patronage (millions)	Rail Employees	Employees Per Million Passengers
Atlanta	39.9	715	17.9
Boston	124.9	2,995	24.0
Chicago	149.8	4,286	28.6
Cleveland	6.8	302	44.4
Montreal	164.2	1,837	11.2
New York City	1,005.3	33,046	32.9
Philadelphia			
Lindenwold (PATCO)	10.7	319	29.8
SEPTA	98.3	1,837	18.7
San Francisco (BART)	57.7	2,010	34.8
Toronto	243.1	---	----
RANGE	---	---	11.2-44.4
AVG., Non-Weighted	---	---	26.9

Source: "APTA 1984 Operating Statistics"

Table 37. Regular Route Bus Service, Employees Per Passenger

System	Annual Bus Patronage	Bus Employees	Employees Per Million Passengers
Atlanta	84,936,000	2,034	23.9
Boston	102,747,898	2,646	25.8
Chicago	473,985,528	7,423	15.7
Cleveland	73,876,902	1,642	22.2
Dallas	35,810,000	1,108	30.9
Fort Worth	5,282,367	242	45.8
Houston	52,138,837	2,194	42.1
Los Angeles	415,865,888	8,361	20.1
Milwaukee	76,574,249	1,462	19.1
Miami	64,132,677	1,918	29.9
New York City	1,062,142,366	15,328	14.4
Ottawa	111,518,192	1,882	16.9
Philadelphia	186,466,939	3,470	18.6
Pittsburgh	83,545,438	2,381	28.5
Portland, Oregon	47,355,400	1,716	36.2
San Antonio	33,433,000	911	27.2
Seattle	60,563,944	2,374	39.2
Vancouver, B.C.	102,876,624	2,941	28.9
Washington, D.C.	178,038,930	4,410	24.8
RANGE	-----	-----	14.4-45.8
AVG., Non-Weighted	-----	-----	26.9

Source: "1984 APTA Operating Statistics"

Table 38. Heavy Rail Systems, Estimated Capital Cost and Current Daily Ridership

System	Service Date & Status	Length (miles)	Cost ($ Millions)	Cost/Mile ($ Millions)	Current Daily Ridership
Athens, Greece	Proposal	15	$ 1,000	$ 66.7	NA
Atlanta ($ 1979)	1979	25	1,700	68.0	160,000
	Ultimate	53	3,400	64.1	NA
Baltimore	1984	8	797	99.6	38,000
	Extension	6	198	33.0	--
Houston	1983 bond proposal	18	1,700	94.4	NA
Los Angeles	Initial Plan	4.4	1,180	268.2	NA
	Ultimate	18.6	3,400	182.8	NA
Miami	1984-85	20.5	1,050[1]	51.2	15,000-20,000
San Francisco ($ 1972) BART	1972	71.5	1,600[2]	22.4	200,000
Washington, D.C.	1976	39[3]	2,700	69.2	360,000 (60.5 mi. System)
	planned	89.5	7,100	79.3	NA
	Ultimate[4]	101	12,000+	120.0	NA
RANGE	---	----	----	$22.4-$268.2	--
AVG., Non-Weighted	---	----	----	$93.8	--

[1]Connects to a 1.9 mile people-mover for downtown distribution. People-mover cost is $146 million, or $76.8 million per mile. See "Automated Guideway Transit" section.

[2]This is 1972 dollars. Currently valued at over $5 billion, or about $70 million per mile.

[3]This is the initial 39 mile section. Currently, 60.5 miles are in operation.

[4]Current dollars.

Note: In general, costs shown are in construction year dollars. No attempt has been made to express all costs in current dollars.

