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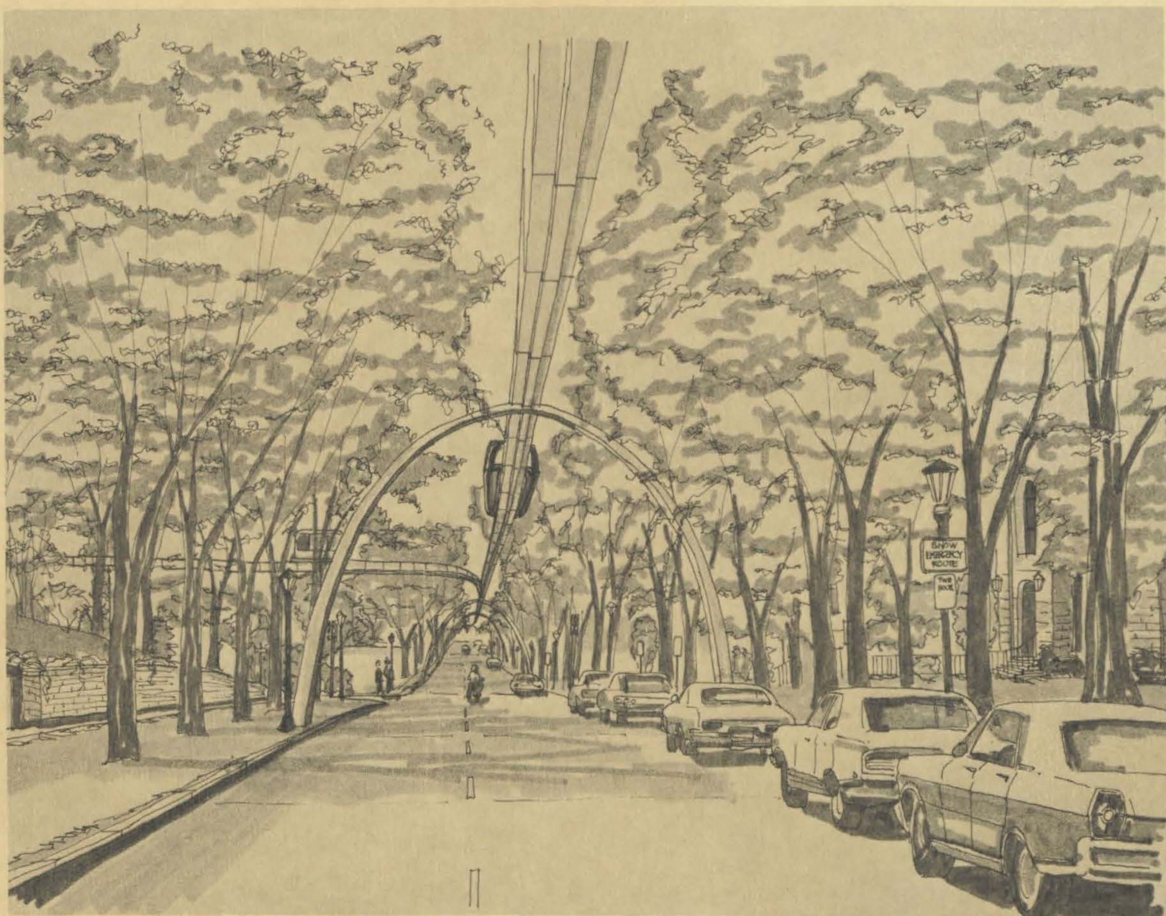
for

PERSONAL RAPID TRANSIT



a report by the

Task Force on New Concepts in Urban Transportation

Center for Urban and Regional Affairs

University of Minnesota

December, 1972

Planning for Personal Rapid Transit. Task Force on New Concepts in Urban Transportation, U of M.

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PREFACE

The purpose of this report is to present information useful to planners and decision makers interested in planning personal rapid transit (PRT) systems into communities, to engineers engaged in development of PRT systems, and to students of transportation engineering and planning. Results of analyses of PRT for the Twin Cities and Duluth are presented.

The work of this report was done by members of the Task Force on New Concepts in Urban Transportation, Center for Urban and Regional Affairs, in partial fulfillment of the purposes of an Act of the Minnesota State Legislature (Minnesota Laws 1971, Chapter 915). The Act directed the Center for Urban and Regional Affairs at the University of Minnesota to develop a proposal for demonstration of an advanced form of public transportation in Minnesota. The Task Force interpreted this directive broadly in light of the federal program of research, development, and demonstration of PRT systems as it was emerging during the study period from July 1971 to the present time, and with a view to aim the effort toward systems which have potential for offering a serious alternative to the automobile. The type of system which has this capability is called high-capacity personal rapid transit and at this writing is conceived of as a system of vehicles and guideways in which the vehicles may be captive to the guideway or may be pallets capable of carrying a variety of types of passenger and freight modules or small automobiles. The latter option makes the system dual mode without the major disadvantages of pure dual-mode systems.

A basic conclusion reached by the Task Force is that the type of system which should be demonstrated in the Twin Cities is not yet ready for demonstration. Therefore, the work of this report is aimed at development of knowledge needed by both planners and engineers to bring the development of high-capacity personal rapid transit to the point at which urban demonstration is advisable and to recommend further steps in that process. At the present time, the process requires continued detailed planning and research in cities interested in possible deployment of these advanced systems coupled with a federally sponsored development program to bring the hardware to maturity.

While the volume has been edited by several members of the Task Force on New Concepts in Urban Transportation, primary authorship of the various chapters is as follows:

Preliminary Results: Professor Jack L. Dais

Chapter 1: Professor Daniel L. Gerlough

Chapter 2: Roger A. Peterson, Mechanical Engineering Student and Professor J. Edward Anderson

Chapter 3: Catherine McCann Murphy, Editor of "New Concepts in Urban Transportation"

Chapter 4: John Zehren, Research Fellow in Architecture

Chapter 5: Professor Anderson

Chapter 6: Professors Dais and Alain L. Kornhauser

Chapter 7: Professor Dais

Chapter 8: Professor Anderson

Chapter 9: Professors Dais, William L. Garrard, and Harold L. York

Chapter 10: Professors Dais and York

Chapter 11: Professor Anderson

The Task Force acknowledges, in particular, the strong support of Professor John R. Borchert, Director of the Center for Urban and Regional Affairs, without which this work would have been impossible. Professor Anderson likewise acknowledges similar support from Professor Richard C. Jordan, Head of the Mechanical Engineering Department. The assistance of Brady Reed in the large amounts of computer programming required to generate the results cited, and of Sherry H. Romig in meticulous editing of the entire manuscript are gratefully acknowledged.

J. Edward Anderson
Professor of Mechanical Engineering
and Coordinator of the Task Force on
New Concepts in Urban Transportation

December 20, 1972

CONTENTS

CONTENTS (continued)

CONTENTS (continued)

CONTENTS (continued)

CONTENTS (continued)

CONTENTS (continued)

CONTENTS (continued)

FIGURES

FIGURES (continued)

FIGURES (continued)

FIGURES (continued)

FIGURES (continued)

TABLES

PRELIMINARY EXAMINATIONS OF THE POTENTIAL OF PRT

The Potential for Duluth

Duluth is a city with a total population of 100,000 people and a population density of about 1,600 people per square mile. However, since the population and major activity centers appear in clusters, the majority of trip-ends lie in a relatively small land area. Nevertheless, Duluth's low density undoubtedly makes it one of the more difficult cities for which to plan economically feasible PRT.

As a partial test of the feasibility of PRT, a network of 75 one-way miles with 128 stations was evaluated by means of a computer model. The network, which is shown in Figure 1, was designed by W. Brady Reed, a student who had lived in and is familiar with the general character of Duluth. The network consists largely of one-way guideways as indicated. The guideways would be elevated and consequently the network follows the existing street network. Each arrowhead defines a station as well as the direction of flow. All intersecting lines are connected by a vehicle interchange. The stations and interchanges are described in detail in the body of the report. Mr. Reed attempted to provide excellent station access to most major activity centers, and attempted to place most residences within walking distance of a station. The network is by no means an ultimate solution for Duluth; however, it did provide a specific example for evaluation.

An origin-destination trip table with 1985 travel forecasts, obtained from the Minnesota Highway Department, was used as an input to

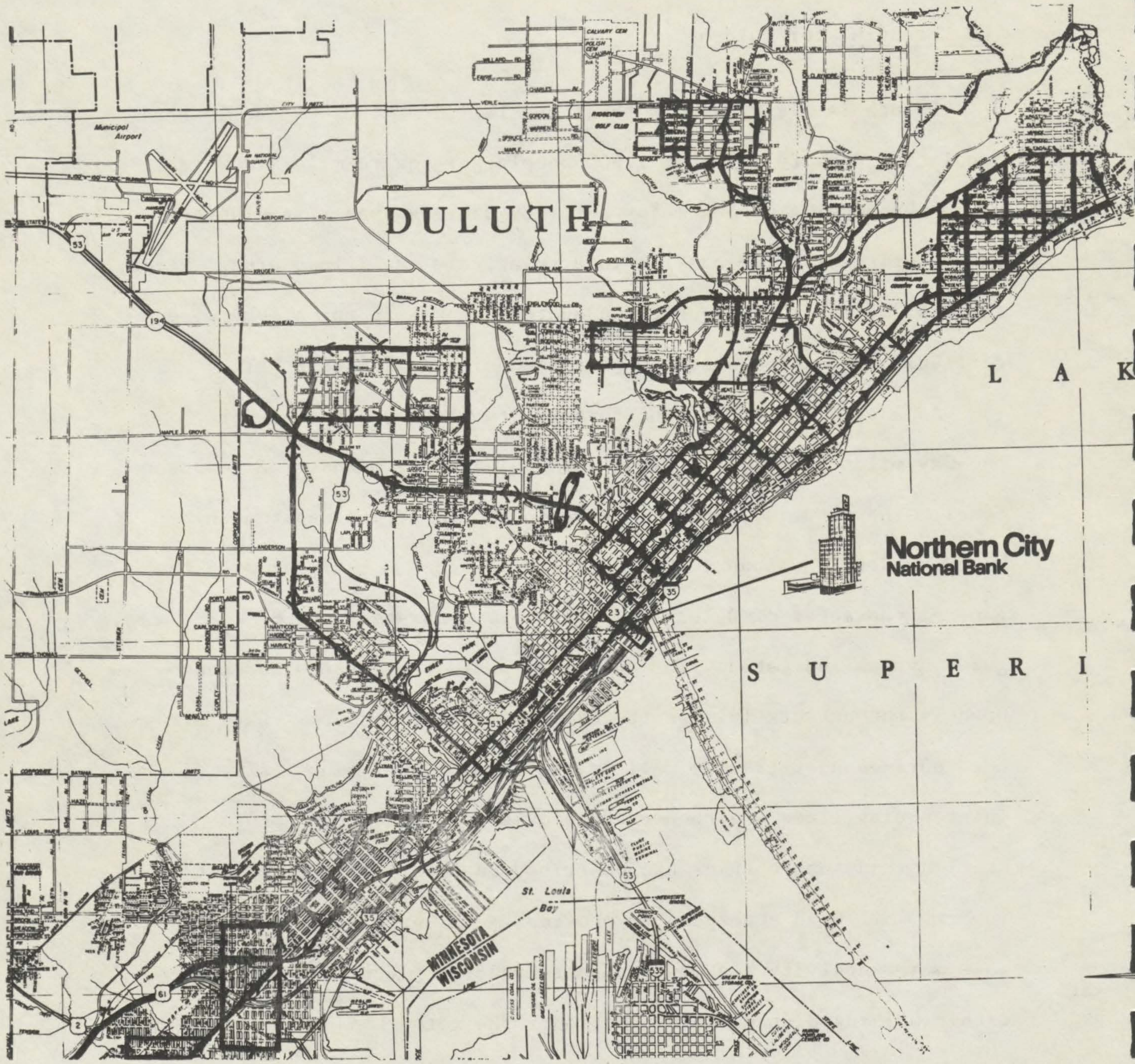

Figure 1. Network evaluated for Duluth

Table 1 Evaluation of PRT for Duluth

Ridership	
Per cent of trips by PRT	40%
Per cent of passenger miles by PRT	45%
Total number of annual trips by PRT	32,000,000
Economics	
Total cost per ride	\$0.65
Total cost per passenger mile	\$0.14
Total capital cost	\$177,000,000
Annual fixed costs	\$13,000,000
Annual variable costs	\$8,000,000
Total annual costs	\$21,000,000
Annual reduced auto usage benefit	\$16,000,000
Annual safety and pollution benefit	\$2,000,000
Annual time savings benefit	\$4,000,000
Total annual benefits	\$22,000,000
Electrical Power-Plant Requirements	
Peak hour	13 megawatts
24-hour average	5 megawatts
Design Data	
Vehicle fleet size	3400
Time-headway requirement	1 second
Largest peak-hour station requirement	900 pass/hour
Typical peak-hour station requirement	50 pass/hour

the computer model. The computer model is described in detail in the body of the report. Briefly, however, the model computes statistics on ridership, economics, the environment and system specifications. Trips are assigned to either the auto or PRT on the basis of comparing travel times and user costs via the two modes. The study considered passenger transport only. The economically important area of freight movement by PRT was left for future studies. A 35-mph PRT speed and an 8¢ per occupied-vehicle-mile fare were assumed. The major results obtained are given in Table 1. The reader should be cautioned that the methods employed in the computer model are both speculative and controversial. The major uncertainties are in estimating ridership and estimating costs for nonexisting transportation systems. It is felt that a major value of the study is to provide guidelines to potential system developers on pricing.

Cost Assumptions: The analysis assumed a 6% interest rate. Fixed facilities are amortized over 30 years and vehicles over 10 years. Table 2 summarizes the cost assumptions for the study. If cost estimates this low are to be realized, it is necessary that the small vehicles and other components be manufactured in quantity.

The benefits quantified in dollar terms were: reduced auto usage and air pollution, increased safety and travel-time savings. PRT would of course offer many additional benefits which were not quantified. The prediction of 40% transit ridership can be compared with the present level of about 5%. The cost-per-trip and cost-per-passenger-mile estimates are complete, including all capital and operating costs. The 14¢ per-passenger-mile figure translates into about 18¢ per occupied vehicle mile.

Table 2 Cost Assumptions for Duluth Study

Item	Fixed Costs		Variable Costs	
	Capital	Other	Capital	Other
Guideway and supports, right of way, electrification	$1 million per mile	Annual maintenance of 1/2%	---	---
Station including ramps, building and elevators	$400,000	Annual maintenance of 1/2%	---	---
Single interchange ramps	$200,000	Annual maintenance of 1/2%	---	---
Adminstration	$225,000	15 people @ 15K	---	---
Maintenance garage	---	---	$100/vehicle	1/2% maintenance
Carbarn	---	---	$3000/vehicle	1/2% maintenance
Vehicles	---	---	$4000/vehicle	3¢ per mile oper.

FIGURES (continued)

45% mileage attraction to PRT means a 45% reduction in automotive air emissions.

The Potential for the Twin Cities

Eight networks, shown in Figures 2-9, were evaluated for the Twin Cities. The networks, which were developed by Professor Anderson, show how metropolitan area-wide networks can evolve in stages from an initially small network. The networks consist of one-way lines interconnected by vehicle interchanges. The arrowheads identify station locations. The schedule for staging would be a matter of social and political policy. Stage 1 or some subset of it could be a possible demonstration project. In drawing the networks, attention was paid to providing station access to major activity centers. The networks reflect a knowledge of topography and characteristics of streets obtained from extended residence in the metropolitan area. The layout was facilitated by a theory of flow developed in Chapter 5 of this report. The theory relates line spacing to population density, average trip length and a gross indicator of trip-making habits. The larger networks provide walking access to large numbers of Twin Cities residents. The networks shown are by no means optimum and many improvements are undoubtedly possible; however, they do provide specific designs for computer evaluation.

Each of the eight stages was evaluated individually and the main results are summarized in Table 3. The study was facilitated by an auto-trip table and travel-time table provided by the Minnesota Highway Department. The tables reflect the 1970 pattern for the seven county*

* The seven county area includes Anoká, Carver, Dakota, Hennepin, Ramsey, Scott and Washington Counties.

area. Stage 1 and part of Stage 2 were assumed to be a 15-mph network. Vehicles on other lines of the other networks were assumed to travel at 40 mph. An 8¢ per occupied-vehicle-mile fare was assumed. Trips are assigned to the auto or PRT based on a comparison of travel times and user costs via the two modes. It must be emphasized that the statistics presented in Table 3 are tentative in that they were obtained by using unproven ridership estimation techniques. Furthermore the numbers are sensitive to cost estimates on nonexisting technology, which must be regarded as uncertain.

Cost Assumptions: The analysis assumed a 6% interest rate. Fixed facilities are amortized over 30 years and vehicles over 10 years. Table 4 summarizes the cost assumptions for the study. The assumptions are based on estimates supplied by Aerospace Corporation, El Segundo, California. Each item on the list equals or exceeds Aerospace's estimate.

By comparing the seven-county-area passenger trips by PRT with the present level of 3% to transit, it is seen that PRT can effect significant increases in transit ridership. Furthermore, as will be discussed in the next section, it is felt that these numbers are conservative estimates of what can eventually be obtained when the attributes of PRT are more fully exploited. The statistic in Table 3 "Per cent of trips in network area by PRT" requires clarification. This statistic gives the percentage of trips taken by PRT which have both ends within a one-mile walking distance to a station. The statistic shows that the system is attracting a high percentage of the trips with ends in the network area. The cost-per-trip and cost-per-mile estimates given in

Table 3 Statistics on Twin Cities Study

Stages	1	2	3	4	5	6	7	8
Network Statistics								
Miles of one-way guideway	21	65	159	234	290	339	369	442
Number of stations	64	119	218	296	361	395	432	506
Number of single-ramp interchanges	49	92	170	231	281	308	337	395
Vehicle fleet size	870	4200	8100	10200	12500	13600	15100	17600
Average station demand	87	91	96	94	93	92	92	88
CBD Average vehicle flow (vehicles per hour)	330	540	810	1000	1200	1600	1700	1800
Network average vehicle flow (vehicles per hour)	330	570	660	600	600	560	560	560
Ridership Statistics								
Per cent of trips in network area by PRT	96	77	58	48	43	38	37	34
Per cent of trips in 7-county metro area by PRT	1	3	5	7	9	10	11	12
Per cent of passenger miles by PRT	1	3	5	8	9	11	13	14
Economic Statistics								
Total capital cost, millions	87	223	465	645	794	896	980	1230
Total annual cost, millions	12	32	65	88	107	120	132	154
Annual variable cost, millions	3	13	25	31	38	41	46	53
Annual fixed cost, millions	9	21	40	57	69	79	86	101
Annual capital cost, millions	7	19	39	54	66	74	82	93
Annual revenue, millions	4	19	37	47	58	63	70	81
Annual benefits, millions*	22	38	59	84	93	102	113	133
Benefit cost ratio	1.84	1.18	.91	.96	.87	.85	.86	.86
Total cost per ride, dollars	.59	.83	.96	.88	.89	.91	.92	.97
Total cost per passenger mile, dollars	.18	.10	.11	.11	.09	.12	.12	.12

* Benefits quantified include reductions in auto-travel cost, travel-time savings, air pollution and auto accidents.

Table 3 Statistics on Twin Cities Study (Continued)

Stages	1	2	3	4	5	6	7	8
Environmental Statistics								
Peak electrical power requirement, megawatts	6	27	52	66	80	88	97	113
Average electrical power requirement, megawatts	2	11	22	27	34	37	41	47
Urban transporation energy savings, per cent	1	2	4	7	8	9	10	11

Table 4 Cost Assumptions for Twin Cities Study

	Fixed Costs		Variable Costs	
Item	Capital	Other	Capital	Other
Guideway and supports, right of way, electrification	$1.3 million per mile	Annual maintenance of 2%	---	---
Stations including ramps, buildings and elevators	$400,000	Annual maintenance of 2%	---	---
Single interchange ramps	$300,000	Annual maintenance of 2%	---	---
Computer facility	$70,000/ station	Annual maintenance of 10%	---	---
Local computers and sensors	$50,000/ station $50,000/ interchange	Annual maintenance of 10%	---	---
Administration	$750,000	15 people @ 15K	---	---
Maintenance garage	---	---	$400/vehicle	2% maintenance annually
Carbarn	---	---	$3000/vehicle	2% maintenance annually
Vehicles	---	---	$7000/vehicle	2¢ per mile oper.

Table 3 are complete, including all capital and operating costs. It is interesting to compare the per-passenger-mile costs with an average automobile per-passenger-mile cost of 10 or 12 cents. We see that PRT costs are in the same range. The cost per trip estimates are in the same range as dial-a-ride costs (50¢ - $1.50) in other cities and somewhat higher than bus costs (40¢ - 70¢).

A widely held notion is that a PRT network would have to cover an entire metropolitan area before it could be economically attractive. The benefit-cost ratios and cost-per-ride estimates of Table 3 indicate that this notion is a myth. In fact, Stage 1 and Stage 2 exhibit more favorable cost-per-ride and benefit-cost-ratio statistics than do the large networks. Furthermore the modest capital investment associated with these stages warrants further consideration of them as possible demonstration projects.

Discussion of the Methodology

As a result of limitations due to time, budget and available research methodology, it cannot be claimed that the results of this study are as complete as would be desired. Current and planned research by the University of Minnesota Task Force on New Concepts in Urban Transportation is, however, aimed at improving the methodology. Some of the limitations of this study are discussed in the following paragraphs.

1. The study considered access to the PRT systems by walking only. Access methods like park-and-ride, kiss-and-ride and dial-a-ride were not considered. These access methods along with PRT spur lines into suburbs and outlying areas could increase ridership significantly.

More importantly, the alternative of a dual-mode system was not actively studied.

2. The economically important topic of freight movement was not considered. It is felt that a significant portion of urban freight movement could be performed by PRT. The revenues obtained from freight movement could substantially reduce the requirement for subsidies from federal capital grants and state and local taxes.

3. Reliable ridership estimation techniques for PRT systems are not available. The technique employed in this study was to assign a trip to PRT or the auto based on a comparison of travel time and cost via the two modes, in which travel time was converted to cost by valuing time at 25% of the area-wide wage rate. The dollar value of walk and station process time was taken at 50% of the wage rate. The model did not incorporate several important factors like reliability, comfort, etc., because the modeling techniques are not available. Also the value assigned to certain model parameters (like perceived auto cost and perceived PRT fare) are open to serious criticism. Compiled data on parking costs was not available so our study simply took our best guesses. The study did not account for induced demand due to improved travel availability. The Twin Cities study estimated ridership by considering <u>only</u> trips diverted from the automobile. Additional ridership diverted from buses was not included. Furthermore, the Twin Cities study was based on 1970 trip patterns. Projections, however, call for significant increases through 1985.

4. The cost estimates used are subject to uncertainties. Perhaps the most significant uncertainty lies in the cost of vehicles indicated

in Tables 2 and 4. The auto-like costs listed there would require a large production operation; however, the market for this level of operation has not yet developed. The cost assumptions given in Table 2 were made earlier than those given in Table 4. Table 1 was not recalculated; however, if it were, the capital cost figures for Duluth would be increased by about 25%.

5. The estimation of benefits in dollar terms is subject to several uncertainties. Based upon the ridership projections, a reduced auto-usage benefit was computed on the basis of 10¢ per auto mile not driven and parking costs not encountered. An extra 2¢ per auto mile not driven was attributed to safety and pollution. This is based on estimates made elsewhere of increased auto costs to meet 1976 safety and pollution standards. The time-savings benefit (or loss) arises from two sources. First, many trips are faster (or slower) by PRT than auto. This can be accurately computed. Secondly, the remaining auto trips move faster because of the unloading of the streets. This effect was computed in the study through the use of an unproved technique. Time savings (or losses) were converted into dollars by valuing time at the area-wide wage rate.

6. The determination of potentially significant economic and environmental impacts were beyond the scope of the study. For example, what effect would a major new alternative have on the economy? How will it affect the job mix? What new industries will it stimulate? On the environmental side, what would be the reduction in street noise? An area-wide automotive air-pollution reduction equal to the fraction of trips by PRT can be conservatively expected; however, the extent of relief to the trouble spots in Duluth and the Twin Cities remains to be investigated.