Table 39. Heavy Rail Transit Systems, Estimated Operating Cost Per Passenger and Per Passenger Mile

System	Annual Passengers (millions)	Annual Passenger-Miles (millions)	Avg. Trip Length (miles)	Annual Operating Cost ($ millions)	Est. Operating Cost ($)	
					Per Passenger	Per Passenger-Mi
Atlanta	39.8	131.4	3.3	22.3	$0.56	$0.17
Baltimore	11.4	-----	---	18.0	1.57	----
Boston	124.9	374.1	3.0	118.4	0.95	0.32
Chicago	149.8	1,093.2	7.3	174.9	1.16	0.16
Cleveland	6.8	69.9	10.3	12.2	0.79	0.17
Montreal[1]	164.2	574.7	3.5[2]	109.8	0.67	0.19
New York City	1,005.3	7,060.0	7.0	1,694.0	0.68	0.24
Philadelphia						
Lindenwold	10.7	92.8	8.7	16.2	1.51	0.17
SEPTA	98.3	540.3	5.5	95.0	0.97	0.17
San Francisco (BART)	57.7	725.1	12.5	125.3	2.17	0.17
Toronto[1]	243.1	851.0	3.5	110.0	0.45	0.13
Washington, D.C.	105.4	453.3	4.3	122.4	1.16	0.27
RANGE	---	-----	3.0-12.5	----	$0.45 $2.17	$0.13 $0.32
AVG., Non-Weighted	---	-----	7.5	----	$1.06	$0.20

[1]Canadian dollars

[2]Assumed to be the same as the Toronto trip length.

Note: Some of the values in this table are different from values in Table 33 due to differences in the year of the data.

Sources: Estimated from data included in: "APTA 1984 Operating Report", "APTA 1983 Operating Report", "1982 UMTA Section 15 Data", and data developed for the Interim Dallas Transit Board.

Table 40. Heavy Rail Transit, Characteristics of Riders

Characteristic	System						
	Atlanta	San Francisco	Washington, D.C.	Boston	Chicago	New Jersey (PATCO)	Toronto (TTC)
% Work Trips	80%	77%	69%	--	--	--	---
Previous Mode of Travel							
Bus	52%	35%	54%	--	--	--	---
Auto	35%	56%	28%	--	--	--	---
Other	13%	9%	13%	--	--	--	---
Arrival Mode to Station							
Bus	58%	18%	43%	33%	36%	8%	72%
Auto	31%	38%	30%	12%	1%	37%	14%
Walk	11%	44%	27%	55%	63%	55%	14%
% College Graduates	--	46%	66%[1]	--	--	--	---
% With Income Over $25,000	--	55%	50%	--	--	--	---
% Male	40%	48%	--	--	--	--	---
% Ride Every Day	64%	70%	76[2]	--	--	--	---

[1]Income over $24,000

[2]4 or more days per week

Source: References 11, 12, 13 and 14 and "Public Transportation in Toronto", TTC, 1975.

LIGHT RAIL TRANSIT TECHNOLOGY

Due to certain flexibilities that decrease implementation costs, light rail transit has become the more popular form of rail transit in recent years. It is characterized by a tracked transit guideway which incorporates the use of overhead catenaries as a power source.

The use of the overhead power source eliminates the need for the fully grade separated and protected guideway characteristic of heavy rail transit. Thus, at-grade operation is possible with light rail transit. It is the at-grade operating potential that allows lower implementation costs. A fully grade separated light rail system costs as much as a heavy rail system.

Relative to heavy rail, the principal advantage is flexibility that permits lower implementation costs. Depending upon the characteristics of the at-grade oepration, interference with auto traffic may cause operating problems; the result is also likely to be somewhat lower operating speeds (for comparable station spacing) than heavy rail systems.

Capacity Considerations and Existing Volumes

While light rail does not have the capacity of heavy rail, light rail systems do have the capacity to serve the demand that can be expected in Texas corridors. Capacity is, essentially, a function of car size, train length (often controlled by platform length), and minimum headway.

Modern light rail systems, in order to attain higher speeds, generally do not operate at headways of less than 2 minutes. Train consist will generally be no more than 2 to 4 cars per train. Based on data presented by Pushkarev (2), light rail operation with articulated 2-car trains moves 6,800 persons per direction per hour; this is increased to 15,900 if trains of 4 somewhat larger cars are assumed. This value is more than 30% greater than the highest estimated transit demand for a Texas corridor (Table 10).

Various systems in Europe have demonstrated the capacity to serve the demands expected in Texas (Table 41).

Table 41. Line Capacity for Selected Light Rail Systems

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

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

Current volumes on selected North American light rail systems are shown in Table 42. All those peak-hour volumes are well below the estimated maximum Texas demands shown in Table 10.

Light Rail Transit System Characteristics

Characteristics of light rail, such as miles per system, average speed, and employees per passenger are presented for selected light rail transit systems.

Rail Miles and Ridership by System

Table 43 presents characteristics of some of the more recently developed and/or proposed light rail systems. Table 44 presents daily ridership data for selected North American systems.

Average Speed and Trip Length

Average speeds for light rail systems are less than for rail rapid (heavy rail) systems. Operating speed data for selected systems is presented in Table 45. As was the case for heavy rail transit, station (or stop) spacing directly influences operating speed.

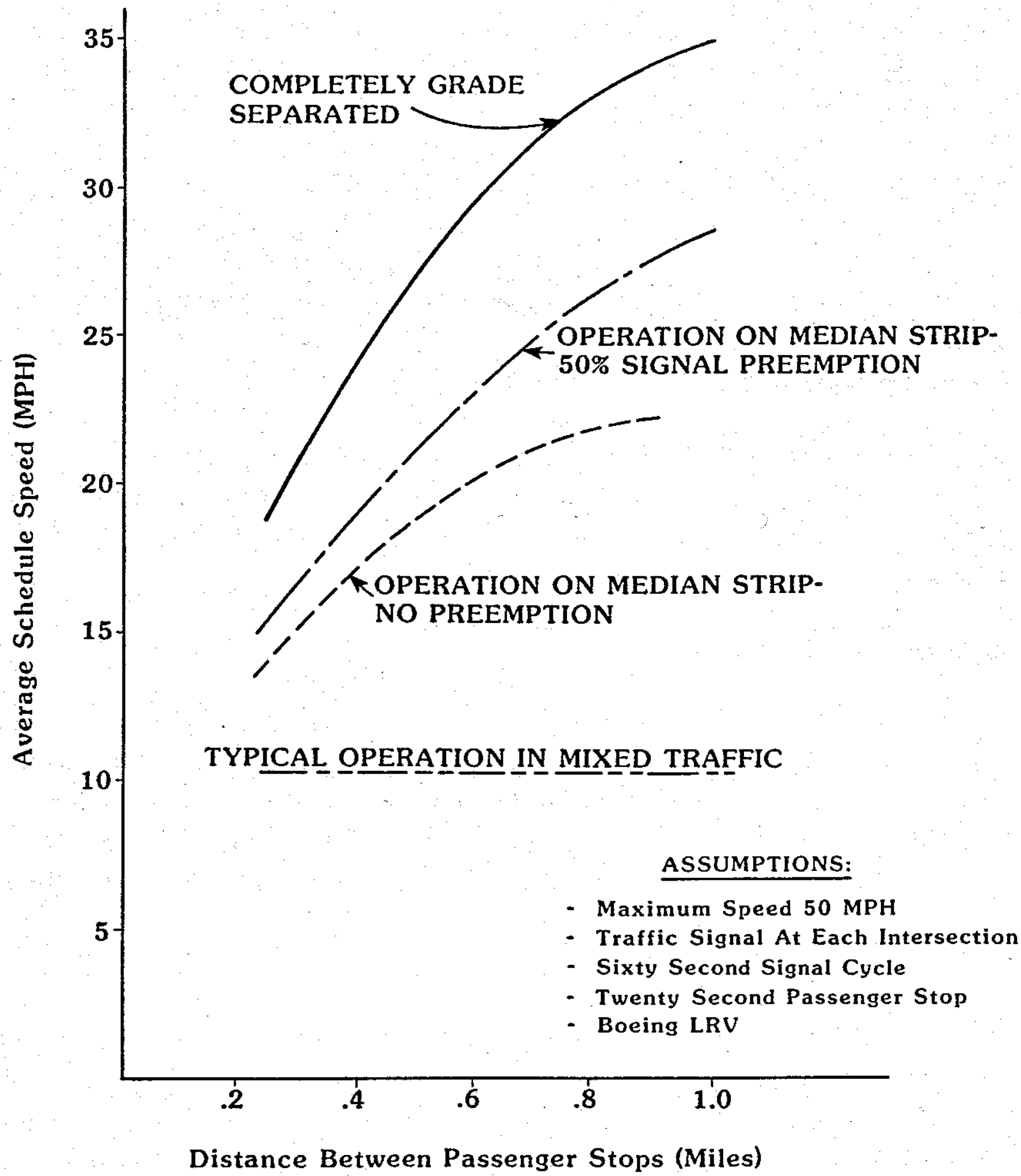
Speed is also a function of the extent of grade separations and at-grade operation. Those systems operating in the range of 10 mph are, essentially, streetcar operations. Figure 9 overviews a speed relationship for light rail systems.