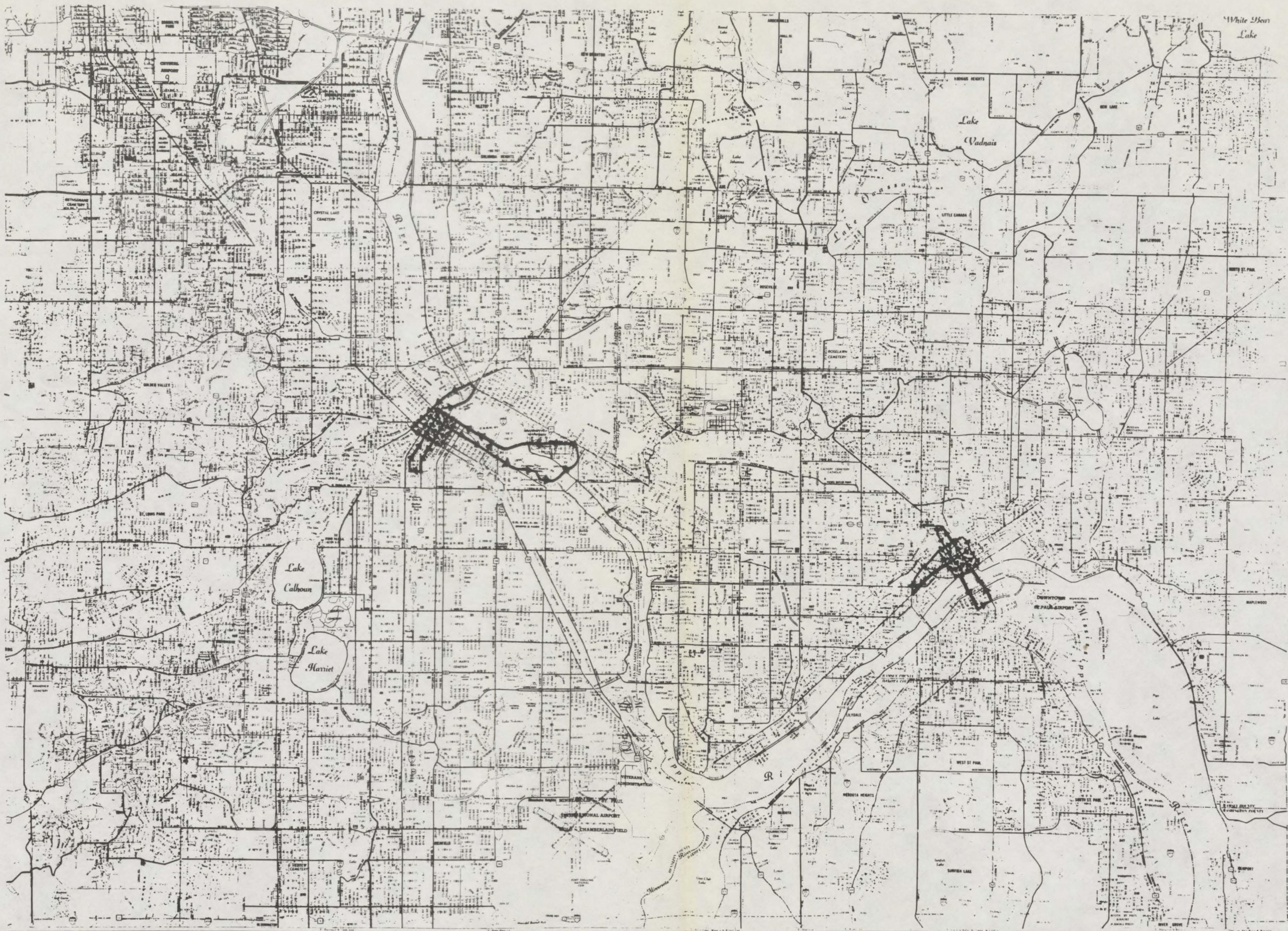

Figure 2a. Network evaluated for the Twin Cities--Stage 1

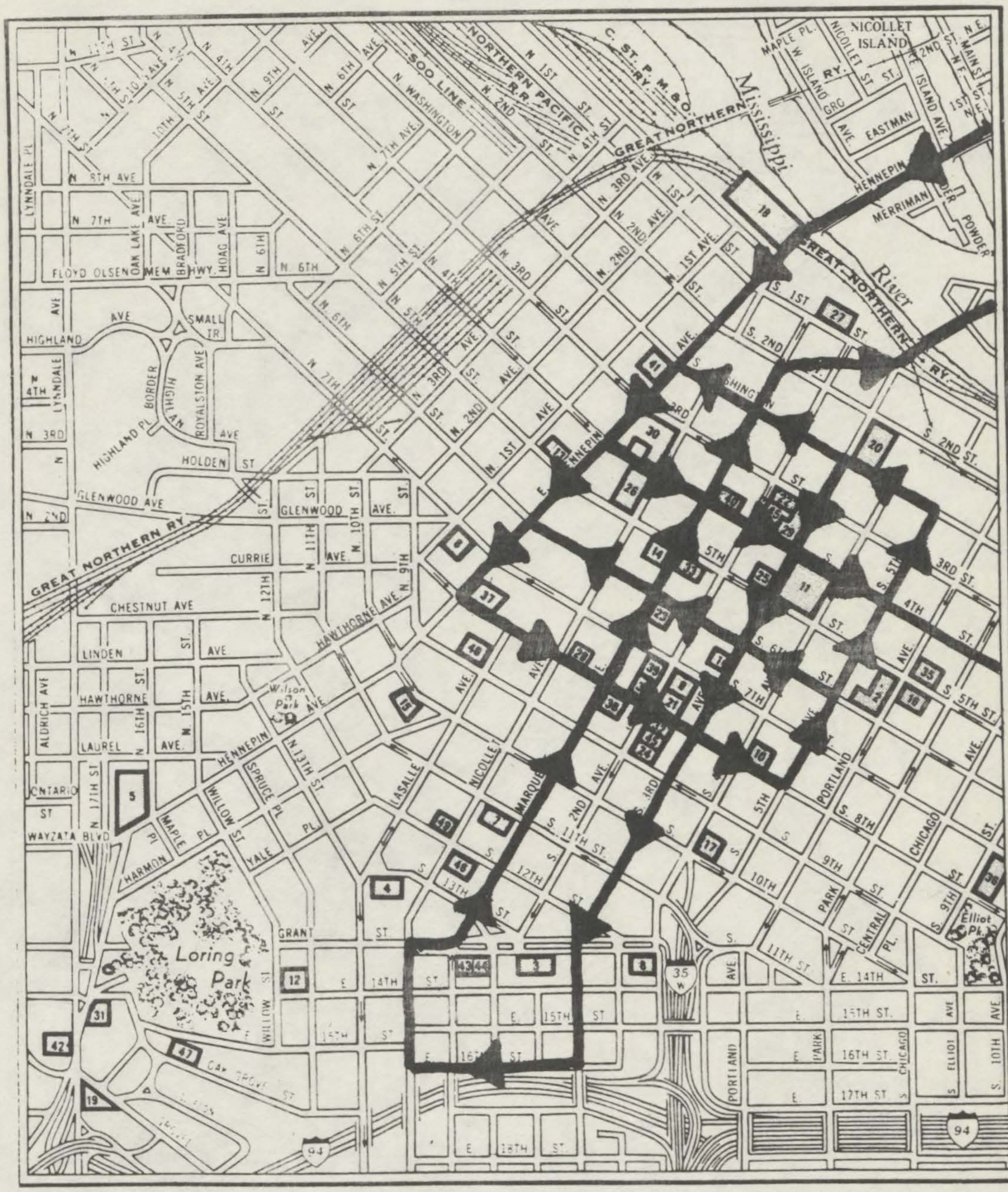

Figure 2b. Downtown Minneapolis portion of Stage 1 Network

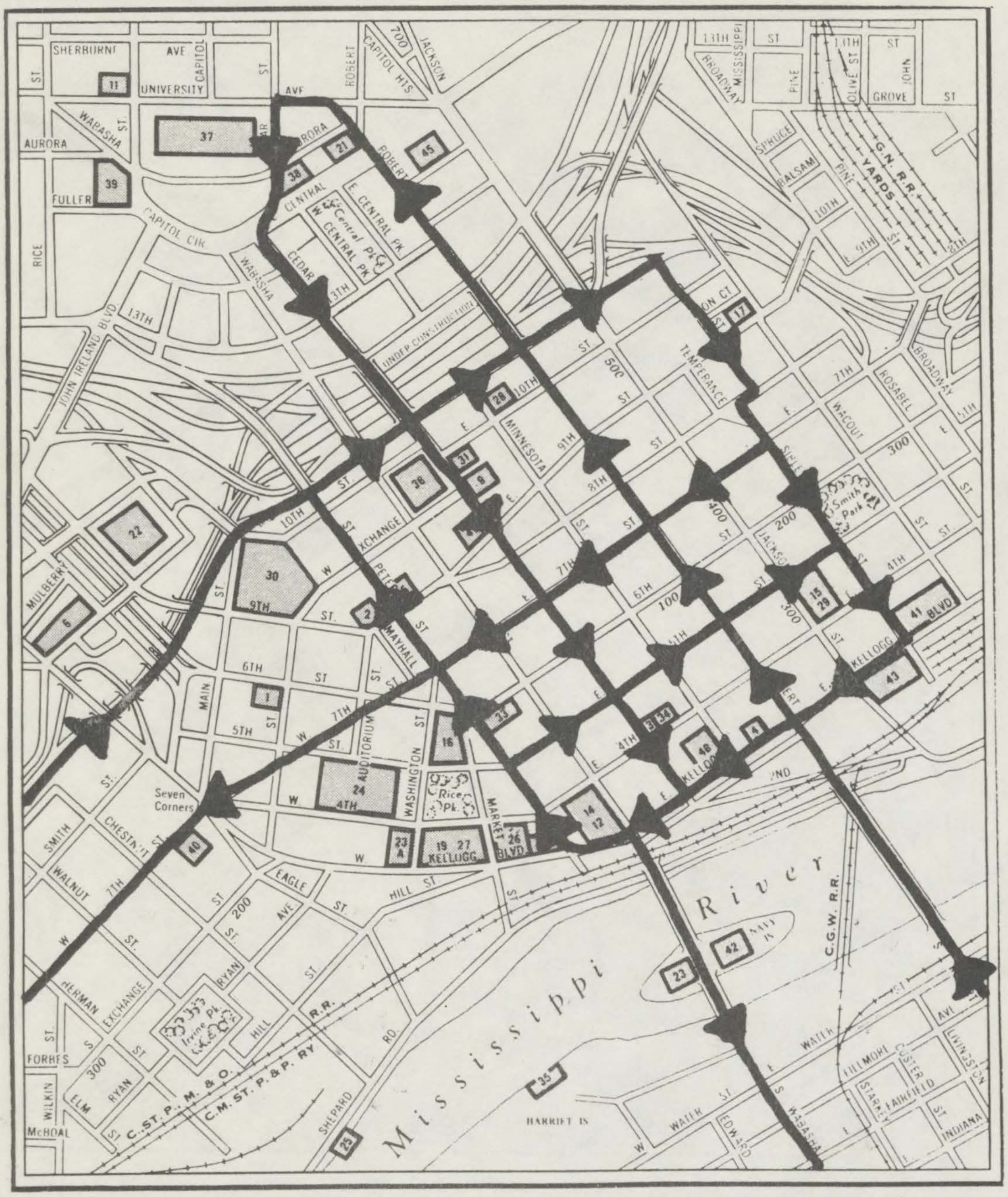

Figure 2c. Downtown St. Paul portion of Stage 1 Network

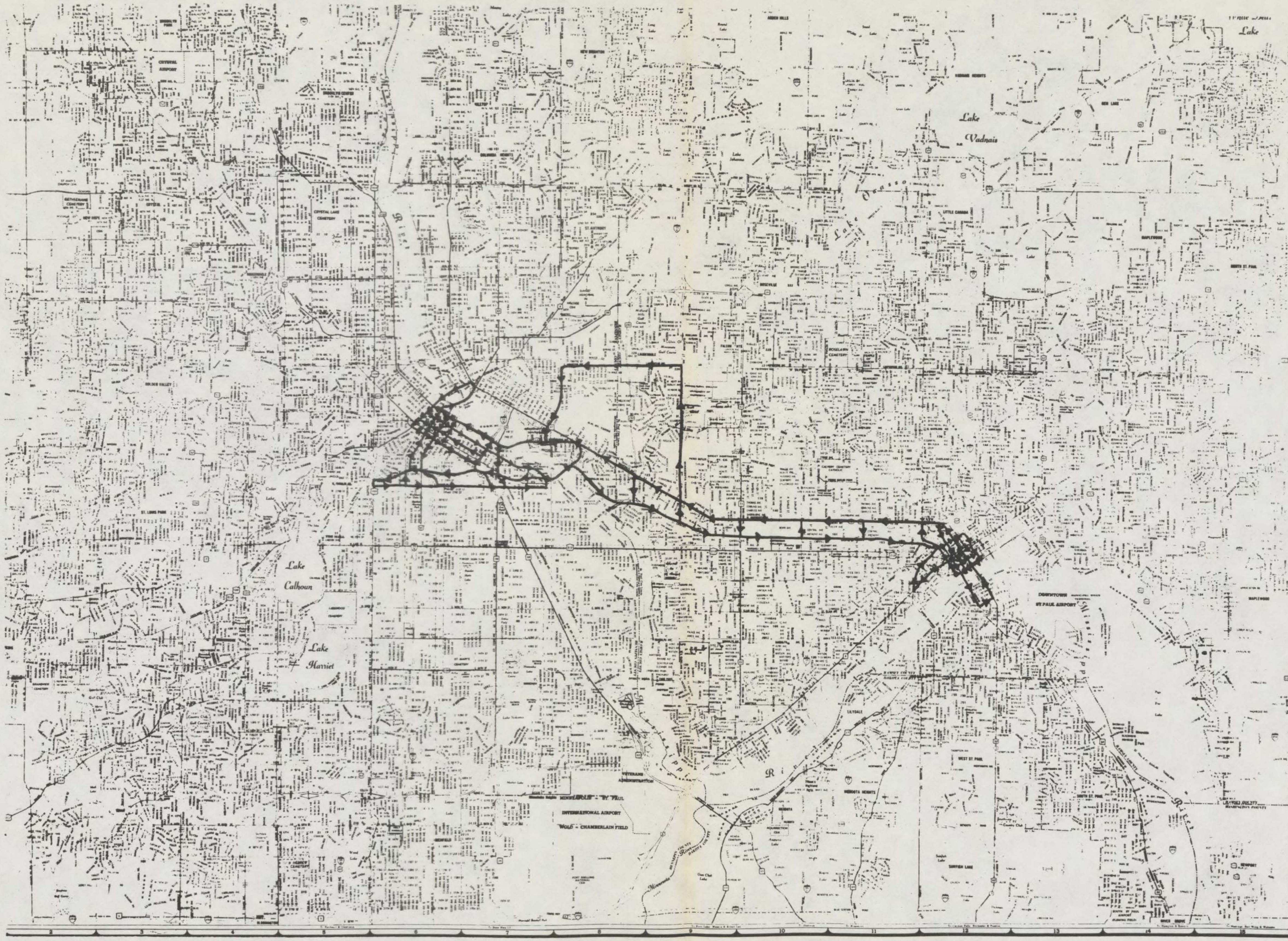

Figure 3. Network evaluated for the Twin Cities--Stage 2

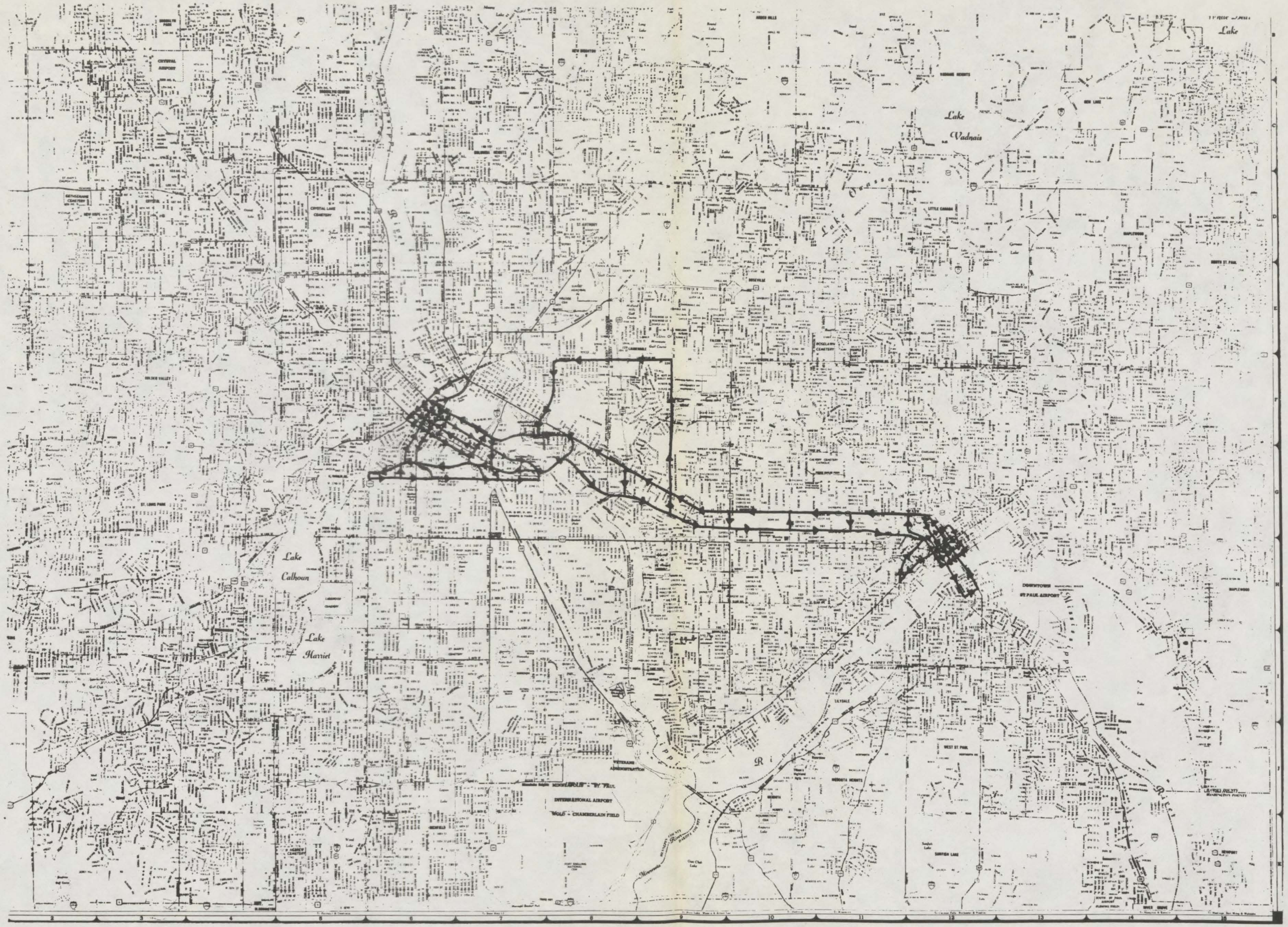

Figure 3. Network evaluated for the Twin Cities--Stage 2

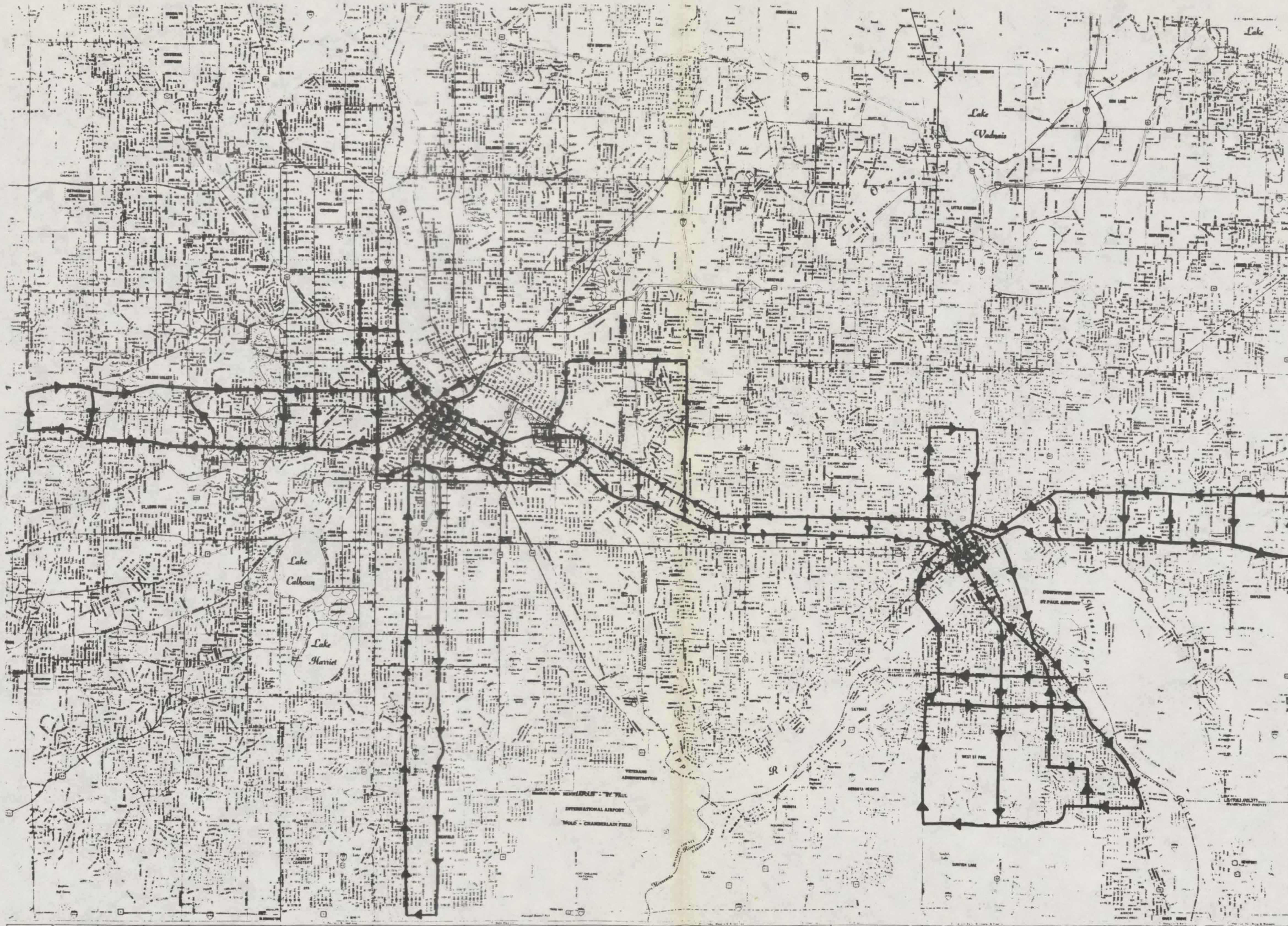

Figure 4. Network evaluated for the Twin Cities--Stage 3

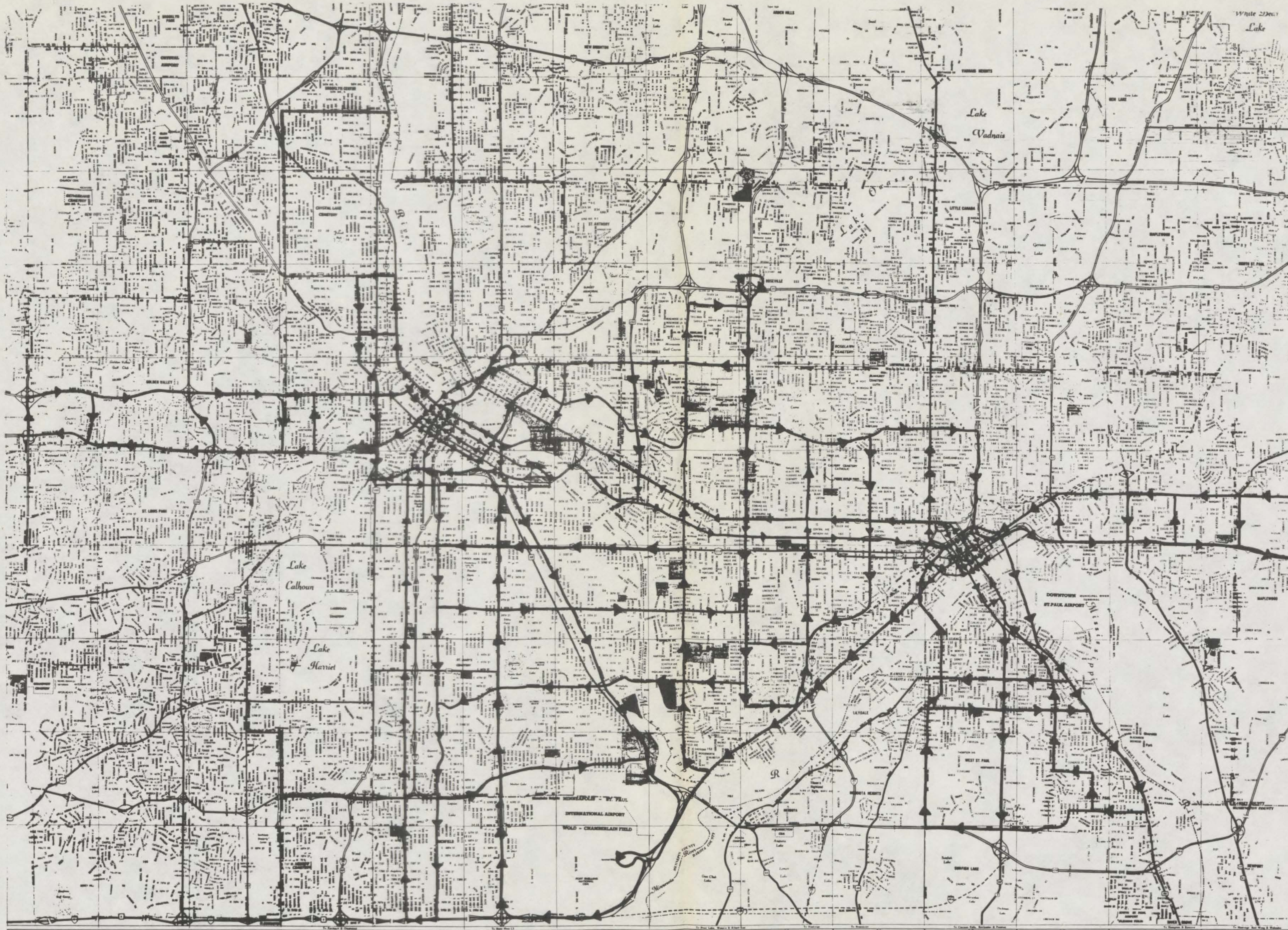

Figure 5. Network evaluated for the Twin Cities--Stage 4

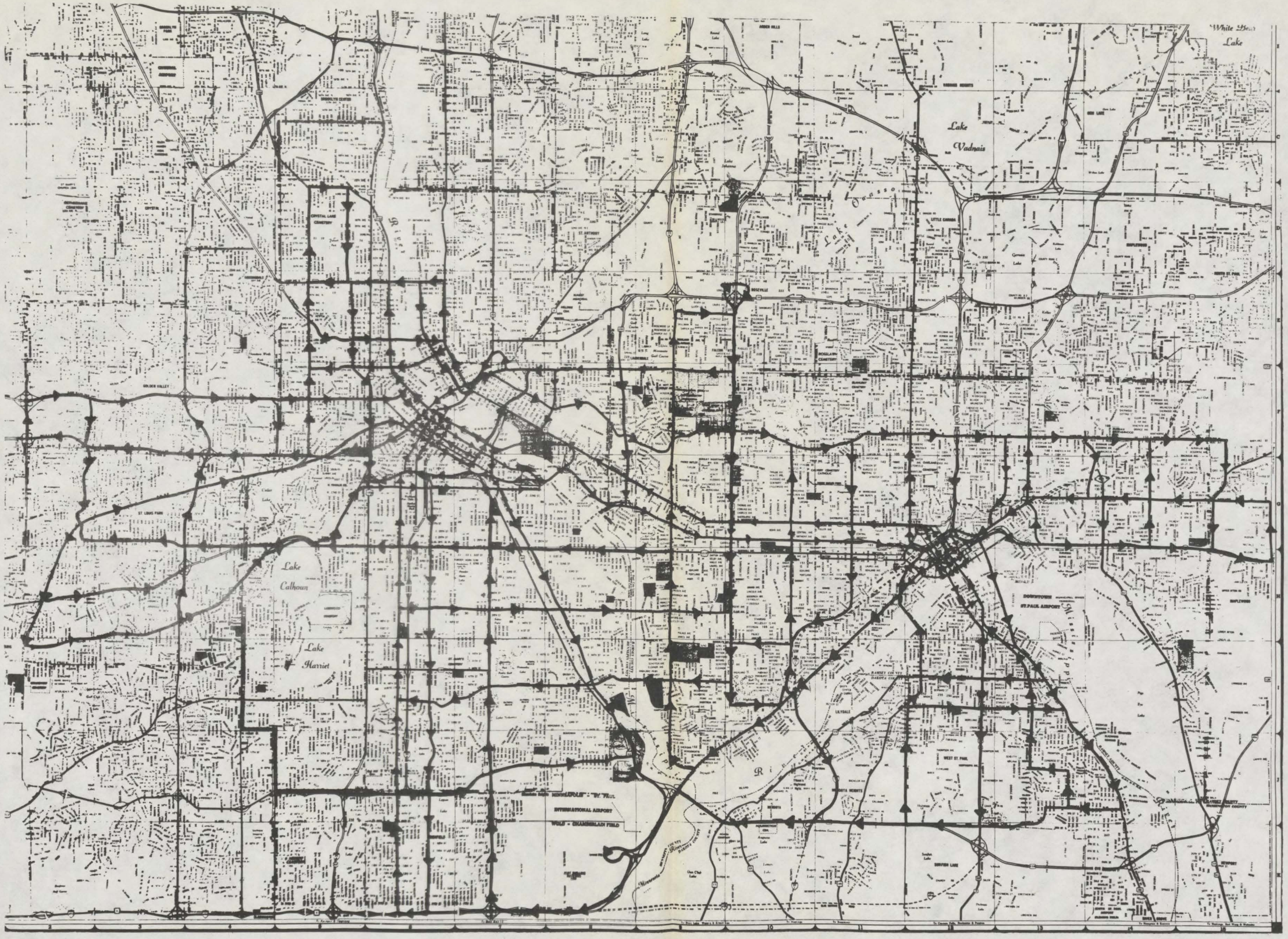

Figure 6. Network evaluated for the Twin Cities--Stage 5

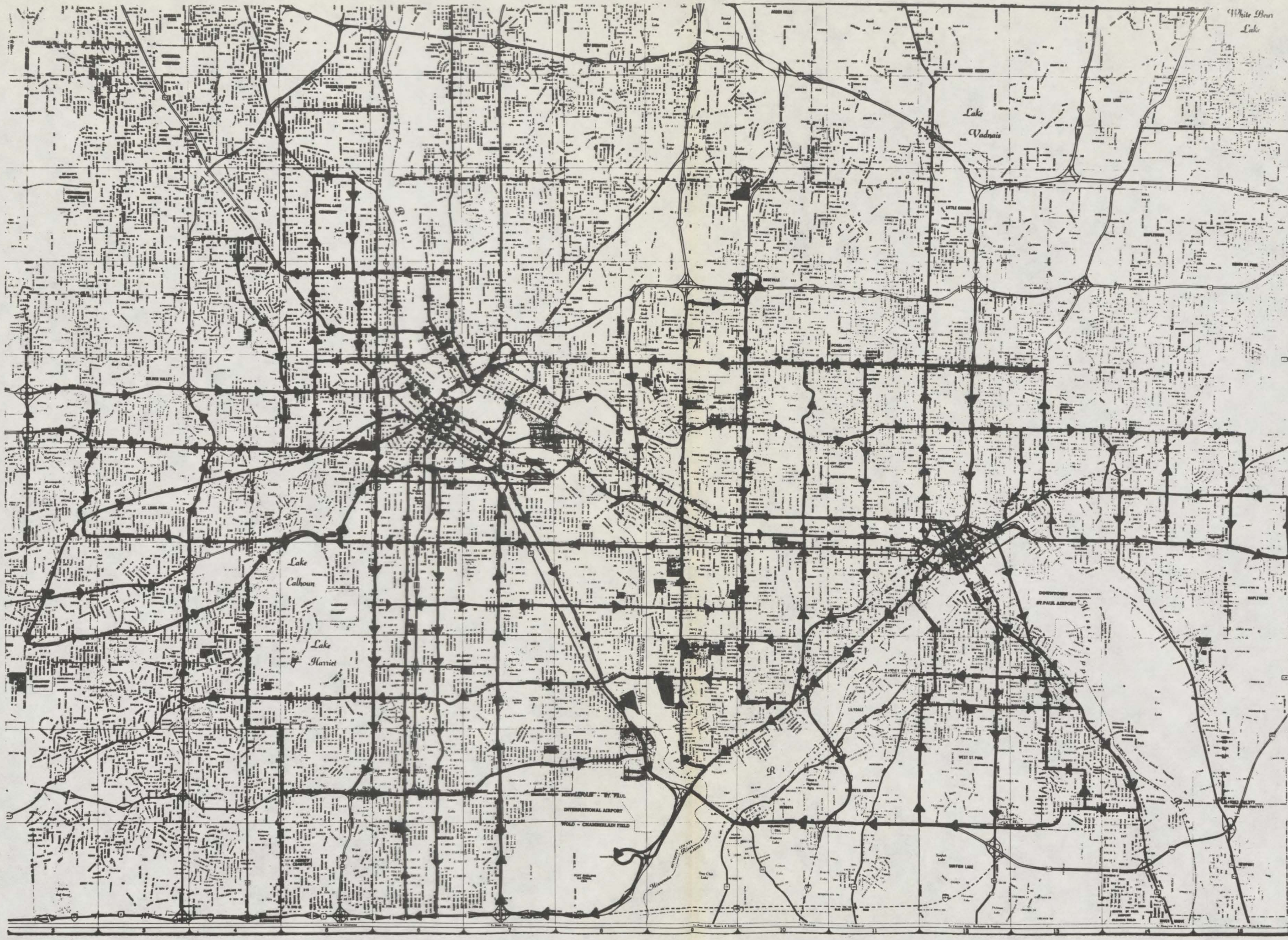

Figure 7. Network evaluated for the Twin Cities--Stage 6

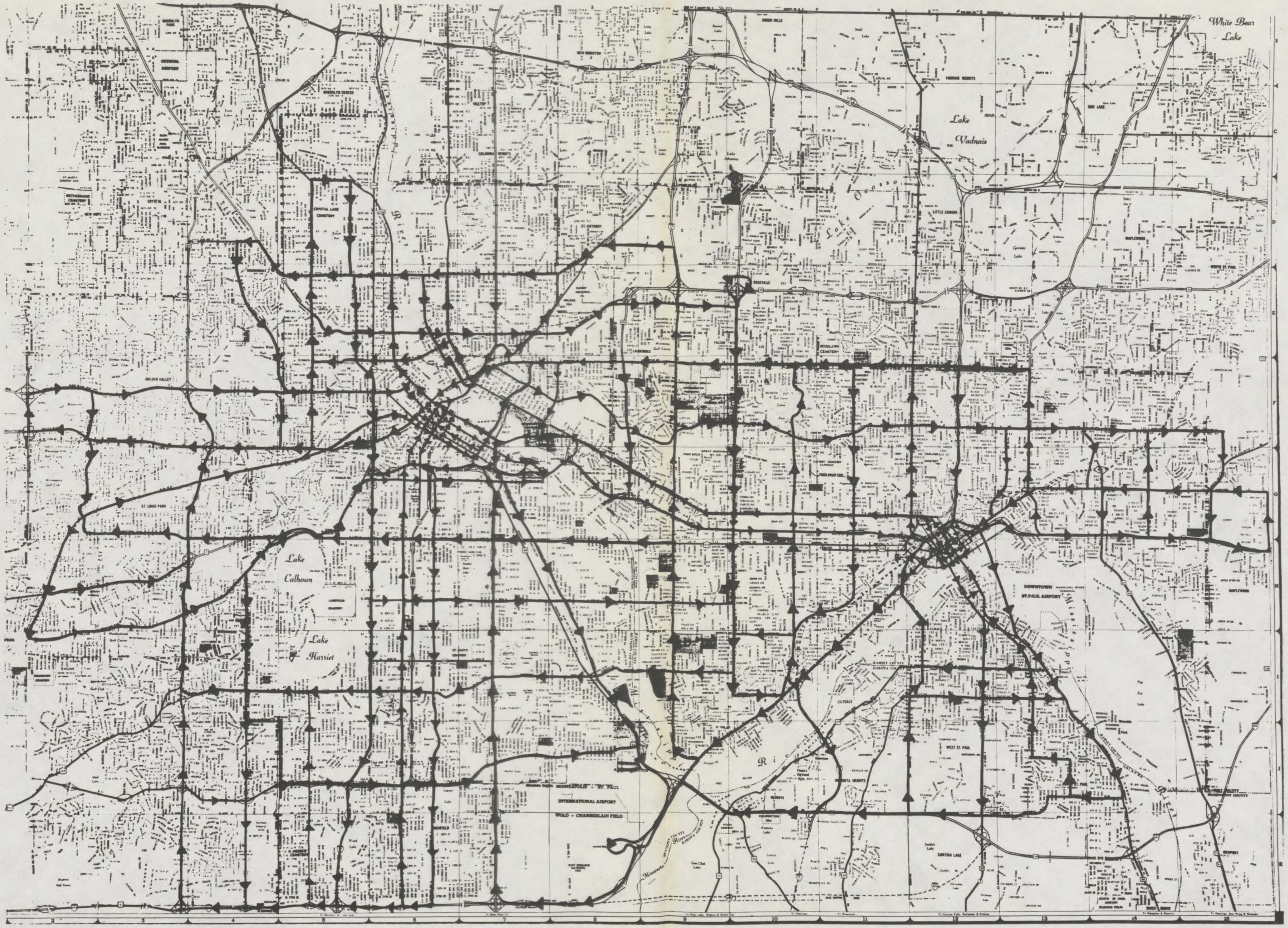

Figure 8. Network evaluated for the Twin Cities--Stage 7

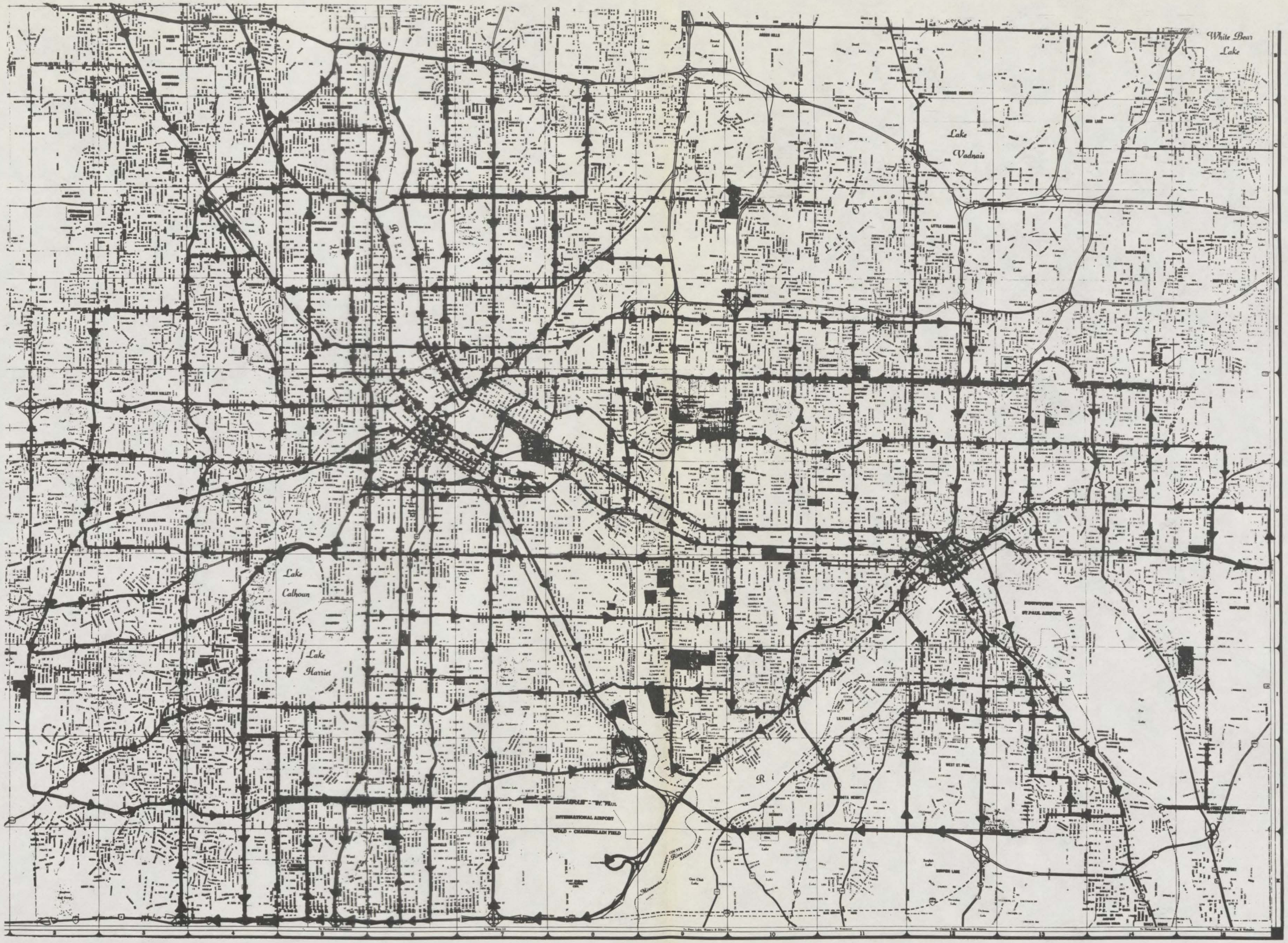

Figure 9. Network evaluated for the Twin Cities--Stage 8

Chapter 1

The Present State of Urban Transportation

The present state of urban transportation is one of the nation's major problems. While nearly all major cities have some form of public transit, the fraction of trips taken by automobile has continued to increase. The success of the automobile in providing desired service has made it possible to obtain political support for condemnation of valuable urban property for freeways and parking ramps. The freeway, however, has destroyed and divided neighborhoods and has created intense sources of noise and air pollution. As a result, citizen groups have formed in many cities to block construction of additional freeways.

As a result of the effects of excessive dominance of urban transportation by the automobile, all major cities are looking to some form of public transit in order to balance the transportation system. In the following paragraphs, we explore some of the experiences cities have had with public transportation and discuss some of the characteristics of these systems in order to provide some insight into the failure of conventional transit to compete with the automobile. We then examine some of the characteristics which need to be incorporated into public transit if it is to become sufficiently attractive to the potential patron so that the desired balance can be achieved.

Historical Background

The first public transportation system incorporating vehicles operating over a fixed route and on a specified schedule appears to be the one started in Paris by Blaise Pascal in the year 1662 (Ref 1). Stage coaches provided regular service over five routes. The first system in the United States was started in New York in 1786 with Hackney coaches providing regular service between Wall Street and the Dry Dock (Ref 1). Other writers consider the origin of the transit industry in this country to have taken place in 1827 when Abraham Brower ordered a horse-drawn vehicle with a seating capacity of twelve and operated it along Broadway in New York City (Ref 2).

The first trolley line began operation in Richmond in 1888. (Ref 2) From that time the extent of street-railway tracks in the United States increased to a maximum of nearly 45,000 miles in 1917, after which it declined to 5,000 miles in 1955 and to less than 1,000 miles today. (Ref 3)

As streets became congested with street cars and horse-drawn vehicles, subways and elevated tracks were built to reduce travel time. Every major city was considering this form of rapid transit even though the Bureau of the Census in 1902 reported:

> The chief difficulty which stands in the way of rapid development of subway systems...is the heavy cost of construction...In New York...the present subway and tracks, exclusive of power houses and equipment, and of damages to abutting property, will cost...$1,750,000 per mile...From the standpoint of profits...both elevated and subway railways intended for fast traffic are confronted by the facts that most of their passengers ride long distances, that a majority must be carried to a single business center; and that a very large proportion of the traffic is during rush hours. As population, aided by the facilities offered, extends farther from the center of the city, these peculiarities will become more marked. Nevertheless, there is every reason to believe that, either through private or public enterprise, additional subways will gradually be constructed in New York and other cities. (Ref 4)

Automobiles began coming into wider use in the 1920's. In the 1930's, the growing use of the automobile served to decrease transit ridership by about one-third. (Ref 2) Many companies fell into bankruptcy; public ownership, which started in 1912, began to accelerate.

With World War II, the restriction of automobiles combined with high employment levels gave the transit industry a brief period of renewed vigor which peaked in 1946.

In the 1930's buses had started to replace trolley cars on some lines. Wartime conditions delayed this transition. Following the war there was a strong movement to use buses in order to:

--Provide greater route flexibility to keep up with changing population patterns;

--Decrease labor costs by using one-man crews on buses instead of two-man crews on trolley cars;

--Take advantage of the lower price of equipment produced by mass production.

Thus the transit industry is now dominated by rubber-tired vehicles running on streets, a third of which are taxicabs. Table 1 shows the 1970 breakdown of transit by mode.

Urban Ridership Characteristics

Figure 1 portrays the trends in total transit passengers and rides per capita from 1920 to 1960. In 1971 total transit passenger-trips fell to 5.5 billion. In following paragraphs urban trip-making patterns and their implications for the future of public transit are discussed. We start with some examples from a few major cities.

New York City. The New York subway system accounts for more than 80% of the rail transit trips in the United States (8.5 million passengers per day). (Ref 5) However, travel to the CBD has not increased significantly in 30 years. There has been some minor growth, but it is well below the growth of population. (Ref 6) Commuting traffic from New Jersey into New York City across the George Washington Bridge is equalled by commuting traffic across the bridge from New York City into New Jersey. (Ref 6)

Chicago. Though Chicago has the second largest transit system in the country, it handles less than 30% of the traffic handled in New York. (Ref 2) Of those trips which do come downtown, 85% are by public transit and 13% are by car. (Ref 7) But those trips which do come to the Loop represent only 10% of the total travel, and by 1980 this figure is expected to be down to 5%. (Ref 5) More specific information on Chicago as well as Pittsburgh is given in Figure 2.

Detroit. During the period of 1953 to 1965 the number of workers in the Detroit area increased very little, as shown in Table 2. However, the percentage living and working in the city dropped very significantly while the percentage living and working in the suburbs rose significantly. This represents a pattern of major importance in many cities - the decrease in the percentage of persons working in the city and the increase of the percentage of persons working in the suburbs.

TABLE 1 DISTRIBUTION OF PUBLIC TRANSIT PASSENGERS BY MODE*

MODE	MILLIONS OF REVENUE PASSENGERS 1970	PERCENT
Trolley Coach	128	1.5
Commuter Rail	247	2.9
Rail Rapid Transit and Street Cars	1746	20.4
Taxicabs	2378	27.8
Bus	4058	47.4
Total	8557	100.0

* Source: Wells, J., and Selover, F., "Characteristics of the Urban Taxicab Transit Industry", Economic Characteristics of the Urban Public Transportation Industry, (ed. by J.D. Wells, et al), Institute for Defense Analysis for U.S. Department of Transportation, February 1972, page 8-6.

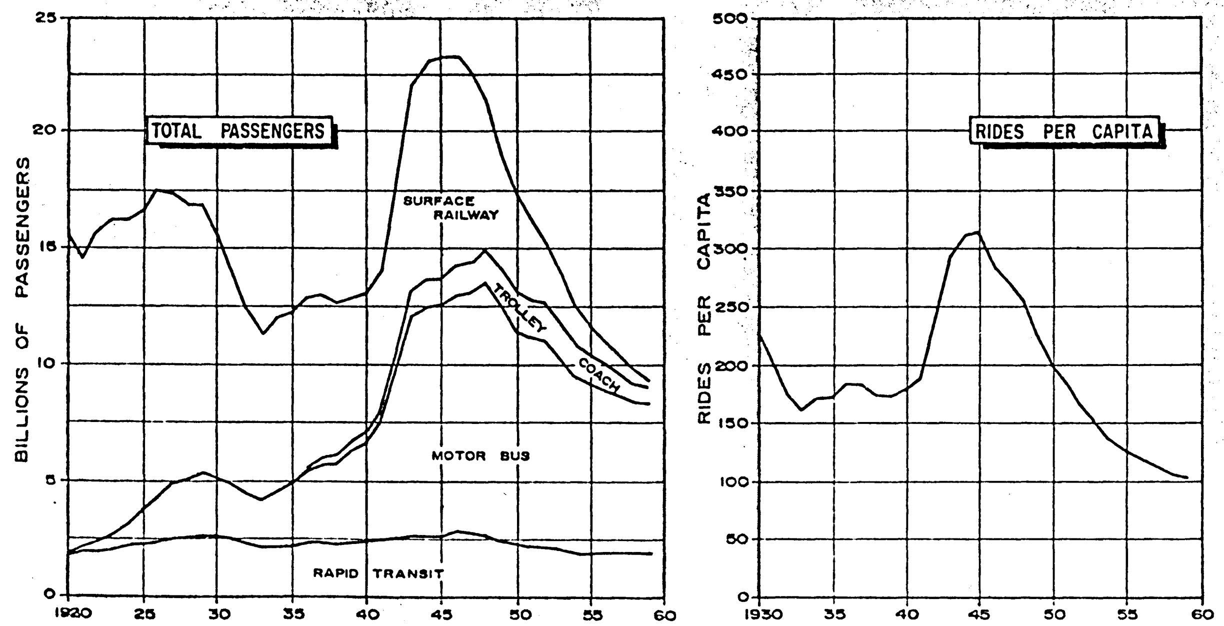

Figure 1. Trends in total transit passengers and rides per capita per year.

Source: Wilbur Smith and Associates, Future Highways and Urban Growth, February 1961, p. 115.

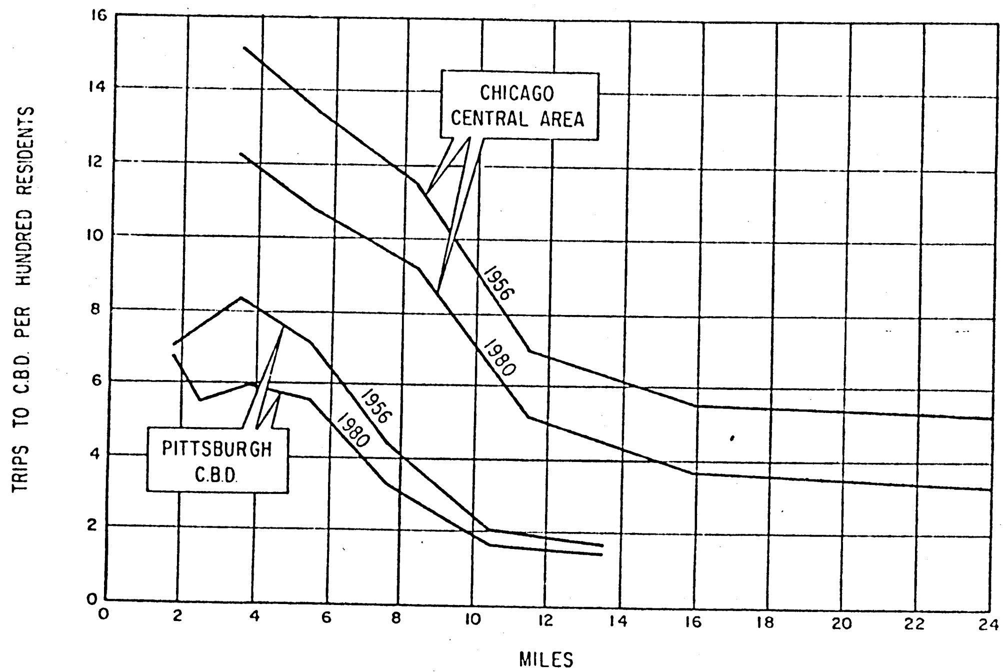

Figure 2. Mass Transportation Trips Per 100 Residents to Selected Central Business Districts

Source: Wilbur Smith and Associates, <u>Transportation and Parking for Tomorrow's Cities</u>, 1966, p. 38

TABLE 2 TRAVEL CHANGES IN DETROIT AREA

	1953	%	1965	%
Workers living in Detroit (thousands)	510	50.8	302	29.8
Persons living in suburbs but working in Detroit or vice versa (thousands)	304	30.3	342	33.7
Persons living and working in suburbs (thousands)	190	18.9	370	36.5
Total	1,004	100.0	1,014	100.0

Los Angeles. While Los Angeles has experienced phenomenal growth, travel into the central business district has not increased significantly in the past 30 years. (Ref 6) In Los Angeles, the dominant trip pattern is from one suburb to another with a minor portion of traffic going to the CBD. For instance, all of the major aerospace firms and movie studios are in the suburbs rather than in the city.

Minneapolis - St. Paul. Table 3 shows the changes in travel patterns in the Twin Cities from 1949 to 1958. According to current data from the Metropolitan Council of the Twin City Area, only 4.7% of the daily trips originate or terminate in the two downtowns. At present only 3.2% of the daily trips in the metropolitan area are taken by transit.

Taxicabs

Taxis may be considered a form of demand activated, origin-destination, usually personalized, public transportation. It has been stated that taxis "are used extensively by businessmen, housewives, the old, the handicapped, the young, out-of-town visitors, and others who cannot or do not wish to drive, or who have no automobile available to them and need the door-to-door service that scheduled mass transit vehicles do not provide." (Ref 9) The importance of the taxis may be grasped by noting in Table 1 that in 1970 taxis carried 27.8 percent of the passengers using urban public transportation, and were second only to bus transit. "In a good system of urban transport, the taxicab or other mini-vehicle is a necessity not a luxury - it becomes a luxury only on the long haul." (Ref 10)

Because rapid transit operations are so expensive and now, in most cases, under heavy subsidy, one writer has suggested that public monies for subsidies of transit might be better spent by paying for taxi trips for all necessary travel by non-car owners. (Ref 10)

Transit Routings

Rail-transit lines now in existence in the United States were laid out on a radial pattern with the objective of bringing people into the CBD. As a result, it was impossible to go across town on rapid transit without passing through the CBD. When bus routes were developed they were also predominantly oriented to the CBD because travel demands then centered on the CBD. The automobile, on the other hand, has made it possible to travel from one suburb to another without passing through the CBD.

Economic Problems of the Transit Industry

The transit industry has been in a deteriorating economic condition since the depression of the 1930's except for a brief respite resulting from World War II. With declining ridership, operating agencies have raised fares and reduced service in order to meet operating expenses. Figure 3 shows the historical trend in passengers carried per mile. At the present time, transit service is considered healthy if it carries three revenue passengers per vehicle mile. Figure 4 shows how, for many transit systems, operating expenses have exceeded revenue to an increasing extent.

This increase in operating deficits is due only in part to decreased ridership. Another factor is the rising cost of operating transit systems, the largest portion of which is labor. In 1971, labor accounted for 68 to 82 percent of transit operating costs. (Ref 8) For example, in the bus system operated by the Twin Cities Area Metropolitan Transit Commission, an increase of wage rates of one cent per hour results in an annual expenditure of $30,000 by the Commission.

An important factor which complicates the operation of a transit system and leads to high costs is the lack of uniformity of travel demand. Figure 5 illustrates this phenomenon. The transit agency must provide additional equipment and drivers to handle the peak periods. While it would be more economical to have drivers for peak periods only, labor unions require drivers to work continuous shifts.

As a result of the excess of costs over revenues and the consequent bankruptcy or imminent bankruptcy of bus companies, subsidies for transit have become a fact of life. In most cases, acquisition of the system by a public agency has been a prerequisite to subsidization. With public ownership, the system is immediately relieved of taxes, thus reducing the deficit. Usually, however, this is not sufficient and other forms of subsidy must be provided. Often this additional subsidy takes the form

TABLE 3 CHANGES IN CENTRAL BUSINESS DISTRICT TRIP ATTRACTION

Minneapolis - St. Paul

1949-1958

MINNEAPOLIS CBD RING	DAILY CBD ORIGINS PER 100 DWELLING UNITS 1949	1958
1	31.4	19.8
2	37.7	23.3
3	33.9	23.0
4	29.8	20.5
5	26.5	17.9
6	21.0	13.0
7	14.5	6.7
8	6.5	4.6

SOURCE: Minnesota, Department of Highways, Twin Cities Area Transportation Study, Vol. I (St. Paul: 1962). This study includes trips made for shopping, personal business, social, recreational, and "eat meal" purposes.

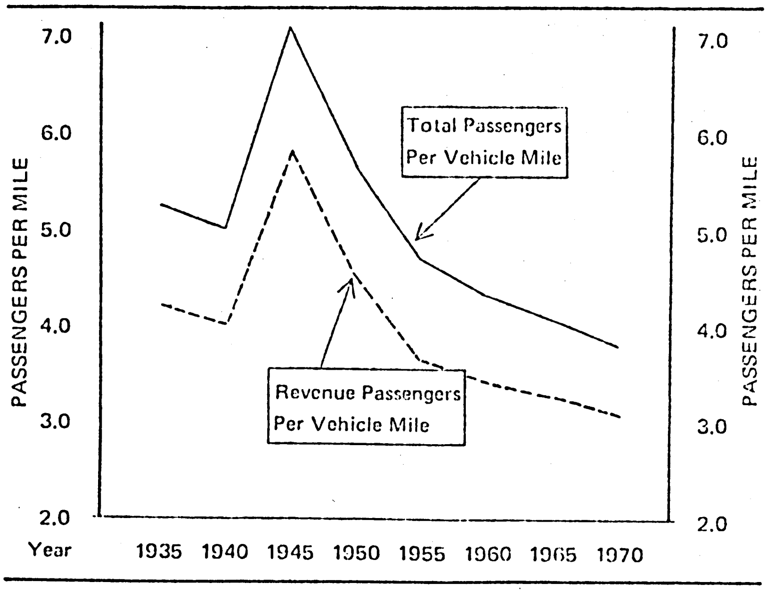

Figure 3. Trend of Passenger Ridership

Source: American Transit Association, <u>'71-'72 Transit Fact Book</u>, 1972, p. 13.

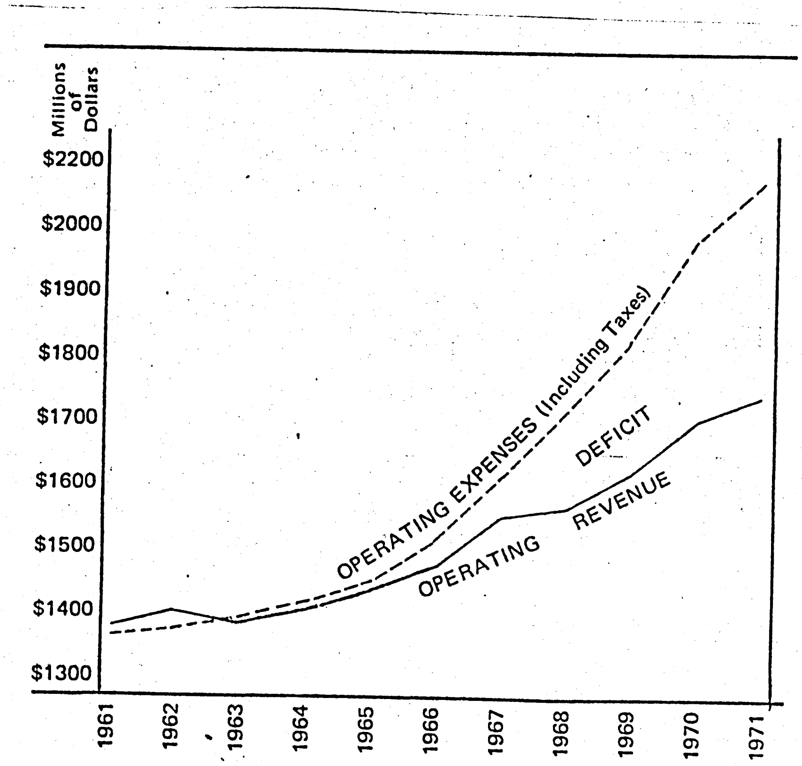

Figure 4. Trend of Transit Operating Expenses and Operating Revenue

Source: American Transit Association, '71-'72 Transit Fact Book, 1972, p. 5.

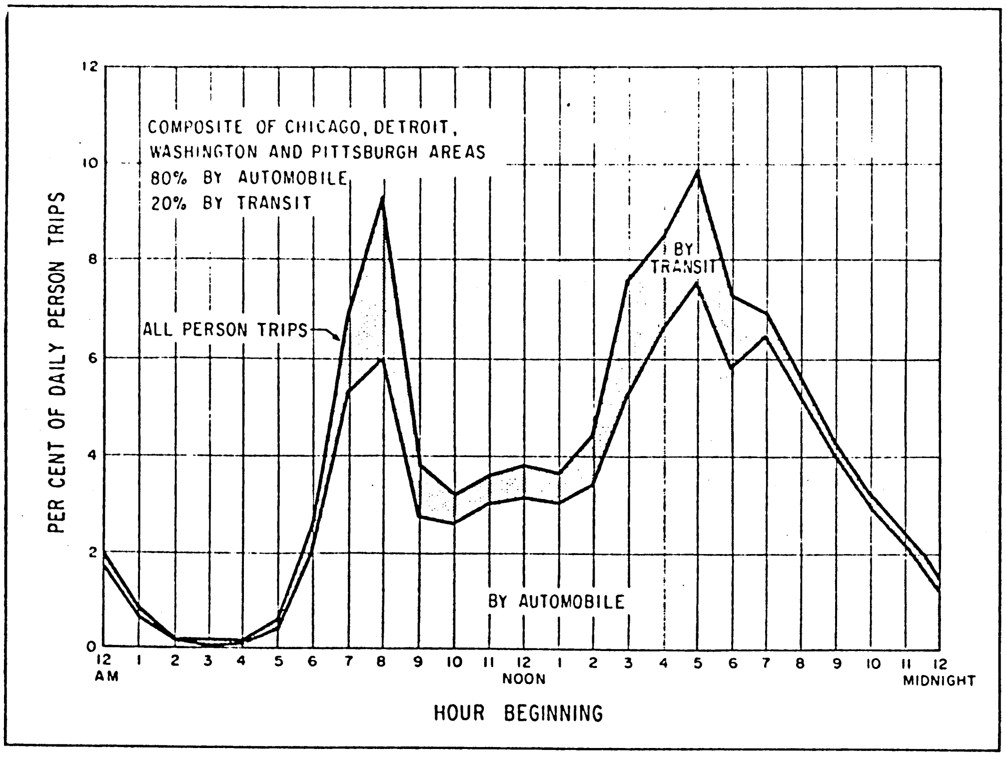

Figure 5. Composite Hourly Variation of Urban Person Trips by Mode

This drawing presents a composite of the hourly variation pattern of urban person trips by private and public transportation for Chicago, Detroit, Washington, and Pittsburgh. It is significant to note that the proportion of daily person travel by automobile in mid-evening hours exceeds that during the morning peak hour because of the high car occupancies associated with social and recreational trips. This increase in evening motor travel, however, is not concentrated on approaches to major work work centers; rather it is dispersed throughout the area. For current conditions about 85 per cent of all person trips in these urban areas are made by private automobile.

Source: Wilbur Smith and Associates
Transportation and Parking for Tomorrow's Cities, 1966, p. 99.

of public purchase of capital equipment, with the requirement that operating expenses be provided from fares. Recently, however, some systems have not been able even to meet operating expenses without additional subsidy.

The Energy Crisis

While it is not yet evident to the general public, a serious problem for all forms of transportation is the growing shortage of energy, especially from fossil-fuel sources. The importance of this energy crisis to transportation lies in the fact that 25% of the nation's energy usage is devoted to transportation. (Ref 9) Of petroleum products devoted to transportation, 55% are consumed by automobiles and 21% by trucks. Recent anti-pollution devices are expected to decrease the efficiency of both autos and trucks, thus worsening the situation. To meet the need for fossil fuel, the United States is importing more and more oil, the need for which is indicated in Table 4. The usage of foreign oil will increase costs of fuel and may place the United States in an untenable diplomatic situation. This new factor provides an important incentive to uncouple the dependence of transportation on oil as a primary energy source.

Criteria for Public Transit

In this chapter, we have discussed the decline of transit ridership in the United States. It is trite but true to say that this decline is due to the superior attractiveness of the automobile in providing service to the user and, often just as important, in its ability to fulfill non-transportation needs of the individual. It is success in meeting needs that has caused the automobile system to become one of the major problems of urban society. It is this success that has caused society to provide more and more space for the operation of automobiles and has numbed its senses to the noise and air pollution produced by large numbers of automobiles. While catering to the needs of the individual, the automobile system has required the city to shape itself to its needs.

Table 4 ESTIMATED FUTURE NEEDS FOR FOREIGN OIL

Millions of barrels per day

1971	1975	1980	1985
3.7	6.5 to 8.4	9.2 to 11.6	13.8 to 16.5

Source: Executive Office of the President, Office of Emergency Preparedness, The Potential for Energy Conservation - A Staff Study, 1972.

It has become evident that a transit system is needed which will not only meet the needs of individuals but the needs of the community as well. A great deal of discussion of needs of both has led us to the following abbreviated list of criteria which should guide the selection of a system which will meet the needs of both the individual and the community.

People's transit needs require a system which:

- permits the patron to arrive when planned;
- provides good access to a large variety of origins and destinations;
- provides on-demand service when needed, not only in the rush hour;
- is easy to understand and use by all;
- is faster than the auto for many trips;
- does not require transfers;
- produces no anxiety in its use;
- is convenient for all to use;
- provides a comfortable ride;
- is safe; and
- can be built and operated at moderate cost to the individual.

Some of the qualities the community needs in transit are obtained by a system which:

- minimizes land use for transport;
- does not divide communities;
- does not disrupt the community during installation;
- is acceptable in appearance;
- does not pollute the air;
- can lead to reduction in the need for oil;
- makes efficient use of energy;
- is quiet;
- is feasible with desired and practically attainable population densities; and
- is acceptable in cost.

Rankings of features of transit are shown in Figure 6. In the following chapters, we develop the characteristics of systems which promise to meet these criteria. These ideas have been developing gradually over the past two decades by a large number of people and as the ideas are

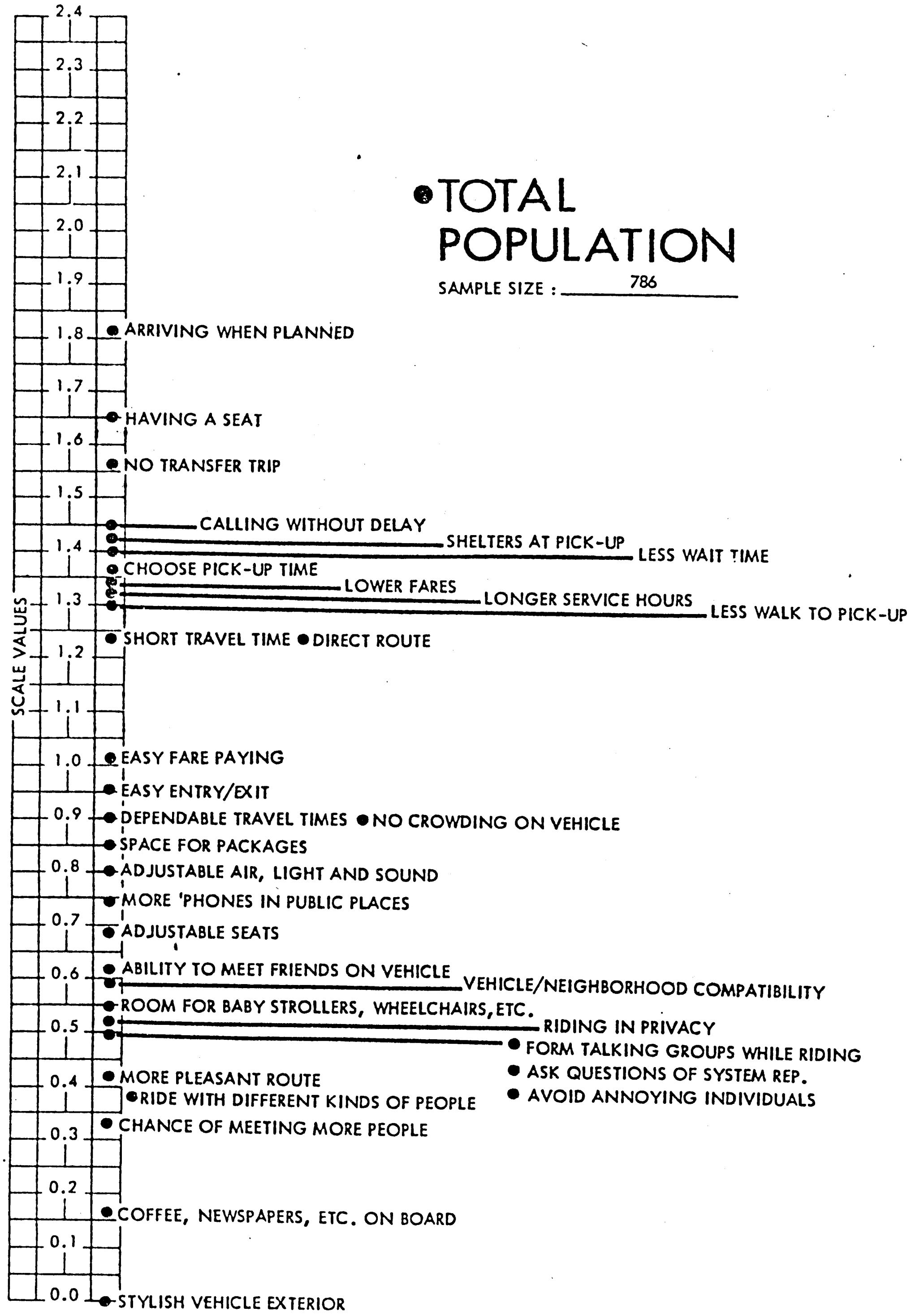

Figure 6. Rating of Various Characteristics of Public Transit System

Source: Thomas F. Golob, Eugene T. Canty, Richard L. Gustafson, and Joseph E. Vitt, An Analysis of Consumer Preferences for a Public Transportation System, General Motors Research Laboratories, Research Publication GMR-1037, October 26, 1972.

clarifying definite recommendations are emerging. Such recommendations are given in subsequent chapters.