Employees Per Passenger

As was the case for heavy rail transit, the average number of employees per passenger for light rail transit is not that different than it is for bus transit (Tables 37 and 46). However, the relatively wide variation in employees per passenger between LRT systems makes the average value at least somewhat suspect. The newer systems (i.e., San Diego, Calgary and Edmonton) do have fewer employees per passenger.

Capital Cost

The capital cost of light rail transit depends largely on the extent of grade separation. When grade separation becomes extensive, as in Buffalo, light rail can cost as much as heavy rail. On the other hand, systems built entirely at grade on readily available right-of-way can be built for as little as $8 to $10 million per mile. Table 47 summarizes capital cost data



Source: "Light Rail Transit, State-of-the-Art Overview": UMTA Report DOT-UT-5009, 1976.

Figure 9. Relationship Between Average Schedule Speed and Station Spacing

for recent or proposed light rail systems. Characteristics of those systems are provided in Table 43. In reviewing the capital costs, the qualifying statements presented in the "Summary" need to be recognized.

Operating Costs

Limited operating cost data are available. The information provided by APTA is presented in Table 48.

The average for the 5 systems shown is 19 cents per passenger mile. Excluding Boston from the calculations results in an average of 11 cents per passenger mile.

Table 42. Light Rail Transit, Peak-Hour Patronage on Selected Rail Lines (8-9 a.m., inbound to CBD)

System, Line, Year	Peak-Hour Inbound			8-9 a.m. as a % of all day inbound	
	Trains	Cars	Passengers	Cars	Passengers
Philadelphia, 1976					
Market St. Tunnel	73	73	3700	10.8%	24.8%
Boston, 1976					
W. Green Line	36	88	6900	8.0	19.1
San Francisco, 1977					
Muni[1]	68	68	4900	9.3	12.3
Pittsburgh, 1976					
South Hills[1]	51	51	3800	16.1	30.7
Newark, 1976					
Newark Subway	30	30	1500	12.8	25.7
Edmonton, 1978	12	24	2100	9.2	23.2
Range	--	--	--	8.0%-16.1%	12.3%-30.7%
Avg., Non Weighted	--	--	--	10.6%	22.9%

[1]Street operation prior to tunnel completion

Source: Reference 2.

Table 43. Light Rail Transit, Characteristics of Selected Systems

System/Location	Length (miles)	Characteristics
Canada		
Edmonton	6.4	Operational Subway in CBD, otherwise at grade in RR R/W 8 stations (4 in subway)
Calgary	7.7	Operational CBD mall, mostly at grade with separations at major streets, 15 stations (8 downtown)
	4.5	Began operations in May 1985 Incl. grade separations, located in fwy. median, and tunneling to avoid traffic.
France (new systems)		
Paris	5.6	Under construction, 22 stations, operational in 1988 At grade
Nantes	6.6	Operational, 22 stations
Grenoble	5.5	Operational in 1987, 20 stations
Strasburg	8.1	Operational in 1987, 28 stations
United States		
Buffalo	6.4	Operational, 1.2 mi. in CBD mall, 5.2 mi. in subway, 14 stations (6 in CBD)
Dallas	160.0	Conceptual plan, 98 stations, mostly in RR R/W
Detroit	15.0	Preliminary eng., 4.2 mi. in CBD subway, 3.5 mi. elev., 7.3 mi at grade, 17 stations (6 in CBD)
Houston	varies 0 to 75	CBD subway, mostly in RR or Fwy. R/W
Los Angeles		
Long Beach	22.5	CBD subway, planned for 1988 opening, 25 stations
Century Freeway	17.5	Located in freeway median, in engineering, 10 stations
Milwaukee	14.3	Planning stages
Oklahoma City	17.4	Preliminary Planning
Pittsburgh	10.5	Stage 1 upgrade, incl. 1.2 mi. subway and maintenance facilities
Portland, Ore.	15.0	Open in 1986, reserved area on CBD st., uses RR, fwy. & st. R/W, at-grade, 25 stations
St. Louis	18.0	Prel. plng., existing CBD RR tunnel, mostly at grade, new R/W east of CBD, RR R/W west of CBD
Sacramento	18.3	Open in 1987, CBD mall, single track, virtually no new R/W, 27 stops

Table 44. Light Rail Transit, Typical Daily Passenger Volumes

System, Year	Length (miles)	Typical Weekday Patronage
Canada		
Calgary, 1981	7.5	38,000
Edmonton, 1981	4.5	20,000
Toronto, 1976	46.3	350,000
United States (1976)		
Boston		
Green Line	27.2	151,000
Mattapan-Ashmont	2.6	14,000
Cleveland, Shaker Hts.	13.1	19,000
New Orleans, St. Charles St.	6.5	25,000
Newark, Subway	4.2	12,000
Philadelphia		
Streetcars	51.2	130,000
Subway-Surface	22.3	65,000
Media-Sharon Hill	11.9	14,000
Norristown	13.6	10,000
Pittsburgh, South Hills	24.8	24,000
San Diego (1984)	16	16,000
San Francisco, MUNI	18.2	35,000

Sources: Reference 2, "Evaluations of Operating Light Rail Transit and Streetcar Systems in the United States" by John Schumann, "This is LRT" prepared for third National Conference on Light Rail Transit, 1982, and data provided by individual properties.

Table 45. Light Rail Transit, Estimated Average System Travel Speed and Trip Length

System, Year	Avg. Stop Spacing (miles)	% Grade Separated	Avg. Trip Length (miles)	Avg. Speed (mph) Incl. Layover	Avg. Speed (mph) Excl. Layover
Canada					
Calgary, 1983	---	---	5.5	----	20.0
Edmonton, 1976	0.9	22%	3.5	18.0	22.0
Toronto, 1976	---	---	6.2	9.0	9.7
United States					
Boston, 1976					
Green Line	0.58	55	4.5	10.1	12.4
Mattapan-Ashmont	0.6	99	---	----	12.0
Buffalo	0.45	81	---	----	23.0
Cleveland, Shaker Hts. 1983	0.76	53	7.9	16.8	23.0
New Orleans, St. Charles, 1976	---	0	2.2	----	9.3
Newark, Subway, 1976	0.40	99	2.8	15.0	21.5
Philadelphia, 1976					
Streetcars	---	0	---	----	9.0
Subway-Surface	---	---	3.1	9.0	11.2
Media-Sharon Hill	0.42	---	---	----	16.0
Norristown	1.05	100	---	22.0	30.0
Pittsburgh, South Hill, 1976	0.37	3	7.0	11.8	13.6
Portland	0.60	---	---	----	20.0
San Diego, 1983	0.88	0	8.5	----	29.0
San Francisco, MUNI, 1976	0.23	17	2.9	9.4	----
Range	0.23-1.05	0%-100%	2.2-8.5	9.0-22.0	9.0-30.0
Avg., Non Weighted	0.60	44%	4.9	13.5	17.6

Sources: "1984 APTA Operating Statistics", Reference 2, "Evaluation of Operating Light Rail Transit and Streetcar Systems in the United States" by John Schumann, "State of the Art of Primary Transit System Technology." SEWRPC, 1981, and data provided by individual properties.