Summary

Traditional transit systems have been laid out in a radial fashion. In the days when this was the principal form of transportation, people lived near transit routes. As the automobile became generally available people began moving to the suburbs. In many metropolitan areas there are now major shopping centers and places of employment in the suburbs, and there is less of a tendency for people to go downtown. Governing bodies of central cities, however, attempt to maintain central business districts as major centers of activity in order to maintain a strong tax base.

People have become accustomed to using the automobile because of its comfort and convenience. In order for public transportation to attract people from automobiles it will be necessary to provide a system which gives high-speed, nonstop service from origin to destination with a high level of comfort, convenience, and security.

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Chapter 2

An Overview of PRT

Predictions abound as to how much worse the problem of urban transportation will become in future years if we continue to rely on the automobile for transportation. In order to keep congestion from growing significantly worse, to remove pressure for more and more urban freeways and street widening, to reduce auto-produced air pollution, to reduce auto accidents, and to forestall foreboding implications of continued reliance on oil for transportation in an era of declining oil resources, we need to develop new systems of urban transportation capable of attracting at least half of the urban trips by 1990. Conventional transit technology falls far short of this goal.

A system which appears capable of attracting up to half the urban trips is under development in the United States, Western Europe and Japan. In the United States this system has come to be known as Personal Rapid Transit (PRT). The Urban Mass Transportation Administration exhibited four systems having characteristics of PRT at the International Transportation Exposition (TRANSPO) in June 1972, and has a prototype demonstration under construction at Morgantown, West Virginia. A second urban demonstration is being planned at Denver, Colorado. Serious planning for PRT is under way in many cities in the United States and in many other countries. In this chapter, the ideas which have become known as PRT are developed and compared with the characteristics of conventional transit.

The Rationale for PRT

In order to attract a significant fraction of automobile drivers to public transit without coercion, the transit trip must be faster than the auto trip for a very significant number of the trips typically made by urban residents. This requires that the transit vehicles travel on an exclusive guideway either above or below the street level. Accessibility and convenience further require an area-wide network of interconnected guideways.

The major innovation which leads to PRT is obtained by following the history of highway development. Decades ago, state highways were built around cities in order to speed up interstate travel. This led to the urban freeway. The urban freeway attracts auto drivers in great numbers because, under unsaturated conditions, the trip on a freeway is nonstop. The driver starts and stops only when these actions have something to do with his own trip. Because he does not have to stop for reasons unconnected with his own trip, his trip is accomplished in minimum time, with minimum frustration and maximum comfort to himself.

By adopting this eminently successful characteristic of the urban freeway, one is led to a system of fixed guideways in which the stations are on by-pass tracks off the main line. The off-line station has the advantage that it permits vehicles to wait for people rather than people to wait for vehicles. Maximum capacity is obtained if all acceleration and deceleration maneuvers associated with leaving and entering the stations are accomplished on the by-pass tracks.

The use of close headways (i.e., spacings) between vehicles is needed to provide adequate capacity with auto-sized vehicles. Advances in the understanding of safe operation of PRT systems show that headways as close as one-half second are wholly practical. This gives a maximum flow of 7200 vehicles per hour. Small vehicles have two primary advantages. Frist, the guideways can be light, low cost and have low visual impact. It appears now that the guideway so dominates the overall capital cost that the minimum-size vehicle leads also to the minimum overall system cost even though more vehicles are necessary. Second, the option of truly personal service is available. Truly personal service means that each cab is occupied only by persons traveling together, and that it is unnecessary to travel with strangers. Many conversations with citizens about PRT have led us to believe this is a very important feature. In the personal cabs, each passenger would be provided with a seat. This not only increases comfort and hence patronage, but also permits acceleration and deceleration to be approximately double that tolerable if passengers are allowed to stand. The result is to cut the ramp lengths approximately in half.

Safe and reliable control of a large number of small vehicles switching in and out of stations and from line to line requires use of advanced techniques of automatic control and reliability engineering developed during the past two decades. When compared with manual control, automatic control has the advantage that the labor costs of transit are considerably reduced. Service can continue twenty-four hours a day. Automatic control also permits considerably shorter headways and, hence, increased capacity.

By interconnecting the network, not only can each trip be nonstop through the network, but a system of one-way lines becomes practical. One-way lines will approximately double the percentage of urban land area within walking distance of stations for a given investment. The mileage of lines and number of stations needed to serve a given percentage of the population is minimized by placing the stations midway between the line junctions. Use of one-way lines also means that the visual impact of the system on a given street is minimized. The provision of vehicle transfer throughout the network has the further advantage that the network of guideways can be used for movement of goods and for many kinds of specialized services not possible with conventional transit. All of this means that the system can be amortized over many more vehicle trips than can be attracted to conventional transit, and hence revenues will pay a much larger share of the capital and operating costs than is possible with conventional transit. In fact, Canadian studies have shown that PRT used for goods movement as well as people movement may be self-supporting.

The above combination of ideas represent what is, in our opinion, the best of PRT as the concept has emerged in the past decade. These ideas represent a practical goal toward which hardware development programs should be aimed. While we believe the feasibility of PRT has been well established on paper, by laboratory tests, and by means of experimental test tracks, much remains to be done to bring PRT into full maturity as an alternative means of transportation. Further engineering development is needed in control-system reliability, in minimum-cost guideway design, in propulsion and suspension systems, in proper vehicle and station design, in development of optimum operational strategies and in engineering PRT systems into the community.

Figure 1 is a logic diagram to show how the use of off-line stations with an exclusive guideway transit system can lead to significant improvements in the urban environment. The off-line station first permits (1) adequate capacity with small cars, and (2) the possibility of nonstop service. The small car leads to (1) a guideway of small volume, (2) private transportation, and (3) the important option of using the system for goods movement of many kinds - the guideway becomes, in fact, a general facility usable for many kinds of transportation. The small guideway leads to (1) a minimum cost system and (2) minimum cross section - both of which are needed to build an extensive system. This together with the nonstop trip decreases total trip time for many people.

Use of small cars requires automatic control in order to reduce operating costs to a reasonable range. Automatic control permits low-cost, 24-hour, on-demand service and can lead to good safety records. (By controlling line speed and providing safety devices in and on the vehicles, we are confident now that specifications can be set so that under the worst conceivable system failure conditions, no occupant would get hurt. See Chapter 9.) Privacy, low trip time and good safety records lead to high patronage. This, together with low labor requirements and multiple use of the guideway, leads to low trip costs. Low cost plus good access to the community leads to political feasibility, i.e., a system that can be built.

A Comparison of the Service Characteristics of PRT with Conventional Transit

Conventional transit requires people to wait for vehicles whereas with PRT, the vehicles wait at the off-line stations for people. Computer studies have shown that at rush periods, PRT systems can be designed so that the wait period is no more than 30 seconds to one minute. Conventional transit requires people to stop and start many times between the origin and destination for purposes unrelated to the purpose of the individual trip but due to inherent limitations in the service concept. PRT provides nonstop trips to all patrons. Conventional transit requires people to transfer from line to line thus producing further delay and discomfort. With PRT, the system computer

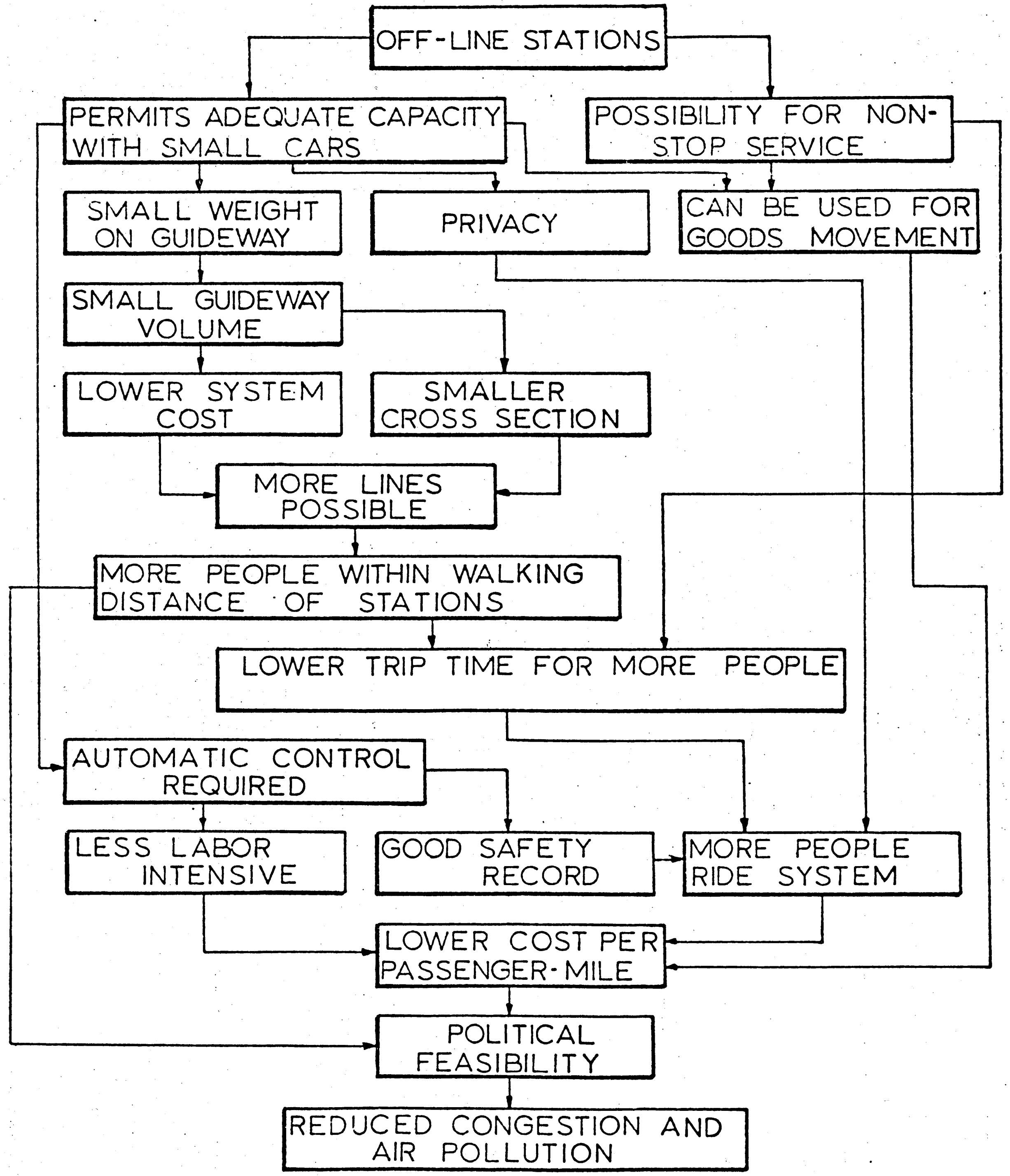

Figure 1. CONSEQUENCES OF OFF-LINE STATIONS

automatically transfers the vehicles according to the demands of each trip. Conventional transit requires the user to master complex and changing routes and schedules - a significant deterrent for many people. With PRT every station is connected with every other station by a non-stop trip. Therefore, the patron goes to the nearest station where he is assured of immediate nonstop service to any destination in the network. Conventional transit requires people to ride in crowded, impersonal conditions, whereas, a trip on a PRT system is taken in privacy with one's own traveling companions. Personal security is thereby substantially increased. In off-peak hours, it is very expensive to provide frequent service with conventional transit; therefore fewer vehicles are run and often no service at all is given between midnight and 6 a.m. With PRT, it costs nothing to store vehicles in stations waiting for people 24 hours per day. For these kinds of reasons conventional transit provides much too inferior a service concept to attract many people from autos whereas for many types of trips, PRT provides a level of service considerably superior to the automobile.

Some Questions about PRT

In this section, the concept of PRT is further developed by providing answers to questions hundreds of people have asked about PRT following presentations of the system made over a two-year period.

Acceptance of Overhead PRT Guideways. The smallest cross-section guideways for PRT systems are only about two feet wide by two feet deep. For a significant portion of the guideway an extra off-line guideway is needed. There is no question that the best possible architectural designs are needed to make these guideways attractive. On streets on which a guideway is planned, the residents must be offered compensation for the guideway. In many cases, this can be done by offering to narrow the street, i.e., widen and beautify the boulevard and in some cases convert the street into a linear park. It needs to be emphasized that an alternative to PRT guideways is more freeways. Freeways are objectionable for five reasons: (1) Use of urban land; (2) Division of communities; (3) Noise; (4) Air pollution; and (5) Visual impact. Frequent contacts with community groups opposed to freeways has led us to conclude that the fifth reason is considered the least important. It is also the only remaining impact of the five listed with PRT guideways.

System Safety. PRT can be made safe if it is designed from the beginning for the unique circumstances in which it will operate. It may not be safe if one starts with conventional systems and controls and tries to adapt them to PRT. For example, linear electric motors can be used to accelerate and brake PRT vehicles. This not only removes the noise of the propulsion system, it uncouples traction from suspension, i.e., the wheels, if there are wheels, do not have to provide friction for braking. Now, instead of trying to increase the grip between the tire and the surface as much as possible, it should be reduced as much as possible so that if a wheel locks the vehicles will slide. In this case, the braking system can be designed so that even if the separation between vehicles is only a few feet no collision will occur. The system can, in fact, be designed so that collisions would require the simultaneous occurrence of very improbable failure modes, and even then by use of shock absorbing bumpers and padded interiors no one would be hurt.

The Number of Vehicles. If each vehicle is occupied by one person or his traveling group, won't there be just as many vehicles in the system as there now are automobiles? During a rush period each PRT vehicle can make a number of round trips and, thus, is used by many more people than just one individual and his group. Also, the same vehicles can be used throughout the day for other purposes. Seats can be removed and replaced by freight containers so that the vehicles can be used for moving freight during the night. Our studies show that for a typical city one PRT vehicle will replace about 10 autos.

Operation of Large Numbers of Vehicles on the Network. PRT vehicles would operate under three levels of control. First, position and speed controllers would be placed on board the vehicle or in the track to maintain proper position on the guideway. Second, at each interchange or merge point, a computer would handle merging of vehicles from one line to another causing vehicles to accelerate or decelerate in order to allow other vehicles to merge into the line. Third, a central computer would be used for two functions: a) to dispatch empty vehicles to stations where they are needed, and b) to determine the route and the exact time of departure of each vehicle. By optimizing the computer routine for dispatching of empty vehicles, the vehicles can be sent to wherever they are needed, when they are needed, at minimum cost. If at the time a trip is ordered, that trip would either congest one of the lines on the way to the destination station or the destination itself, this information can be made available within the computer and can be used either to reroute the vehicle, to ask the patron to delay his trip until the congestion lessens, or to route the patron to a nearby station. By use of procedures like this, congestion on the system can be completely avoided. Computer studies show that delays of the type described would occur very infrequently.

Capacity to Handle Downtown Traffic. It must be remembered that at the present time, typically two-thirds of the downtown traffic in most moderate-size cities in the United States is handled by individual automobiles in a completely disorganized way. PRT is a managed system. In addition, the capacity of each line, counting the empty spaces needed for merging from one line to another, is about 3800 vehicles per hour at a downtown speed of 15 mph. This is the equivalent capacity of two and a half lanes of freeway in vehicles per hour. In the downtown area, lines could be placed approximately every two blocks in which case there could be two stations per block, each having the capacity of between 500 and 1000 vehicles per hour. When one compares this capacity with the capacity of present system, it becomes apparent that the problem of capacity is not present with a well designed PRT system.

Personal Security. As mentioned previously the trip in the PRT vehicles would be taken in private with one's own traveling companions. On the outside chance that someone would force himself into a vehicle with a patron, alarm systems aboard the vehicle would ring in a nearby police station and the vehicle would be dispatched to a particular station, patron and abductor alike into the hands of the police.

Stations of the PRT system are not large gathering places, hence vehicles come and go very quickly. There is no reason to loiter around a PRT station. At odd hours of the night service is on-demand, as one goes to the station and immediately leaves. Stations can be well lit and surveyed by television.

System Costs. Studies of PRT for both the Twin Cities Metropolitan Area and the Duluth Metropolitan Area discussed in this report indicate that even if a PRT system is used for moving passengers only, it is cost-competitive with other forms of public transit and at the same time provides a much higher level of service. If the system is also used for moving freight, it appears quite probable that the entire cost of the system can be paid for out of revenues. In a typical example, for the same number of dollars a PRT system could put ten times as much of an urban area within walking distance of stations as a rapid-rail transit system.

PRT Technology

Some of the physical characteristics of PRT have been described, but there is a wide variety of technology in the PRT systems now being developed and demonstrated. The various technologies use different approaches in the size and shape of guideways and in the system for propulsion, braking, suspension and control. All, however, are pursuant to the same concept of service. All PRT systems are electrically powered, thus producing no pollution at their location of use. Power is generally picked up by contact with a power rail in the guideway. Guideways are designed for both bottom-supported and suspended vehicles. Several bottom-supported designs are under development. The road-bed variety provides a flat surface somewhat wider than the vehicle, or two parallel flat strips spaced as the running gear of the vehicle. Automotive-type suspension and rubber tires are used, particularly with the larger-vehicle systems. Propulsion in some systems is by heavy-duty conventional electric motors through a rear-axle differential drive. These designs have the advantages of use of tested, "off-the-shelf" components, but are cumbersome to switch into stations and result in a heavier system of larger dimensions throughout. The first stage of a road-bed guideway PRT system begins system testing at the West Virginia University, Morgantown, West Virginia in October 1972. Similar Systems are being developed by the Ford Motor Company and the Bendix

Corporation. Alternately, two developers, Transportation Technology, Inc. (TTI) and Uniflo, Inc., levitate their vehicles on a thin layer of air. Air lubricated pads skim along on flat surfaces, replacing the wheels and suspension. Because the gap between the pad and the guideway surface is very small, the air flow is exceptionally low and the power requirement for levitation is small. The only requirement is a continuous, smooth surface for the guideway. TTI has a small blower aboard each vehicle that delivers air, and Uniflo Systems Company uses air valves in the guideway that issue a stream of air when the vehicles pass. Air-cushion suspension is quiet and vibration-free, allowing unobtrusive operation of vehicles in the urban environment, including passage through buildings. The Uniflo vehicle is also propelled by the air streams issuing from the guideway, with additional series of valves for more thrust in acceleration ramps. TTI uses a linear electric motor for propulsion and braking. Both systems can effectively brake by stopping the air flow and allowing the pads to slide against the guideway surface.

A second bottom-support method uses an inverted "U" shaped channel with a tandem set of small rubber wheels against the bottom and sides inside the channel. Aerospace Corporation proposes this design with guideway dimensions of 2.5 by 2.5 feet. The TTI air pad and Aerospace channel bottom support systems both use the linear electric motor, which is described as the armature and field arrangement of a conventional electric motor spread out flat. The linear motor is a very reliable means of propulsion, as it has no moving parts and does not depend on friction for traction. The linear electric motor can also be used to brake the vehicle while recovering most of the kinetic energy of the vehicle as electricity.

A third bottom-support concept is the mechanically-linked vehicle. The vehicles do not contain propulsion equipment, and must be physically attached to a continuously moving cable drive with an arrangement to release from the cable for entering stations. Mechanically-linked systems permit close spacing of vehicles since the headway is rigidly maintained; however, the maximum speed is probably limited to about 20 mph. This speed limitation confines their application to short-distance operations.

Rohr-Monocab has developed a vehicle that is suspended overhead on a guideway about 18 inches wide and 24 inches deep. The advantages of small dimensions are obvious.

A Typical Trip on PRT

How would a typical trip be made on a captive-vehicle PRT system? Beginning at home, the patron has several choices for access to the station; walking, bicycling, driving, or using a public vehicle that circulates to collect passengers for a particular station. The public vehicle would respond to called-in demands and pick up passengers at their doors. One such system, called Dial-a-Ride, is being demonstrated in several cities as a public transportation system of itself. With this system a vehicle with eight to twelve seats is routed by a central computer that takes incoming demands and determines an optimum route. Dial-a-Ride access would be most popular in sparsely populated areas where the PRT network spacing was very large. In fairly dense residential areas, the nearest station would generally be less than three blocks away. Here the patron would probably walk to the PRT station.

Once at the station the customer would simply insert a credit card in a slot and request his destination by number in an arrangement similar to the push-button telephone. Perhaps a verification would light up on a map of the entire network to assure the patron that he pressed the numbers correctly. The fare could be based on a variety of factors such as trip length, location of the origin and destination, time of day, age of patron, etc. It would be calculated by an accounting computer and added to a monthly statement. The fare could be paid by coin in lieu of the credit card. If a vehicle is available in the station, its doors would open, and the destination would be displayed above that vehicle. After boarding the vehicle, the patron would push a button to close the doors and the trip would begin as soon as an opening in the stream of vehicles on the main line appeared. As was noted earlier, an empty vehicle can be called into the station to create an opening. In any case, the time from entering the station to merging onto the main line would usually be less than one minute. The station does not present the customer with myriad levels, passageways, route signs, or directions.

It can be a simple layout that requires only nominal participation by the user.

If the trip is terminating at a major activity center (MAC), the patron steps out of the vehicle into a PRT station in a building near his destination point. In general, PRT gives better access at MAC ends of trips, and the auto is more favorable at the residential ends. If the trip to the MAC were made by auto, the driver would commonly park in a lot or multi-story ramp some distance from his destination.

Service Potential of PRT

A PRT system would provide improvements in transportation service for diverse social and economic groups. At present, urban transportation is dominated by the auto and tends to immobilize and isolate non-drivers. Those members of urban society that are too young, too old, poor, handicapped, or otherwise have limited access to auto transportation find that it is often extremely inconvenient and time-consuming to reach a desired destination. They frequently must forgo trips and thus are denied equality of opportunity in urban life. Present public transit is characterized by excessive walking, poor connections, transfers, unreliable and infrequent service, slow travel, delays, crowding, noise, uncomfortable accommodations, and confusing information for the patron's use. These are the concerns of the transportation poor. To more fortunate urban citizens the onus of a bad image is added. Thus when cleaner, faster equipment of conventional service policy is introduced, a majority of those who are unaccustomed to public transit find it difficult to accept transit even on improved terms.

Let us compare a trip by PRT and auto from home to office in a major activity center. The auto has the advantage of being available immediately at the home, whereas access to the PRT station is not as convenient. The inclination of an individual to use PRT would relate closely to his distance from the station or to the travel mode available to get to the station. Once on the guideway, he is assured of a safe, fast, reliable trip and the terminal end involves only a short walk, possibly indoors. Generally speaking, the auto driver must stop and start many times unrelated to his own trip and negotiate in congested traffic during rush hours. Many work trips involve a stretch of freeway, which usually covers distance rapidly, but is often slowed by overloading, accidents, or weather conditions. Upon leaving the freeway in the activity center, the driver is again in regular street traffic with stops and congestion. It is common to park in a ramp, where the driver must wind his way up the levels looking for a place to park. He then takes the elevator to ground level and walks to his destination. Alternately, he may have to search out a spot on the street or in a large lot and then have to walk several blocks. Five to ten minutes may be required to park in the morning and as much again in the afternoon to depart. Auto trips require driver concentration to insure safety.

Work trips generally constitute about 33 per cent of the total daily trips, and are concentrated during the morning and evening rush hours. During the off-peak hours, when driver-operated conventional transit is forced to cut back service, PRT offers immediate service on demand. Mothers who spend a great deal of time chauffering their children about will be freed from this chore. Shopping trips can be assisted by a cart designed to fit and be secured in the PRT vehicle.

PRT can be used to provide special services between medical, educational, and cultural centers. Hospitals could use special vehicles to transfer staff and patients between hospitals, with the advantage of allowing certain diagnostic and treatment facilities to be concentrated at a single hospital. Schools could easily move students between unique learning experiences and specialized equipment and faculty. These examples represent only a few of the efficient interconnections that an area-wide PRT network would form.

Freight Movement

Moving freight on the PRT network has substantial possibilities. Presently, the flow of commodities in cities is a slow and expensive process. The breakdown of total urban transportation from a cost standpoint has been estimated as follows: (Ref 3)

--transport of people	50%
--transport of freight	40%
--service travel	10%
	100%

As street and freeway traffic congestion increase, so do the shipping costs of raw materials and consumer products. In the mid-Atlantic region, the cost per 100 pounds of freight involved in pickup and delivery movements is estimated at 20¢. The influence of congestion is reflected in the corresponding cost in New York City of 33¢ per 100 pounds. Revenues obtained from freight transport by trucks are estimated at 9 per cent of the gross national product (Ref 4), a large share of which is in urban areas. Shipping expense has been increased by the rapid dispersal of commercial vehicle trips as the downtowns have changed function from commerce and production centers to business office activity. "A typical city daily produces about 200 intracity truck trips per 1,000 residents. Excluding the central business district, each developed acre of land attracts 1.6 to 1.8 truck trips daily...retail shops generate about 11 daily truck trips per 1,000 square feet of floor area. Convenience and general merchandise stores generate about 5 trips per 1,000 square feet." (Ref 5) This activity adds its share to congestion, and trucks are often singled out for their obnoxious exhaust and noisy operation. Placing PRT stations at terminals and warehouses could eliminate many truck trips, and the lessened person-trips on the streets and highways would ease the freight movement remaining by truck. At present the two important criteria for freight terminal locations are the desirability of being in the midst of the customers to minimize pick-up and distribution costs, and the need for ready access to main highways to minimize the line-haul costs. The first of these objectives can be met by a reasonably closely spaced PRT network to the extent that commercial districts were centered on stations. The terminals can then be located convenient to intercity routes. This has the added benefit of keeping large semi-trailers on the fringes of the urban area. For a great many shippers who at present must be truck owners, the availability of a public freight-movement system will eliminate the high-overhead expense of a truck and driver. A study based on a theoretical city with a population of 1.2 million in 2001 and with 84 miles of one-way PRT guideway serving people resulted in a $32/capita/year savings. (Ref 1) The savings accrued mostly because freight vehicles remaining on the streets were less obstructed.

The Dual-Mode Concept

In a variation of PRT known as Dual-Mode, the vehicles can operate on both the guideway and ordinary streets. Dual-mode systems possess the important advantage that the passenger can remain in one vehicle from origin to destination just as in an automobile. Thus the travel habits required for dual-mode would vary as little as possible from those of the automobile. This advantage, however, does not come without several disadvantages which have led many developers to favor captive-vehicle personal rapid transit. The desirable but mutually exclusive characteristics of the two systems lead to the need for a system which combines the characteristics of both systems. A possible way of combining the desirable characteristics of captive-vehicle PRT and dual-mode is to use a pallet system in which pallets captive to the guideway contain all the suspension, propulsion and control equipment and bumpers needed for operation on the guideway. These pallets are moving platforms to which small automobiles, passenger compartments and goods containers can be clamped in accordance with demand.

Non-palletized dual-mode systems appear to have the following disadvantages when compared with captive-vehicle PRT systems.

1. Since a dual-mode vehicle is driven on both the ordinary street system and on the guideway, it is inherently a more complex device than a single-mode vehicle, and thus will be probably more expensive than either a PRT vehicle or an ordinary automobile.

While operating on the street the dual-mode vehicle would use wheels for both suspension and traction; hence, in order to minimize cost, the temptation would be strong to use the same suspension and traction system on the guideway. In so doing, two advantages of the captive-vehicle system are lost: 1) The possibility of uncoupling traction from suspension; and 2) The possibility of using a suspension system that can operate with a narrower guideway. The second point is discussed in item 4 below. Traction can be uncoupled from suspension by the use of linear motors such as linear induction motors, linear pulsed dc motors, or possibly air motors, and permits braking independent of the coefficient of friction between the vehicle and the roadway. The coefficient of friction can vary considerably under different conditions and from vehicle to vehicle. This possible variation would seem to mean that the problem of maintaining the close headways needed would be more difficult with a dual-mode system than with a captive-vehicle system. Also, by eliminating the requirement that the wheels provide traction, both the tires and the roadway can be made smooth, thereby minimizing noise. Thus it appears that a captive-vehicle system may be both safer and quieter for the given headways and speeds than a dual-mode system.

2. Privately owned dual-mode vehicles would still be reserved for one individual as is the case with an ordinary automobile, and, as a consequence the total number of vehicles in the system would not be reduced compared with the auto system. Studies performed by the Task Force on New Concepts in Urban Transportation for the Duluth metropolitan area indicate that with a captive-vehicle PRT system each PRT vehicle replaces approximately ten automobiles, because of the multiple use of the vehicles. One can, of course, think in terms of publicly owned dual-mode vehicles, in which case a person leaving work in the evening would go to a station area, rent the first vehicle in line, drive it home, park it in his garage overnight, drive it onto the system and back to work in the morning, and then turn it over to the system for use by other people. On a dual-mode system, one can also think in terms of demand-activated vehicles which come through neighborhoods and pick up people by reservation; then the vehicle is driven by either a hired driver or by one of the riders onto the guideway, where it is carried automatically to its destination. In the case of captive-vehicle PRT, this kind of demand-activated service would only carry people from neighborhoods to PRT stations, where they would have to disembark and transfer to the PRT system.

3. When a dual-mode vehicle enters the automated guideway, there must be some kind of inspection to ensure that the vehicle's propulsion and control systems are functioning normally, and that the vehicle is in reliable operating condition. This procedure would not detract from the idea of dual-mode if it takes very little time. At present, however, there is inadequate information as to how much time this inspection would take. If it is not much shorter than the time required for a person to disembark from his own automobile at a PRT station, walk to the entrance of the station, and board a PRT vehicle, the advantage of dual-mode is diminished.

4. Since a dual-mode vehicle must run on the ordinary street system, it would have wheels in four corners just as an ordinary automobile. Thus, on the guideway, it would require a guideway at least as wide as the vehicle for support. On the other hand, if the vehicle is designed to only run on the guideway, it is possible to use alternate types of support which could result in a much narrower guideway. This means that the visual impact of the captive-vehicle system could be smaller than the case of the dual-mode system. Viewed from the side, there would be little difference; however, viewed from underneath, the dual-mode guideway would be approximately three to four times wider than the PRT guideway.

Extensive experience obtained in giving presentations on automated systems to audiences in many parts of the United States has led us to the conclusion that the visual acceptance of the overhead guideway is the most important single factor in gaining widespread acceptance for PRT or dual-mode systems. These systems could of course be placed underground, but in so doing, the cost is usually considerably greater. Before a decision can be made between dual-mode or captive-vehicle PRT, comprehensive visual-impact studies need to be conducted of both types of guideways, remembering of course that the visual impact of either of those guideways is increased if the guideway is full of vehicles than if it is empty.

Since off-line tracks are needed for stations and interchanges, there must be a double track in many parts of the network. Thus the width of two side by side two-foot tracks could detract considerably less from the acceptance of the PRT than the width of two six- or seven-foot tracks. Since the cost of guideways is related to the volume of material in the guideway, it appears likely that a properly designed captive-vehicle PRT guideway would be less expensive per mile than a corresponding dual-mode guideway. These considerations lead us to feel that it may be possible to develop a more extensive network of captive vehicle lines than dual-mode guideway lines, which may compensats for the need to transfer at the PRT stations.

5. In downtown areas there is a concern that congestion on the streets beyond the control of the automated system could cause vehicles leaving the system to be blocked and hence backed up onto the guideway.

This could of course be sensed by the system so that vehicles approaching such a demerge point would be routed to other demerge points. It is not known whether this would be a significant problem.

A more significant problem is the fact that, if private dual-mode vehicles are used, the dual-mode vehicles would have to be stored in the downtown area. This poses the same kind of problems with vehicle storage as we have with the automobile system. For this reason, many advocates of dual-mode feel that the system would have no off-ramps in the downtown area, but only off-line stations. One would disembark from a station just like a PRT station and the vehicle would then be automatically shunted to a storage barn on lower-cost land, just as would be the case with a PRT system.

Even with these disadvantages, the idea of dual-mode is a very appealing concept and should not be easily dismissed. As indicated above, the characteristics of both dual-mode and captive-vehicle PRT can be attained by use of a system in which the captive vehicles would be pallets capable of carrying a variety of types of pods and street vehicles. Pallet systems will be advantageous as long as the total moving weight does not become too large and as long as the greater complexity of system operations which will ensue remain manageable.

History of the PRT Concept and Development

The urban transportation problem prompted Congress in 1966 to direct the department of Housing and Urban Development (H.U.D.) to examine the entire field of possible solutions. The legislation, which was an amendment to the Urban Mass Transportation Act of 1964, reads as follows: "The Secretary shall undertake a project to study and prepare a program of research, development, and demonstration of new systems of urban transportation that will carry people and goods within metropolitan areas speedily, safely, without polluting the air, and in a manner that will contribute to sound city planning. The program shall (1) concern itself with all aspects of new systems of urban transportation for metropolitan areas of various sizes, including technological, financial, economic, governmental, and social aspects; (2) take into account the most advanced technologies and materials; and (3) provide national leadership to efforts of States, localities, private industries, universities, and foundations."

The series of studies that were sponsored by H.U.D. in 1967-68 were a major highlight in the history of PRT. H.U.D. awarded 17 study contracts to a wide variety of groups, including university researchers, industrial research organizations, and research institutes. A contract awarded to Stanford Research Institute (SRI), Menlo Park, California, called for a "...study and report of ideal technological futuristic solutions to urban transportation problems, solutions available in from five to ten years." (Ref 6) SRI defined the basic characteristics of the most promosing technologies in the near future of urban transit. After thoroughly describing the probable variations in systems, SRI set out to evaluate each in terms of cost, service, and advantages that could justify a research, development, and demonstration (RD&D) program at the federal level. Their studies concluded that benefits from development, installation, and operation of PRT would "amply justify" the cost of such a program. With inter-connected area-wide PRT networks in all of the major metropolitan areas of the nation, the potential for national savings was cited as $19 billion per year. (Ref 6) These findings have provided both theoretical foundation and strong encouragement for development of new systems. The organized explanation of the concepts did a great deal to facilitate discussion of PRT.

Another major study sponsored by HUD was performed by General Research Corporation (GRC), Santa Barbara, California. GRC developed analytical tools for dealing with systems in terms of average speeds, congestion, job accessibility, central traffic, downtown accessibility, and patronage division among alternative modes. Their sophisticated treatment of the subject is foundation work referred to often in current literature. GRC built a mathematical model of urban transportation and with the aid of a large computer tested the effectiveness and the costs of various strategies for improvement to the transportation systems of several real cities. As the work proceeded, experiements revealed that the possible strategies fell into two sharply divided categories from the consideration of effectiveness. One category was called the "gradualism" approach. It consisted of making improvements upon existing methods of transportation. The other approach was labeled "new technology," consisting of revolutionary transition to new systems. An excellent summary of the GRC research is found in Scientific American, July 1969, titled "Systems Analysis of Urban Transportation." The results of this extensive study showed that "the gradualistic approach could not meet the future transportation needs of the cities, whereas innovations already in sight promise to do so." (Ref 7) More precisely, the GRC answer was that "increased investment in conventional transit is not likely to arrest the persistent patronage decline that plagues public transit; that RD&D enabling a substantial improvement in conventional performance would not very much improve matters; and that any real hope for maintaining and improving transit attractiveness rests with the new systems of personal and dual-mode transit." (Ref 8) The dual-mode transit concept has accompanied PRT thinking since the early stages, but hardware development in dual-mode has not progressed as rapidly as in PRT.

The conclusion of the HUD studies was that development and installation of new systems could improve urban transportation considerably. Though no immediate surge of government RD&D funding or corporate interest was apparent, the attention to PRT has since increased in significant steps.

Several PRT systems were already under engineering development prior to the HUD studies. Research on air-cushion technology by General Motors in the early sixties was adopted by Transportation Technology, Incorporated (TTI). TTI, now affiliated with Otis Elevator Company, has a system using air levitation and electromagnetic propulsion under full-scale test. Another early developer, the Alden Self-Transit Systems Corp., in 1968 built a 1/24 scale model PRT system with four off-line stations, ten vehicles, and a multiple-line network. The system was managed by a digital computer which performed the functions of route selection, acceleration into and out of stations, position control, and merging at intersections and stations. A full-scale prototype was operating less than two years thereafter. By the fall of 1969 Monocab, Inc. had constructed a full-scale loop configuration guideway with a single off-line station to test the design of its overhead-supported cab. Uniflo Systems Corp., a Minneapolis-based firm, had a half-scale prototype of an air-supported and propelled vehicle operating in 1968. Several other developers had various stages of hardware built more than two years ago.

Several larger-vehicle (up to 20 to 30 passengers) systems that are sometimes called "quasi-PRT" have been developed recently with a marketing focus on major activity centers and airports. Operation would be scheduled in peak hours. This has some advantage for capacity but adds to the waiting time of customers. Service would be on demand in off-peak hours. Larger vehicles mean larger and more expensive guideways, stations, and interchanges. Since the capacity of small-vehicle PRT is generally sufficient and the service far more attractive, the quasi-PRT systems will not be discussed further in this report.

Stimulated by public interest and the results of the HUD-sponsored studies on new systems, the U.S. federal government organized in 1964 to deal effectively with the urban transportation problem. In that year, Congress passed the Urban Mass Transportation Assistance Act which resulted in average funding of $170 million per year for urban mass transit through 1970. Throughout this period, the funding was directed primarily towards capital grants for improvement of facilities and purchase of bus and rail vehicles. The cumulative amount allocated to research, development, and demonstration of new systems was about $10 million through fiscal year (FY) 1971. The 1964 Urban Mass Transit Assistance Act was amended in 1970 to provide substantially increased funding for transit - $3.1 billion was scheduled for a five-year period. The amounts allocated to RD&D in new systems are as follows (dollars in thousands):

FY 1971	FY 1972	FY 1973
$19,964	$35,892	$46,280

The prospects for development of high-capacity PRT at the time of this writing are well summarized in a "Transportation Report" in the National Journal, November 25, 1972.

Conclusion

PRT has broad implications for our urban centers. It appears able to contribute substantially to the restoration of vitality to urban life and to the preservation of the community from the onslaught of growing demands for mobility. If PRT systems are deployed, cities may again become places to live rather than just to work and entertain. Development of outlying areas can be more rationally planned with PRT networks than the scattered and piecemeal growth that presently spreads into valuable scenic or farming areas. Widespread availability of PRT service will prevent oil shortages from crippling the nation's transportation. The heavy drain on natural resources for short-lived autos will be lessened to avoid critical scarcities in the years to come. In short, PRT is not only a sensible solution to urban transportation problems, it is becoming a necessary one.

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Chapter 3

Transportation and Land Use

Since World War II urban areas have experienced a "thinning-out," a tendency toward fringe-area development. The downtown area, traditionally the center of economic and social activity, faces strong competition from modern diversified centers which followed the population into the suburbs. Theories and explanations of the large-scale emigration from the central cities are numerous and diverse but most agree that the advent of the auto era enhanced the attractiveness of suburban living. With the help of the highway, businessmen could seek homesteads beyond the city limits while enjoying freedom from congestion and pollution without increasing travel time. Today, many individuals concerned about the future of our cities are attempting to isolate the dominant factors influencing land-use decisions and to evaluate their relative importance. Because of the many variables active in land-use decisions,[1] a great deal more will need to be done before definitive conclusions can be reached concerning the actual role of the individual elements in influencing patterns of land development. As a result of the impact that highway construction appears to have had on suburban developments, the relationship between transportation and land use has become the subject of much debate.

Factors Contributing to Suburban Growth

Accessibility of Transportation Facilities. Although the primacy of transportation in land-use decisions remains to be established, evidence suggests that the accessibility provided by transportation is at least one of the essential determinants of non-rural land disposition. The history of American settlement is closely connected to progress in development of new transportation modes. Early communities settled along the natural transportation corridors provided by the rivers. As the railroad expanded across the country, towns and commercial centers clustered around its lines and interchanges. Finally, with the emergence of the urban railroad (commuter railroad and subway) the cities began to subdivide.[2] The city, as the medium for cooperation and communication necessitated by the industrial revolution became "a place to make a living" circumscribed within a "commuting distance" rather than a united community.[3] Gradually the affluent relocated beyond the city limits to enjoy the benefits of country living and commuted to the city to reap the economic rewards of the city without enduring the negative effects produced by industries.

Land-Use Controls. Basic land-use regulations were established during this period but the orientation of their ordinances was toward stabilizing property values rather than reinforcing a planned municipal development. A description of the situation is presented in The Quiet Revolution in Land Use Controls:

> Where development would not harm property values it went unregulated. Zoning permitted residential uses to be built in the most polluted industrial districts on the theory that any development which did not reduce the value of the surrounding land should not be prohibited. Land-use regulation was limited to urban areas where the close proximity of land use made it likely that the particular use of one man's land might reduce the value of another's, but there was no regulation of land outside urban areas, where such a reduction in value was not likely to take place.[4]

Zoning power rests generally at the level of the individual local municipality. Competition between municipalities to attract the development desired by their constituency has seldom considered the effect this development would have on the surrounding areas. Random development flourished under these conditions.

Control of the access to public utilities such as water or sewer facilities has also been a means of controlling, at least to some degree, the type of use planned for any given section of undeveloped land.

Post-War America. Post WWII America, however, witnessed the migration of the middle-class to the suburbs and the bedroom communities expanded in every direction. Minnesota Settlement and Land Use 1985 identifies 4 basic influences upon the size and population distribution of America which were heightened by WWII:

1) the continuing high level of military-space spending;

2) the explosive birth rate;

3) the adjustment of both rural and urban settlement patterns to automotive transportation; and

4) the rising affluence and resultant greater range of choice of residential location.[5]

The Department of Public Works constituted an institutional spur to relocation in the suburbs since it constructed both the new housing to which city dwellers were to be enticed and the roads to facilitate the move without forcing an individual to change jobs. Moreover, the economic policies adopted by the majority of financial institutions, at the encouragment of the federal government, provided low down payment loans and easy credit for many families formerly unable to assume liability for major purchases such as houses or private automobiles. The urban worker was then afforded a plethora of possible residences within a reasonable travel-time area.[6] Through the development of the road network the benefits of location were equalized in many areas offering the prospective homeowner the opportunity to choose a place for the physical characteristics of its site rather than just because it was convenient.[7]

The rapid growth of suburban areas during this period seems to indicate that there are significant numbers of people who will choose to live in lower-density areas when given the choice. As more and more members of the urban community began to make their homes in the suburbs, service facilities formerly concentrated in the Central Business District (CBD) also began to emigrate to locations which would provide easy access for suburbanites. Convenience of location soon became one of the most important considerations for the facilities competing to serve the suburban population. Lowdon Wingo, Jr. contends that:

> Efficient organization of activities in space becomes an even more critical metropolitan problem when one adds in the satisfactions which the citizens of the city desire from the web of interactions. Here public investment in facilities and services can militate against or facilitate the ability of the metropolitan region to function well. Communication and transportation facilities will define the basic conditions of interaction among firms and households; investment will flow into profitable locations and away from unprofitable ones; and the accumulation of these effects will transform the spatial organization of the metropolitan region.[8]

Wingo's notion of the significance of a "web of interactions" seems to reflect the trends in urban-suburban development that have occurred since WWII. Increasing numbers of commuters forced larger segments of downtown land to be surrendered for parking facilities[9] and roads with more capacity. This compounded the problems of congestion and pollution while at the same time encouraged development of "full-service" centers in outlying areas.

Taxation. Rising tax assessment based on the potential of the land rather than the activity for which it was actually being used forced many home owners and small businesses to move from the central core of the city, thus producing a decentralization of the business district.

Trends in Land Development and the Role of Transportation Facilities

In a nation where land has always been plentiful, there seems to be little concern about the trends of land development. Urban Planner Edgardo Contini states that:

> We have allowed the city to grow unrestrained wherever forces for growth prevailed. We have allowed the city to decline unrestrained whenever the tendency was to decline. We have never realized that we could have such a thing as an "urban policy" at a national level. We have never realized that the transition of the use of the land from open, rural land to urban land--land used for living in the city--is a subject for concern and for a programmed direction.[10]

Developments of recent years have brought to our attention many problems connected with use of highways to facilitate suburban growth and movement around the urban area. As a result of the urban freeway, many inner-city communities have been effectively isolated from the amenities of the suburban society and open country. Mobility needs of non-automobile users have often been overlooked, and the environment of the city has been left to decay.

Back to the Cities. Some urban areas have turned to various types of rail transit to attempt to turn the balance in favor of the cities again. Most metropolitan areas that have had completed rapid-rail transportation facilities operating during the auto era are, however, experiencing many of the same symptoms exhibited in cities without such transit systems. New York, Boston, Chicago and Philadelphia all suffer from stand-still traffic and critical automobile-emission pollution, all of these cities are divided by urban freeways, and all of these cities are surrounded by expanding suburbs. But, the rapid-rail transit facilities of these large cities are nonetheless an important part of the total effort to move people in these high-density communities. In cities where such facilities are either currently under construction or recently completed it is difficult to judge their effect on net growth.[11] Each instance would require investigation of the likelihood of development occurring in the absence of the facility; the amount of relocation and displacement required by the system; the utility/service demand created by the installation of the system; and the benefits derived from having the development occur in close proximity to the transportation facility.

There are some basic explanations, however, of the role of transportation facilities with relation to land-use decisions. The most obvious is that it provides accessibility to people, employment, services and recreation. Transportation facilities offer opportunities for interaction and face-to-face communication, or for sending or receiving necessary supplies and information. Through the mobility available because of a transportation system, an individual can expand his area of activity and sphere of influence; he can participate in functions and activities from which he would otherwise be segregated. Transportation facilities permit independence and freedom of movement and schedule.

The transportation section of the Development Guide produced by the Twin Cities Area Metropolitan Council describes the role of transportation facilities in the following way:

> The building of transportation facilities should emphasize far more than just the solution of some existing traffic problems; it should allow people to take full advantage of the employment, shopping, recreation, culture and educational opportunities available throughout an area. Transportation facilities should also aid the efficient movement of goods and facilitate the conduct of business. Good accessibility to opportunities for all social and income groups is the major objective of a regional transportation system and should be uppermost in all metropolitan transportation planning and development work.[12]

If transportation facilities are to fulfill such an expectation they must be compeltely integrated into a comprehensive area-wide plan that allows for feedback interaction between the movement needs of the area and the potential of the planned transportation facilities to meet these needs. The 1968 Annual Report of the Joint Legislative Committee on Mass Transportation to the State of New York points out that:

> As Commissioner of Transportation J. Burch McMorran testified at a Committee hearing in Hempstead on January 12, 1968, 'traffic comes from land use; certain types of land use generate far heavier demands than others. Transportation facilities are largely built in response to these demands. In this there is a lesson for all those who shape our communities --the traffic potential of various land uses must be firmly in mind when non-transportation projects are undertaken.'"[13]

Urban Planning. A transportation system is an important complement to any urban plan because it provides for the possibility of successful completion of the planning design by assuring internal and external accessibility for the unit. Careful transportation planning can be used to reinforce any type of development configuration desired. "City X, for example, may be said to have a shortage of open space or industrial area, or land for houses only if the supply is insufficiently accessible to linked activities. The supply of metropolitan space depends on the communication and transportation facilities which determine relative levels of accessibility among the parts of the metropolis."[14] Largely in response to the settlement and development patterns that have become evident since World War II, urban planners have been seeking urban designs that would strengthen the viability of the city. Many new approaches to urban design are being considered in order to attempt to provide a variety of choices for individual citizens and commercial organizations while enhancing benefits for the community at large. Open Space Zoning and Planned Unit Development [15] are two of the more prominent efforts to preserve the natural beauty of an area and provide the opportunity for a diversity of life styles within a single community. These new types of land use planning foster the development of unified communities with an awareness of surrounding communities. Because of the importance and degree of interaction between communities which modern life styles require, intercommunity planning seems to be crucial to the vitality of a metropolitan area as a whole.

Regional Planning. One of the most significant developments in the field of urban planning is the recent emphasis on coordinated regional planning. As boundaries between municipalities have become less clearly defined it has become apparent that piecemeal development must be avoided if the urbanized areas are to maintain any sort of individual identity. With this recent awareness of the need for regional planning has also come the recognition of the importance of compatibly interfacing the factors affecting settlement and development to promote the most desirable land uses.

Because of the role transportation appears to have played in the rapid growth of suburban areas discussed earlier, consideration of the potential of transportation facilities has been recognized as an essential element of the comprehensive planning process. Many communities are attempting to link transportation planning to other types of planning activities. In 1969 Minnesota, for example, passed legislation establishing an Interdepartmental Task Force on Transportation within the State Planning Agency. The three major responsibilities of this Task Force are:

1. To assess the transportation needs of the state and develop comprehensive statewide plans to meet these needs utilizing all forms of transportation.

2. To coordinate all present and future transportation studies and to assure that they are coordinated with other urban and regional development plans.

3. To investigate the problems of urban mass transit and to report to the Governor and the Legislature on the problems and needs of urban mass transit and to report on the need for state financial assistance. [16]

Transportation operates as one component in a complex cycle of interaction. This Task Force offer the following comments on the interdependence of housing and transportation:

> The impact on housing is twofold. First, housing and housing-related plans will be taken as input to transit planning in order to assure that there is the necessary coordination of effort and that the urban and regional development goals will be reflected in transportation planning. Second, transit planning will be taken as input for housing and related planning to assure that it is compatible with availability and capability of transportation facilities.
>
> Inner city neighborhoods and housing available for lower income families may be the most directly affected by transportation planning since they rely more heavily on urban mass transit for mobility. The availability of adequate mass transit will, therefore, have a great effect on where such families are physically able to locate and will subsequently affect the whole matter of availability of housing.[17]

Furthermore, J. Douglas Carroll, Jr., Executive Director of the TRI-STATE TRANSPORTATION COMMISSION, discussing the problems of providing public transportation facilities in urban areas points out that: "The department stores have moved to the suburbs and offices, insurance, even restaurants and cultural facilities are being built in the suburbs today because this is where the large increases of the people and the urgent new capital demands are."[18] In view of the mutual influence of these factors upon each other they must be carefully balanced in planning for future development.

The desire for rapid mobility which has become a driving force in the modern American life-style creates many problems for the urban planner faced with attempting to satisfy the mobility needs of a community whose basic development is the result of either random development or CBD orientation. According to McMorran, "one other factor that is of great importance in affecting mass transit versus auto usage is the change in the concentration of day-time population at the very core or center of cities, their Central Business Districts

(CBD). These, too, have not been growing....As a matter of fact, most large metropolitan CBDs in the United States are receiving fewer daily travellers now than they did in 1947."[19]

Recent community opposition to urban freeway development has brought this problem more clearly into focus. Alternatives to building more highways are currently being examined in cities throughout the world. Transportation facilities like highways which have often been planned to alleviate crisis situations in the past must now also consider future mobility needs. Commenting on the correlation of transportation and land use, the transportation committee of the 1968 N.Y. legislature reported that:

> Transportation planning by itself is insufficient to ensure the orderly and most desirable pattern of development. To be effective, transportation planning must be part of a comprehensive planning program for each metropolitan area which considers all aspects of future development, including population growth and changing transportation requirements. The transportation problem is a regional one and is not confined to any one city. Each urban area through the planning process first must determine the goals it wishes to achieve in terms of future development, and next develop the modes of transportation which best can assist the area to achieve its goals. The comprehensive planning process, including the transportation component, must be long-term in nature and flexible in order to meet the challenges of changing conditions. Too often, a decision to locate a new transportation facility is made after intensive development has occurred and the taking of land for the facility causes hardships for those forced to relocate, and by changing adjacent land values may promote an undesirable type of development in the area from the standpoint of the residents of the community. Consequently, rights-of-way for future transportation facilities should be reserved, where possible, prior to the intensive development of the area.[20]

An amendment to the Urban Transportation Act of 1964 (discussed in Chapter 2) directed that new transportation be sought to fulfill metropolitan mobility needs "in a manner that will contribute to sound city planning."

Transportation in Evolution

How then can transportation facilities be planned to promote the desired development goals of a community if the actual role of transportation facilities in urban development decisions remains undetermined?

As mentioned at the outset many factors appear to affect particular land-use decisions. Transportation possibilities must, nonetheless, be considered in any development decision, even a decision not to develop. It is readily apparent, however, that research is necessary to promote the wisest possible uses of our land and resources. Although it is not a question of scarcity of land in general, we must ensure that the land is used for those purposes to which it is best suited. Likewise various types of transportation must be coordinated so that they are commissioned to fulfill the function for which they were designed, designing new systems when necessary.

Conventional Transportation. The history of transportation has been discussed in the introductory chapter of this report. Therefore, we will only briefly mention the history of public transit and the land development pattern that accompanied it.

1. Fixed Route. Conventional public transit is designed to move large numbers of people between a limited number of origins and destinations. Becuase of the large capital investment required for the fixed-route systems, large numbers of daily person-trips are necessary to keep such systems economically feasible. In order to sustain the necessary level of daily person-trips, high concentrations of people in the immediate vicinity of the transit facilities are essential. At a time in the past in which most of the population was dependent on transit, many people

settled in the areas adjacent to transit facilities to increase the convenience of these facilities. As long as the activity orientation was to the CBD and large segments of the population continued to provide high population density in the transit system sphere of influence, this type of system (street-car, trolley or subway) remained viable. Strip-development along the transit radials was the dominant form of urban-suburban growth during this period.

2. Flexible-Route. Bus transit was basically a by-product of the auto-road transportation network. With the onset of the auto era and its accompanying characteristics (discussed earlier in this chapter) flexible-route bus transit became the major form of public transportation in most cities in America. Because of the exceptional flexibility and adaptability of the auto-road system, the development configuration began to reflect a diversity in settlement decisions based upon personal preference. Lack of public utilities proved an insufficient deterrent to scattered development. As population densities decreased and the population dispersed, conventional bus transit on the road system became time-consuming, expensive and inconvenient for many. These considerations all have some influence on public-transit patronage and patronage trends often cause alterations in bus-route plans. Since the bus routes are always subject to change and are generally dependent upon the auto-road system for right-of-way, it is unfeasible to attempt to determine the effect of bus transit on urban development.

The most flexible transit system in existence today is the private automobile. In modern America the automobile is no longer considered a luxury, but rather a necessity. The auto-road system has been instrumental in changing the face of many urban areas; the great success of the auto has generated new questions about what defines a community. Spatial proximity, formerly the basic determinant, became just another factor in the definition. Social, economic, political, and cultural characteristics emerged as important considerations in identifying a community. A community's vision of itself, e.g., as basically residential with an emphasis on natural amenities, as industrial, or as a combination of commercial and residential, began to exert an influence upon the types of uses for which it would zone its land. The desire to develop a strong tax base encouraged some communities to accept more commercial or industrial developments. The Weaver Bill passed by the 1971 Minnesota State Legislature created the Fiscal Disparities Law for the Twin Cities Metropolitan Area which provides for intercommunity sharing of metropolitan area tax bases. Measures of this type are an important step in coordinating metropolitan area communities into a metropolitan identity. Lack of a comprehensive regional planning board with the authority to zone at the regional level instead of the municipal level permitted the random development characteristic of the modern suburb. Recognizing the importance of providing adequate means of transportation, transportation planners began attempting land use models in the 1940's in an effort to coordinate highway facilities with projected growth patterns.[21]

The growing complexity of urban problems spurred rapid development of land-use models which became separate from earlier transportation-based models,[22] but continued to consider transportation as an input. Such models have become an integral part of both the urban planning and regional transportation planning processes. In designing these models, planners began to consider regional development with several feedback loops to attempt to account for the many factors affecting land-use decisions.

PRT and Urban Development Patterns

The question of the ideal urban size and population density has elicited a number of diverse opinions.[23] Although it has become obvious that modern populations are opting for lower-density communities, very low densities may create problems which should be balanced against conditions in areas with more moderate densities. This section is an abridged version of an article written by Professor J. Edward Anderson in which he addresses this problem.[24]

Since World War II, the auto system has emerged as the major transportation factor in the growth pattern of cities. The random, low-density development which has accompanied the auto era is considered undesirable by many people. Before examining the effect new transit systems may have on urban development and redevelopment, we need to examine more closely what it is about this type of uncontrolled development that is undesirable and what if anything can be done about it. The observations given here are based on discussions with planners and geographers, literature and several decades of observation as an urban resident.

The present pattern of urban development in the United States has resulted from the compounding of individual decisions about where to live and the lack of enforceable land-use plans. The automobile has been a prerequisite to random low-density development but, by itself, could not have produced it. The fundamental driving forces appear to have been simply a desire for privacy, fresh air, closeness to nature, and a nice place for one's children to run and play. In the early days of the auto, only wealthy people could afford both a home in a nicely wooded area on the outskirts of town and a car for transport to the office. Wealthy people influenced town politics and had better and better roads built to their then isolated communities.

As these communities grew, they built schools and made certain that these schools were of high quality. Two more driving forces them came into play: first, the desire of many parents who could not quite afford it to take advantage of the better education they felt their children could receive by attending suburban schools; and second, the fact that taxes were lower outside the city limits. After World War II, low-down-payment, low-interest GI home loans and auto loans were the final factor needed for development of a market for single-family suburban homes for people of average income. Land developers were ready to supply this market and, from the viewpoint of most of them, profits would be maximized if every possible lot were developed. Community objectives like parks and playgrounds appear to have been of minor concern to private developers. Also, since these facilities do not contribute directly to the tax base, suburban leaders often overlooked them. From the viewpoint of the individual family, the move to the suburbs was an exciting event. It would have been difficult indeed to persuade people that there might be serious problems associated with such a move.

Random low-density urban development has, however, produced detrimental effects. Some of them are the following:

1. The lack of regional planning in the United States has resulted in a deficiency of good parks in suburban areas. As a counter example, in Minneapolis foresighted community leaders, almost sixty years ago, persuaded the city to purchase lands around the chain of lakes on the periphery of the city. Many scoffed at this as a waste of public funds, but these lands now form a chain of parks which are a prime asset to the whole community. They not only have recreational value but have been an obvious factor in keeping many of the more affluent residents within the inner city. The parks have been a magnet to attract desired development.

2. The cost per dwelling of providing utilities is higher in the lower-density suburban communities. When people first moved to the suburbs the pattern was to have a cesspool and well for each home. Power lines were provided to meet the demand. As the lots filled up, cesspools became overloaded and wells contaminated. Pressures built for sewers and waterlines as well as for better roads, schools and playgrounds. One result has been a great deal of pressure to do something about rising property taxes which these improvements have generated.

As a minimum, it would seem desirable for metropolitan authorities to insure that families are fully informed about the obligations they will incur in moving to a new suburb. One of the problems now is that families are simply unaware of the total financial burden they are assuming when making the down payment on a new suburban home. To so inform people would of course run counter to past policies of encouraging maximum growth.

3. Low-density housing tends to isolate families and to decrease the sense of community. In the case of families that have been able to afford only one car, the wife is much more isolated than when she lived in town and could walk to many places of interest. Another important factor in this isolation is the frequency with which Americans move.

4. The cost per ride of providing public transit is inversely proportional to the population density. Thus bus systems which were economically viable in the inner city could not survive in the suburbs. Lack of public transportation of course increases the isolation of those with no access to an automobile.

5. Conservationists have warned that too much valuable farm land is going into housing and have calculated that if this continues for a few more decades, the United States will actually have to worry about an insufficient supply of good farm land. For example, many formerly fertile agricultural valleys in California are now smog-filled suburbs.

Because the current form of urban development appears to be detrimental, policies should be developed to shape growth in more desirable ways. The basis of these policies should be a very thorough quantitative understanding of the underlying factors which have determined current growth patterns, and which may determine growth patterns in the decades ahead. It is important to appreciate that for many reasons the future will not be a mere extrapolation of the growth trends of the past.

Some of the policies which should be developed (and in some areas are being developed) to control urban development are the following:

1. Identification of and purchase of appropriate lands for park and playgrounds.

2. Development of information for the potential suburban homeowner in order to inform him of the full potential cost of moving to the suburbs.

3. Review and approval by a central and democratically elected authority of all requests to build roads, transit lines, sewers, water lines, and power lines; and identification of areas in which such approval will not be granted.

4. Concentration of non-residential activities in well-located major centers of predetermined maximum daytime population. The maximum population of each should be determined from consideration of the ability to supply all utilities including transportation. These maxima should apply to the downtown as well as to other major centers. The philosophy of the greatest possible growth of any one center should be abandoned as being socially undesirable to the community at large.

5. Establishment of the desirable range of population densities. We have pointed out difficulties if the population density is too low. Too high a population density is also socially undesirable.

6. Creation of a transportation plan with sufficient capacity to provide for the needs of the community. Recognition should be given to the fact that the flow in any transportation corridor is proportional to the average trip length. A pricing system should therefore be worked out to discourage longer trips.

7. Develop specifications for more economical use of land in creative ways which will increase quality of life.

Within a framework of policies such as those suggested above, it is meaningful to discuss the possible effect of a particular mode of transportation on urban development. A public transit system may have significant influence on urban development if it can attract a significant fraction of the total number of trips within the entire urban area, not just trips to the downtowns; and if it can help to reverse the major driving forces which cause people to want to move out of the cities.

In most of our auto-oriented cities, no conventional transit system is able now to fulfill these criteria in a significant way. In the case of bus systems, routes can be changed too easily to cause development decisions to be influenced. Also the service concept of conventional bus lines does not address the real transportation needs of people. People instead are asked to adjust their habits to meet the needs of the system, i.e., waiting for vehicles, picking up and letting off other people unconnected with one's own trip, and transferring. New service concepts like door-to-door subscription service or dial-a-ride may increase transit ridership--a desirable goal--but they are too dependent on the road system to produce changes in development patterns.

Studies of the influence on development of potential new on-line-station, fixed-guideway transit, i.e., rapid-rail transit, come to similar conclusions because the cost per ride is too high in low and medium-density communities to build a sufficiently extensive system. The cost per ride is too high both because of the high construction cost and because the service concept is so inferior to the auto. These systems may cause some concentrated development near downtown stations, but will do practically nothing about the overall development pattern.

Now let us consider Personal Rapid Transit (PRT). If PRT does influence urban development and redevelopment in significant ways it will first have to be a very successful system in terms that will be reflected in the cost-per-ride equation. For many reasons, we believe the cost per ride will be close to, if not below, a reasonable fare, particularly if the system is used for moving freight as well as passengers. In the following discussion, it is assumed this is true and that properly designed guideways will be acceptable at least along major arterial streets, since only then can PRT affect development decisions.

In the downtowns, these guideways may be as close together as two blocks, but in residential areas the minimum spacing should be about one-half mile. In most areas a spacing of one mile or more would appear appropriate. A major point is that the location of the lines should be determined in accordance with an overall development policy. If PRT becomes accepted, there will be pressure to extend the lines farther and farther into the suburbs. But if this is done according to a carefully developed plan, it would not produce the undesirable features of uncontrolled urban development. Because the lines would be designed to be physically attractive and would not produce excessive noise, residential communities could be planned and built near them to minimize the walk to stations. The spaces farthest from the lines could be planned as open spaces for a variety of purposes. Small electric cars and bicycles could be provided for those too far from the lines to walk.

With a network of lines in the inner city, the use of automobiles could be reduced. This would reduce the negative side effects of the auto such as noise, air pollution, physical blight, accidents, and excessive land use. Many parking lots could become parks. The result would be a city which would begin to attract and hold people rather than drive them away. Downtowns could restrict the use of automobiles without causing economic stagnation because people would have a viable alternate mode of travel, in fact, an alternative far more convenient as a means of access to downtown than exists today. With easy access to the downtowns and other major centers, people would go to them because of the attractions they offer. Thus, it would seem that PRT would satisfy the needs of downtown interests as well as the interests of the community at large. Coupled with other policies, PRT appears capable of producing very significant positive influences on the whole community.

Summary

Throughout this chapter we have attempted to point out the nebulous character of the relationship between transportation facilities and land use. Although it may be disappointing to discover that an easy answer is not available, it is important to recognize that there is no panacea for shaping land development in the future. There are, however, some significant insights to be gained through this type of review. Probably among the more basic are the conclusions reached by the Survey Research Center at the University of Michigan:

> First, the forces which have led in recent years to the rapid expansion of cities into the surrounding countryside are still strong. The opinion that the tendency to reduction in density is now over seems to be in error. Second, the forces which are leading to the spreading out from cities, however, are not primarily desires to live far out from the city center. The demand for low density neighborhoods is derived from more fundamental desires. These desires...include desires for privacy, for a good neighborhood, and for home ownership.[25]

Current evidence suggests that control of future land disposition can effectively be achieved only through careful coordination of all the tools available to planners in light of the evident preferences of the population.

NOTES

1. John Borchert, "Realities of Transportation Planning," PRT Bi-Weekly, 1, #17 (June 15, 1972), p. 150. When discussing what he calls myths of transportation and development Borchert says that transportation determines the type of development only in minor detail, not in a general pattern. Borchert lists the following five factors among the variables affecting urban development patterns: "(1) the credit situation; (2) the family cycle; (3) the population age and structure; (4) the growth rate; and (5) the house replacement rate."

2. Christopher Tunnard and Henry Hope Reed, American Skyline: The Growth and Form of Our Cities and Towns. (New York: Mentor Books, 1956), p. 131.

3. Hans Blumenfeld, "Transportation in the Modern Metropolis," Internal Structure of the City (New York: Oxford University Press, 1971), p. 231.

4. Fred Bosselman and David Callies, The Quiet Revolution in Land Use Control, (Council on Environment Quality, The President's 1971 Environmental Program, 1971), p. 316.

5. John Borchert and Donald D. Carroll, Minnesota Settlement and Land Use: 1985, (Minnesota State Planning Agency, 1970), p. 4.

6. Edgardo Contini, "The American City--A Forecast," The Futurist, VI, (February 1972), p. 10. The author describes a reasonable commuting time as 1/2 hour to one hour. See page 70 for map of area within one hour's drive of the Twin Cities.

7. Laurence A. Brown and Eric G. More, "The Intra-urban Migration Process: A Perspective," Internal Structure of the City (New York: Oxford University Press, 1971), p. 201. The authors explain that:

   > Geographers have traditionally recognized two sets of attributes of a location: those which relate to the physical characteristics of the site, and those which relate to the accessibility characteristics of the situation.

8. Lowdon Wingo, Jr., "Urban Space in Policy Perspective," Cities and Space,: The Future Use of Urban Land, (Baltimore: Johns Hopkins Paperbacks, 1966), p. 9.

9. Allan T. Demarie, "Cars and Cities on a Collision Course," Fortune Magazine, (February 1970), p. 125. According to Demarie, "Between 250 and 300 square feet of space is needed for every car that commuters park in the city. Cities typically devote 10 to 20 percent of their downtown land solely to parking cars..."

10. Edgardo Contini, "The American City--A Forecast," The Futurist, VI, (February 1972), p. 11.

11. Joseph P. McKenna, Urban Travel in St. Louis (St. Louis, Mo.: University of Missouri Press, June 28, 1971), pp. 28-29.

12. Metropolitan Development Guide: Transportation Policies, Systems Planning, Program, Adopted by the Metropolitan Council of the Twin Cities, (February 25, 1971), p. 5.

13. Joint Legislative Committee on Mass Transportation, State of New York, 1968 Annual Report (New York: Maynard Printing and Lithograph Corp.) pp. 80-81.

14. Lowdon Wingo, Jr., p. 9.

15. For a detailed discussion of these concepts see the articles by Lee Syracuse in:

    ----, "Why Communities Should Adopt Open Space Zoning," Land Use, 1, (March 1972).

    ----, "The What and Why of the Program," Building Our Communities, (Home Builders Association of Cost-Solano Counties, California).

    ----, "Residential Open Space Zoning," Building Our Communities, (Home Builders Association of Contra Costa-Solano Counties, California).

    ----, "Answering Questions about 'The What and Why of the Program' and 'Residential Open Space Zoning'," Building Our Communities, (Home Builders Association of Costa-Solano Counties, California).

16. State of Minnesota Initial State Housing Element issued by the Governor's Urban Affairs Council, Minnesota State Planning Agency, 1970, pp. 105-106.

17. Ibid., p. 106.

18. J. Douglas Carroll, Jr., "The Interrelationship of Land Use and Transportation Planning," The Crisis in Mass Transportation, (State of New York, 1970), p. 62.

19. Ibid.

20. Joint Legislative Committee on Mass Transportation, State of New York, 1968 Annual Report, p. 80.

21. Urban Development Models, Special Report 97, (Highway Research Board, Division of Engineering, National Research Council, National Academy of Sciences--National Academy of Engineering, 1968), p. 3.

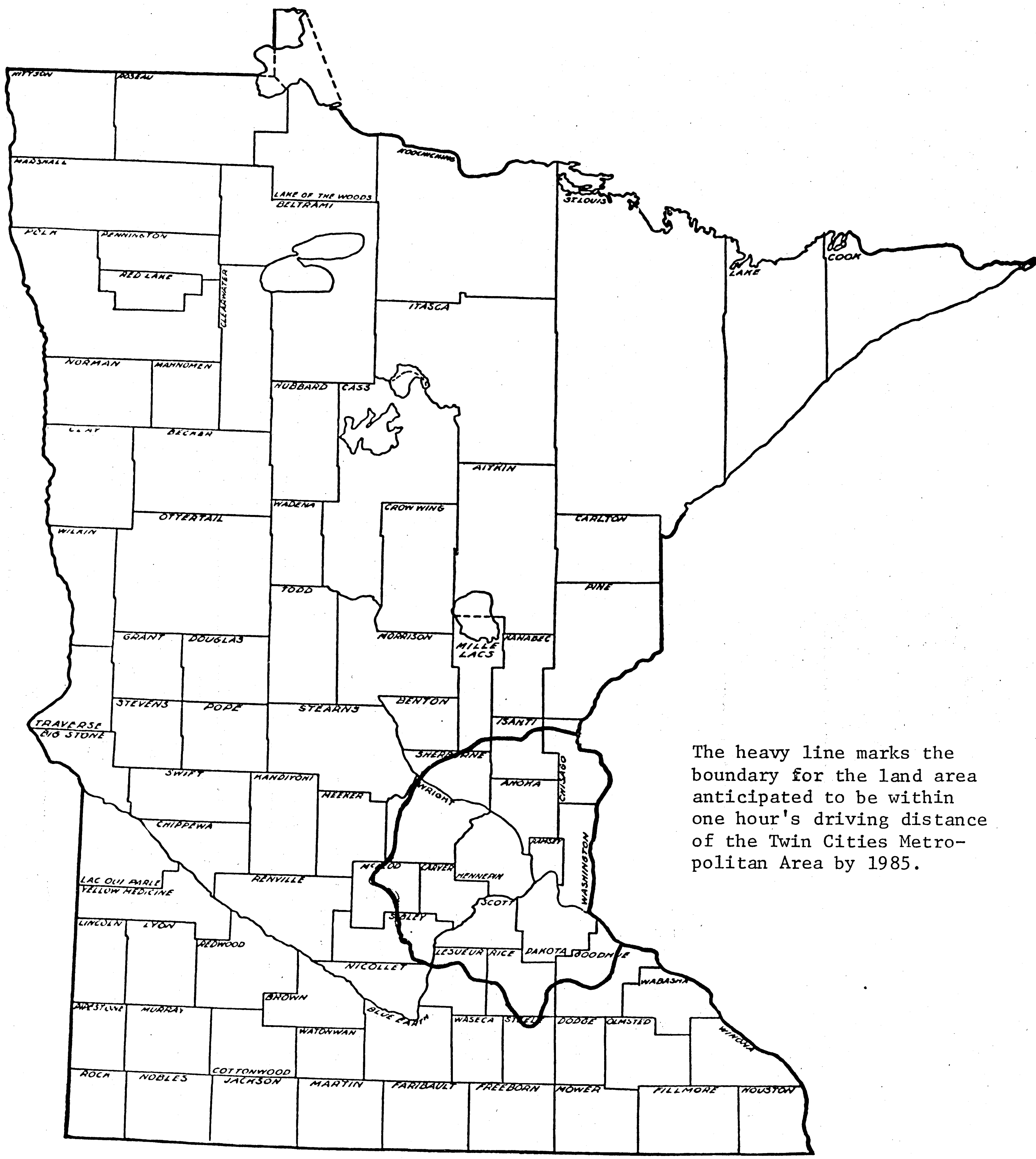
22. Ibid., p. 5.

23. For a brief history of the search for the ideal community see: Jean Gottmann, "Urban Sprawl and its Ramifications," Metropolis on the Move: Geographers look at Urban Sprawl, (New York: John Wiley and Sons, Inc., 1967).

24. J. Edward Anderson, "PRT and Urban Sprawl," PRT Bi-Weekly, I, #10, (January 24, 1972) pp. 88-91.

25. Joint Legislative Committee on Mass Transportation, State of New York, 1968 Annual Report, p. 79.

MINNESOTA STATE MAP



The heavy line marks the boundary for the land area anticipated to be within one hour's driving distance of the Twin Cities Metropolitan Area by 1985.

Map prepared by the Minnesota Land Management Information System Study, Center for Urban & Regional Affairs, University of Minnesota.

Chapter 4

Architectural Impact Study

Transportation channels, be they streets, walkways, transit lines, railroads, or canals, are not only the means by which the city is traversed, but for many people they are the setting from which the predominant image of urban life is conceived. The city is observed as people move through it along transportation pathways by which other urban elements are related and arranged. (Ref 1) Changes in transportation technology, through the eras of horse and buggy, streetcar, and automobile have had a profound bearing on the physical structuring, visual image, and accessibility of modern cities; and, as new technologies in urban transportation approach technical and practical feasibility, an assessment of their architectural impact on the city gains increased concern. The work of Wallace Russell which assessed the impact of CABTRACK (an elevated personal rapid transit system) in London exemplified this growing awareness and concern for urban changes brought about by transportation technology. (Ref 2) The purpose of this paper is to evaluate the architectural impact of Personal Rapid Transit (PRT) in Minneapolis, Minnesota.

Minneapolis was selected for study due to its proximity to the University of Minnesota where the study was conducted. However, the characteristics of Minneapolis in terms of density, spatial organization, infrastructure, and socio-economic patterns are typical of many American cities; and therefore, although the specific locations are unique to Minneapolis, the evaluative procedures may be applied to many areas with the same general characteristics.

Locations depicting varied urban situations were selected from a PRT network for Minneapolis developed by Dr. J. Edward Anderson of the School of Mechanical and Aerospace Engineering of the University of Minnesota. Locations representing residential, commercial, industrial, institutional, and mixed use areas were selected in order to assess the effect of PRT in a range of urban settings. The uniqueness of each area and its relationship to other elements and locations within the urban complex was considered a critical factor. Characteristics and trends in such urban parameters as density, activity, building type, demography, and economic situation, established a unique set of conditions within each selected location. A meaningful appraisal of PRT could be achieved only after having gained a familiarity with the "personality" of each location and its relationship to other areas of the city. It has therefore been a goal of this study to determine the impact of a new transportation system which has been integrated into the urban complex rather than added to the existing cityscape.

It is impossible through a few sketches and photomontages to determine the architectural impact PRT would have on a metropolitan area. However, it is hoped that the essence of visual and physical change in the selected locations has been clearly represented through casebook studies, and that an increased insight and awareness of the complexity of change brought forth by the integration of PRT into an urban environment will be gained.

Since so much of our interpretation of architectural impact depends upon our visual awareness, a major portion of this study is devoted to visual impact. However, in addition to visible image, the introduction of PRT will have an effect on the movement patterns within the city. Not to be dismissed are the complex interactions of spatial organization, density, accessibility, and land use, all of which would be affected by the introduction of a new transportation technology, such as PRT. The impact of transportation on the physical structuring of the city, although complex and difficult to define, is as much a part of architectural impact as is change in visual image.

The casebook approach used in this chapter is meant to identify unique effects, whether in visual image or physical structuring, at a particular location. It is hoped that the sum effect of the individual cases will provide an overall awareness of the impact of PRT within an existing urban environment. The focus of this chapter has been directed towards interactions in the urban environment that are perceptible at the human scale - changes in existing townscape and functional arrangement which would be perceptible to people as they move about the city - either exploring new locations or following routine patterns in local areas.

The Technology

The transportation system under investigation in this chapter, referred to as PRT, includes a number of Personal Rapid Transit Systems presently under development. The concept of PRT provides small vehicles with a capacity of 2 - 6 passengers that travel on exclusive guideways which are generally elevated. Vehicles are automatically controlled through computer programming which allows nonstop routing to any destination requested by the passenger. Off line stations, short headways between vehicles, and automated control systems allow line capacities of approximately 6000 vehicles per hour. Lightweight guideways and small vehicles reduce the cost per mile of the system so that a fine network which provides accessibility to numerous points within even a low density city becomes economically feasible.

This chapter does not evaluate any particular PRT system against another, but rather the total concept of PRT is assessed as a potential solution to the growing transportation dilemma in our urban areas. The guideways, vehicles, and stations represent various hardware systems which are presently under commercial development, as well as some innovative solutions (which have been suggested by the Task Force on New Concepts in Urban Transportation under the direction of Dr. J. E. Anderson at the University of Minnesota).

Visual Image

> ...there is an art or relationship just as there is an art of architecture. Its purpose is to take all the elements that go to create the environment: buildings, trees, nature, water, traffic, advertisements and so on, and to weave them together in such a way that drama is released. For a city is a dramatic event in the environment. Look at the research that is put into making a city work: demographers, sociologists, engineers, traffic experts; all co-operating to form the myriad factors into a workable, viable and healthy organization. It is a tremendous human undertaking.
>
> An yet...if at the end of it all the city appears dull, uninteresting and soulless, then it is not fulfilling itself. It has failed. The fire has been laid but nobody has put a match to it. (Ref 3)

In his book Townscape, Gordon Cullen has identified the visual relationships, the aesthetics, and the subtle qualities which create emotional response to our environment. Since it is through our faculty of sight that we gain nearly all our comprehension and awareness of our surroundings, the visual impact of PRT within the urban environment will have a profound effect upon our response to the transportation system, and indeed to the urban environment itself.

Cullen has identified three ways in which the visual image of our environment produces emotional response: optics, place and content. Optics concerns the drama of juxtaposition the relationship established by the existing view and the emerging view. Place is the awareness of our position within the environment, the impact of exposure and enclosure. Finally, content identifies the fabric of the city: the texture, scale, style, character of each unique location.

The following casebook studies assess the visual impact of PRT through sketches which typify the urban situation prior to the introduction of PRT as well as after the integration of the system into the area. Although the immediate awareness of guideways, stations, and elevated vehicles is an obvious visual effect of PRT, there are many subtle but far-reaching visual changes which would accompany the deployment of PRT. These less obvious changes would be the result of the adjustment within the entire urban complex, the interactions among the elements of the city, to accept and adapt to the change in perhaps the most critical of all urban elements - the transportation facilities.

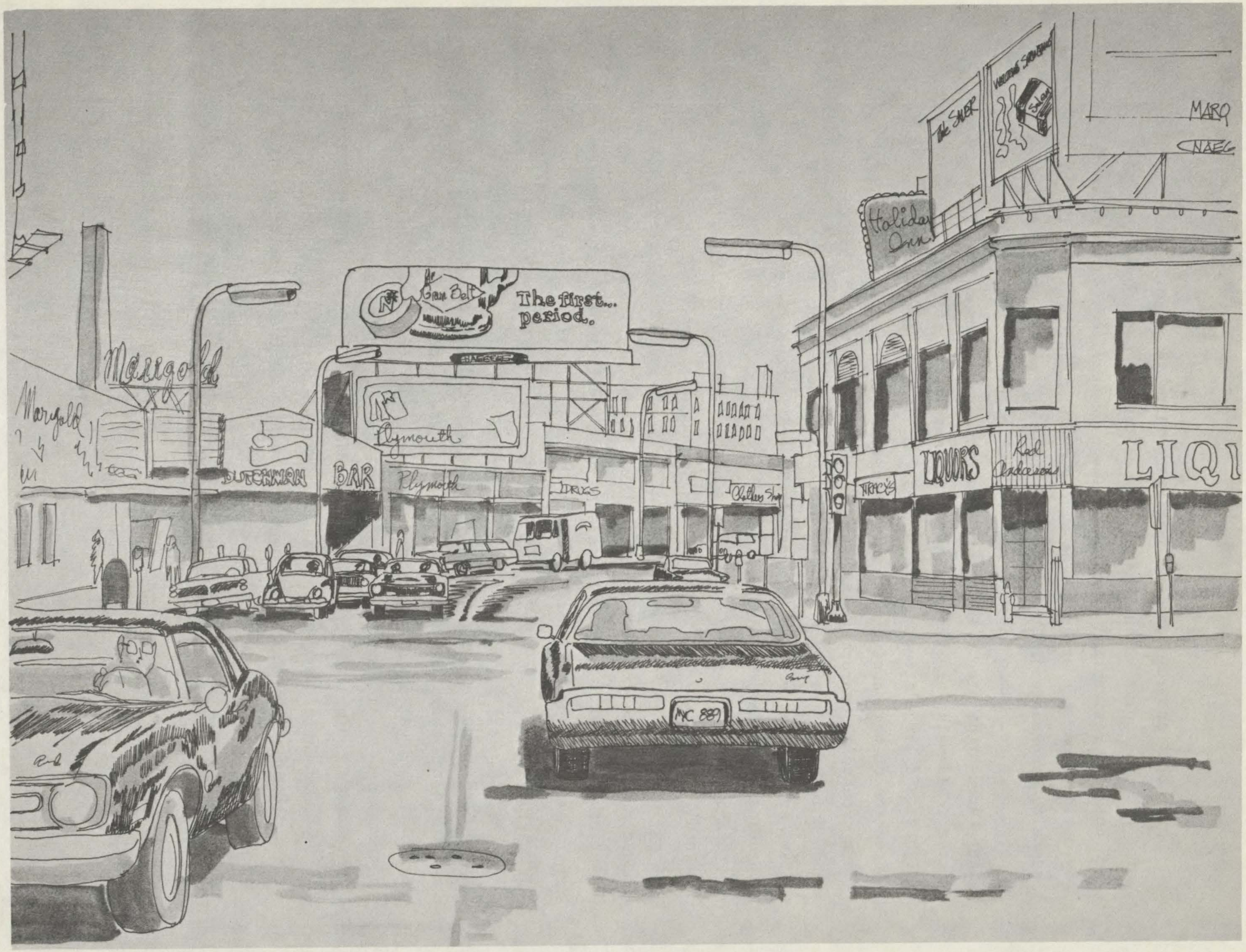
Motion and Rest

> Mobility-tranquility represents, of course, a spectrum of experiences through hierarchies of functional components. Close to the maximized tranquility option may be found those ranges of mobility which include various means of slow motion, which in turn permit leisurely unhampered observation and exploration of the small and intimate. Western man's current intoxication with motion and speed per se of course inhibits this; focus is lost and a generalized or superficial view only remains. This appetite for motion and speed is being constantly fed by technological advance, and if it is not placed in its proper context, appetite can become addiction.
>
> Under such circumstances, a priority in any urban system must be the development of environments which induce slow or non-motion facilities as well as those for travel. (Ref 5)

The dominance of mobility over tranquility is exemplified in an area of Minneapolis which lies along Nicollet Avenue between the CBD and outlying residential areas. The image of the location is dominated by motion along the street. The wide expanse of automobile-filled asphalt, accompanied by the noise and fumes of traffic, have left no opportunity for human interaction or even leisurely pedestrian movement through the area. The pedestrian risks unsafe crossing of the street; sidewalks are impeded by parking meters, traffic signs, stop lights, and large street lamp fixtures. Billboards compete for the attention of the passing motorists, and in their greed for space they have created an unproportioned skyline which dominates the buildings upon which they are perched. The pedestrian who cannot compete with heavy automobile traffic has vacated the area; shops are passed by thousands each day, but are visited by few.

The elevated PRT separates movement through the area from the tranquil activities within the area. The human scale of the buildings is restored by removing billboards and relating signs and lighting to pedestrians. The ground surface is textured to define varied uses and degrees of activity so that areas safe for pedestrian use become dominant. Although the PRT would carry the bulk of traffic through the area, the street could remain available for service, delivery, and local traffic. By providing safe and comfortable areas free from fumes, noise, and danger of vehicular traffic, the residents could more easily relate to the character of the shops and establishments of this neighborhood. Sidewalks with plantings, benches, and areas for leisure activity provide an incentive for pedestrian activity with perhaps increased shopping and other social interaction.

The overhead guideway and passing vehicles provide accessibility without dominating the entire image and functional use of the area. A balance and complementary mix of motion and rest can be achieved by replacing automobile traffic with PRT in this location. The image changes from one of dominant motion, congestion, and impersonality to one receptive to human participation with a range of motion and tranquility as options.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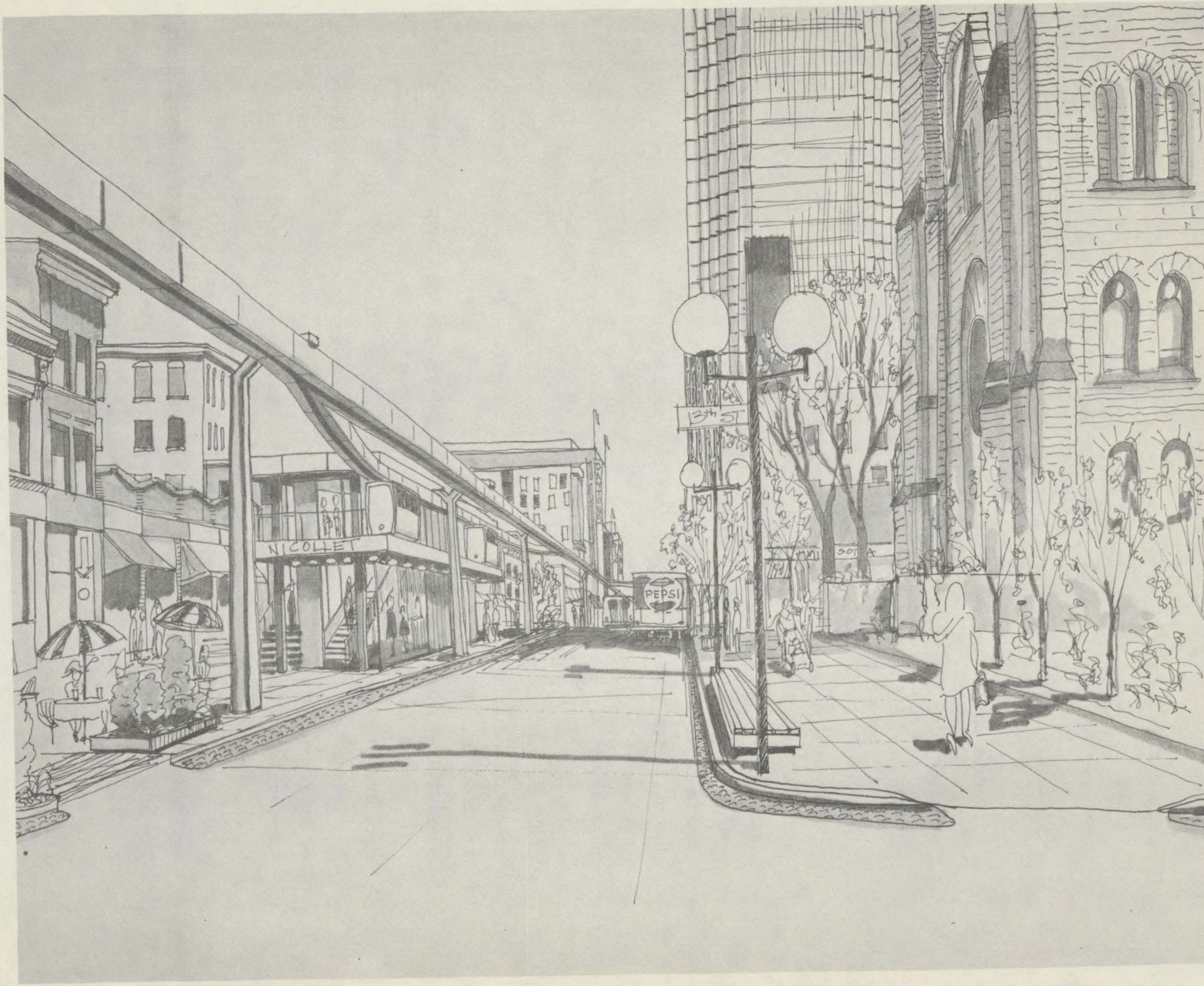

NICOLLET
PEPSI

Sense of Place

> A city is a multi-purpose, shifting organization, a tent for many functions, raised by many hands and with relative speed. Complete specialization, final meshing, is improbable and undesirable. The form must be noncommittal, plastic to the purposes and perceptions of its citizens.
>
> Yet there are fundamental functions of which the city forms may be expressive: circulation, major land uses, key focal points. The common hopes and pleasures, the sense of community may be made flesh. Above all, if the environment is visibly organized and sharply identified, then the citizen can inform it with his own meanings and connection. Then it will become a true place, remarkable and unmistakable. (Ref 6)

An area along Nicollet Avenue approaching the CBD just west of the Nicollet Mall has become fragmented in scale and activity to the point that it has lost a sense of place. There is a confrontation in scale, with the cathedral and the immense IDS building on the right having little relationship to the small commercial buildings on the left. Any intimacy offered by the shop fronts is overpowered by the noise and confusion of passing traffic. There is little relationship to be noticed between the street, the grandiose buildings, and the small shops, for each seems to have little regard for the other.

Although the church certainly must be a destination for some, the general character of the area is one of transition and movement to the Nicollet Mall which lies ahead, with the few pedestrians in the area showing no evidence of interest or intrigue in the immediate vicinity.

The integration of human scale areas, buildings, and facilities with the grand scale of immense buildings offers the opportunity for an exciting urban scene. The PRT provides the catalyst for the integration of scales. The station relates well to the small commercial building; the pedestrian areas beneath the guideway flow into the shop fronts which gain a new importance along this area of pedestrian proprietorship. At the same time, the guideway has a dynamic quality which contrasts horizontally to the strong vertical axis of the IDS tower. The scale of the cathedral becomes more apparent when placed in juxtaposition to the human activities which front it.

With the bulk of through traffic elevated on the guideway, one finds that the station, church, shops, and the pedestrian areas which relate to them create a "sense of place" which has a unique and exciting quality. Certainly the area need not serve only as a transition zone for better things to come on the Nicollet Mall. PRT, by reducing congesting traffic, providing access, offering ground area for pedestrian use, and helping to integrate the scale of the elements of the vicinity has aided in creating an improved urban environment - one which has a unique quality - a sense of place.

Here and There

> ...to postulate an environment which is articulated; as opposed to one which is simply a part of the earth's surface, over which ant-like people and vehicles are forever swarming, over which buildings are plonked at random. Consequently, instead of a shapeless environment based on the principle of flow, we have an articulated environment resulting from the breaking up of flow into action and rest, into corridor street and market place, alley and square (and all their minor devolutions). The practical result of so articulating the town into identifiable parts is that no sooner do we create a Here than we have to admit a There, and it is precisely in the manipulation of these two spatial concepts that a large part of urban drama arises. (Ref 7)

The intersection of Lowry Avenue and Marshall Street in northeast Minneapolis is composed of two popular restaurants amid smaller commercial firms, private residences, and apartment buildings. The general area, which lies on the east bank of the Mississippi River, is predominantly industrial in character stemming from its early history as the site of saw mills and lumber yards. The intersection gains added importance since Lowry provides access to the west side of the river, and Marshall leads to the Minneapolis CBD.

The concept of "here and there" is exemplified in this location. As previously identified, the area has an importance in the activity and flow patterns of the city. However, at present, the force of movement through the area dominates to the extent that the immediate location lacks any real focus. The PRT station identifies this critical spot in the urban pattern and the related facilities, sidewalks, and plaza provide a breaking up of flow, both pedestrian and vehicular, into movement and rest. The station becomes the central transition from the motion along the route to the static facilities which surround it.


LIQUOR
STORE


LIQUOR
STORE
LOWRY

The station and guideway also indicate accessibility from the immediate location to all other areas of the city. By reinforcing the concept that we are "here", at Marshall and Lowry, the immediate location takes on a new importance but we also increase the significance of "there". In this instance, the IDS building punctuates the CBD and identifies a location which is unique and different, yet accessible from the immediate location to which we are presently identifying and relating. We are in a particular location, we see the landmark of another location, and clearly available to us is the means of getting from the one location to the other.

Outdoor Room

> If the outdoors is to be colonized, architecture is not enough. The outdoors is not just a display of individual works of architecture like pictures in a gallery, it is an environment for the complete human being, who can claim it either statically or in movement. He demands more than a picture gallery, he demands the drama that can be released all around him from floor, sky, buildings, trees, and levels by the art of arrangement. (Ref 8)

Marshall Street in northeast Minneapolis at the location of the Grain Belt Breweries provides a study of outdoor space.

Marshall Street is an important north-south artery in an industrial area of northeast Minneapolis along the Mississippi River. At the intersection of Broadway, the Grain Belt Breweries and the Northeast State Bank have landscaped their sites to provide a pleasant garden and park atmosphere in contrast to the typically unsightly industrial plots along Marshall. Although truck and auto traffic is heavy along both Marshall and Broadway, the Grain Belt Gardens are a popular and relaxing attraction for visitors and touring groups. Although the area is an intersection of two major movement paths, there is a feeling of "place" which survives amid the ceaseless motion of the adjacent streets.

The introduction of a PRT interchange adds a complexity to the intersection which is accepted by the openness of the corner and even adds a sense of excitement which complements the "outdoor fair" characteristics of the Grain Belt Gardens. The curving guideway visually encloses a space around the garden pavillion which enhances its importance and increases its influence on the intersection. Thos passing overhead


GRAIN BELT BREWERIES INC.


GRAIN BELT BREWERIES INC.

can enjoy the garden from above while they are in transit. In contrast, those below enjoy the restful qualities of the static space enclosed by motion.