Table 46. Light Rail Transit, Employees Per Passenger

System	Annual Rail Patronage (millions)	Rail Employees	Employees Per Million Passengers
Canada			
Calgary, 1983[1]	12.2	106	8.7
Edmonton, 1976[2]	6.3	113	17.9
Toronto, 1976[2]	112.6	1048	9.3
United States			
Boston			
1983[1]	22.6	380	16.8
1976[2]	46.0	1391	30.2
Cleveland			
1983[1]	4.7	263	56.0
1976[2]	4.7	147	31.3
New Orleans, 1983[1]	6.1	115	18.9
Newark, 1976[2]	2.2	44	20.0
Philadelphia			
1983[1]	44.6	1371	30.7
1976[2]	14.8	407	27.5
Pittsburgh			
1983[1]	4.9	387	79.0
1976[2]	6.5	403	62.0
San Diego, 1983[1]	4.2	71	16.9
San Francisco			
1983[1]	48.2	899	18.7
1976[2]	19.3	329	17.0
Range	----	---	8.7 - 79.0
Avg., Non Weighted	----	---	22.9[3]

[1]Data presented in "APTA 1984 Operating Statistics"
[2]Data presented in Reference 2
[3]Pittsburgh data not included in the average. Including Pittsburgh data results in an average of 28.8, greater than the bus or heavy rail data.

Table 47. Light Rail Transit, Estimated Capital Cost

System/Location	Length (miles)	Capital Cost ($ millions) Total	Cost/Mile
Canada			
Edmonton	6.4	$ 92.2[1]	$ 14.4
Calgary	7.7	$176.0[1]	22.6
	4.5	234.0	37.3
France			
Paris	5.6	66.6	11.9
Nantes	6.6	66.0	10.0
Grenoble	5.5	88.0	16.0
Strasburg	8.1	124.0	15.3
United States			
Buffalo	6.4	500.0	78.1
Dallas	160.0	3,200.0	20.0
Detroit	15.0	720.0	48.0
Houston			
Consultant Report[2]	106.5	3,185.0	29.9
METRO Plan[3]	62.9	1,158.0	18.4
Los Angeles			
Long Beach	22.5	690.0	30.7
Century Freeway	17.5	255.0	17.5
Milwaukee	14.3	166.0	11.6
Oklahoma City	17.4	154.0	8.9
Pittsburgh	10.5	559.0	53.2
Portland	15.0	210.0[4]	14.0
St. Louis	18.0	229.0	12.7
Sacramento	18.3	156.0	8.5
San Diego	15.9	224.0	14.1
	4.5	33.0	7.3
San Jose/Santa Clara	20.0	382.0	19.1
Range	----	-----	$7.3-$78.1
Avg., Non Weighted	----	-----	$22.6

[1]Canadian dollars
[2]Outside consultants assessment of a previous Houston LRT plan
[3]Data for Westpark, FW&D, and MKT corridors. Does not incl. yards and shops, SC&C and rolling stock.
[4]An additional $100 million is being spent for freeway improvements.

Table 48. Light Rail Transit, Estimated Operating Cost Per Passenger and Per Passenger Mile

System	Annual Passengers (millions)	Annual Passenger Miles (millions)	Annual Operating Cost ($ millions)	Operating Cost ($)	
				Per Passenger	Per Passenger Mile
Canada[1]					
Calgary	11.4	63.0	$ 3.84	$0.34	$0.06
Toronto	92.3	572.0	44.65	0.48	0.08
United States					
Boston	22.6	31.7	15.90	0.70	0.50
Cleveland	4.7	37.2	6.83	1.46	0.18
San Diego	4.2	35.5	4.20	1.01	0.12
Range	----	----	----	$0.34-$1.46	$0.06-$0.50
Avg., Non Weighted	----	----	-----	$0.80	$0.19

[1]Canadian dollars
[2]Excluding Boston, the average is 11 cents/passenger mile

Source: "1983 APTA Operating Statistics" and "1984 APTA Operating Statistics"

AUTOMATED GUIDEWAY TRANSIT

Of all the technologies discussed in this report, the amount of consistent data for automated guideway transit (AGT) is relatively small. In general, these systems consist of relatively small, electrically-powered vehicles operating on fully grade separated guideways. Automatic control (i.e., no train operator is required) is a typical characteristic.

The role of the AGT technology is not easy to define. These systems, sometimes referred to as people movers, are used to provide an internal circulation function (refer to the first section of this report). However, in some instances, referred to a intermediate capacity transit systems (ICTS) or advanced light rail transit (ALRT), this technology is used to provide line-haul transit service and is similar to light rail transit technology.

In reviewing the data presented in this section, it is important to realize that: 1) the data base is relatively small; and 2) some of the system data presented are for "people mover" systems while other data refer to ICTS. Thus, the reliability of the data presented is more open to question; this is especially true in considering "average" values due to the substantial variation between systems.

Capacity

Automated guideway transit capacity is a function of train headways, cars per train, and passengers per car. As would be expected, there is a wide range in capacities.

The so-called intermediate capacity transit systems were developed to serve demands in the 10,000 to 25,000 passenger per hour per direction range. The capacity of the Lille MATRA System is estimated to be 12,500 persons/hour per direction with a 2-car consist and twice that with a 4-car consist; this operation is providing train service at one-minute headways.

In terms of the people movers, high capacity is not necessarily a required attribute; maximum daily ridership of 40,000 to 50,000 might be expected; this might translate to peak-hour demands per direction of below 7500. The Dallas Airtrans system can theoretically handle about 9800 passengers per hour per direction, while the Morgantown system can handle about 4100 passengers per hour per direction. The ICTS systems have the capacity required to serve the demand that might be expected to exist in Texas corridors (Table 10).

Automated Guideway Transit System Characteristics

Characteristics such as extent of systems, average speed, and employees per passenger are presented for selected properties.

Guideway Miles By System

Table 49 shows selected data on system length and average operating speed. The people movers, which generally have more than 1 station per mile, have average operating speeds between 9 mph and 18 mph. The ICTS system has an average speed of 22 mph; this is roughly 70% of the average speed characteristic of heavy rail transit.

Employees Per Passenger

Table 50 presents available employment data for AGT systems. Due to the limited data and the substantial variation in the data, the value of the averages is highly questionable. Perhaps the appropriate conclusion would be that the various systems have unique characteristics and requirements; no general conclusions can be drawn from this table.

Capital Cost

Table 51 summarizes available capital cost data for AGT systems. The 3 data points for ICTS are reasonably consistent; the average cost is right at $40 million per mile.

A wider variation exists in capital cost for people mover systems. For the new systems, costs typically are in the range of $40 to $75 million per mile.

In reviewing these capital cost data, the qualifying statements presented in the "Summary" should be recognized.

Operating Cost

Table 52 summarizes operating cost data for AGT systems. Again, the data sources are limited and the range in values is substantial. It is difficult to draw any conclusions, and the average values need to be viewed with extreme caution.