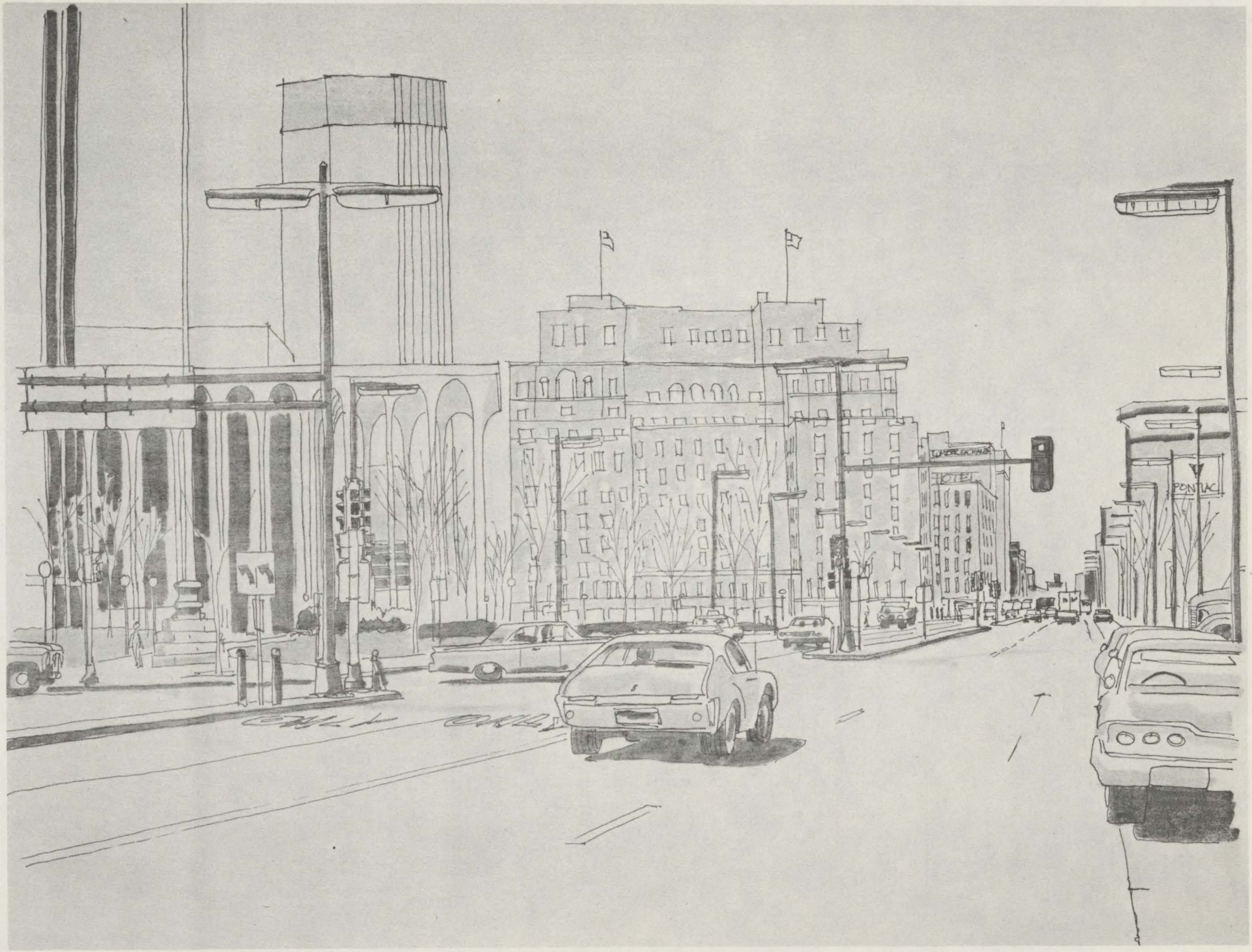
The PRT system could reduce the traffic load on Marshall, especially if goods were also moved along the guideway. As a result, the street could become part of a one-way pair system, the street width could be reduced, and more land could be released for non-transportation uses.

Legibility

> It must be granted that there is some value in mystification, labyrinth, or surprise in the environment. Many of us enjoy the House of Mirrors, and there is a certain charm in the crooked streets of Boston. This is so, however, only under two conditions. First there must be no danger of losing basic form or orientation, of never coming out. The suprise must occur in an overall framework; the confusions must be small regions in a visible whole. Furthermore, the labyrinth or mystery must in itself have some form that can be explored and in time be apprehended. Complete chaos without hint of connection is never pleasurable. (Ref 9)

The "Gateway" area of Minneapolis along Hennepin Avenue provides an opportunity to sense arrival to the CBD after crossing the Mississippi River from the east. Hennepin Avenue is presently a wide automobile street which eventually leads into the entertainment district and is paralleled by streets of commerce, government, and finance. Landscaping and greenspace around new building in the immediate area provide contrast to the glass and concrete of the CBD, but continuity is lacking between the CBD, the gateway, and the river.

The legibility of the Gateway as an arrival to the CBD is reinforced by the introduction of PRT into the area. The guideway establishes a strong edge to a linear park which links the river to the CBD through the Gateway district. By reducing the need for a wide automobile street, land is made available for the linear park between the potential riverfront activities and the CBD and entertainment districts. The edges of each district can be reinforced by the guideway and greenspace, activity modes within each district can be linked by PRT, and areas of intrigue and pedestrian interest can develop within the general orientation framework established by the PRT. The relationship between each district

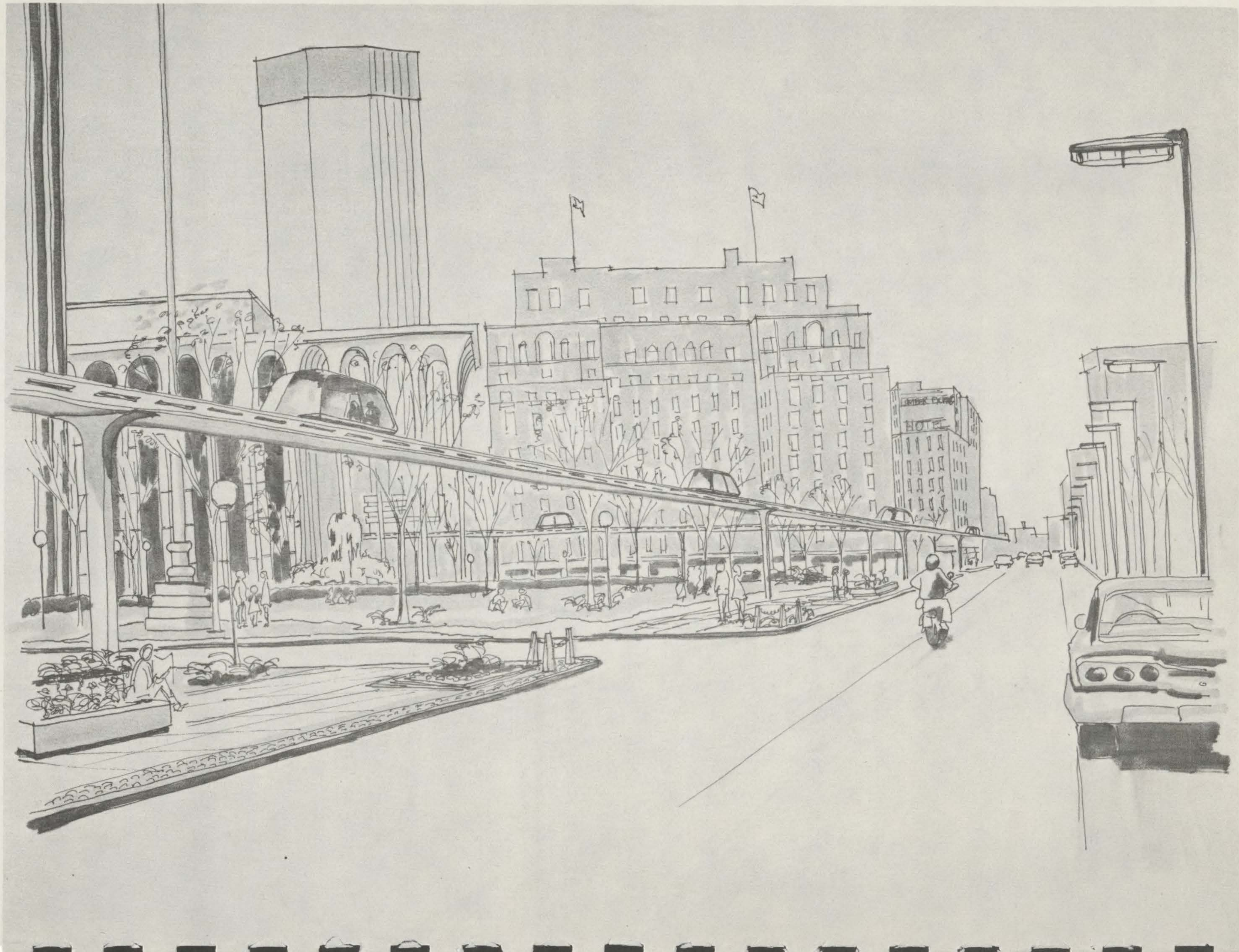

HOTEL
PONTIAC

could have a stronger clarity and the pattern of the urban environment could become more legible through changes catalyzed by PRT.

Physical Structuring

> It has been recognized for many years now, even by the most rigid planners, that a 'master plan' like Utopia, an ideal completed form, can no longer serve the purposes of design in which change and growth may be the essential determinants of order. Forms in their great diversity must become apparent and significant; no single 'master form' can do this.
>
> Urban design cannot be form alone. Purposeful social commitment must precede all action in the design process without concern for the techniques or shapes through which the commitment may finally be translated into physical reality. Although our present concern is for the existence in any urban system of places which may generate concourse and intercourse as a structuring device, before we start this analysis we have to clarify our humanistic commitment. (Ref 10)

Movement arteries within the city provide a means of ordering and relating activities and people. The physical structuring of cities in terms of space, time, and form has been influenced by increased accessibility and improved communications which have accompanied advancements in transportation technology. Linear development along streetcar radials, immense tracts of grid-pattern streets, and dispersed centers within suburban sprawl have formed the American city. Overlapping urban systems have often been incompatible, and the sudden and unpredicted changes in urban development have left our cities in economic and humanistic shambles. Central city cores, often with narrow streets and intense land use which developed during the streetcar era, have become inaccessible due to the congestion of increased populations jamming radial arteries with automobiles of a new transportation era. The automobile system which enhanced suburban sprawl has required wide rights of way and excessive land for parking. The result has been drastic changes in urban land use within previously developed portions of the city. Neighborhood and social disruption have often been the extreme costs of improved transportation. Clarity and legibility in the movement paths of our cities have been lost in the transformation from one technology to another.


HOTEL

Recent experiences in transportation systems have indicated that technological innovations can be beneficial to the urban environment only if the change is integrated into the entire urban system. The complex interactions between elements of the city disallow the restructuring of any single element without effecting change in other facets of the urban ecology.

It becomes imperative that the impact of PRT in terms of structuring of all urban elements such as Lynch's paths, edges, districts, nodes, and landmarks be understood prior to the deployment of the new transportation technology. Only through deep analysis of the urban complex and a subsequent design of its interrelated elements in terms of an overall system, can the physical structuring of the urban environment approach the optimum conditions to satisfy human needs and expectations. PRT provides a promising technological innovation to improve movement within the city - the impact can, however, be far more effective and beneficial if PRT is viewed as a single entity within a very complex and interrelated system.

PRT as a technological advancement of the movement system provides a potential tool by which the city can be organized and related - a possible means by which purposeful social commitment can be translated into physical reality. However, the potential impact of PRT, as any other technological innovation, can be fully realized only if it is understood in context within the entire urban system and not viewed only as a technological breakthrough in itself.

Spatial Organization

The spatial organization of cities is dependent upon many factors such as density, activity, and certainly accessibility. Whether this spatial organization is compatible with human and social need is often overlooked. Linear commercial strip development may well suit the automobile technology, but it lessens the possibility of face to face human interaction at the pedestrian scale. Grid patterns of urban development may provide a means of ordering rapid growth and allowing efficient installation of utility systems, but unique landscape characteristics, existing vistas, and natural movement corridors may be sacrificed in the process. Any solution to the optimization of spatial organization must be based upon an initial statement of social and human goals. Only then can technology be used to physically synthesize a responsive urban environment.

A great potential of cities lies in the opportunity for human interaction, planned and unplanned through face to face interaction or efficient remote communications systems. As improved mobility is provided, places must also be provided for leisurely human interactions.

Hennepin Avenue in southwest Minneapolis is a mixed use area of commercial, residential, and professional activity. The wide avenue is an important artery from the CBD to the Lake of the Isles and Lake Calhoun residential areas. Residences along the avenue consist primarily of apartment buildings, while residences along adjacent streets are often large single family houses. In the vicinity shown, the green-space on the left of the avenue provides a contrast to the busy street, but the area still lacks any sense of closure; there is no visually digestible and coherent locale along the avenue as it progresses through the city. Little feeling of anticipation or a sense of irregularity in the route which would provide an identification or uniqueness to the locale is experienced along the route.

The PRT station which is located on the corner of a plaza provides a focus to the vicinity while it serves as a transition point from the dynamic PRT guideway to the static open space. This point of interest, the station, reduces the sense of motion along the PRT line and provides visual opportunity for subdivision of the route and the establishment of a unique place along the "pathway". The pedestrian walkways and rest areas beneath the guideway, coupled with the reduction of the roadway width, tend to reinforce the influence of the open space. The station, adjacent open space, and surrounding buildings create a closure which is human in scale and which articulates the flow along the PRT route into motion and rest. The closure becomes a node for those travelling the route, as well as a focal point for the residents of the immediate vicinity. Activity is clustered about the closure within a pedestrian scale, and access from this cluster to other districts of the city is available at the PRT station.

Accessibility (Nicollet Mall)

One of the most obvious impacts of PRT is the increased accessibility that would result within presently congested urban areas. An efficient means of transportation would become available to members of society who don't drive automobiles--the young, elderly, handicapped, and poor. Non-stop travel on separate guideways would reduce travel time presently spent on crowded roadways. The narrow right of way could penetrate isolated locations, bringing a new accessibility to all parts of the city.

There may be situations, however, where the introduction of motion and immediate accessibility to other parts of the city may diminish the intrigue, explorability, or quaintness of an established locale. There may be areas of the city which should be left to pedestrian or local vehicle traffic only, isolated to some degree from the outside urban activity. In these cases, PRT could provide accessibility to the general areas, while not penetrating or traversing the area of unique character.

The Nicollet Mall, which has been devoted to pedestrian shopping, excludes all automobile traffic, and is presently serviced by mini-buses which follow a curving street through the center of the mall. The area is free of the congestion and other typical problems of an automobile-serviced street in a CBD. The character of the area promotes a leisurely shopping activity and, in addition, provides relief from the fast pace of the other Minneapolis CBD streets. Through seasonal exhibits and outdoor displays, the mall often becomes a concourse of pedestrian activity and social interaction.

The PRT guideway and vehicles passing overhead bring a movement and a symbol of motion into the mall which, without the PRT, has a leisurely character. The mall is presently a place to be experienced in itself - the introduction of the PRT may tend to make the mall another area to be passed through. The impact of the mini-buses seems less suggestive of a connecting link to other parts of the city and allows the mall an independent character. An important cost of PRT along the Nicollet Mall may be the loss of this leisurely atmosphere which presently can be perceived by the pedestrian as a static relief free from the dynamic


PARK
LADIES APPAREL

transportation links which dominate the rest of the CBD. In the case of the Nicollet Mall, PRT may best serve the area by providing accessibility to convenient points on cross streets or at the ends of the mall. The mall itself could then be devoted to pedestrian activity and the immediate area would provide a shoppers bazaar of explorability and leisurely human interaction.

Reclaimed Space (The Mall)

There are many areas within the city which have been by-passed, vacated, or overlooked. These areas are often unkempt eyesores with an image of blight and decay which degrade adjacent facilities. These unused spaces within the city provide opportunities for parks, greenspace, nature areas, and other recreation facilities which can humanize the surrounding urban environment and provide areas for social interaction and neighborhood gatherings.

Just east of Lake Calhoun and Lake of the Isles in southwest Minneapolis is an area called "the Mall". To the right are walkup apartments facing onto a "mall" which is composed of a pedestrian walkway following a greenspace bordered on each side by roadways. Service and access to the apartments is by auto, although there is some use of the walkway by pedestrians to and from the lakes to the west and Hennepin Avenue to the east. Just to the left of the mall are railroad tracks which act as a barrier to any movement or activity in that direction. The mall itself has little activity and seems at best to be a movement zone from Hennepin Avenue to the lakes. Due to potential high-speed movement along the rail right of way as well as the roadways, the greenspace is less than ideal as a play area for children or leisurely walk area for adults.

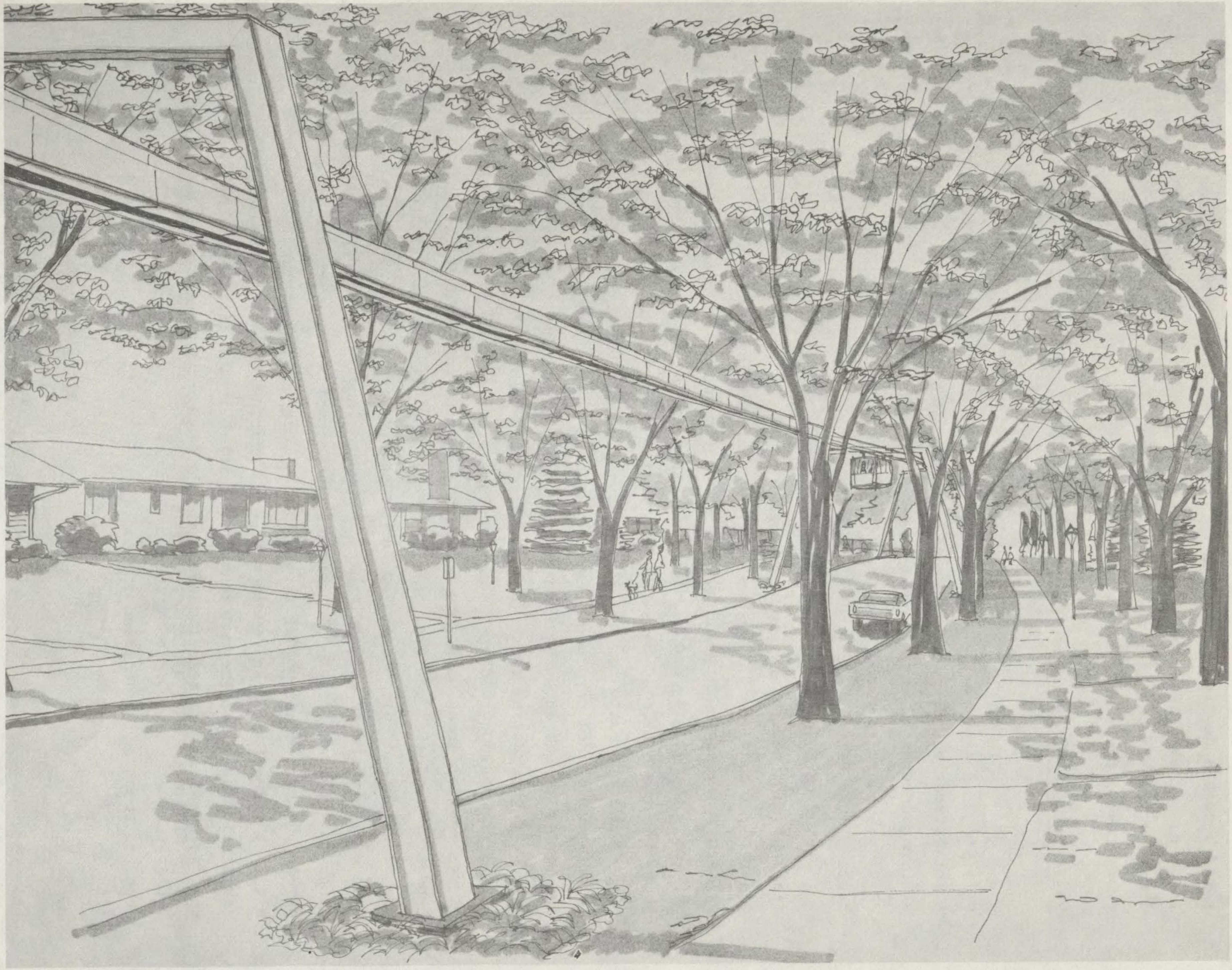
"The Mall" represents an area ideally suited for a PRT system. By providing service access from lateral streets, the roadways could be eliminated and the PRT could reinforce the barrier edge along the railroad. Plantings and fencing could then be used to define a safe greenspace in front of the apartments, thereby reclaiming a lineal park connecting Hennepin Avenue and the recreation lakes. The park could be upgraded with tot lots and recreational equipment, and the adjacent area

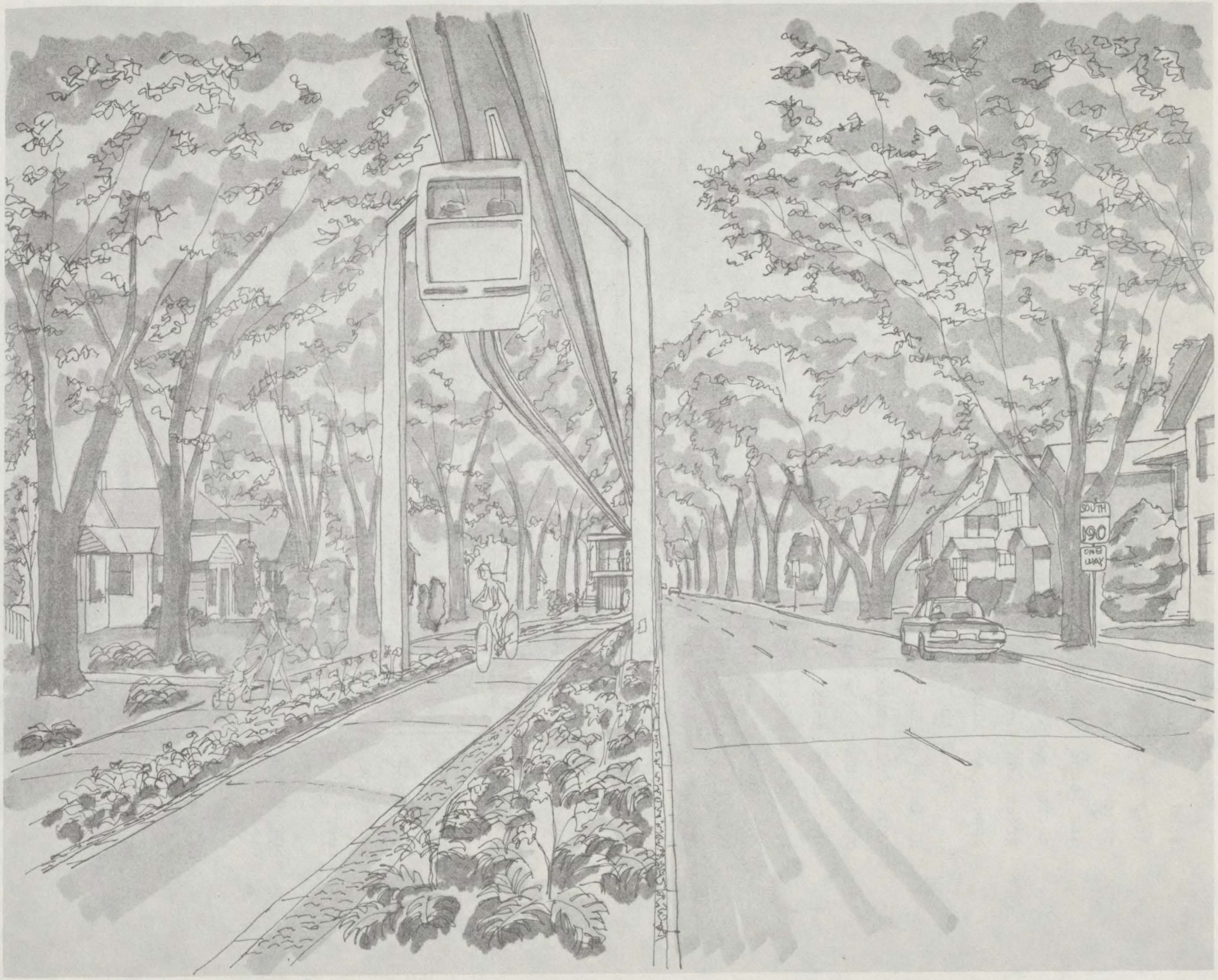
could become a desirable location for family residents. The PRT would provide all residents with convenient access to the CBD as well as other locations within the city from a station interchange within close proximity to their housing.

Residential Consideration

The impact of a PRT system in residential areas is extremely critical. It is here that the system encounters a variety of building types, street configurations, and landscapes, but more important, it also encounters the various social groups and their numerous life styles which make up a city and whose residences and activities lie along the route of the PRT system.

Prior to determining the required spacing and locations for stations and interchanges in residential areas, it is essential to consider the impact the PRT system will have in changing residential patterns. Accessibility and availability of transportation may help to integrate the elderly and handicapped into residential areas. The young and the poor will have the opportunity to pursue activities and work in distant parts of the city. Reduced congestion and the transformation of black top to greenspace may tend to lure residents back into the city and curb the thrust of suburban expansion. Certainly the areas along potential routes should be considered for changes, such as linear parks along guideways which replace streets, increased densities of residential areas with good accessibility, and clusters of neighborhood stores, social centers, and recreation activities near stations. The gridiron and cul-de-sac plans of present residential sectors may give way to patterns more suitable to new and innovative transportative concepts. Certainly, the residential systems which grew with the streetcar and later the automobile should not be accepted blindly as the ultimate forms for urban development. However, within established residential sectors, one can study the initial impact of integrating a PRT system with the present residential development. Immediately identifiable are the factors of visual impact, safety, and interface of other movement and pedestrian systems.

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190
ONE WAY

In typical residential areas of Minneapolis, there are single family residences on narrow frontages lining both sides of the street. In some instances, houses have given way to 3- or 4-story walkup apartment buildings, and periodically churches, schools, and other institutions are found along the residential street. Side yards are extremely narrow, back yards adjoin alley ways, and front yards are set back of grass and large elm or ash trees. Sidewalks parallel the streets which appear as tunnels beneath the foliage of overhanging tree limbs.

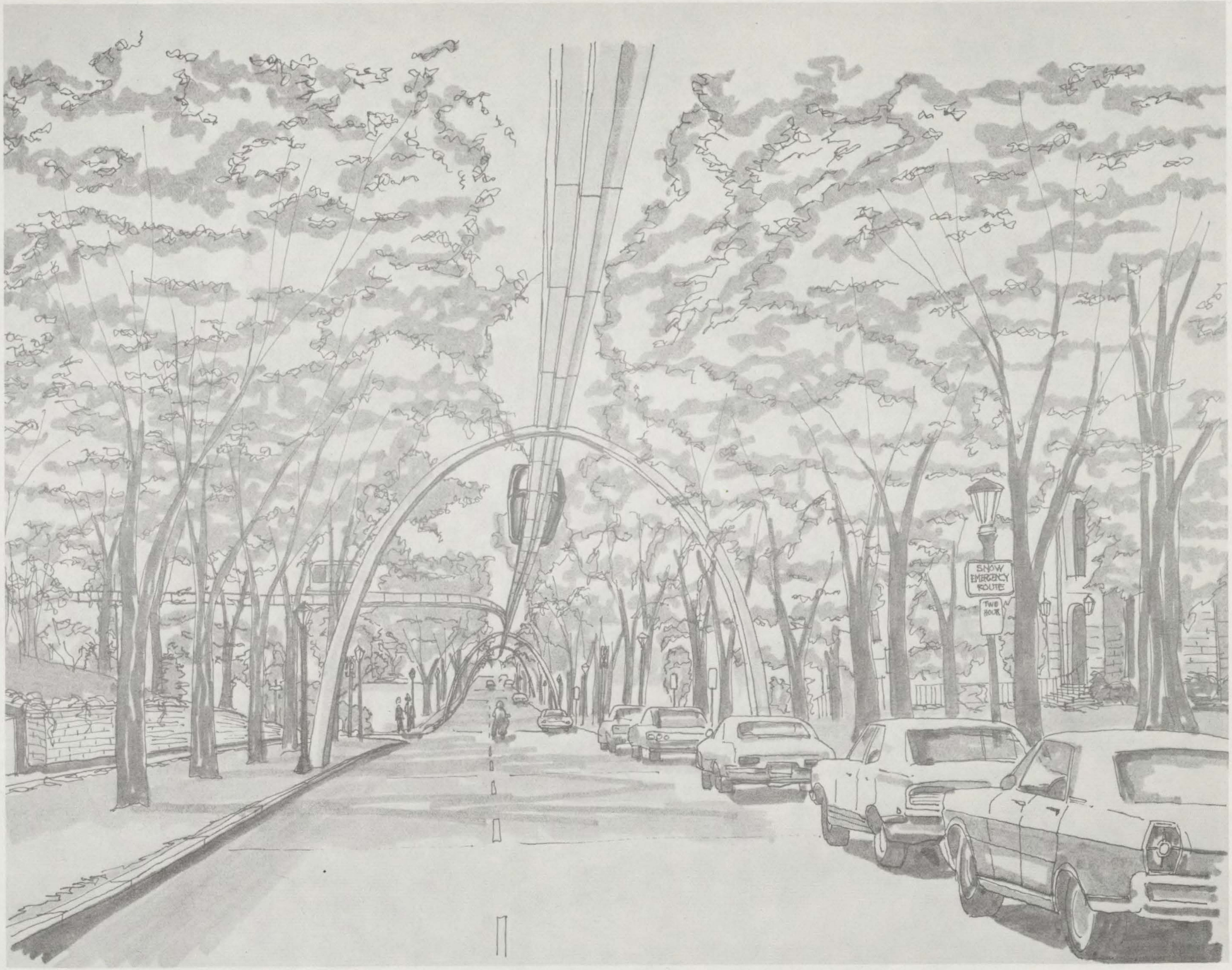
Since the typical column and guideway would either require removal of large numbers of mature trees or would penetrate the privacy of individual yards, alternatives using arches and frames have been developed. Since the scale of the arches and frames can be reduced from that of a cantilevered column, they also relate more favorably to the residential scale.

Another alternative suited for residential areas is to cut a half-level grade for the PRT guideway rather than to use an elevated system. This proposal has inherent safety problems, and would require extensive fencing and other controls to insure that children, animals, and potentially dangerous objects were kept off the guideway. This approach would preserve the skyline which may at times be an influencing factor, but conversely would absorb potential greenspace and would require periodic bridging for pedestrians and vehicles.

Overhead guideways supported by lightweight arches or frames provide a flexibility which would be extremely beneficial in a residential area. Stations of an adaptable modular composition which could be expanded or contracted as demand required coupled with a lightweight guideway would provide a flexible system which could respond to the needs of residential areas as changes occur.

Summary

The architectural impact of PRT, if combined with coordinated design efforts of all urban elements, may result in vast improvements in the image and physical structuring of the city. However, no single aspect of urban technology can be expected to improve the urban environment if installed as mere substitute for an obsolete system.


SNOW
EMERGENCY
ROUTE

The casebook studies presented have been meant to initiate an awareness of a limited number of visual and physical impacts which may accompany PRT. The actual architectural impact of an entire PRT network within a metropolitan area would require intensive study of each sector of the city with respect to human, social, and comprehensive planning goals.

PRT has the capability of providing convenient transportation for all members of society. The lack of age or monetary discrimination alone would initiate changes in the mobility, life styles, and physical needs of many people which in turn would have an impact on the interactions of people and their urban setting.

The capacity of narrow right-of-way PRT guideways would have the potential impact of replacing vast areas of paved roads and parking lots with other urban activities - housing, open space, and many other uses. This change in land use, as well as the reduction of pollution, noise, and danger from automobiles could produce a humanizing influence on the city. The impact of such a change could include the return of residents to the presently blighted and forsaken portions of the city and thereby reduce the rapid consumption of land through suburban sprawl.

In contrast to quantitative studies of mechanical and economic feasibility of PRT, the casebook studies presented here have been extremely subjective and qualitative in nature. The visual image studies have identified some of the perceptual impacts PRT would have on people within existing urban settings. The impact of motion and rest, of distance and time, of space and closure, all create a response to an urban setting.

Success of the townscape in satisfying the expectations of people may well rest in the legibility and clarity with which the urban elements are related. PRT, while providing accessibility, can also provide an ordering and legible relationship to the functional districts of the city.

Change, growth, and adaptability are essential to the modern city and its changing social and human needs. PRT should not be looked upon as the sole salvation to present urban problems. However, as an adaptable and flexible transportation system, PRT can have a beneficial impact on the humanization of the urban environment.

References

(1) Kevin Lunch, The Image of the City, p. 47.

(2) Wallace Russell, "Architectural and Environmental Studies of an Automated Public Transport System in an Urban Context".

(3) Gordon Cullen, The Concise Townscape, p. 7.

(4) Ibid, p. 9-11.

(5) Chermayeff, Serge and Aberander Tyonis, Shape of Community, p. 78-79.

(6) Lynch, op. cit., p. 92.

(7) Cullen, op. cit., p. 182.

(8) Cullen, op. cit., p. 28.

(9) Lynch, op. cit., p. 6.

(10) Chermayeff, op. cit., p. 14-15.

Chapter 5

Preliminary Analysis of PRT Systems

The purpose of this chapter is to develop formulas which aid in preliminary estimation of certain PRT system parameters. This kind of analysis is important because it enables the planner to make rough calculations by hand without the aid of a computer, gives a means of checking the reasonableness of computer results, and gives greater understanding of the theory of PRT systems. This chapter is in part an extension and refinement of the work of Reference 1.

The Flow in a PRT Network

A real city has many variations in density, points of concentrated attraction, and nonuniformity in the general directions of travel. We therefore begin the analysis with the assumption of nonuniformity and then let the theory show how uniformity can be introduced for simplicity in preliminary analysis.

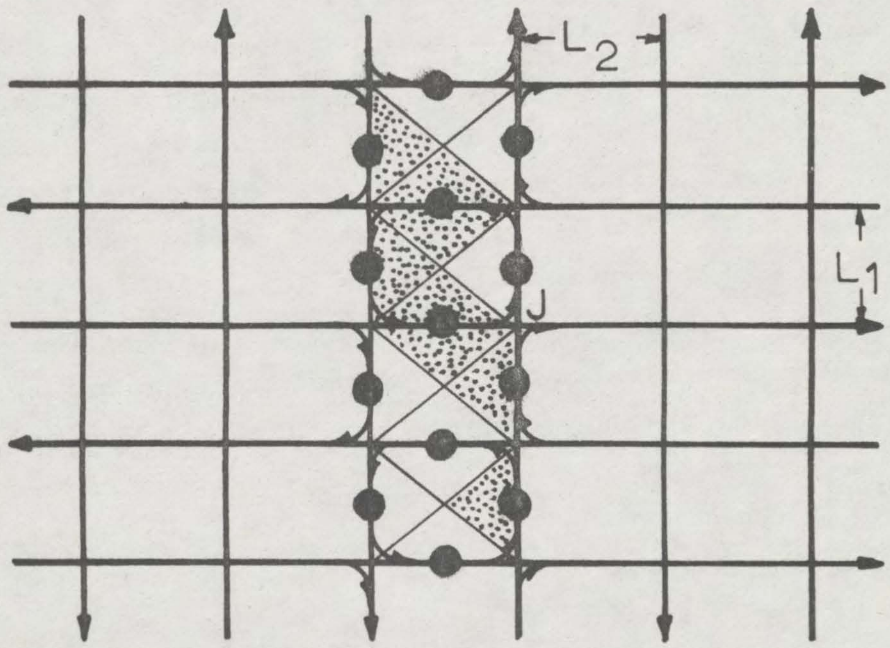


Figure 1. An Interconnected Network of One-Way Transit Lines

Consider a network of guideways as shown in Figure 1. Stations are assumed to lie approximately at the midpoint between intersections of lines. The flow of vehicles along each guideway is assumed to be unidirectional in the direction of the arrows.

This configuration is of interest as compared to a configuration of bidirectional lines in which each pair of lines is side by side for the following reasons: 1) The interchanges are much simpler; 2) The area placed within walking distance of stations for a given number of miles of line is doubled; and 3) If the lines are elevated, the visual impact is cut in half. These advantages are obtained at the expense of a somewhat longer trip time, calculated in this chapter. An alternate bidirectional configuration is under development by the MBB-Demag team in West Germany. In this configuration one set of vehicles suspended below the guideway goes in one direction and another set supported on top of the guideway go in the opposite direction. This system is a superposition of two unidirectional networks and doubles capacity. Computation of flow in the bidirectional systems is a trivial extension of the theory presented.

Referring to Figure 1, we concentrate on the people between the middle pair of vertical lines who wish to travel to the right. Each dot represents a station on a given segment of the line. The fine diagonal lines separate the zones of attraction of the several stations if the grid is square. As shown in Figure 2, the boundaries of these zones are more complex if $L_1 \neq L_2$. All that is of interest here, however, is the fact that there is a defined zone of attraction for each station.

If we assume the vehicles are programmed to take the shortest path, the people who wish to travel to the right from within the middle pair of vertical lines and who are transported to the right on the <u>center</u> horizontal line come from the dotted regions. Let the portions of the zones of attraction to each of the stations which are bounded by the guideways be numbered as subzones. Then let the number of people within subzone i be denoted by P_i. Next let the fraction of these people who travel during the most heavily traveled hour be f_i. Finally, let the fraction that pass point J be denoted by r_i. Then the number of people from the eight dotted subzones who travel to the right during the peak hour on the center guideway is $\sum_1^8 r_i f_i P_i$. If the average population density in each subzone is p_i, this expression can be written $\frac{1}{4}L_1L_2\sum_1^8 r_i f_i p_i$. If f, p are the average values of these quantities over the eight subzones, this expression becomes $\frac{1}{4}L_1L_2 fp\sum_1^8 r_i$.

In a uniform city, in which the trip distribution is isotropic, one fourth of the people in each subzone travel in each of the four directions. The fraction passing point J, i.e., the value of r_i is one fourth for the upper four zones of Figure 1. However, for the lower four zones trips headed both to the right and down pass point J. Therefore, for these subzones $r_i = 1/2$. For a uniform city with isotropic flow we therefore have $\sum_1^8 \bar{r}_i = 4(\frac{1}{4}) + 4(\frac{1}{2}) = 3$ and the contribution to the total flow past point J of trips from between the two center vertical lines is $\frac{3}{4}L_1L_2 fp$.

The total flow past point J is the sum of similar expressions for all pairs of vertical lines to the left of point J. With nonuniform conditions, the total flow is therefore

$$\text{Line Flow} = F_L(J) = \sum_{i=1}^{8}\sum_{j=1}^{J-1} r_{ij,J-j} f_{ij} P_{ij} \qquad (1)$$

in which the same notation is extended to two dimensions. The index i is summed over the indicated eight subzones within the j-th region defined by a pair of vertical lines. The index j is summed over all regions to the left of region J. The meaning of the symbol r is now extended to r_{ijk} to indicate the fraction of the trips from subzone ij which travel at least k regions to the right.

Equation (1) is the most general form of the flow equation, and applies to nonuniform as well as uniform mesh spacings. If the mesh spacing is uniform, as indicated in Figure 1, and if p_{ij} is the population density in subzone ij, equation (1) becomes

$$F_L(J) = (L_1L_2/4)\sum_{i=1}^{8}\sum_{j=1}^{J-1} r_{ij,J-j} f_{ij} p_{ij} \qquad (2)$$

If variations between the eight subzones between each pair of vertical lines in Figure 1 is small, let the symbols in (2) with the index i dropped indicate average values. Then (2) becomes

$$F_L(J) \quad = \quad 2L_1 L_2 \sum_{j=1}^{J-1} r_{j,J-j} f_j p_j \tag{3}$$

Next assume that f_j and p_j are approximately uniform in the j direction and can be replaced by their averages f and p. Then (3) becomes

$$F_L(J) \quad = \quad 2L_1 L_2 fp \sum_{j=1}^{J-1} r_{j,J-j} \tag{4}$$

Finally assume trip demands are split equally between the four directions. The symbol r_{j1} represents the fraction of trips from the (J-1)th region which pass point J. As indicated above, this fraction includes the quarter of the total number of trips which are headed toward the right plus the trips from the lower four subzones which are headed south, since these trips pass point J going east and then head south at the next interchange. Thus, under uniform conditions, $r_{j1} = \frac{1}{8}\left(\frac{1}{4}\cdot 4 + \frac{1}{2}\cdot 4\right) = 3/8$. For $k > 1$, $r_{jk} = \frac{1}{4}\beta_{jk}$, in which $\beta_{jk} \leq 1$ is the fraction of trips from region j which travel k or more mesh spacings to the right. If the average length of the trips in the easterly direction is nL_2, $\beta_{jk} = 1$ for $k \leq n$ and $\beta_{jk} = 0$ for $k > n$. Then the summation in (4) becomes $3/8 + \sum_{j=1}^{n-1} \frac{1}{4} = \frac{1}{4}\left(\frac{1}{2} + n\right)$. Thus, if we let the average trip length be $\iota = nL_2$, (4) becomes

$$F_L(J) = F_L = \frac{1}{2} f \rho L_1 (\iota + L_2/2) \tag{5}$$

But, ι is not the total trip length, it is only the portion of the trip length in the easterly direction. If destinations are uniformly distributed, the total trip length ι_T is 2ι. Thus, equation (5) becomes

$$F_L \quad = \quad \frac{1}{4} f \rho L_1 \iota_T (1 + L_2/\iota_T) \tag{6}$$

Usually $L_2 < \iota_T$. Therefore we can often use the approximate equation

$$F_L \quad = \quad \frac{1}{4} f \rho L_1 \iota_T \tag{7}$$

The station flow F_s can be derived from similar considerations. If ρ_m is the average population density within the zone of influence of station m and the total zone of influence has area A_m, the station flow is simply

$$F_s = \rho_m A_m f \tag{8}$$

With the uniform grid of Figure 1, $A_m = L_1 L_2/2$. Then

$$F_s = \frac{1}{2} f \rho L_1 L_2 \tag{9}$$

Consider an example. During a two-hour morning rush period, typically one third of the people travel. Thus $f = \frac{1}{6}$ x fraction of trips attracted to network (modal split). Assuming a 50% modal split, f = 1/12. Suppose L_I in Figure 1 is one mile. Then

$$F_L = \frac{1}{36}\rho \iota_T, \qquad F_s = \frac{1}{24}\rho L_2 \tag{10}$$

Assume a population density of 10,000 people per square mile. Then

$$F_L = 278\iota_T, \qquad F_s = 418L_2 \tag{11}$$

If, for example, $\iota_T = 10$ mi and $L_2 = 1$ mi, $F_L = 2780$ people/hr and $F_s = 418$ people/hr. Nonuniformities will of course increase the maximum flows considerably but equations (7) and (9) show how to vary the line spacing to accomodate them when the maximum permissible flow is given.

If the lines shown in Figure 1 are bidirectional, the capacity is doubled and the flow on any particular line is one half the values given above.

Network Parameters

In this section we relate physical parameters of the network of guideways.

For the configuration of Figure 1, the length of lines per unit area is

$$\frac{\text{Length of lines}}{\text{Area}} = \lambda = \frac{L_1 + L_2}{L_1 L_2} \qquad (12)$$

In the case $L_1 = L_2$, (12) reduces to $2/L$. As an example, if $L_1 = 1$ mi, $L_2 = 1/2$ mi and the area covered by these lines is 100 sq mi, the total line length is 300 mi. Even though no area would be uniformly covered with lines, (12) is useful in making rough approximations.

For the configuration of Figure 1, the number of stations per unit area is

$$\frac{\text{No. of stations}}{\text{Area}} = s = \frac{2}{L_1 L_2} \qquad (13)$$

In the above example the number of stations would be 400.

The next parameter is the average walk distance to a station. Consider the rectangular configuration of guideways in Figure 2.

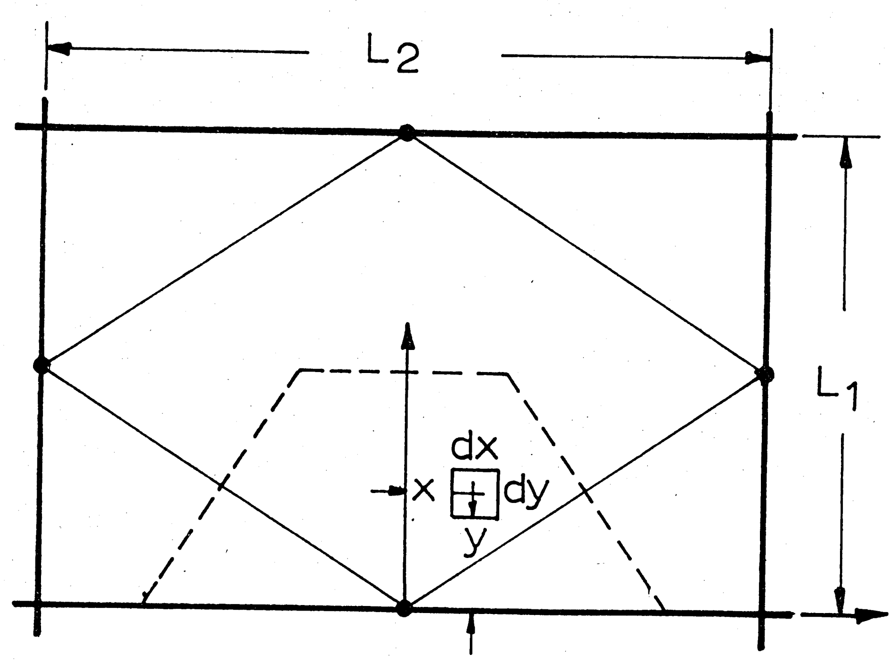


Figure 2. Determination of average walk distance

We assume as before that the stations are at the midpoints. Then, the zone of attraction of each station is bounded by connected segments of perpendicular bisectors to the lines which connect a given station to the neighboring stations. The boundary of the upper half of the zone of attraction to the lower station in Figure 2 is shown by dotted lines. By examining the symmetry it may be seen that the zones of attraction of all four stations in Figure 2 are made up of four trapezoids identical to the one dotted in the figure. Thus the average walk distance to the lower station from the dotted region is the average walk distance to any station.

We assume a rectangular street pattern parallel to the guideways. Therefore we can compute the average walk distance w_{av} from the integral

$$w_{av} = \int_{y=0}^{L_1/2} \int_{x=0}^{f(y)} (x + y) \frac{dxdy}{L_1 L_2/8} \qquad (14)$$

in which from analytic geometry the equation of the diagonal perpendicular bisector is

$$x = f(y) = (1 + \alpha^2)L_2/4 - \alpha y \qquad (15)$$

in which $\alpha = L_1/L_2$.

Performing the indicated integration, we obtain

$$w_{av}/L = (3 + 6\alpha - 2\alpha^3 + \alpha^4)/24 \qquad (16)$$

Note from Figure 2 that the maximum walk distance is

$$w_{max}/L_2 = (1 + \alpha)/4 \qquad (17)$$

Equations (16) and (17) are plotted in Figure 3.

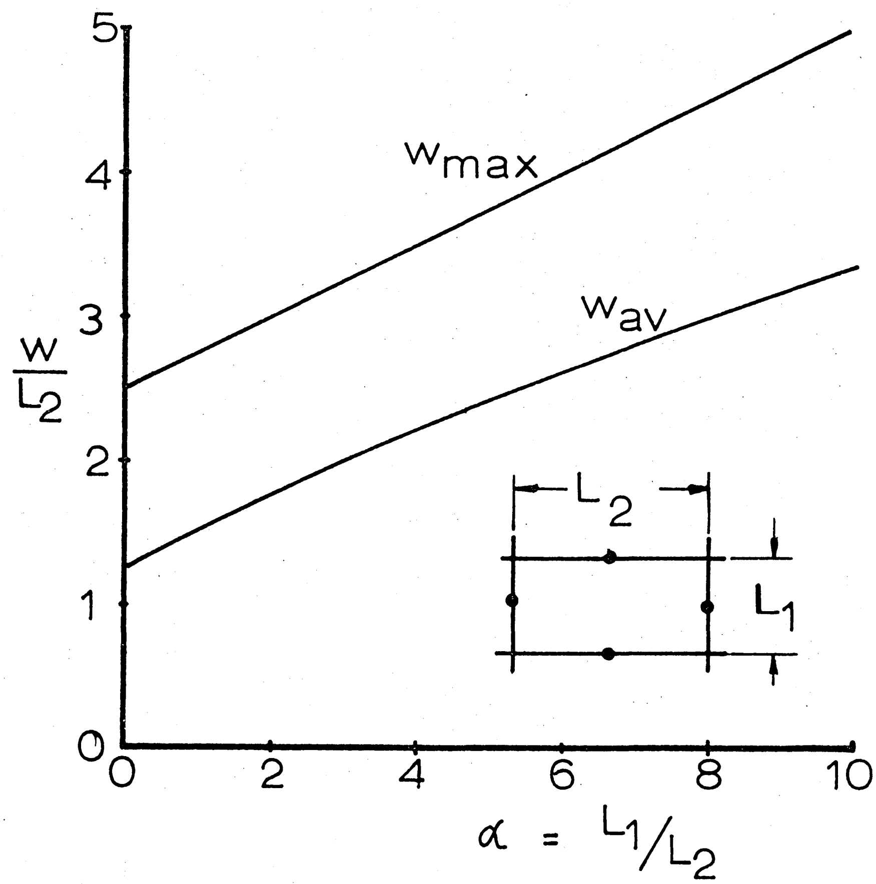


Figure 3. The walk distance in a rectangular configuration with midpoint stations

As an example, compare the above parameters for the three cases given in the following table. All lengths are assumed to be in the same units.

L_1	L_2	w_{max}	w_{av}	λ	s
0.5	0.5	0.25	0.167	4	8
0.5	1.0	0.375	0.243	3	4
1.0	1.0	0.5	0.333	2	2

If the dimensions are in miles, the first case gives a value of w_{max} corresponding to the accepted maximum walk distance. In the third case the maximum walk distance doubles, half the area is within a third of a mile of a station, and only one fourth of the area is within 0.25 mi of a station. In the first case there are four times as many stations as in the third case, as would be expected, but these are obtained with only twice as many miles of line.

Time Penalty for One-Way Lines

Advantages of one-way lines have been mentioned above. As also mentioned, one-way lines have the disadvantage that the average trip time will be longer. This time penalty is estimated here.

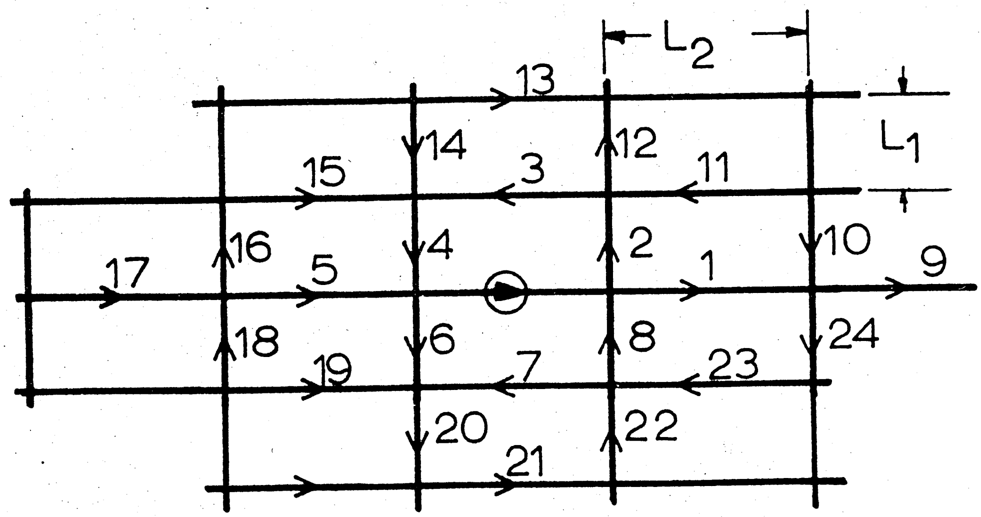


Figure 4. Determination of time penalty for one-way lines

Consider the portion of a network shown in Figure 4. The arrows indicate station locations and the direction of flow. With the circled station in the center as the origin station, we first determine the extra distance required to travel to each of the numbered stations if the lines are one-way instead of two-way. The extra distances are as given in the following table:

Sta.No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
a	0	0	0	1	2	2	0	1	0	1	2	0	2	3	0	2	2	1	1	1	1	3	0	0
b	0	0	0	1	4	1	2	2	0	2	1	0	1	1	1	3	2	3	2	2	2	2	2	0

in which the extra distance is $aL_1 + bL_2$.

The average values of a and b are as follows:

	a_{av}	b_{av}
Ave for Sta 1-8	.75	1.25
" " " 9-24	1.19	1.50
" " " 1-24	1.04	1.42

The average extra distance and the extra time assuming a speed of 30 mph (0.5 mi/min) is as follows:

L_1,mi	L_2,mi		Extra dist,mi	Extra time,min
.5	.5		1.23	2.5
.5	1	ave	1.85	3.7
1	.5			
1	1		2.46	5.0

The Cost per Trip

The cost per trip on any transit system is given by the equation

$$\text{Cost/trip} = \frac{\text{Cost/yr}}{\text{Trips/yr}} \tag{18}$$

The cost per year is the annual amortization cost of the capital equipment per year plus the annual operating costs. It is convenient to write this in terms of the total annual cost per mile of line. Thus we let the cost/yr be expressed as (cost/mi/yr) ℓ, where ℓ is the total length of the network in miles. From equation (12), we have $\ell = \lambda A_t$, in which A_t is the area covered by the network. Thus we can express (18) in the form

$$\text{Cost/trip} = \frac{(\text{Cost/mi/yr})\lambda A_t}{\text{Trips/yr}} \tag{19}$$

The number of trips per year is approximately the number per working day multiplied by 300. Then if β is the number of trips per person per day using the transit system, we can write

$$\text{Trips/yr} = 300\beta\rho A_s \tag{20}$$

in which ρ is the average population density in the service area A_s. Generally $A_s > A_t$ because some people who use the transit system live outside the area A_t. Thus, equation (19) becomes

$$\text{Cost/trip} = \frac{(\text{Cost/mi/yr})(A_t/A_s)}{300\rho(\beta/\iota)} \tag{21}$$

The number of stations per unit area is a better indicator of service than the number of miles of line. In a square grid (12) and (13) give $\iota = Ls$ where L is the grid spacing. Then (21) becomes

$$\text{Cost/trip} = \frac{L(\text{Cost/mi/yr})(A_t/A_s)}{300\rho(\beta/s)} \tag{22}$$

Within the network area we assume as a rough approximation that the number of trips per person per day attracted to the system for movement of both people and goods is proportional to the station density, s. Thus the quantity β/s is insensitive to the mesh spacing and, other things being equal, the cost per trip increases in direct proportion to the mesh spacing. Thus a greater investment in guideways reduces the unit cost, a fact which will probably be considered counterintuitive (This can be true of course only for values of L above some minimum level at which most of the traffic is attracted to the automated system.)

Let us estimate β/s for the case $L = \frac{1}{2}$mi. At this value, $s = 8$. The total number of person trips per person per day in typical metropolitan areas is about three. Generally there is about one truck on the roads for every 13 automobiles, but if goods are moved by a PRT system, it may take about 10 PRT vehicles to carry the load of one truck. Thus we can estimate β as $3(1 + 10/13)$(modal split). With $L = \frac{1}{2}$ mile, the maximum walk distance is $\frac{1}{4}$ mi so that the PRT system is relatively convenient to everyone; however, many trips are too short to be attracted. Therefore assume only a 50% modal split. In this case $\beta = 2.6$.

If A_s is much larger than A_t, β will decrease roughly in the same proportion. Therefore if we use $\beta = 2.6$, we should let $A_t = A_s$. With this assumption, and $\beta/s = 0.33$, (22) becomes

$$\text{Cost/trip} \simeq \frac{L(\text{Cost/mi/yr})}{100\rho} \qquad (23)$$

We see here the basic parameters which determine the cost per trip. The cost per year in a capital intensive system like PRT is, from a large number of estimates, of the order of 10% of the capital cost. Then we could express (23) as

$$\text{Cost/trip} \simeq \frac{L(\text{Capital cost/mi})}{1000\rho} \qquad (24)$$

Consider a typical example: Let the capital cost/mi be $4 million, ρ be 5000 people per square mile and L be 0.5 mi. Then

$$\text{Cost/trip} \simeq \$0.40$$

Equation (24) shows how this figure will increase or decrease in other cases.

The Time Headway, Line Capacity, and Vehicle Size

The time headway between vehicles moving in a cascade is given by the equation

$$T = \frac{H + L_v}{V} \qquad (25)$$

in which L_v is the length of the vehicles, H is the nose to tail distance between vehicles, and V is the line velocity. This expression is plotted in the following figure for various values of $H + L_v$ in the range of T of interest in high-capacity PRT systems.

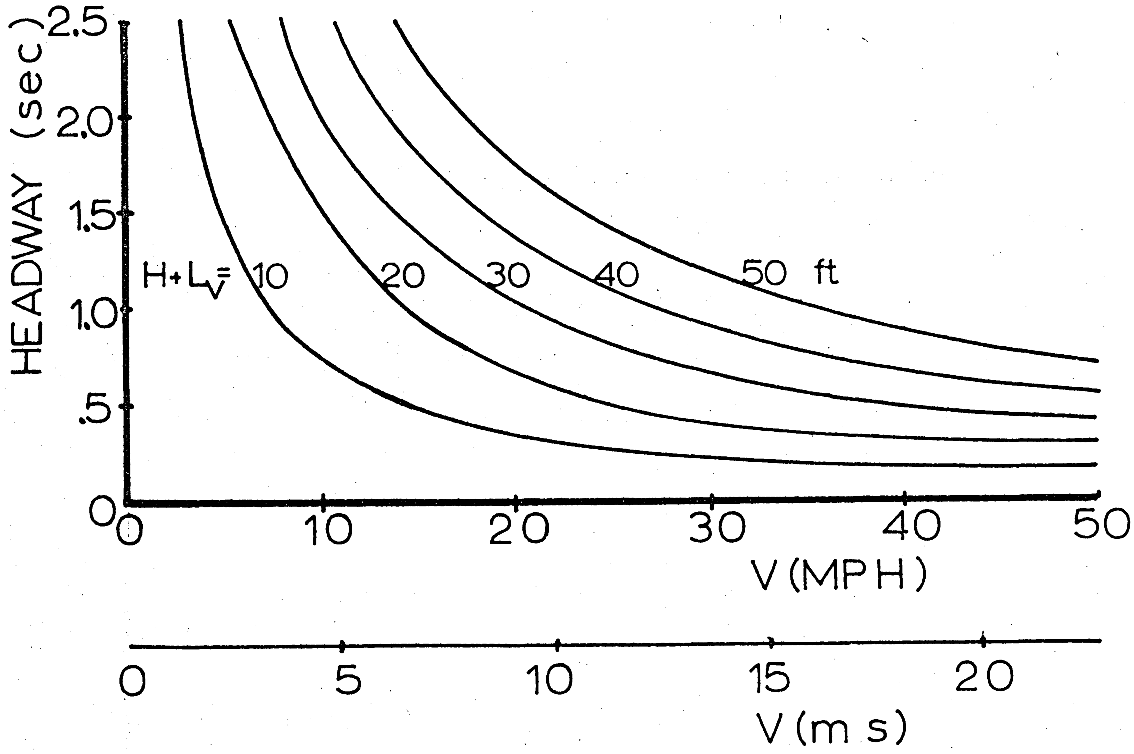


Figure 5. Time headway for various values of $H + L_v$.

Small PRT vehicles will be about 10 ft long, therefore the curve corresponding to $H + L_v = 10$ ft gives approximately the minimum possible headway. In downtown areas where we may have $V \simeq 15$ mph; $T_{min} \simeq 0.45$ sec, in which case the spacing between vehicles vanishes. Chapter 9 develops specifications for safe operation at such close headways. Calculations elsewhere in this volume indicate it is sometimes necessary in some places in the guideways to operate with headways of the order of 0.5 sec. Figure 5 may be used to determine the vehicle spacing for various values of V at $T = 0.5$s. Thus, at $V = 40$ mph, $T = 0.5$s, the nose to nose spacing is about 3 vehicle lengths, i.e., the nose to tail spacing is about two vehicle lengths.

The capacity in vehicles per hour is given by

$$C_v = \frac{3600}{T,\text{sec}} \text{vehicles/hr} \tag{26}$$

Thus, Figure 5 can also be used to determine capacity. At $T = 0.5$ sec, $C_v = 7200$ vehicles per hour. With this headway at 40 mph, in a quasi-synchronous system, we say vehicles would travel in 30 ft slots, each of which may or may not contain a vehicle. At 20 mph the slots reduce to 15 ft, at 15 mph to 11 ft, etc.

The line capacity in people per hour is

$$C_p = P_v C_v \qquad (27)$$

in which P_v is the number of people per vehicle. We see that with $P_v = 1$, $T = 0.5$ sec the theoretical capacity is 7200 people per hour. $P_v = 1$ corresponds to the practical case in which the average occupancy of occupied vehicles is about 1.3 and the fraction of empties is about one fourth. Practical considerations, discussed in Chapter 8, reduce this by about 20%, i.e., to about 5800 people/hr. This is close to the capacity now carried in automobiles on a three-lane freeway and should be considered as the approximate line capacity. With this as a constraint, the flow analysis will determine how close the lines must be spaced to stay within this figure. Higher capacities require larger values of P_v, which may be obtained by introducing a fare policy in which a certain fare is charged per vehicle instead of per person. Further work is needed to determine the effectiveness of such a policy.

The seating capacity of each vehicle is determined by the following considerations:

1) The desire to minimize the cost/trip.
2) The size group which from social considerations will want to be able to ride the system together if it is to be patronized.

Minimization of cost/trip means, from equation (24) that the capital cost per mile should be minimized, but from (18), consistent with the requirement that patronage must be maximized. PRT allows both of these conditions to be met by use of vehicles of nearly minimum size for the following reasons: 1) The fixed-guideway cost is minimized with minimum-weight vehicles; and 2) Small vehicles can permit non-stop trips in privacy or with a small group which desires to ride together, i.e., a service comparable to the auto.

For the purpose of pooling to reduce the fare per person, it is probably not practical to think in terms of groups larger than two or three. This is also the size of a small family group. If the vehicle were limited to three seats, larger family groups would have to split up. In the case of the auto, this is considered undesirable; however, the average PRT trip is short enough that a temporary separation may not be considered unacceptable. It is interesting to note the vehicle sizes of PRT systems under development. The West German system has seating capacity for two adults and one child; the British and Japanese systems have four seats; and in the United States the smallest PRT vehicles considered by developers have six seats.

In several of these systems, the seats are arranged facing each other. This simplifies the design of a vehicle with more than one row of seats by permitting use of a single door, but, as shown in Chapter 9 results in a very long throw distance for unconstrained passengers. Under the assumption that everyone would not wear seat belts and that air bags are undesirable, face-to-face seats should not be used. In this case the West German two-and-a-half or three-seat vehicle becomes attractive. We therefore now tenatively recommend this configuration. The larger vehicles being designed by American manufacturers are apparently influenced mainly by the current size of automobiles and not by system considerations such as given above.

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Chapter 6

Economic, Environmental, and Design Aspects of Large Scale PRT Networks

Summary

This chapter summarizes a parametric study of system variables of large scale Personal Rapid Transit (PRT) networks recently accepted for publication and presentation.* An ideal city having uniformly distributed population (trip) origins and destinations serves as the trip model while a square mesh pattern serves as the PRT network model. Independent variables in the analysis are population (trip) density, PRT operating and fixed-cost, mesh spacing, auto speed, perceived auto cost per mile, PRT speed and fare. Dependent variables are modal split (patronage), reduced auto emissions, cost and subsidy per mile, benefit-cost ratio, electrical power requirements, fleet size and needed guideway and station capacity. The analysis identified ranges of population (trip) densities and PRT system performances and costs for which PRT is either economically feasible or of benefit to society. Quantified societal benefits include reduced auto costs, reduced travel time and pollution, and increased safety. The results provide useful guidelines for system designers, urban planners, and decision-makers.

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* J. L. Dais and A. L. Kornhauser, paper accepted for presentation at Winter 1973 meeting of the Highway Research Board.

I. INTRODUCTION

Every urban area is faced with a transportation problem. The problem lies not so much in how to transport people, but in how people wish to be transported. The desire for comfort, convenience, flexibility, and speed has led to the overwhelming success of the automobile. With most American cities being characterized by low density residential areas and a dissolving central core, trip origins and destinations are widely dispersed. Since conventional transit serves only few origins and destinations at high speeds (subways) or many origins and destinations at low speeds (buses) ridership consists primarily of the transit captive--those that do not have access to an automobile. The extensive reliance on the automobile has in turn influenced the development of the city. The auto's ability to serve widely dispersed origins and destinations has spurred development in the city's outer ring which in turn has demanded more dependence on the auto. The result is a transportation problem in terms of pollution, congestion, land-use and reduced mobility for the transit captives.

In an attempt to provide a viable public transit system for the typical auto-oriented city, a substantial effort has been generated in both the United States and abroad for the development of a new technology transit system known as Personal Rapid Transit (PRT). PRT is a class of fixed-guideway transit systems for which the stations are off the main line. The PRT vehicles are small (2-6 passengers) and operate individually under automatic control. Trips would be non-stop from origin to destination--

high capacity is achieved by operating at close headways. Its auto-like characteristics make it a potentially viable competitor with the auto. In its completed form, PRT would serve as an area-wide carrier of people and goods. This would be accomplished by the construction of a network of lines with closely-spaced stations, thus providing easy access to the captive vehicles. PRT networks have been studied for London [1], Los Angeles and Phoenix [2], Freiburg [3], Vancouver [4], and Gothenburg [5]. These studies have provided valuable insight about network design, PRT economics and ridership and certain system requirements such as guideway capacity and the effect of fare on ridership. An excellent study of the visual intrusion of the London network is reported in [6].

This paper presents a parametric study of PRT design and cost variables. An ideal city having uniformly distributed population (trip) origins and destinations is used as the basic model. The PRT network serving the ideal city is one having a square grid with the residential areas having a larger mesh spacing than the Major Activity Centers (MAC). The analysis inputs aggregate information on auto travel time, trip distance and income which characterize the Twin Cities of Minneapolis-St.Paul (and many other American cities). The study was performed concurrently with our study of real-city networks for the Twin Cities and Duluth. The motivation for the ideal network study is that it permits the easy variation of parameters such as mesh spacing and population density.

The core of the analysis consists of a modal-split assumption whereby trip makers are assigned to PRT or the auto on the basis of a comparison of travel time and costs via each mode. As in [2], a random draw procedure is used whereby the modal split is determined by sampling a large number of trips. Once the modal split is determined, other system parameters such as reduction in air pollution, guideway capacity requirements, station requirements, electrical power, fleet size, cost per passenger-mile, revenues, subsidies, and benefits can be calculated. Previous economic analyses [2], [3], [6], quantitatively have focused on costs, revenues and subsidies. The present study broadens the outlook and applies the benefit-cost ratio method of economic analysis. Benefits quantified are reduced auto costs, travel time, air pollution, and auto accidents.

II. SYSTEM MODELS

2.1 Trip and Tripmaker Characteristic. The idealization of a real city into an ideal city consisting of residential areas and major activity centers provides a convenient point of departure for a transportation study. A substantial amount of compiled statistics describing trips and tripmakers are available upon which to build. Major activity centers include schools, shopping centers, employment centers and more generally all trip destinations except residences. Figures 1(b) and 1(f) show some trip characteristics of the Twin Cities. Both figures are based on information from the TCAT study [8]. Figure 1(b) illustrates the predominance of shorter trips. Figure 1(f) indicates that about 80% of the total trips have one end at a residence and the other at an MAC. Residence to residence and MAC to MAC trips each comprise about 10% of the total. As is indicated in Table 1, residents average about 3 trips daily and 0.3 trips during the peak hour. Figure 1(c) is based on 1970 income data supplied by the Metropolitan Council. As can be seen from the figures, average family income exceeds $10,000.

2.2 PRT Network Design Parameters. The Twin Cities street layout is largely rectangular, as is typical of many American cities. The simplest geometric PRT network design which can be aligned with a rectangular street network consists of equally spaced one-way lines as shown in Figure 2. Vehicle ramps connect all intersecting lines enabling passengers to travel without transfer between any two stations in the network. The present paper considers a square network, which is thought to be appropriate when modelling essentially square cities with no predominant direction of travel. Table 1 summarizes nominal values for residential and MAC mesh spacings.

Stations located at the midpoints of grid lines minimize both the largest walk distances (L/2) as well as the average (L/3). Stations serve an area within the dashed line shown

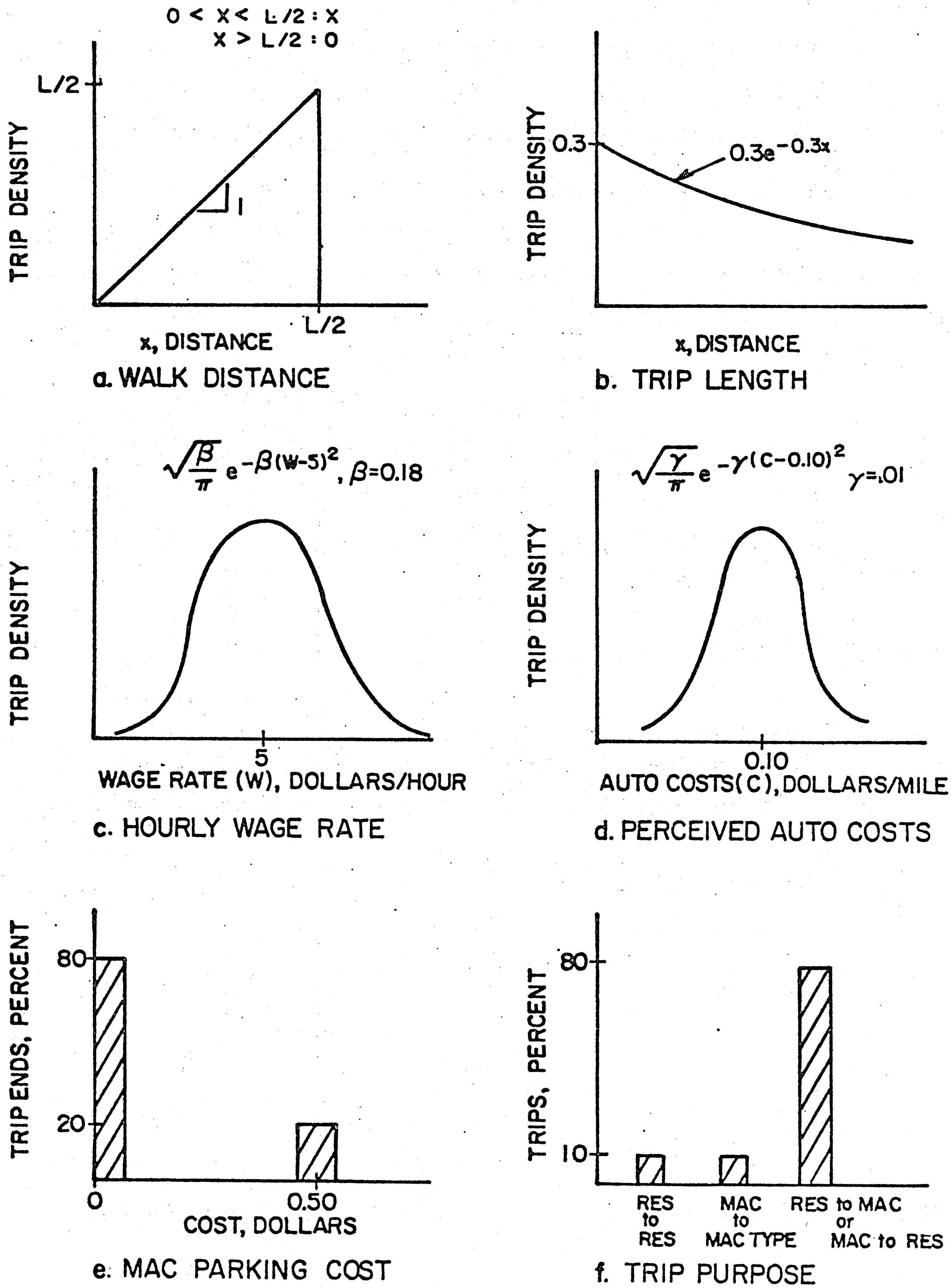

Figure 1. Trip models.

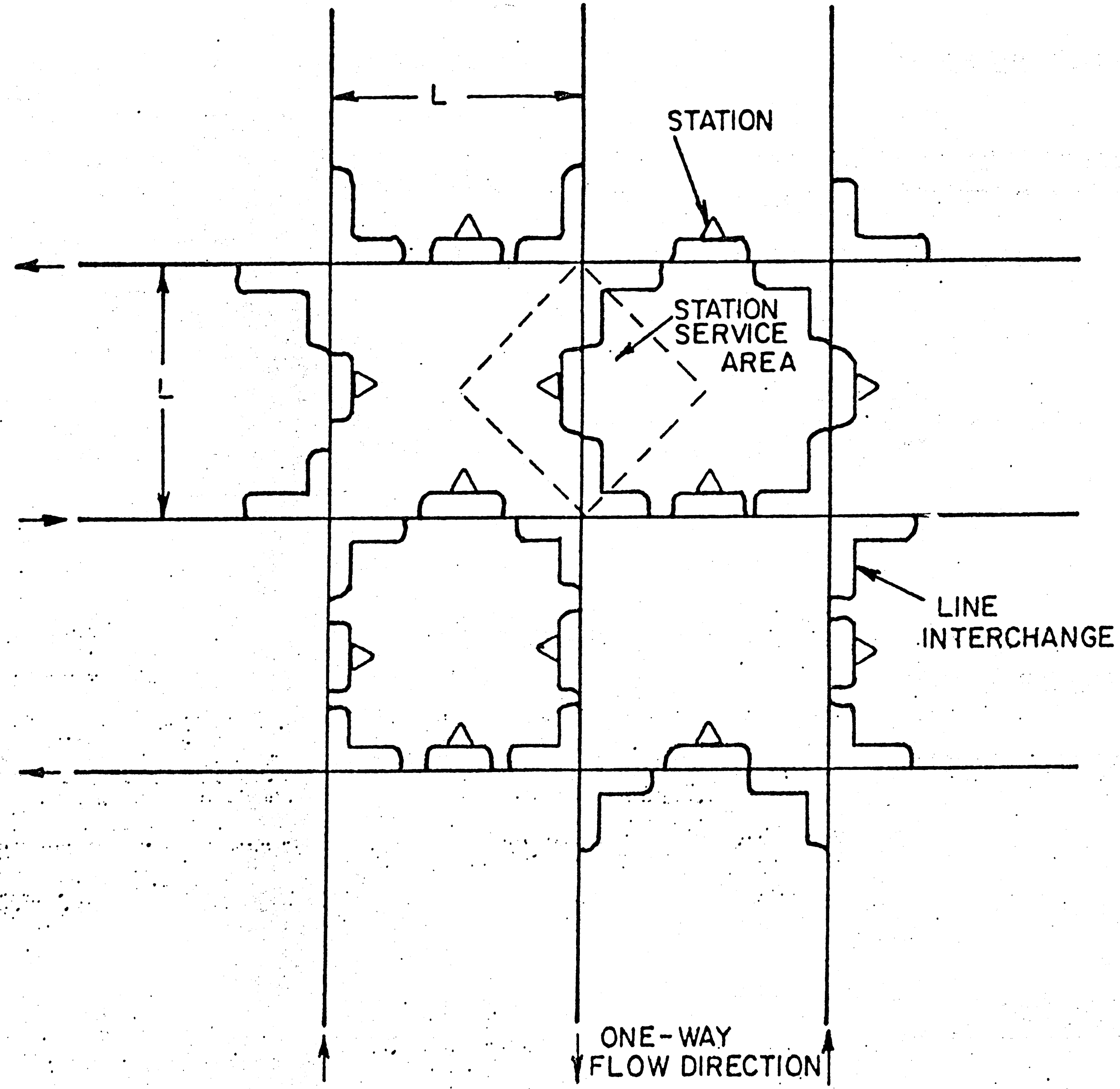

Figure 2. Square-mesh PRT network of one-way interchangeable lines.

TABLE 1

Nominal Values of Parameters

Walk Speed	3 MPH
Residential Mesh Spacing	1/2 mile
MAC Mesh Spacing	.2 mile
PRT Speed	35 MPH
PRT Fare	$.05/occupied vehicle mile
Time Value/Wage Rate	.25
Interest Rate	6%
Amortization Time for Fixed Facilities	30 years
Amortization Time for Vehicle	5 years
Station Process Time	1 minute
Daily Trip Generation Rate	3 trips/person
Peak Hour Trip Generation Rate	0.3 trips/person

in Figure 2. Assuming a uniform trip generation density over the station attraction area, the walk distance distribution is as shown in Figure 1(a). For this network design it follows that:

$$N_s = 1/L; \quad N_i = 1/L; \quad M = 2/L \tag{1}$$

where M is the miles of guideway per square mile of area, N_i is the number of single interchange ramps per mile of guideway and N_s is the number of stations per mile of guideway. Equation (1) will facilitate the determination of system cost in a later section of this paper.

Three vehicle-design parameters have a substantative effect on network design: nominal line speed, jerk and acceleration. Switch and acceleration (deceleration) lane lengths are estimated respectively from:

$$\begin{aligned} L_s &= 1.47V(32\ h/J)^{1/2} \\ L_a &= 2.08V^2/2a + 1.47(Va/J). \end{aligned} \tag{2}$$

The equations are derived in [9]. V is the nominal speed in miles per hour, h is the distance in feet between station and interchange ramp centerlines and guideway centerlines, a is acceleration in ft/sec^2 and J is jerk in ft/sec^3. A vehicle traversing ramps defined by (2) would experience a maximum acceleration a and maximum jerk J. A station ramp consists of two switches, an acceleration lane, a deceleration lane plus additional lane length for queuing, loading and unloading. An interchange ramp consists of the same components. A positive distance must be maintained between station ramps and interchange switches. This places a lower limit on the mesh spacing. This paper assumes $a = 8$ ft/sec^2 and $J = 8$ ft/sec^3. It has been shown experimentally [1], [3] that these values are acceptable for seated passengers.

III. PATRONAGE ESTIMATION

A thorough patronage estimate would include induced travel as well as that diverted from existing modes. This effort is, however, beyond the scope of the present study. This study considers two modes--the auto and PRT--and solves for the patronage diverted from the auto. The prediction is based on auto-trip and PRT-trip cost functions which involve travel time and out-of-pocket cost. A trip is assigned to auto or PRT according to which mode offers the lower cost. A large number (1000) of trips are sampled in a Monte Carlo fashion. The procedure is to sample from a digitized version of the curves shown in Figure 1. That is, trips and trip-makers are drawn randomly from these distributions.

It is recognized that a mode assignment based on travel times and out-of-pocket costs is at best imperfect. User preference studies [3], [10], indicate that several other attributes, e.g. privacy, comfort, safety and reliability (arriving when planned), are also important in mode choice. However, it is expected that a well engineered and maintained PRT system would provide similar (if not better) levels of these attributes than the automobile.

3.1 PRT Trip Description. A PRT trip involves time for several components of the trip: walk, station process, and station to station travel. The station to station travel time can be computed from:

$$t_{ss} = X/s + s/a + 2L/s \qquad (3)$$

where X is the trip distance, s is the PRT line speed, a is acceleration and L is mesh space. The second term on the right-hand side accounts for time accelerating and decelerating. The third represents an average detour penalty because of the one-way grid.

The cost function for a PRT trip is taken as:

$$C_{PRT} = F\ X/1.3 + f\ W\ (t_{ss} + 2t_{proc} + 2\ X_W/V_X) \qquad (4)$$

where F is the fare in dollars per vehicle mile, W is the hourly wage rate, f is the fraction of the hourly wage rate that the tripmaker places on his time, t_{proc} is the station process time, X_W is the combined walk distance at the two trip ends, and V_X is the walk speed. Nominal values chosen for these quantities are indicated in Table 1. The formula assumes an occupied-vehicle occupancy of 1.3 passenger/vehicle. Walk times and station process times are considered as "nuisance" times and are weighted twice as seriously as in-vehicle travel time.

3.2 Auto Trip Description. An auto trip is modelled to include time riding and walking at the ends. The ride time can be estimated from Figure 3 which represents the authors' rough estimation of trip speeds in the Twin Cities. The auto cost function is then:

$$C_A = C_m X/1.3 + C_p/1.3 + f\ W\ (t_{ar} + 2X_w/v_w) \qquad (5)$$

where C_m is the perceived cost per/mile, t_{ar} is the ride time and C_p is the parking cost. C_m and C_p are sampled from distributions given respectively in Figures 1(d) and (e). Both figures represent the authors' best guess. The 10¢ mean of Figure 1(d) is intermediate between operating and total costs. Parking cost, C_p, is automatically taken as zero at residential ends. A zero walk distance was assumed at all residential ends and a 1/10 mile walk was assumed at all MAC ends. Equation (5) assumes an auto occupancy of 1.3 passengers per vehicle.

3.3 Modal Split Estimate. A trip is assigned to PRT or the auto depending on whether the ratio C_{PRT}/C_A is respectively lesser or greater than 1. The trip modal split (TMS) is then determined by sampling 1000 trips. The passenger-mile modal split (PMMS) is given by the ratio $X_{PRT}/(X_{PRT} + X_A)$, where X_{PRT} and X_A are respectively the passenger miles traveled by PRT and the auto for the 1000 trips. The trip modal splits are

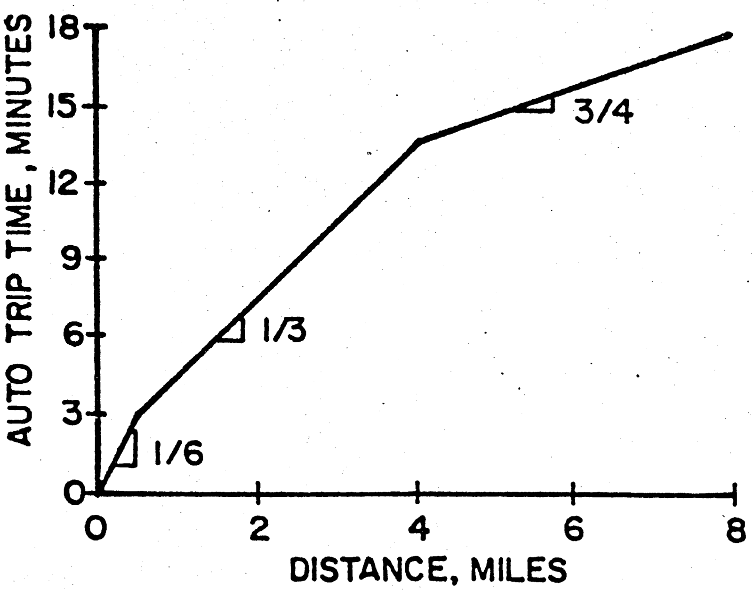

Figure 3. Auto trip time.

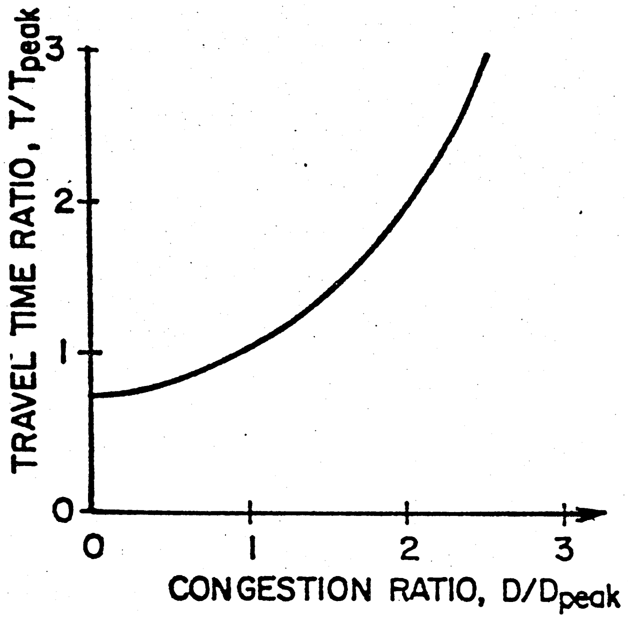

Figure 4. Travel time versus congestion.

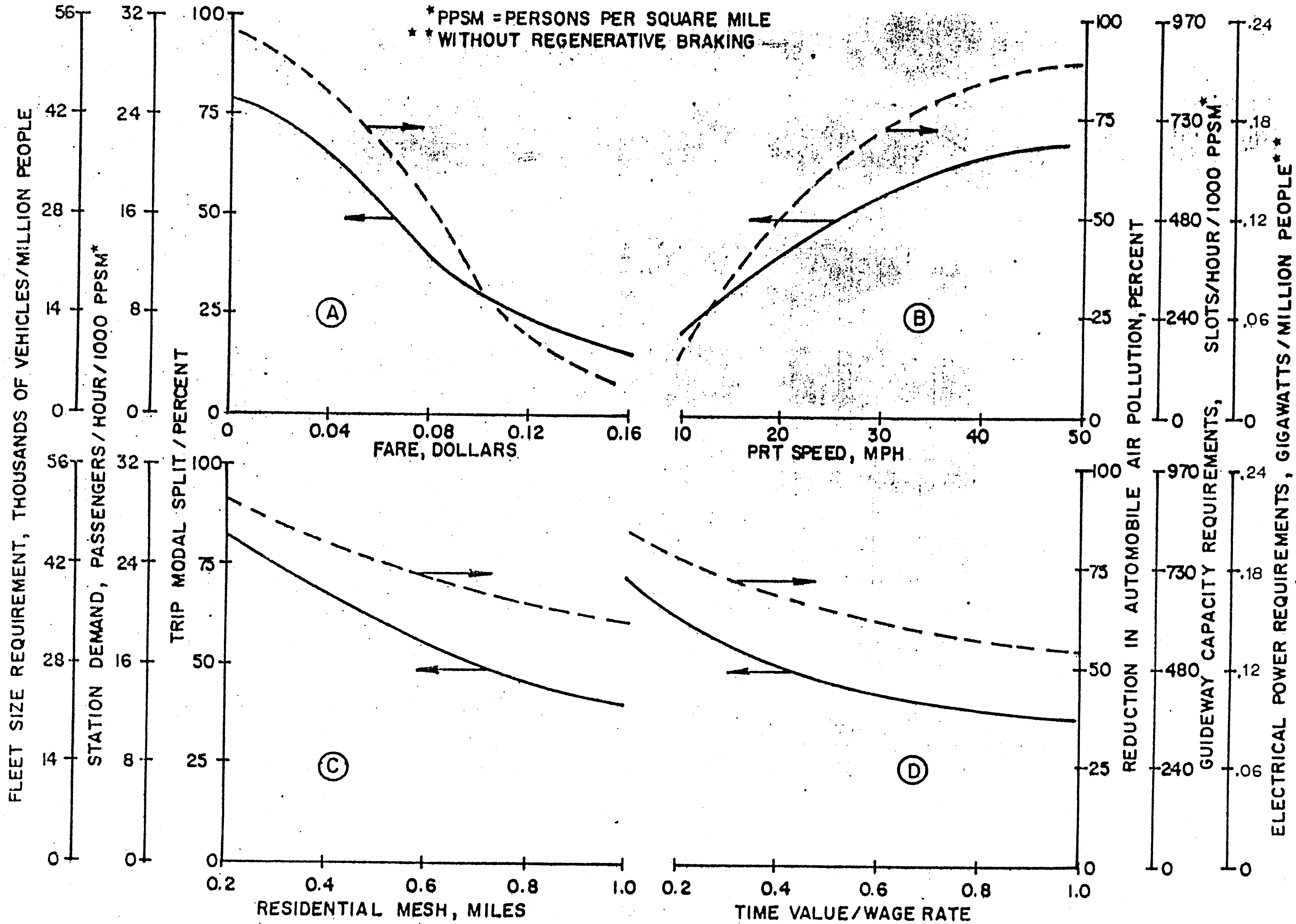

Figure 5. Modal split and PRT system requirements

plotted in Figure 5. Also plotted is the percent reduction of auto emissions which is equivalent to PMMS.

The determination of the modal split permits the easy computation of other system parameters plotted in Figure 5. The formulas are presented in this section but their derivations are deferred to Appendix 1. The peak-hour station demand in passengers per hour is directly proportional to TMS and is obtainable from the formula:

$$D_s = 150 \text{ TMS } L^2 \qquad (6)$$

where D_s is the station demand per 1000 people per square mile. Several more quantities are directly proportional to PMMS. The important ones are: the fleet size per million people, N_v; the number of gigawatt power plants required per million people, P_e; and C_v, the peak-hour guideway capacity requirement which is plotted on a per-hour-per-1000-people-per-square-mile-basis. These quantities are obtained respectively from the formulas:

$$C_v = .2 \; L \; X_{PRT} \qquad (7)$$

$$\left.\begin{aligned} P_e &= .000054 \; X_{PRT} \; * \\ P_e &= .000041 \; X_{PRT} \; ** \end{aligned}\right\} \qquad (8)$$

$$N_v = (2000/L/s) \; C_v \qquad (9)$$

These quantities are plotted in Figure 5.

---

* Without regenerative braking

** Assumes regenerative braking

IV. ECONOMIC ANALYSIS

This section develops quantities of interest to decision-makers. The quantities are cost per passenger-mile, subsidy per passenger-mile, and benefit-cost ratio (BCR). Detailed considerations for financing the subsidy are beyond the scope of the present paper; however, possible sources, some controversial, include federal capital grants, property taxes, general funds and highway-user taxes. Furthermore, studies by N. D. Lea [4], and Wilbur Smith [11], indicate that goods movement should be investigated as a potential source of significant revenue and better system utilization.

4.1 Systems Cost. Cost estimates for the paper are given in Table 2. The estimates are in line with those used in [2], [3], and [12]. The most substantial departure from these works is to assume a higher price for vehicle storage, namely $3000 per vehicle. This estimate is based on the assumption that guideway ramps costing 1.5 million per mile would be used for the storage. $3000 would then buy about 10 feet of ramp. Interest rates are assumed to be 6%, as indicated in Table 2. Fixed facilities are assumed to be amortized over 30 years. Vehicles are amortized over a lifetime of 5 years. The 3¢-per-mile operating cost includes the computer facility and personnel costs, electricity, maintenance and cleaning. All ramp lengths were computed from (2) with $a = 8$ ft/sec^2 and $J = 8$ ft/sec^3. Equation (1) provides an estimate for the number of stations and interchange ramps.

TA[redacted] 2

Cost Estimates

Item		Fixed Costs		Variable Costs	
		Capital	Other	Capital	Other
Guideway, R. of W. Support Electrification		$1.5 million per mile	*Maintenance of 1%	- - -	- - -
Stations	Ramps	$1.5 million per mile	Maintenance of 1%	- - -	- - -
	Buildings and Controls	$200,000	Maintenance of 1%	- - -	- - -
Interchange	Ramps	$1.5 million per mile	Maintenance of 1%	- - -	- - -
	Queue Area and Controls	$100,000	Maintenance of 1%	- - -	- - -
Maintenance Garage		- - -	- - -	$100/vehicle	1% Maintenance
Carbarn		- - -	- - -	$3000/vehicle	1% Maintenance
Vehicle		- - -	- - -	$4000/vehicle	3¢ Operating

* Annual cost equal to 1% of capital cost.

4.2 Cost and Subsidy per Passenger-Mile. The fixed cost per passenger-mile, C_f, is computed by converting fixed costs to an annualized basis and dividing by the number of annual passenger miles, the latter obtainable from the previous section. The variable cost per passenger-mile, C_v, is found by converting the variable costs to a per vehicle-mile basis. Due to an assumed 1.3 passengers per vehicle and total vehicle mileage equal to 1.3 times occupied-vehicle mileage (due to shuttling of empties), the total cost per passenger-mile is given by:

$$C_m = C_v + C_f \tag{10}$$

The subsidy per passenger-mile is then given by:

$$C_s = C_m - F/1.3 \tag{11}$$

where F is the fare per occupied-vehicle mile. The cost and subsidy per passenger-mile are plotted in Figure 6 for a wide range of system parameters.

4.3 Benefit-Cost Ratio. The benefit-cost method of economic analysis obtains a parameter BCR, termed the benefit-cost ratio, defined by the equation:

$$BCR = benefits/costs \tag{12}$$

The present analysis identifies three benefits which are quantifiable in dollar terms. They are auto-cost savings, travel-time savings and auto-pollution/safety savings. The total benefit is assumed to consist of the sum of these.

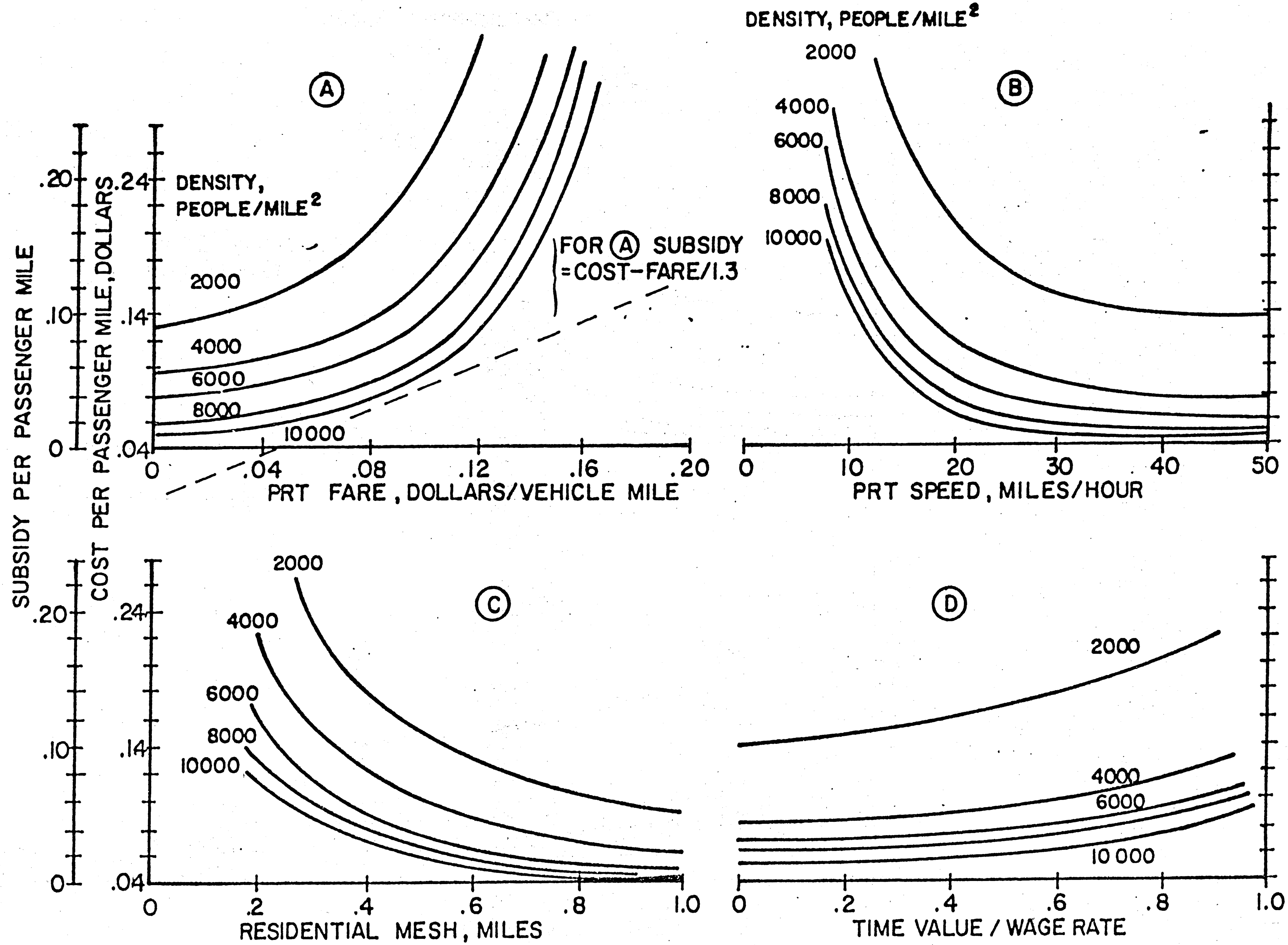

Figure 6. Cost and subsidy per passenger mile.