Table 49. Automated Guideway Transit, System Size and Estimated Average System Travel Speed

System, Year	Line Miles	No. of Stations	Avg. Trip Length (miles)	Avg. Speed (mph)	
				Incl. Layover	Excl. Layover
People Movers					
Dallas (Airtrans), 1977	6.4	28	1.4	10.0	---
Seattle-Tacoma, 1977	0.85	6	0.36	8.2	9.2
Tampa, 1977	0.7	8	0.17	6.8	8.8
Morgantown, 1977	2.1	3	1.62	9.7	16.5
Fairlane, Mich,. 1977	0.5	2	0.47	9.7	17.8
ICTS					
Lille, France (MATRA)	8.5	18	6.4	----	22.0
Toronto (Scarborough)	4.3	5	---	----	----
Vancouver, B.C.	13.5	15	---	----	----
Range	---	---	0.17 - 6.4	6.8 - 10.0	8.8 - 22.0
Avg., Non-Weighted	---	---	1.8	8.9	14.9

Source: Reference 2 and "VAL The 1983-84 Record of Experience", presented at the International Conference on Automated People Movers, March 1985.

Table 50. Automated Guideway Transit, Employees Per Passenger (1977 data)

System, Year	Line Miles	Annual Passengers (millions)	Employees	Employees Per Million Passengers
People Movers				
Dallas (Airtrans)	6.4	6.1	160	26.1
Seattle-Tacoma	0.85	10.1	24	2.4
Tampa	0.7	14.5	16	1.1
Morgantown	2.1	1.9	51	26.7
Fairlane, Mich.	0.5	0.25	10	40.0
ICTS				
Lille, France (MATRA) 1985	8.5	28.0	175	6.25
Range	---	-----	---	1.1 - 40.0
Avg., Non-Weighted	---	-----	---	17.1

Source: Reference 2 and "VAL The 1983-84 Record of Experience", presented at the International Conference on Automated People Movers, March 1985.

Table 51. Automated Guideway Transit, Estimated Capital Costs

System	Line Miles	Capital Cost ($ millions)	Capital Cost Per Mile ($ millions)
People Movers			
Miami			
Initial System	1.9	$145	$ 76.3
Planned Extension	2.1	210	100.0
Detroit	2.9	210	72.4
Jacksonville (planned)	0.7	29	41.4
Houston (planned)	4.5	112	24.9
Tampa[1]	0.7	13	18.4
Seattle-Tacoma[1]	0.9	32	37.4
Morgantown[1]	2.1	42	20.4
ICTS			
Vancouver, B.C.	13.5	615	45.6
Toronto (Scarborough)	4.3	149	34.7
Lille, France (MATRA)	8.5	328	38.6
Range	----	---	$18.4 - $100.0
Avg., Non-Weighted	----	---	$46.4

[1]1977 Cost from Reference 2.

Sources: Reference 2, "Urban Experience with AGT in North America" and "VAL The 1983-84 Record of Service" presented at the International Conference on Automated People Movers, March 1985, and data provided by systems.

Table 52. Automated Guideway Transit, Estimated Operating Cost Per Passenger and Per Passenger Mile

System	Annual Operating Cost ($ millions)	Annual Ridership		Operating Cost (dollars)	
		Passengers (millions)	Passenger Miles (millions)	Per Passenger	Per Passenger
People Movers					
Dallas (Airtrans), 1977	$3.0	6.1	8.6	$0.49	$0.35
Seattle-Tacoma, 1977	0.75	10.1	3.6	0.07	0.21
Tampa, 1977	0.48	14.5	2.5	0.03	0.19
Morgantown, 1977	1.37	1.9	3.1	0.72	0.44
(1984)	2.5	---	---	----	----
Fairlane, Mich. (1977)	0.4	0.25	0.12	1.60	3.33
ICTS					
Lille, France (MATRA), 1985	8.4	28.0	180.0	0.29	0.05
Range [1]	---	----	-----	$0.03-$0.72	$0.05-$0.44
Avg., Non-Weighted[1]	---	----	-----	$0.32	$0.25

[1]Excludes Fairlane data.

Source: Reference 2 and "VAL The 1983-84 Record of Experience", presented at the International Conference on Automated People Movers, March 1985.

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