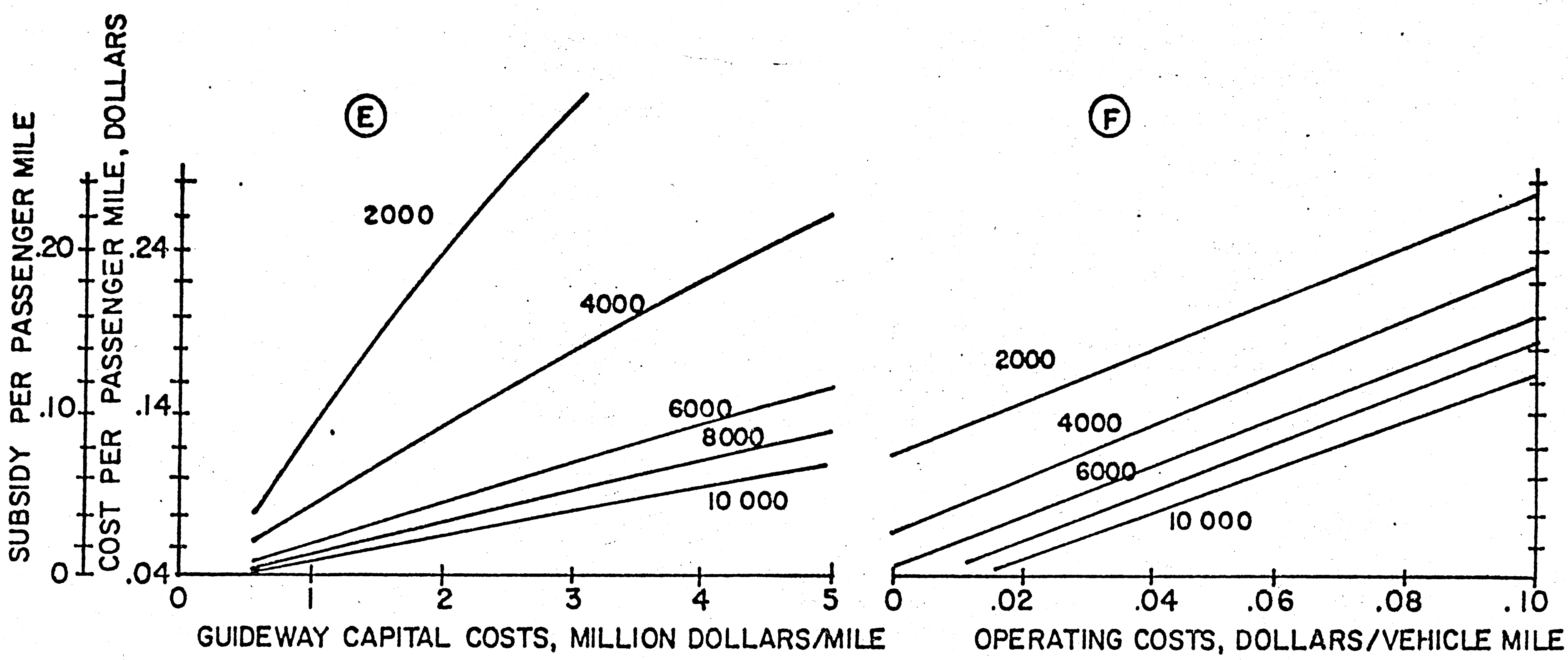

Figure 6 cont. Cost and subsidy per passenger mile.

Auto-cost savings include parking fares not encountered plus a mileage cost taken to be 10¢ per mile (intermediate between total cost and variable cost). Pollution and safety benefits can be estimated from the RECATS [13] report, where it is estimated that by 1976 automobiles will accrue an added retail price of about $870 and require about one-third more fuel to satisfy presently planned auto-emission standards. The added fuel requirement is about 1¢ per mile. Two cents per auto-mile not driven is an approximate figure for the pollution and safety benefit of PRT.

As suggested by Winfrey [14] time savings are valued at the assumed average wage rate. Time is saved by travellers for two reasons. First, most of the trips taken by PRT are faster than by auto. Secondly, PRT will take trips from the roads, thereby alleviating congestion. Methods for estimating the latter effect on an urban-wide basis are not known, so a crude approach is presented here. First, consider congestion to be a problem only during the four peak hours, therefore affecting only about 35% of the daily trips. It seems reasonable to assume a form:

$$T/T_{peak} = \frac{2}{3} + \frac{1}{3}\left(\frac{D}{D_{peak}}\right)^2 \qquad (13)$$

where T is the auto trip time at demand level D, T_{peak} is the trip time at the present level of demand D_{peak}. This representation projects that if there is no traffic, a trip takes 2/3 as long as at peak times. If demand is double the present level, then a trip would take twice as long. The resulting curve is presented in Figure 4. The benefit-cost ratio is plotted in Figure 7 for a range of parameters.

V. DISCUSSION OF NUMERICAL RESULTS

Output of the patronage and economic model of large scale PRT systems is presented in Figures 5, 6 and 7. The data is presented in the form of network performance indices (patronage, Fig. 5;cost/mile, Fig. 6; and benefit-cost ratio, Fig. 7) versus system design and cost parameters (residential population density, fare, vehicle speed, residential–network mesh size, capital costs and operating costs). Nominal values of the system parameters used in this study are listed in Table 1. They are initial values for a base-line Twin Cities PRT system. The mesh spacing (.5 miles) provides reasonable access by walking and the speed (35 mph) and fare (5¢/vehicle mile) are competitive with the automobile. Our model predicts that this nominal PRT system would attract about 60% of the trips which represents 75% of the passenger miles. This 75% diversion of automobile-trip miles to transit implies among numerous things a 75% reduction in auto air pollution and a reduced dependence on scarce petroleum reserves. For a city of one-million people a .15 gigawatt power plant would be needed for the peak–hour power of the PRT system requiring a fleet of 35,000 vehicles assuming no regenerative braking. Approximately 25% less would be required for a system with regenerative braking. The

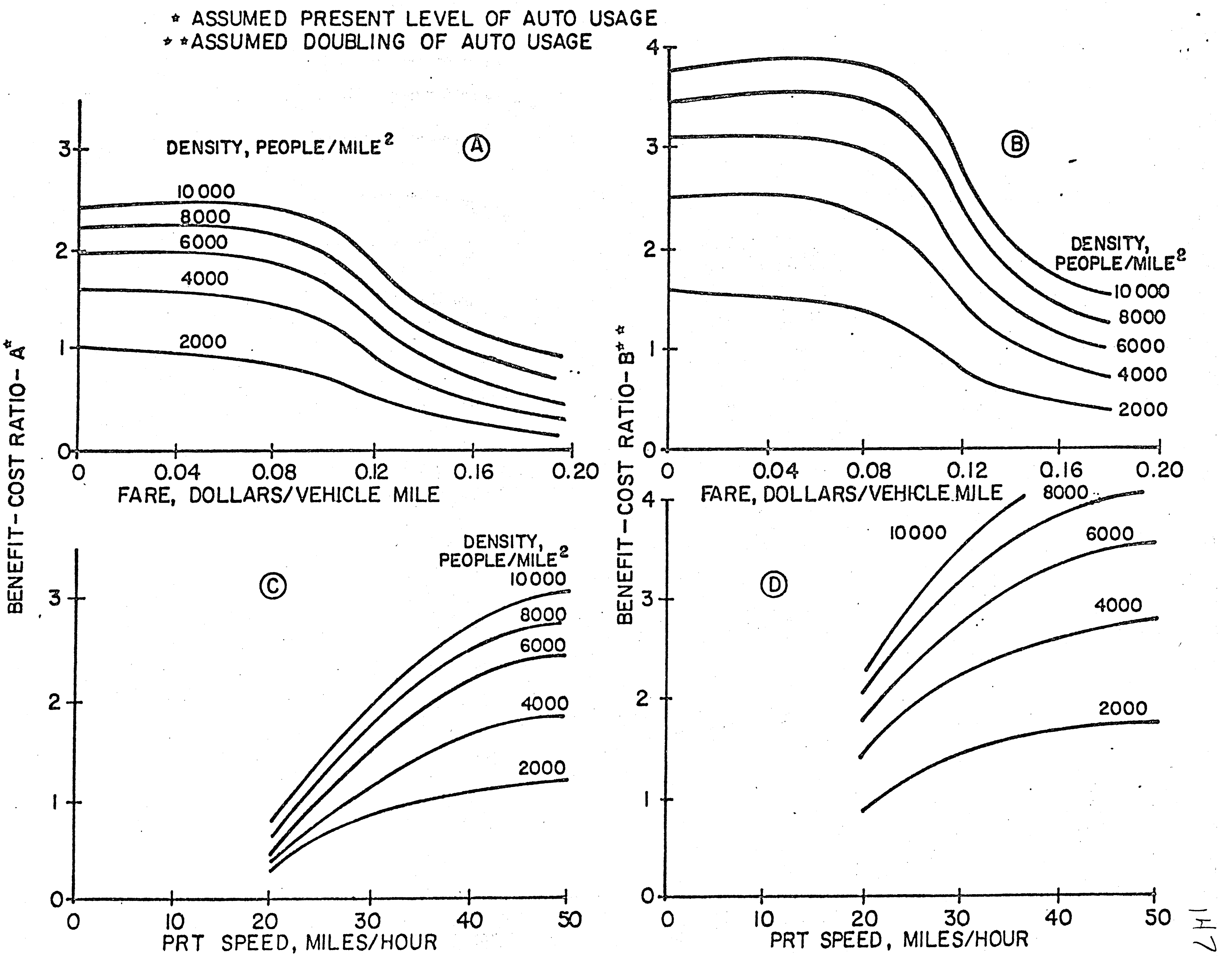

Figure 7. Benefit-cost ratio.

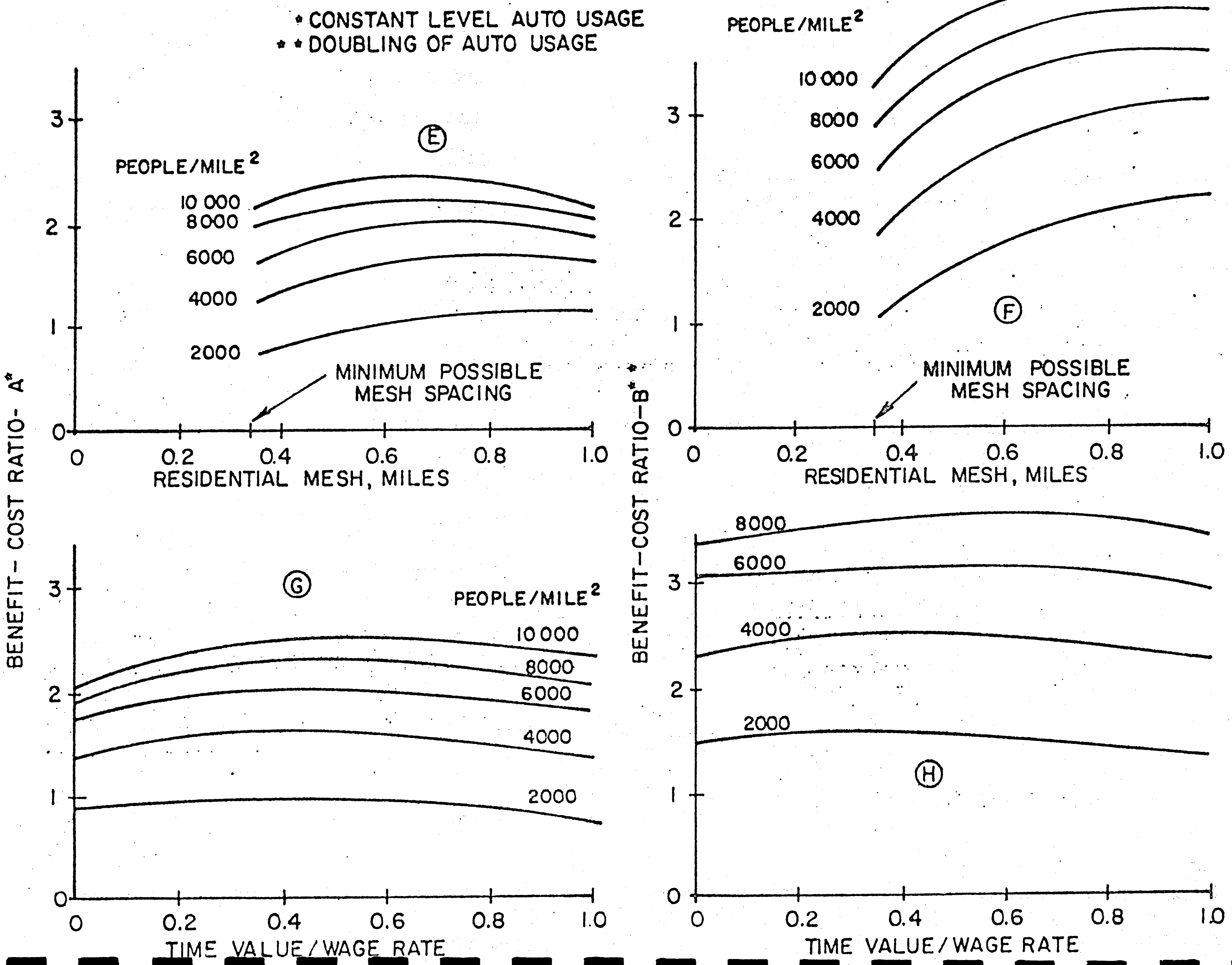

Figure / cont. Benefit-cost ratio.

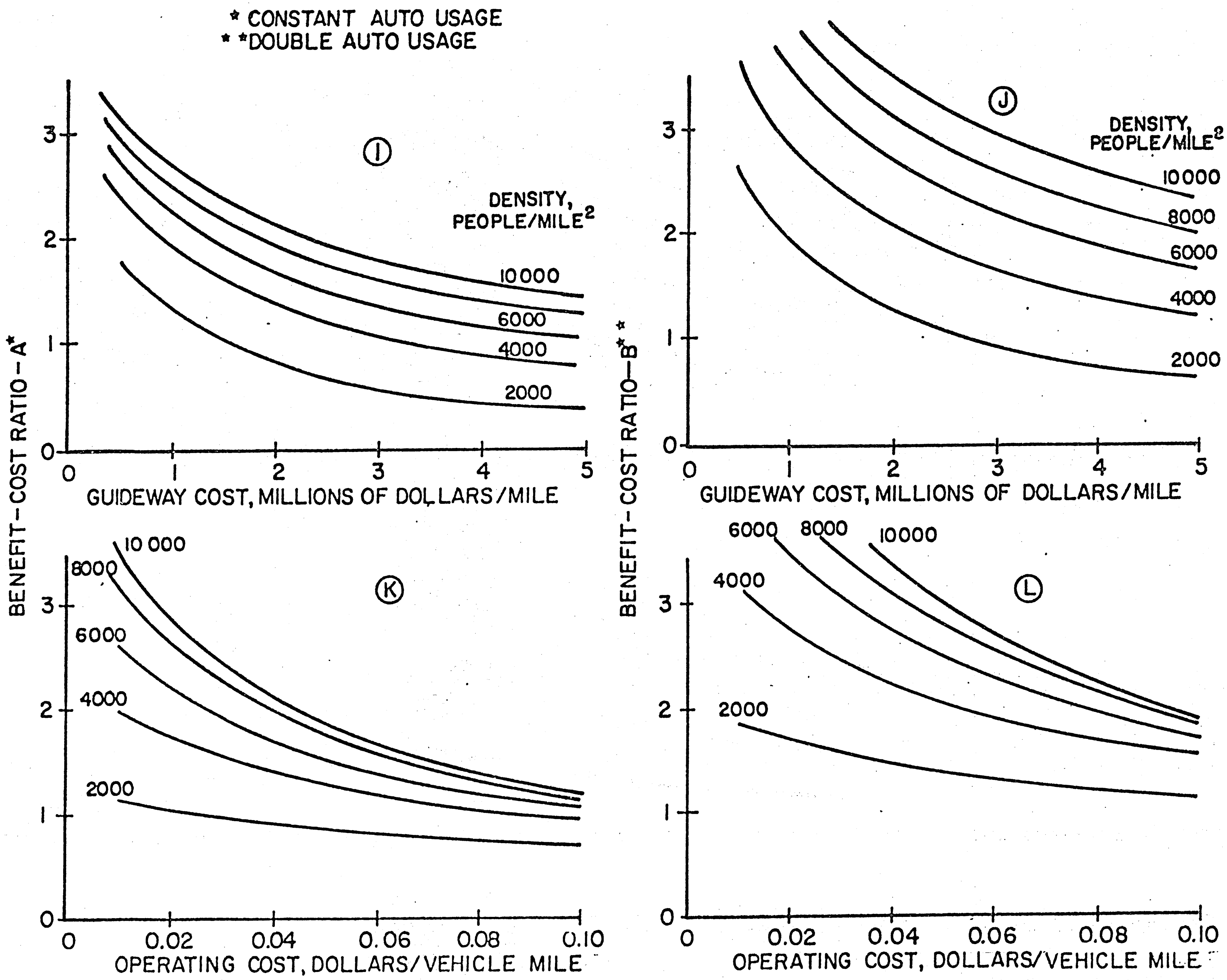

Figure 7 cont. Benefit-cost ratio.

24-hour average power requirement is about 40% of the peak-hour requirement. In an area having a density of 10,000 people per square mile (ppsm), peak-hour station demand would be 200 passengers/hour and guideway capacity at 35 mph would require 1/2 second headways.

It is of interest to consider the energy requirement for PRT travel. Assuming a power plant efficiency of 40%, it follows from (8) that 1500 or 1200 BTU's per passenger mile are required respectively for systems without and with regenerative braking. The requirement for auto travel is 9000 BTU's per passenger mile (assuming 12 MPG and 1.3 passengers per auto). It follows that a PRT system which attracts 75% of the passenger miles from the auto could effect an urban transportation energy reduction of roughly 62% or 65%, depending on whether it does or does not have regenerative braking.

Figure 6 presents the effect of variations in the system parameters on patronage and system requirements. The ordinates are normalized with respect to population density to permit easy application to specific urban areas. Principal results are: a) Modal-split (patronage) is very sensitive to fare in the neighborhood of fare = average auto cost. At lower fares, PRT attracts many (and longer) trips while at high fares only few (and shorter) trips are by PRT; b) Patronage is very sensitive to PRT speed at its lower values. At speeds of 35-40 mph, PRT captures most of the market and a point of diminishing return is reached; c) Residential-mesh size in the range of .4 to 1.0 miles shows little effect on patronage.

Perhaps the most significant result of Fig. 6 is that the total cost (including full capital costs) per PRT passenger mile is less than a dime for cities of 9,000 or more ppsm. This means that PRT travel costs are competitive with travel costs by auto, buses and dial-a-ride. Fig. 6 also provides some insights concerning economic uncertainties of PRT. The guideway-capital-cost-variation curves show that in the higher density areas, the cost per passenger mile is not highly sensitive to guideway cost (and other fixed-cost) estimation errors. For example, if density = 10,000 ppsm, then a doubling of the assumed guideway cost to $3 million per mile would change the per passenger mile cost from 7¢ to 9¢. At lower population densities, per mile costs become very sensitive to fixed costs.

Another uncertainty is the degree of validity of the modal-split assumption. Fig. 6 shows that the cost/ride is largely insensitive to variations in the time value/wage rate ratio, particularly in high density areas. In another computer run it was assumed that the actual ridership was only one-half of that predicted. For 10,000 ppsm, the cost per mile then jumped from 7¢ to only 8¢ , while for 2,000 ppsm, the cost per mile jumped from 17¢ to 27¢. At high densities a large percentage of the cost is variable. This makes the cost/passenger mile insensitive to ridership and fixed-cost estimation errors.

Fig. 7 indicates that the benefit-cost ratios (BCR) are generally favorable for a wide variation of system parameters at densities above 4,000 ppsm. At lower densities BCR is marginal or unfavorable. Two forms are presented. BCR-A is based on present travel demands while BCR-B assumes a doubling of demand. The BCR curves indicate that the fare should be less than 10¢/vehicle mile and an optimum is actually attained between 4¢ and 6¢/vehicle mile. Coupling this data with that of Fig. 6 indicates that a fare of 8¢/vehicle mile would minimize the subsidy requirement and provide an excellent BCR for a wide range of population densities. In areas having 4,000 ppsm or more, this fare would cover operating costs of 4¢/occupied-vehicle mile plus enough of the capital cost to enable the complete financing of a 1/3 local share of a capital grant program. The benefit-cost curves also yield optimum values for residential-mesh size (.6 to .8 miles) and PRT speed (50 mph).

VI. CONCLUSIONS

The analyses presented indicate that large-scale PRT networks have the potential to divert a significant portion of urban travel from the automobile. At population densities above roughly 4,000 ppsm, PRT offers attractive benefit-cost ratios and costs per passenger mile. Furthermore, at these densities, the financing of a PRT system is possible with farebox revenues if a 2/3 Federal capital grant can be obtained. At somewhat higher densities (7000 ppsm), moderate estimation errors in fixed costs and ridership do not significantly distort the favorable system economics. On the environmental side, about .15 gigawatts of electrical power would be required to serve a million people if the PRT system does not have regenerative braking. Somewhat less than that much would be required for a system with regenerative braking. The tradeoffs would be large reductions in auto emissions and petroleum requirements as well as a significant overall reduction in the total urban transportation energy requirement.

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APPENDIX: DERIVATION OF FORMULAS

Station Demand: The demand at stations is directly proportional to population density. Equation (6) is based on a population density of 1000 people per square mile. The demands at other densities are higher by a proportional amount. Assuming a trip generation of .3 trips per person in the peak hour, it follows that there are 300 TMS peak-hour trips per square mile by PRT. Since there are $2/L^2$ stations per square mile, equation (6) follows immediately.

Electrical Power Requirements: A frequently used formula for automobile motion resistance R is $R = (7.6 + .09V + C_s)W + C_D V^2$, where $C_s = 0$ for roadbeds in good condition, V is speed in MPH, C_D is drag coefficient and W is the vehicle weight in thousand of pounds. The formula contains terms accounting for rolling resistance and air drag. The formula will not be directly applicable to air or magnetically suspended systems. It is assumed that the weight and drag coefficient is about the same as for a Volkswagen, which weighs about 2000 pounds. Furthermore, VW's used to have about 30 horsepower and reach speeds of about 75 MPH on flat terrain. It follows that the motion resistance formula would be $R = (15.2 + 18V) + .022V^2$. It follows further that the energy required to travel 5280 feet at 35 MPH is 256,000 ft.lb. Assuming an average of 3 accelerations in a 4 mile trip at 1/4 g for 190 feet, it follows that an additional 71,000 ft.lb. per mile are required for accelerations. Statistics on the amount of grade changes encountered in urban travel are not available. So it will be assumed that vehicles will climb 25 feet per mile, requiring an additional 50000 ft.lb. The total energy requirement per vehicle mile is 386,000 ft.lb. If it is assumed that regenerative braking can recover 80% of the energy used in accelerating and climbing, then the requirement would be 289,000 ft.lb. per mile. Assuming that there are 1.3 people/occupied vehicle and that the total number of vehicle miles is 1.3 times the number of occupied-vehicle miles(due to the shuttling of empties), it follows that the power requirements per passenger mile are also 386,000 and 289,000 ft.lb. respectively. In units of KWH/passenger mile, the respective figures are .145 and .108. Assuming a 10% transmission line loss and 90% motor efficiency, the requirements are respectively .18 and .135. For a million people and .3 peak-hour trips per person, the number of peak-hour trips is 300,000. The number of peak-hour passenger miles by PRT is 300 X_{PRT}. It follows that the peak-hour power requirement in kilowatts are respectively 54 X_{PRT} and 41 X_{PRT}. This is equation (8) of the main text.

Guideway Capacity: Studies by Cabtrack [1] and Godfrey [15] indicate that merging can be handled with a relatively low abort rate, even if more than 80% of the guideway slots are occupied. Our capacity calculations are made on the assumption that 70% of the guideway slots are filled. Guideway capacity is proportional to population density so expressions are derived for a population density on the basis of 1000 people per square mile.

The number of passenger miles of travel generated by 1000 people per square mile is .3 X_{PRT}. The number of guideway miles on that square mile is 2/L, and so the passenger flow requirement is .15 X_{PRT} L. This expression also gives the total vehicle flow requirement, if 1.3 passengers per vehicle and 1.3 times as many vehicles as occupied vehicles are assumed. Since 70% of the slots are occupied by vehicles, the capacity requirement in slots per hour is .15 X_{PRT} L/0.7, which approximate equation (7) in the main text. The time headway T can be then computed from the formula $T = 3600/C_V$.

<u>Fleet Size</u>: The vehicle fleet includes the vehicles on the guideway plus those being processed in stations, stored in carbarns and being maintained and repaired. The fleet requirement for the guideway would be 70% of the slots. It is assumed that the remaining fleet would fill up the remaining slots. Thus, the fleet requirement per square mile (assuming 1000 people per square mile) is $2/L/(S\ T/3600) = 2C_V/(L/S)$ which if multiplied by 1000 gives equation (9) of the main text.

Geometric Design of Stations and Interchanges

Introduction

Chapter 4 on architectural impacts has shown sketches of stations and interchanges in a qualitative way. The purpose of the present chapter is to present a quantified geometric design. Certain critical dimensions will be obtained analytically. Two parameters completely determine the guideway geometry. One is the superelevation, or bank angle. The other is the geometric form of the guideway centerline curve. It is crucial to the success of PRT that stations and interchanges be small and unobtrusive as well as pleasing in appearance.

The primary limitation on the geometric design is human comfort. To insure against discomfort, it is necessary to limit accelerations as well as the suddenness at which accelerations are applied. The technical term for the rate of change of acceleration is jerk. Roughly speaking, accelerations are associated with internal and external forces on a passenger. Jerk is associated with the rate of change of these forces. In the present work, designs will be sought which limit the acceleration and jerk to respectively 8 ft/sec^2 and 8 ft/sec^3. It is known from documented studies [1], [2] that these levels do not cause severe discomforts to seated passengers. These values are quite conservative if the vehicle seats are properly designed. It is important to design with jerk and acceleration levels as high as possible to keep stations and interchanges

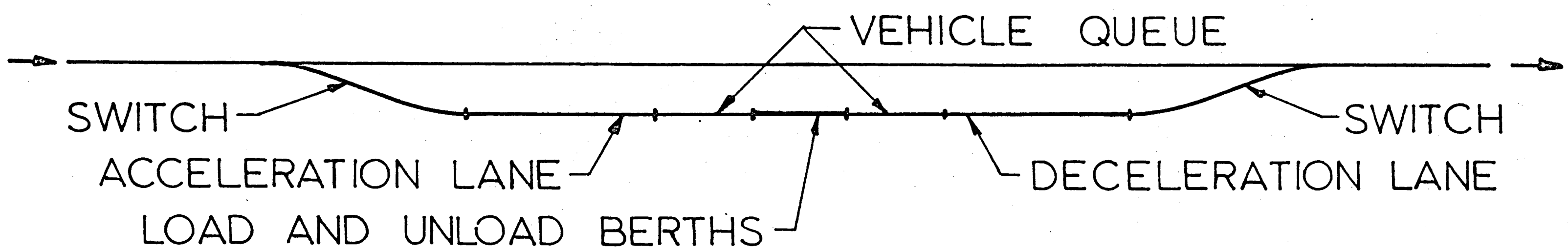

Fig 1 Off-line Station, Plan View

compact. In transit vehicles with standees, such levels would cause discomfort and so the designs presented herein are applicable only to a system with no standees.

Figure 1 shows the centerline geometry for an off-line elevated station. The station is at constant elevation. A vehicle accessing the station would switch off the main line and enter the deceleration lane. The deceleration lane is long enough to allow the vehicle to come to a complete stop. The station can contain several load-unload berths in a linear fashion; the more berths, the higher the capacity in vehicles per hour. In Chapter 9 , it will be shown that the capacity C of the station is given by Table 1, where N is the number of berths. Stations with more than 6 berths are possible also.

Table 1

C - Vehicles/Hour

N	Combined Load-Unload Platform	Separate Load-Unload Platform
1	190	-
2	360	296
3	515	-
4	660	524
5	810	-
6	950	960

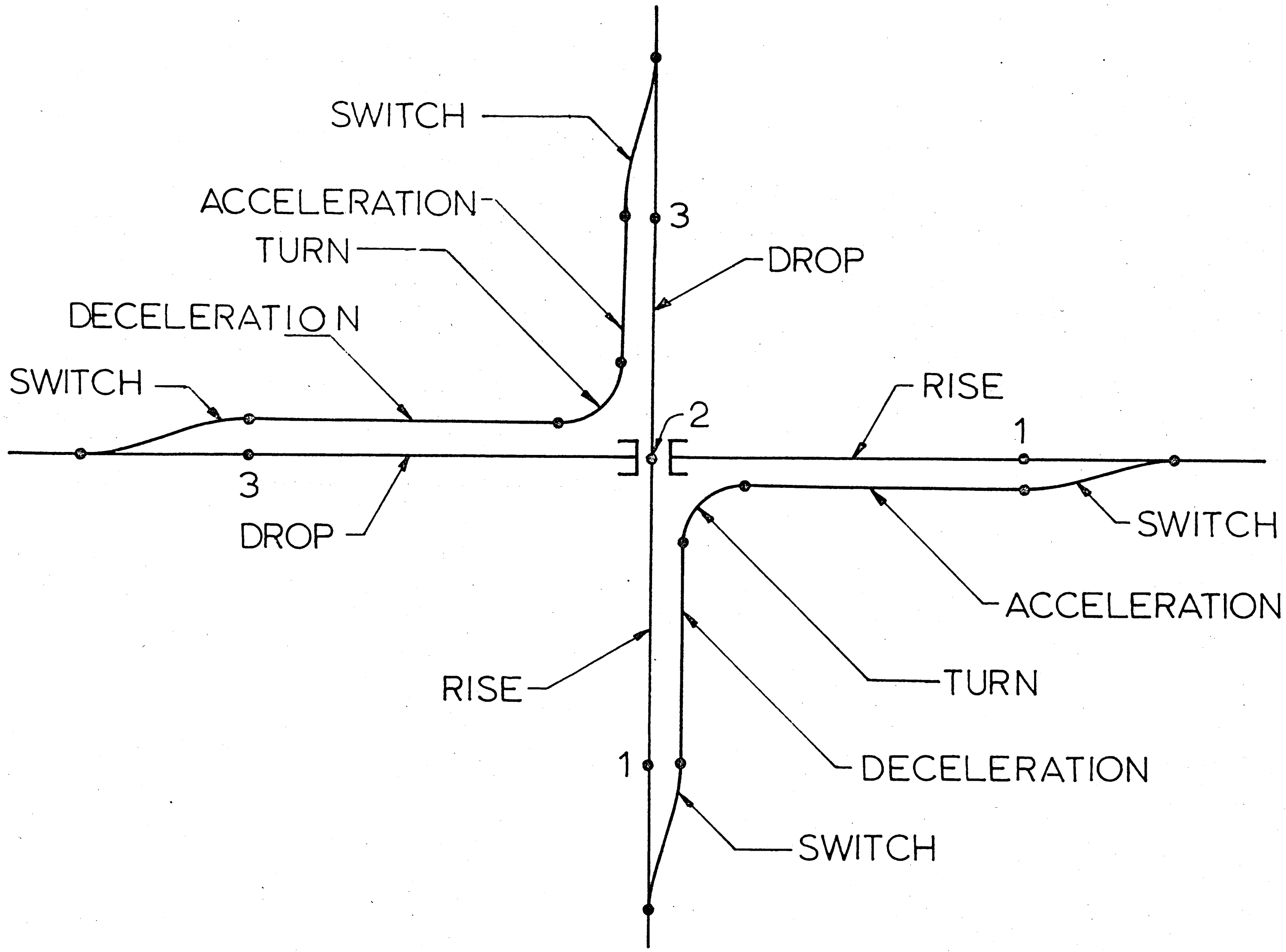

Fig 2 (a) Vehicle Interchange, Plan View; Grade Change on Main Line (not to scale)

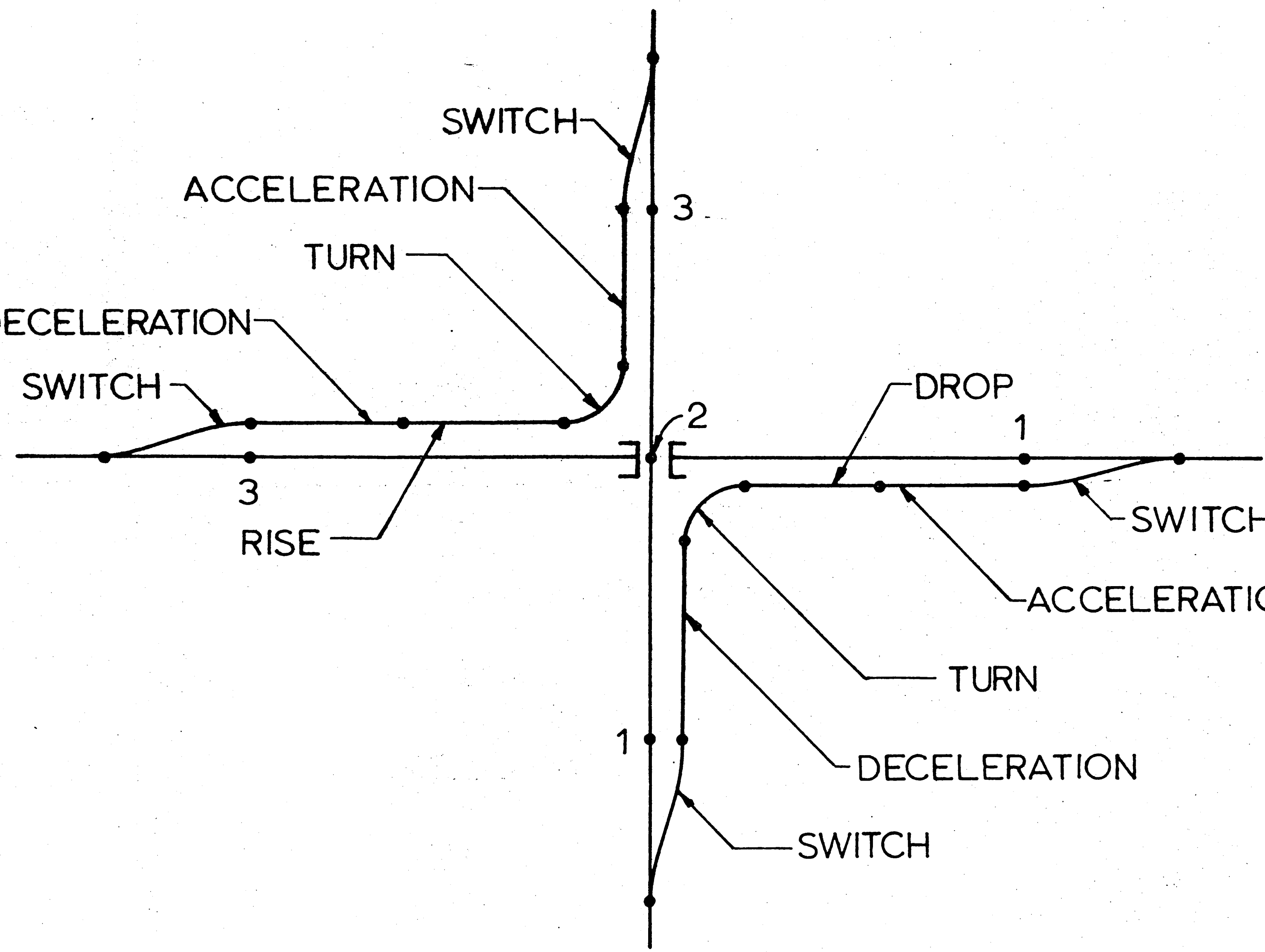

Fig 2 (b) Vehicle Interchange Plan View Grade Change on Ramps (not to scale)

However, the studies presented in Chapter 10 show that trip demand levels in the Twin Cities and Duluth will not require the larger stations. The vehicle queues before and after the load-unload areas are each also assumed to hold N vehicles. It remains to be shown that this will permit a sufficient queue for the station to operate with a low abort rate. Upon leaving the station exit queue, the vehicle accelerates to line speed and accesses the line via the switch. The switches are geometrically similar and have identical length. The acceleration and deceleration lanes have identical length.

Vehicle Interchange

Figures (2a) and (2b) show vehicle interchanges for a network of one-way lines. Vehicles can travel straight through the interchange or execute a turn. Vehicles turning would exit via a switch and do any necessary deceleration in the deceleration lane which would be long enough for a vehicle to completely stop. Any slot slipping or queueing manipulations would take place in the turn. Vehicles would access the main line by accelerating in the acceleration lane and then passing through a switch. The switches and acceleration and deceleration lanes are identical to those for stations.

A vertical clearance is required in the interchanges where the guideways cross. The differences between the two interchanges is in how the vertical clearance is obtained. In Figure 2(a) one of the main lines rises and the other drops to effect the clearance. All four switches are at the same elevation. In Figure 2(b), the grade change is taken up in the turn ramp. Each of the two main lines is at a constant elevation and one is higher than the other. The grade changes are placed to take advantage of gravity in slowing and accelerating the vehicle.

<u>Acceleration Lanes and Switches</u>

An acceleration lane must have sufficient length so that a vehicle can start at rest and reach the speed of vehicles on the main line. It was shown in [3] that the length requirement in feet is given by

$$L = v^2/2a + va/2J \ , \tag{1}$$

where v is speed in ft/sec, a is acceleration in ft/sec^2 and J is jerk in ft/sec^3. Equation (1) is shown plotted in Figure 3 as a function of speed.

Figure 4 shows the centerline geometry for a four-spiral switch. H is the centerline separation between the main line and an acceleration or deceleration ramp. The switch uses 4 spirals of the form

$$\beta = cs^2 \ , \tag{2}$$

where β is the inclination of the spiral to a straight line, s is distance along the curve and c is a constant. The spirals are matched for position, slope and curvature at the junction points 1,2,3,4, and 5. The first spiral winds, the second unwinds, the third winds and the fourth unwinds. The curvature at the

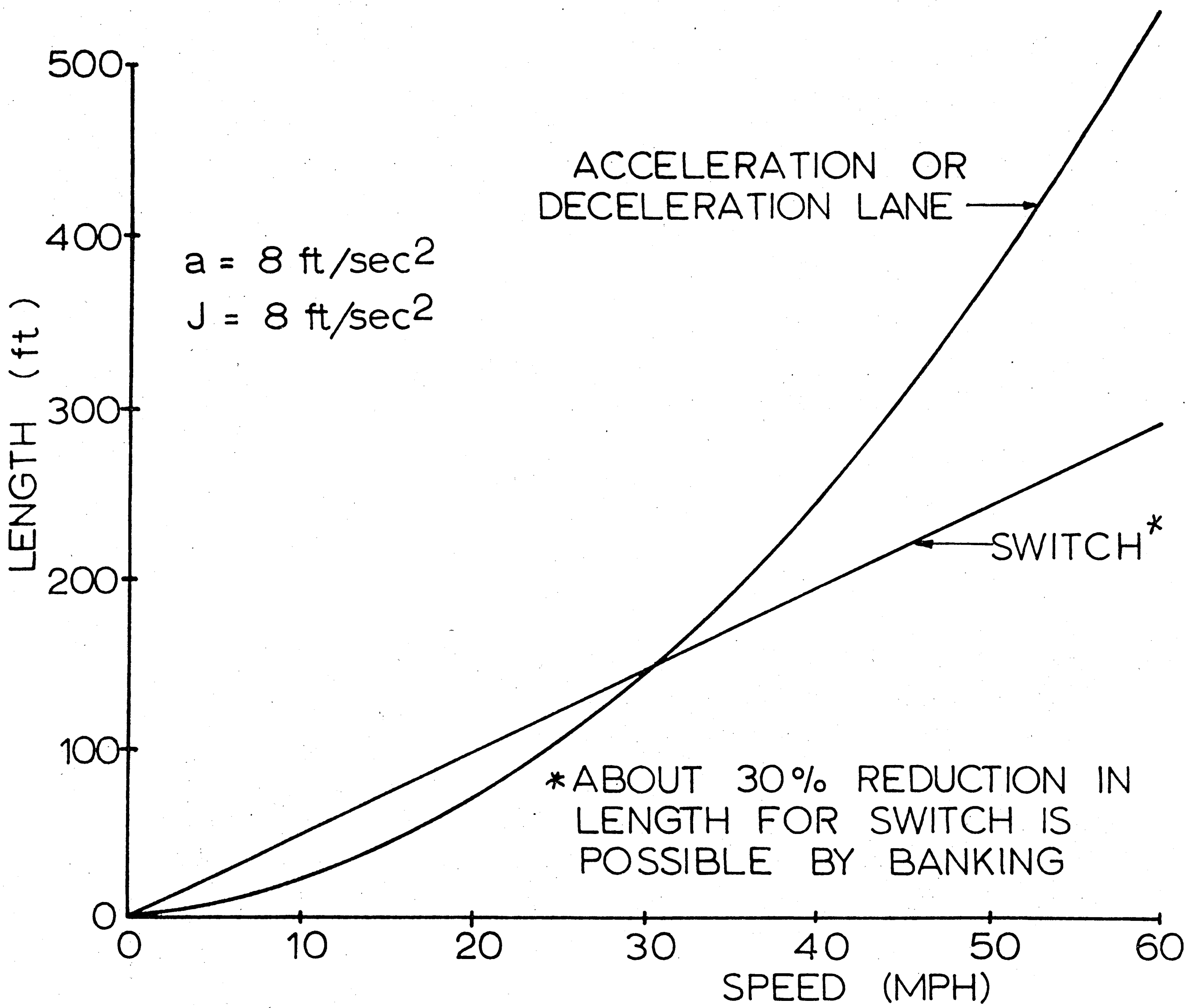

Fig 3 Switch and Acceleration Lane Length

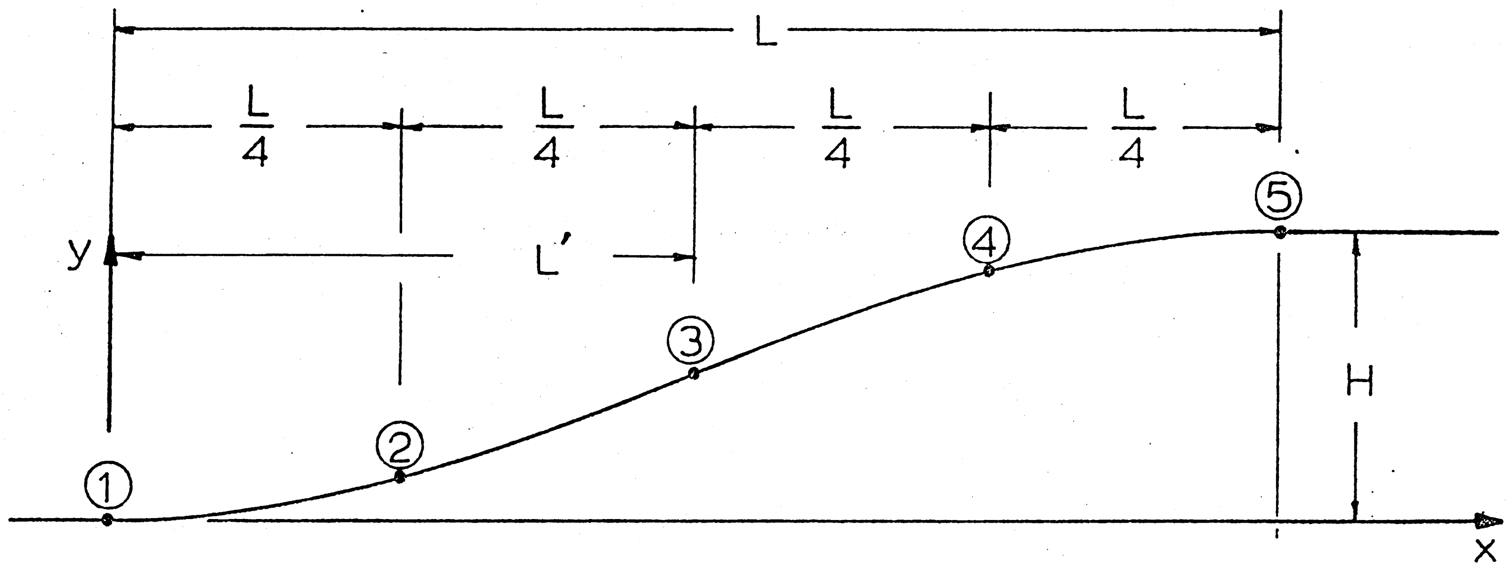

Fig 4 Four Spiral Switch or Grade Changer

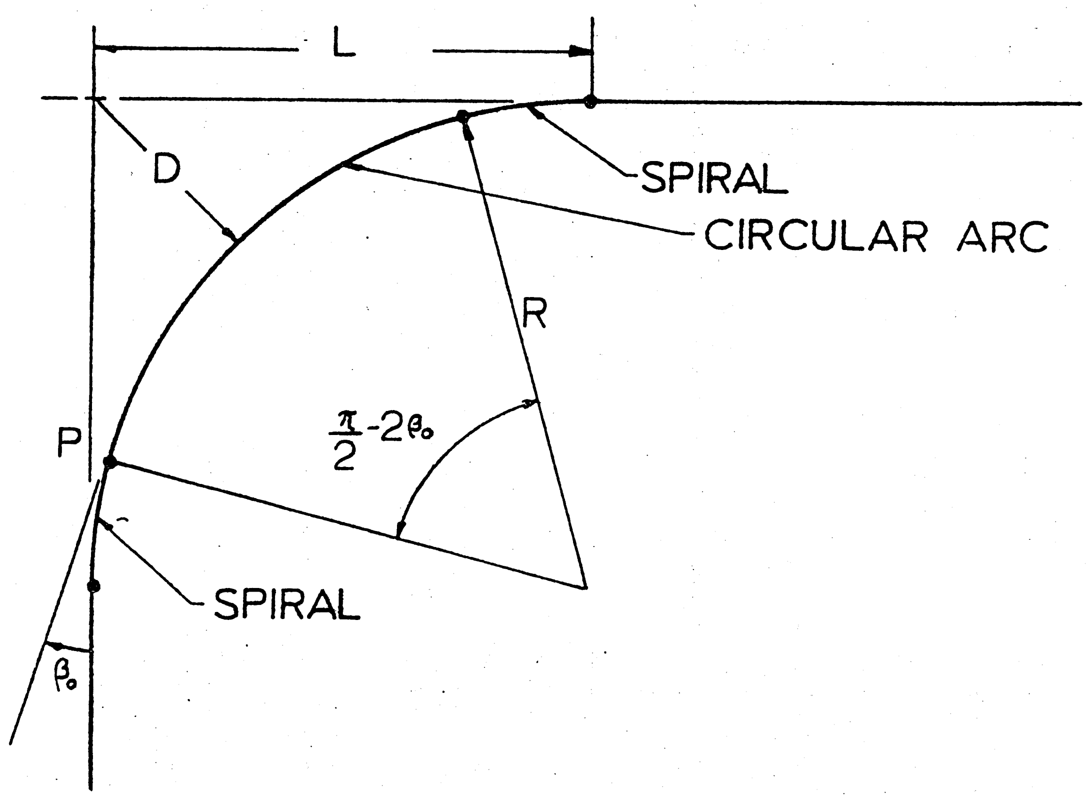

Fig 5 Right Angle Turn

junction points 1, 3 and 5 is zero. Maximum curvature is attained at points 2 and 4. The slope of the spiral set is zero at both ends. The use of the spiral set as a switch permits acceleration and deceleration lanes to be packaged parallel and near to the main traffic lane. Spirals have traditionally been used in railway and highway design to facilitate the gradual change of curvature and to limit lateral jerk. The lateral jerk on any of the four spiral segments is constant and given by

$$J = 32H\,(v/L)^3 . \tag{3}$$

Equation (3) is derived in [3]. As shown in Figure 4, L is the total switch length in feet and H is the guideway separation. Equation (3) can be inverted and there results

$$L = v\,(32H/J)^{1/3} \tag{4}$$

as an equation for the switch length. Equation (4) is plotted in Figure 3 for H = 8 feet and J = 8 ft/sec^3. A detailed investigation of the effect of superelevation on switch length is presented in [4]. It was found that significant reductions in switch length are possible by using superelevation. Furthermore, it appears that banking can be implemented in switches, at least for some forms of suspension.

Horizontal Curve Design

Figure 5 shows a right angle turn for the interchange. The turn uses spirals to blend the straight line acceleration and deceleration ramps to the circular arc. Motion along the curve was analyzed in detail in [4] and some of the main results pertinent to design will be quoted here. The important geometric dimensions are given by

$$L = C^{-1/2}(\beta_o^{1/2} + 1/3\ \beta_o^{3/2} - 1/5\ \beta_o^{5/2} - 1/21\ \beta_o^{7/2}) + \sqrt{2}\, R \sin(\pi/4 - \beta_o) \tag{5}$$

$$D = \sqrt{2}\, C^{-1/2}(1/3\ \beta_o^{3/2} - 1/21\ \beta_o^{7/2}) + R\,\{\sin(\pi/4 - \beta_o) - 1 + \cos(\pi/4 - \beta_o)\}, \tag{6}$$

where

$$\left.\begin{aligned} R &= v^2/a \\ \beta_o &= a^2/2Jv \\ \text{and}\quad C &= J/2v^3 \end{aligned}\right\} \tag{7}$$

Equations (5), (6) and (7) apply to unbanked curves. It was quantitatively shown in [4] that banking can be used to effect substantial reductions in discomfort.

Some numerical results were obtained also in [4] corresponding to $v = 16$ ft/sec, $a = 8$ ft/sec^2 and $J = 8$ ft/sec^3. It was found that $L = 40$ feet and $D = 14$ feet. This means that if a right angle unbanked turn has these dimensions, it will effect a maximum acceleration of 8 ft/sec^2 and a maximum jerk of 8 ft/sec^3. If banking is used, or if the speed is smaller, then the discomfort will be lessened. A right-angle turn with these dimensions will be considered for the remainder of this chapter.

Figure 6 demonstrates the packageability of the interchange on street corners. Say that a building is located at a corner and the guideways are not to interfere with the building. It is assumed in the figure that the total guideway width is 8 feet. This means that for no interference, the acceleration and deceleration lane centerline must have a 13-foot separation from the building. The main guideway must be at a 21-foot separation from buildings. This is possible so long as buildings on opposite sides of the street are separated by at least 42 feet. Under this condition, the interchange can be placed on corners. In the Minneapolis CBD, building separations are typically much larger than 42 feet so that placement would not pose a problem.

Vertical Curve Design

We next consider the problem of designing vertical curves for elevation changes. We will analytically consider the problem of connecting two horizontal lines at different elevations. This can be done using the spiral set of Figure 4. It will be used in the vertical plane instead of in the horizontal plane as for the previously designed switches. The spiral set was previously used by McConnell [5] to accomplish grade changes on automotive test tracks. A detailed analysis of both constant speed motion and zero fore-aft thrust motion along the spiral

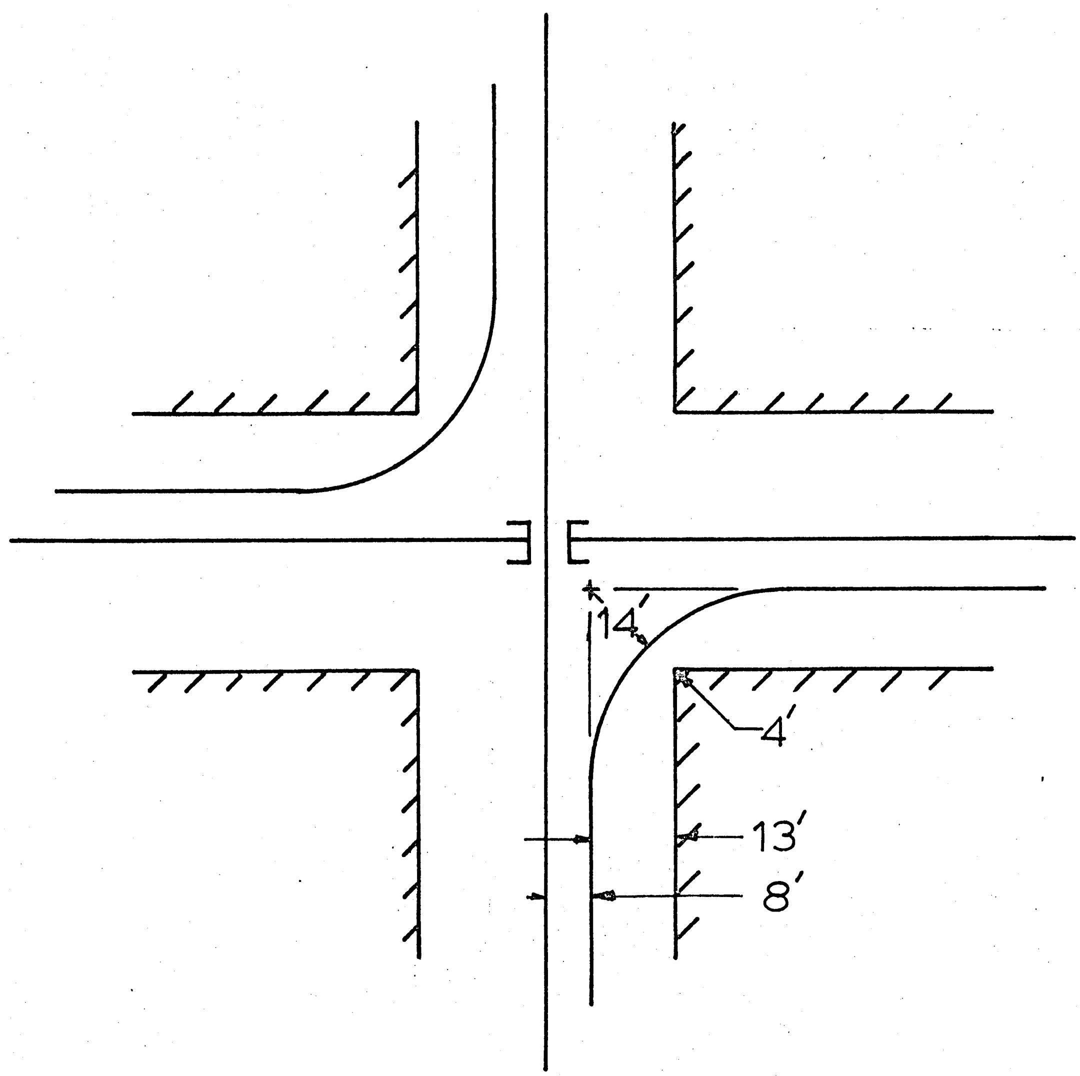

Fig 6 Packaging an Interchange on a Corner

set is presented in [4]. Some numerical values were obtained for the grade rise and grade drop of Figure 2(b). Ten-foot elevation changes were assumed and zero thrust motion was considered. The zero thrust motion uses the elevation changes to accomplish slow-downs or speed-ups of vehicles. 16 ft/sec (about 10 MPH) was taken at the top of the grade changes. Under zero-thrust motion, it follows that the speed at the bottom of the grade changer would be 28 ft/sec (about 18 MPH). It was found that with a 120-foot-long grade changer, the effective jerk and acceleration sensed by a passenger would be respectively about 8 ft/sec^3 and 6 ft/sec^2. So, a 120-foot-long ramp would be required in Figure 2(b) for the grade rise as well as the grade drop.

We will next discuss the problem of constant speed motion on the spiral set of Figure 4. Equations for the effective jerk and acceleration sensed by passengers were derived in [4]. The equations include a parameter α defined by

$$\alpha = H/L'. \tag{8}$$

Geometrically, α is the centerline slope at the point 3 of the figures. The equations are:

In $0 < x < L'/2$,

$$a = [2g^2(1-\cos\beta) + \frac{16\alpha^2}{L'^4} v^4x^2 + \frac{8g\alpha}{L'^2} v^2x\,(1-\cos\beta)]^{1/2} \tag{9}$$

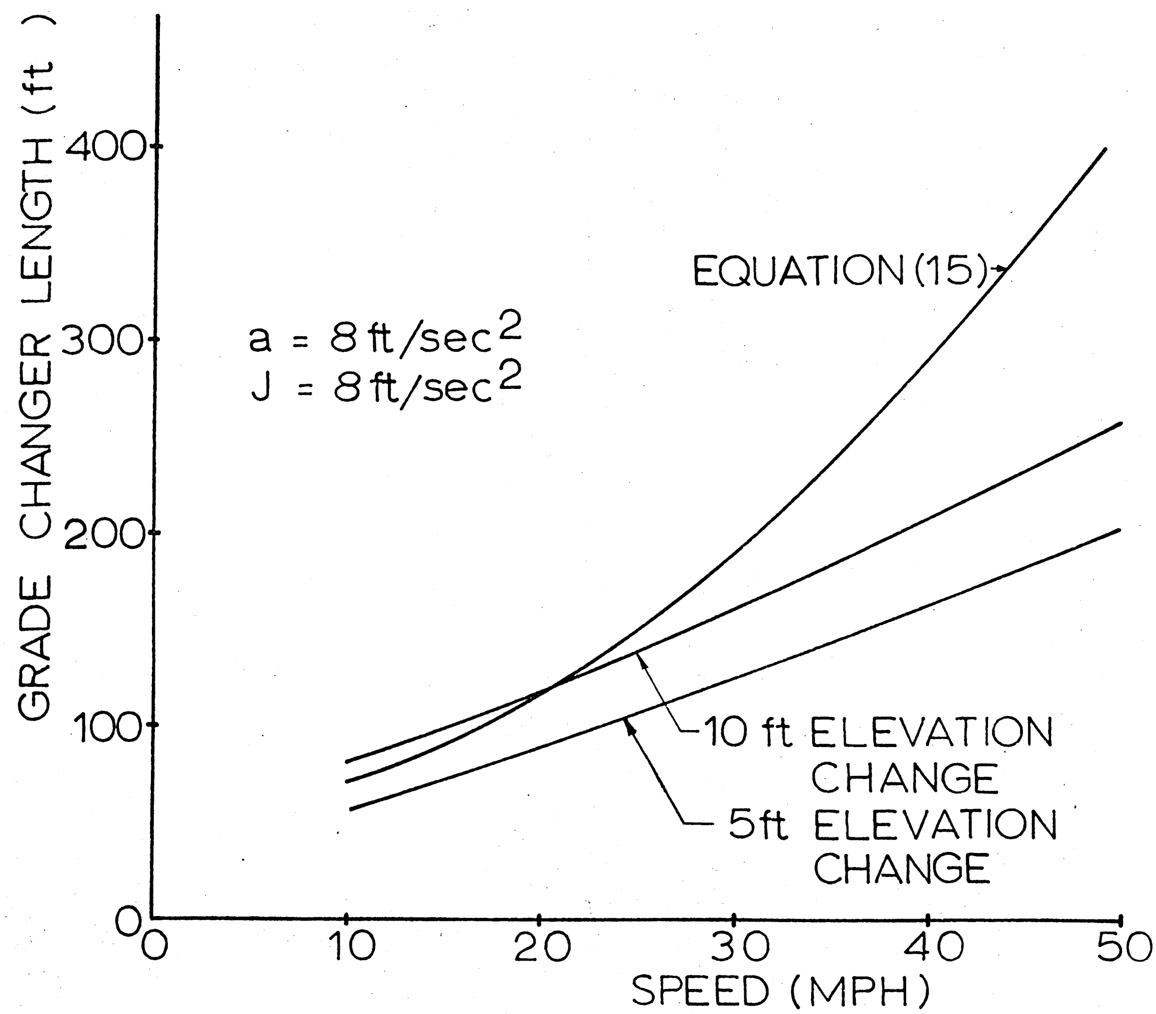

Fig 7 Design Curves for Constant Speed Grade Changes

and $$J = \frac{4\alpha v}{L'^2} [g^2x^2 + v^4 + 2\ gv^2x \sin \beta]^{1/2}, \qquad (10)$$

where $$\beta = \frac{2\alpha}{L'^2} x^2 . \qquad (11)$$

Geometrically, β is the centerline slope at x.

In $L'/2 < x < L'$,

$$a = [2g^2(1-\cos \beta) + \frac{16\alpha^2}{L'^2} v^4(1-\frac{x}{L'})^2 + \frac{8g\alpha}{L'} v^2(1-\frac{x}{L'})(1-\cos \beta)]^{1/2} \qquad (12)$$

and $$J = \frac{4\alpha v}{L'} [g^2(1-\frac{x}{L'})^2 + \frac{v^4}{L'^2} - \frac{2gv^2}{L'} (1-\frac{x}{L'}) \sin \beta]^{1/2} \qquad (13)$$

where $$\beta = -\frac{2\alpha}{L'^2} + \frac{4\alpha}{L'} x - \alpha . \qquad (14)$$

The equations were programmed on a digital computer in order to obtain the design curves of Figure 7. The curves show the length requirements of a grade changer for 5' and 10' elevation changes. 5' would be appropriate if half of the clearance requirement is absorbed by the upper guideway and half by the lower. 10' would apply to the case where all of the clearance requirement is absorbed by the upper. The numerical procedure followed was to fix the speed and find, by trial and error, the shortest length that would keep $a \leq 8$ ft/sec^2 and $J \leq 8$ ft/sec^3.

The design curves of Figure 7 will have many applications in PRT geometric design. The one that will be considered in detail here is the use in the interchange design of Figure 2(a). Another could be to rise above or drop below the existing and proposed Minneapolis skyway system. But this is beyond the scope of the present report which suggests a constant-level downtown guideway system at a higher level than the skyway system. For the interchange of Figure 2(a), it is of interest to see if the grade change requirement will dictate the interchange size or if the guideway centerline separation, turn size and acceleration lane length will govern. The former can be estimated from Figure 7. The latter is equal to the 8-foot centerline separation plus 40-foot turn requirement plus the acceleration lane requirement of (1). If $a = 8$ ft/sec^2 and $J = 8$ ft/sec^3, and since the speed V in MPH is v/1.47, it follows that the latter length requirement in feet is given by

$$L = 48 + .74V + .135\ V^2. \qquad (15)$$

Equation 15 is shown plotted in Figure 7. The figure demonstrates that, except at less than 20 MPH for the 10' elevation change, guideway centerline separation, turn size and acceleration lane length requirement will govern. This means that if an interchange is sized according to the latter requirement, then the ride will not be too uncomfortable in the grade changes in Figure 2(a). It is recommended that whenever possible, some of the clearance requirement be taken in the lower as well as upper guideway. This is particularly true at speeds less than 20 MPH. <u>The interchange in Figure 2(a) is preferable</u>

to that in Figure 2(b) because of the smaller size requirement. It should be pointed out though that the interchange of Figure 2(b) has the advantage the passenger would not encounter as many grade changes in a typical trip. However, the grade changes which would occur would be more severe.

Mesh Space and Speed Restrictions

We next consider the problem of obtaining a minimum possible mesh spacing. Figure 8 will facilitate the derivation of a formula. The figure shows the situation with double guideway along the entire span. That is, the station and interchange switches are contiguous. It would not be possible to further reduce the mesh space. The span contains 4 switches, 2 acceleration lanes, 2 deceleration lanes, 2 turns, 2 guideway centerline separation distances and 1 station length. The station length of 30 N assumes 10-foot vehicles, with N platform spaces and N spaces in each of the two queues. The station capacity would be given by Table 1. It follows from Figure 7 that the minimum mesh spacing would be given by

$$L_{min} = 96 + 30N + 4v\ (32h/J)^{1/3} + 4(v^2/2a + va/2J), \qquad (16)$$

where v is in unit of ft/sec. If V is the speed in miles per hour, $h = 8$ ft, $a = 8$ ft/sec^2 and $J = 8$ ft/sec^3, then L_{min} in feet is given by

$$L_{min} = 96 + 30N + 22V + .54V^2\ . \qquad (17)$$

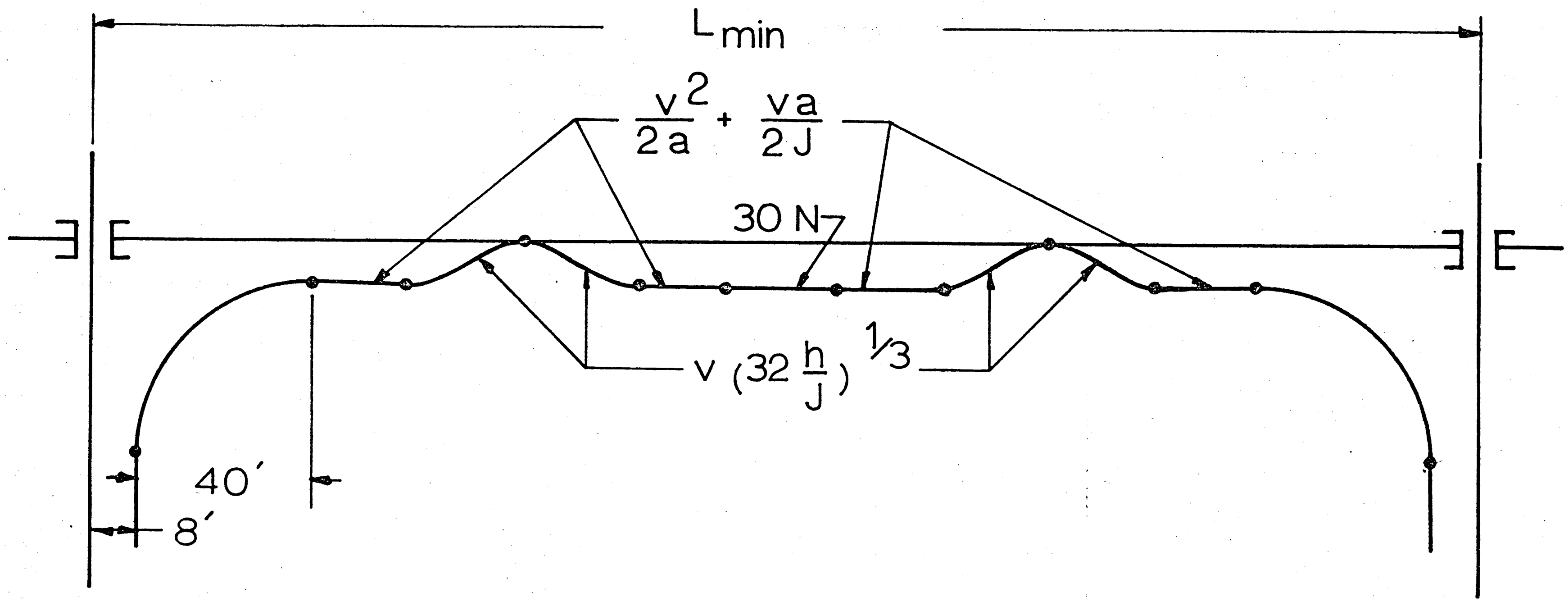

Fig 8 Minimum Mesh Spacing

Figure 9 shows (17) plotted for N = 1 and N = 6. It is worth mentioning that the 8 feet is a conservative choice for the centerline separation since 6 or 7 feet would be possible if vehicles are narrow.

Figure 9 leads to rather stringent design restrictions for downtown networks. For example, in downtown Minneapolis, the blocks are uniformly 1/12 of a mile or 440 feet long. Say that a network plan involves PRT lines every second block and a station at the midpoint of the grid as shown in Figure 10a. Say that furthermore the plan calls for stations with N = 6. Then the maximum possible speed is 18 MPH and 15 MPH would be more reasonable. To maintain a reasonable separation between vehicles (6 feet), the minimum time headway would be 3/4 second. As another example, say that a network plan calls for a line down every block and a station on every block as shown in Figure 10b. Say that the system is a 1-second headway system and that to maintain a reasonable separation (5 feet) between 10-foot long vehicles, a 10 MPH line speed is required. Then it follows from (9) that N = 2 would be the largest permissible station size. Larger stations would be possible with larger headway times and slower speeds. An alternative configuration is that shown in Figure 10c. That configuration would be possible with a 10 MPH line speed.

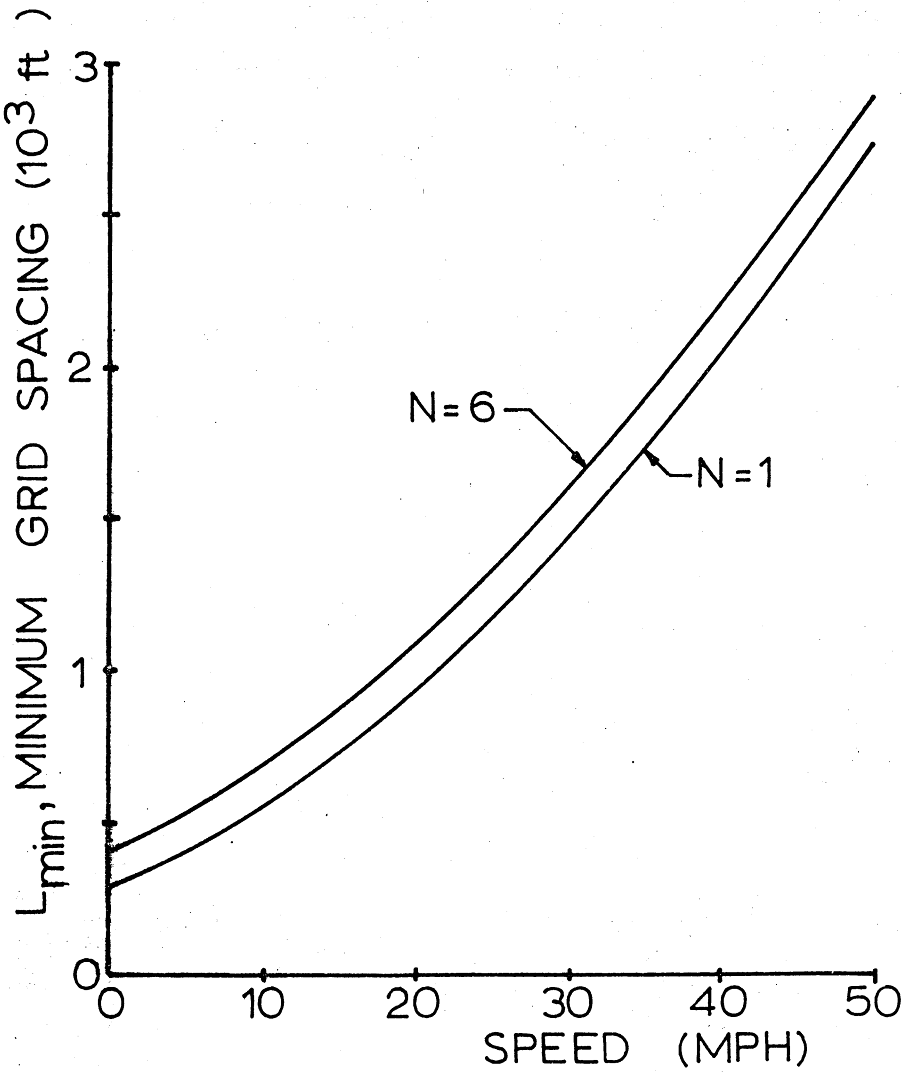

Fig 9 Minimum Mesh Spacing

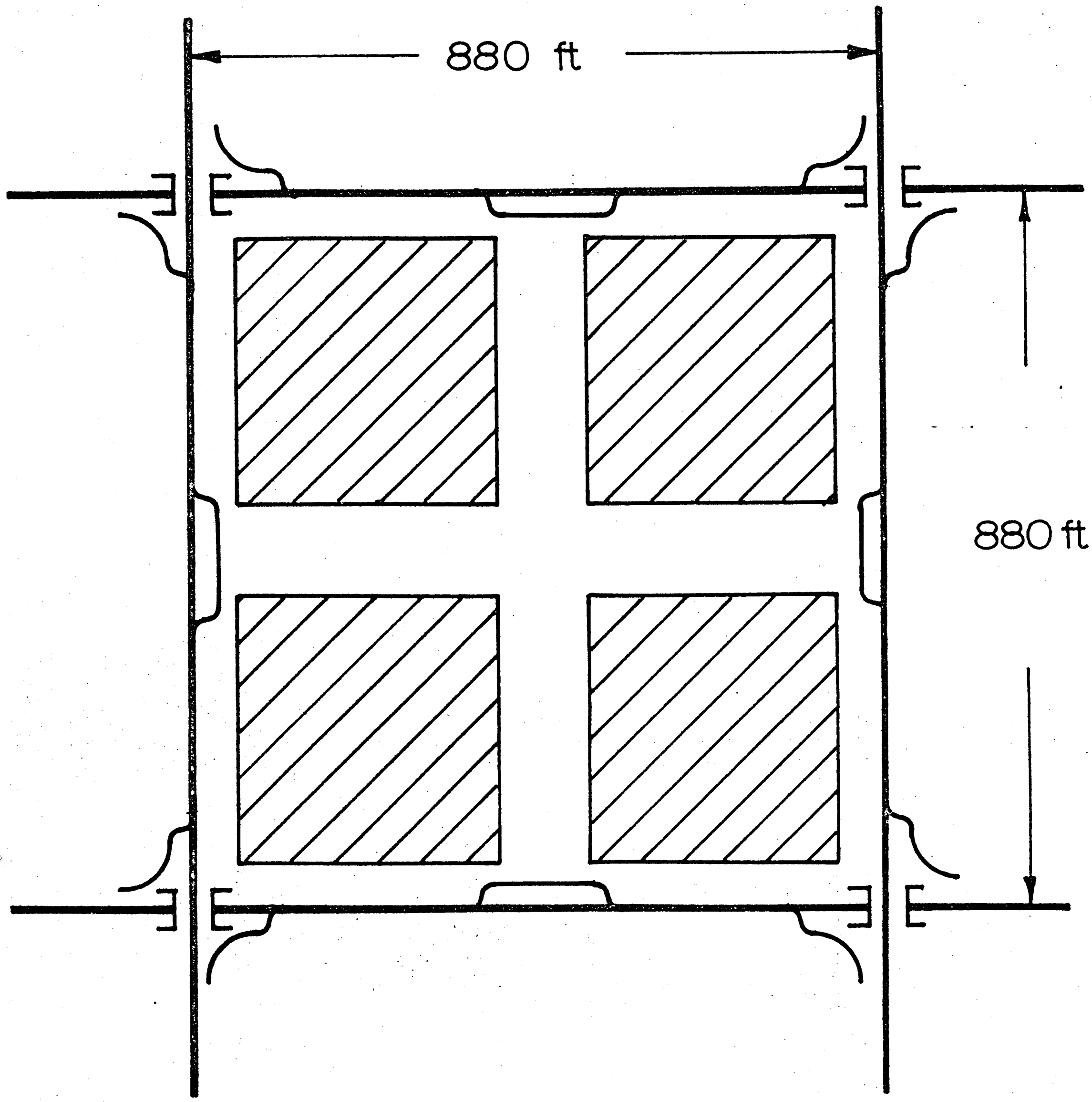

Fig 10(a) Alternate Downtown Network Configuration; 15 MPH, 0.75 sec Minimum Headway

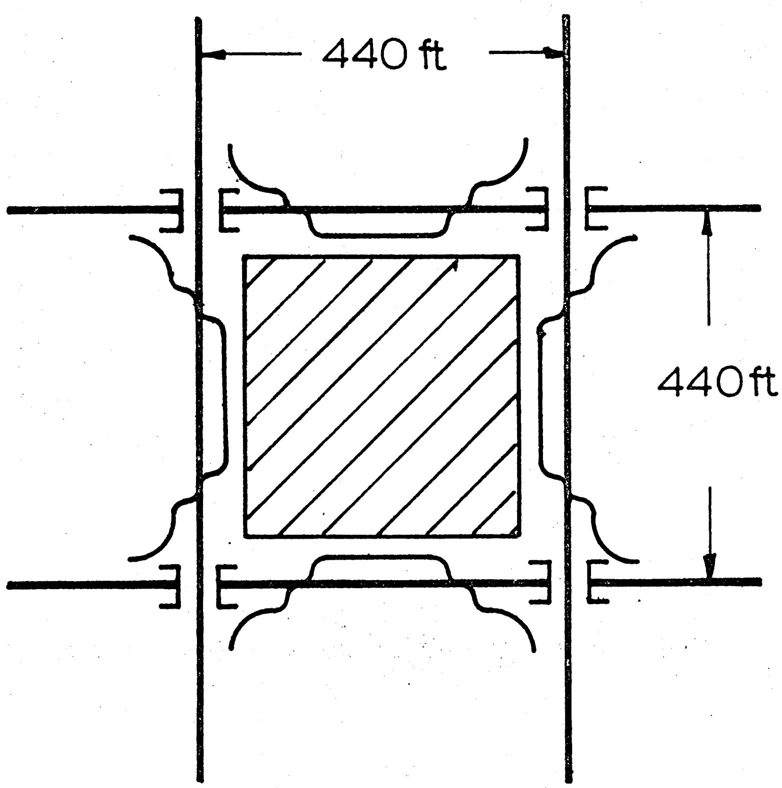

Fig 10(b) Alternate Downtown Network Configuration, 10 MPH, 1.0 sec Minimum Headway

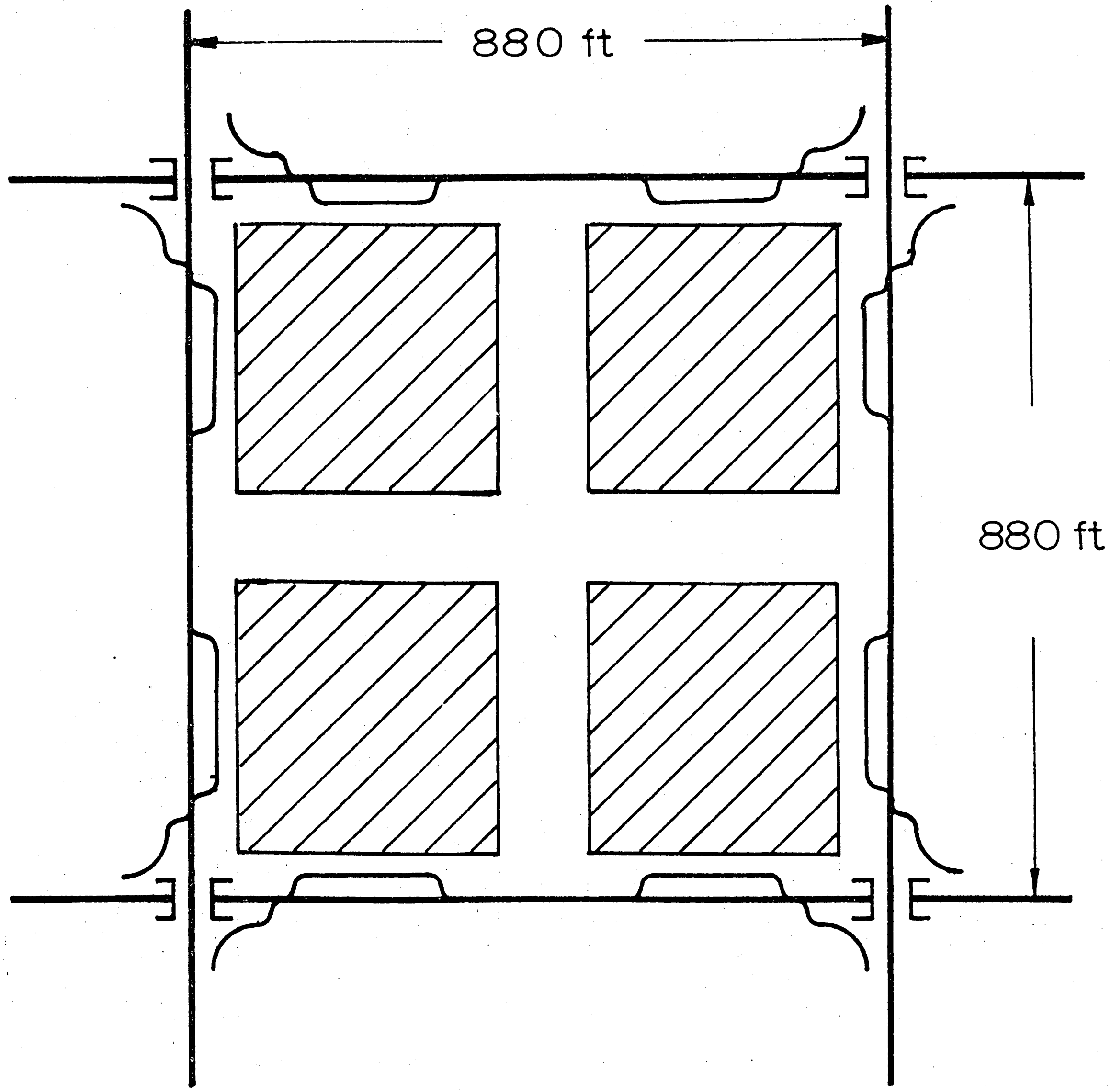

Fig 10 (c) Alternate Downtown Network Configuration; 10 MPH, 1.0 sec Minimum Headway

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Chapter 8

Theory of Design of PRT Systems for Safe Operation

Introduction

The objective of this chapter is to provide the theoretical background needed to develop basic specifications for personal rapid transit (PRT) systems related to safe operation. A safe PRT system is defined as one in which, in the case of the most serious combination of system failures conceivable, no one will be injured. In this chapter, the consequences of failure of a vehicle moving in a string of vehicles are considered and are used to develop specifications for safe operation.

The chapter is divided into three parts. In the first part, the details of the collision between two vehicles containing unconstrained occupants is considered in order to determine tolerable collision velocities between vehicles equipped with energy absorbing bumpers and padded interiors. In the second part, the kinematics of a failed vehicle followed by a string of vehicles is considered both with the failed vehicle on the main line and on the merging line. The failure detection and control system is designed to detect anomalous deceleration of a vehicle and to cause following vehicles to decelerate at a rate such that any collisions occur at a relative velocity below a specified limit. In the third part the frequency of nuisance collisions in a PRT network is related to the mean time to failure of a single vehicle.

Numerical examples are given to illustrate the theory and to provide quantitative insight into the problems. The ranges of variables chosen for the calculations are illustrative. Other combinations of parameters can easily be inserted into the equations derived.

The Dynamics of a Collision

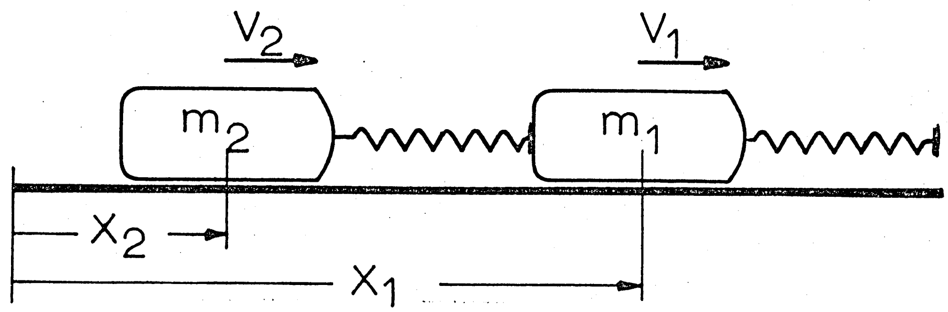


Figure 1. Colliding vehicles

Assume a vehicle of mass m_2 and velocity V_2 collides with a vehicle of mass m_1 and velocity V_1, where $V_2 - V_1 = \Delta V > 0$ is the collision velocity. Let each vehicle be equipped with a spring bumper of spring constant k and maximum deflection δ_M. The vehicles are assumed to be subjected to braking forces f_1 and f_2, respectively. The equations of motion of the two vehicles during the collision are:

$$m_1 \ddot{x}_1 = + k\delta - f_1 \tag{1}$$

$$m_2 \ddot{x}_2 = - k\delta - f_2 \tag{2}$$

in which

$$x_1 - x_2 = \ell - \delta \tag{3}$$

where ℓ is the distance between mass center of two vehicles touching each other with zero spring deflection and δ is the spring deflection.

If (1) is divided by m_1 and subtracted from (2) divided by m_2, and (3) is substituted, the result is

$$\ddot{\delta} + \omega^2\delta = A \tag{4}$$

in which

$$\omega^2 = k(1/m_1 + 1/m_2) \tag{5}$$

and

$$A = f_1/m_1 - f_2/m_2 \tag{6}$$

The solution of (4) subject to the initial conditions $\delta(0) = 0$ and $\dot{\delta}(0) = \Delta V$ is

$$\delta(t) = \frac{\Delta V}{\omega} \sin \omega t + \frac{A}{\omega^2}(1 - \cos \omega t) \tag{7}$$

This solution is assumed valid at least until δ reaches the maximum deflection δ_M. Beyond this point non-linearities can change the solution significantly.

Assume unconstrained passengers are riding in forward-facing positions in the vehicles. Upon collision, the passengers in vehicle 1 are supported by their seats and the passengers in vehicle 2 continue forward at velocity V_2 until they collide with the padded interior of the vehicle a distance L in front of the passengers. We wish to find the relative velocity V_c with which the passengers collide with the padded interior. The solution is obtained by substituting (7) into (2) and integrating. Thus

$$V_2 - \dot{x}_2 = \tfrac{1}{2}\beta\Delta V(1 - \cos \omega t) + \tfrac{1}{2}\beta\frac{A}{\omega}(\omega t - \sin \omega t) + A_2 t \tag{8}$$

$$V_2 t - x_2 = \tfrac{1}{2}\beta\frac{\Delta V}{\omega}(\omega t - \sin \omega t) - \tfrac{1}{2}\beta\frac{A}{\omega^2}(1 - \cos \omega t) + (\tfrac{1}{2}\beta A + A_2)\frac{t^2}{2} \tag{9}$$

in which

$$A_{1,2} = f_{1,2}/m_{1,2}$$

and

$$\beta = 2m_1/(m_1 + m_2) \simeq 1.$$

The quantity $V_2 t - x_2$ is the distance the unconstrained passenger travels from his seat. When $V_2 t - x_2 = L$, the passenger hits the padded interior of the passenger compartment with velocity $V_c = V_2 - \dot{x}_2$ determined by eliminating t between the equations (8) and (9).

Let us consider some examples. First, from (7), ω can be determined in terms of the maximum spring deflection δ_M which is given by

$$\delta_M = \frac{A}{\omega^2} + \frac{\Delta V}{\omega}\sqrt{1 + \left(\frac{A}{\omega\,\Delta V}\right)^2} \tag{10}$$

The solution of this equation for ω^2 is

$$\omega^2 = \frac{\Delta V^2}{\delta_M{}^2} + \frac{2A}{\delta_M} \tag{11}$$

Given the masses of the vehicles, the spring constant follows from (5).

It is helpful to know the conditions under which the terms containing A in equations (7) thru (11) can be neglected. This assumption is acceptable if the ratio $\Delta V\omega/A$ is large. Using (11), this ratio is

$$\frac{\Delta V\omega}{A} = \frac{\Delta V^2}{A\delta_M}\sqrt{1 + \frac{2A\delta_M}{\Delta V^2}} \tag{12}$$

Thus $V\omega/A$ is large if $\Delta V^2/A\delta_M$ is large. A tolerable value of ΔV can be estimated from experience by judging the severity of dropping an object from a certain height h. Then $\Delta V = \sqrt{2gh}$. Assuming $h = 1$ meter, $\Delta V \simeq 5$ m/s. The quantity A can be designed to be of the order $0.2g = 5\ \text{m/s}^2$ or less. An appropriate value of δ_M can be derived by considering from (1) and (2) the accelerations produced by the collision. We see that the component of acceleration of vehicle 1 due to the collision has a magnitude $k\delta_M/m_1$. Assuming the two vehicles have approximately the same mass,

$$\frac{k\delta_M}{m_1} \simeq \tfrac{1}{2}\omega^2\delta_M \simeq \tfrac{1}{2}\frac{\Delta V^2}{\delta_M} \tag{13}$$

If $\delta_M = 0.5$ m, $k\delta_M/m_1 \simeq 2.5g$. This would seem to be reasonable. A value $\delta_M = 1$ meter is probably about as large a value as would be practical. In that case, the deceleration would peak at only 1.25g.

Now consider equations (8) and (9). δ_M occurs approximately when $\omega t = \pi/2$. For this value, assuming $\beta = 1$,

$$V_2 - \dot{x}_2 = \tfrac{1}{2}\Delta V + 0.29\,\frac{A}{\omega} + \frac{\pi A}{2\,\omega^2}$$

From (11), let $\omega \simeq \Delta V/\delta_M$. Then

$$V_c = V_2 - \dot{x}_2 = \tfrac{1}{2}\Delta V + 0.29\,\frac{A\delta_M}{\Delta V} + \frac{\pi A_2\delta_M}{2\,\Delta V} \tag{14}$$

From the above order-of-magnitude analysis, it is clear that the first term in (14) dominates, i.e. V_c in about one half ΔV. From (9), we have for this case

$$L = V_2 t - x_2 \simeq 0.29\delta_M \tag{15}$$

Thus if V_c is to be reduced to one half of ΔV, the space between the passenger and the padded interior dashboard must be no more than 15 cm if $\delta_M = 0.5$ m. If the collision occurs at $\omega t = \pi$, the first term in (8) doubles, and the first term of (9) increases by $\pi/.57 = 5.5$. If we try to double L for a given δ_M, $V_c \simeq 0.73\Delta V$. To reduce V_c to $\tfrac{1}{4}\Delta V$, we must reduce L to $0.5(\pi/3 - \sqrt{3}/2)\delta_M = 0.09\delta_M$. The only way such a small value could be attained would be to incorporate a movable padded dashboard which would move toward the passenger as the spring deflects. This does not appear to be entirely impractical and should be considered.

Another possibility is to take advantage of the fact that δ can be measured on vehicle 2 and used to control braking by making $f_2 = f_2(\delta)$. Let the value of f_2 before collision be $f_2(0)$. Then if in (2) we let

$$f_2(\delta) = f_2(0) - k\delta \tag{16}$$

the deceleration rate of vehicle 2 will not increase during collision, i.e., (2) becomes $m_2\ddot{x}_2 = -f_2(0) = \text{const}$. This type of control of course means that vehicle 1 will accelerate faster than before after the collision, but this means only that the passenger will be pushed into the seat back a little harder - in vehicle 1 no one is thrown forward.

Let us calculate the motion of vehicle 1 and in particular $\ddot{x}_1$ if we assume (16). Using (16), (3) and (2), (1) can be written

$$\ddot{\delta} + \omega_1^2\delta = A \tag{17}$$

in which $\omega_1^2 = k/m_1$ and A is given by (6) in which $f_2 = f_2(0)$. The initial conditions are the same as those used in solving (4) and hence the solution is the same if ω_1 is substituted for ω. The maximum acceleration of vehicle 1 is, from (1),

$$(\ddot{x}_1)_{max} = \omega_1^{\,2}\delta_M - A_1 \tag{18}$$

in which, in analogy to (11), $\omega_1^{\,2} \simeq \Delta V^2/\delta_M^{\,2}$. Thus

$$(\ddot{x}_1)_{max} = \Delta V^2/\delta_M - A_1 \tag{19}$$

In this case we are not constrained to keep ΔV small in order to keep V_c small. We want to allow ΔV to be as large as possible consistent with safety of the passengers in vehicle 1. The safety of these passengers is determined by a limit on $(\ddot{x}_1)_{max}$, the acceleration people can take with seats extended to support the entire body including the head. A great deal of experimental data shows that values up to 30 to 50g's are tolerable without injury. But let us be more conservative and limit $(\ddot{x}_1)_{max}$ to say 10g's. Then from (19),

$$\Delta V^2 \leq \delta_M(10g + A_1) \tag{20}$$

A_1 is the maximum failure deceleration rate of vehicle 1. A reasonable value is obtained under the assumption that vehicle 1 locks wheels, or if it is air suspended, the air supply fails. In either case assume $A_1 \simeq 0.7g$. The possibility that the vehicle could stop much more suddenly is ruled out in this analysis because, in a properly designed system, this type of failure is judged to be in the "Act of God" category. Some discussion of wedging of vehicles is given at the end of the second section. Then

$$\Delta V \leq \sqrt{\delta_M(10.7)(9.8)} \simeq 7 \text{ m/s}$$

for $\delta_M = 0.5$ m/s.

Another important criterion is the amount of overload produced in the motors of vehicle 2. This is determined by the magnitude of $f_2(\delta)$ from (16). We see that as δ builds up, the required braking decreases to zero at which point the thrust must be reversed to a maximum value

$$\frac{|f_2(\delta)|}{m_2} = \frac{k}{m_2}\delta_M - \frac{f_2(0)}{m_2} = \omega_2^{\,2}\delta_M - A_2 \tag{21}$$

From (18), if $m_1 = m_2$, this is exactly $(\ddot{x}_1)_{max}$. If normal acceleration to line speed occurs at about 0.25g, the above suggested value of $(\ddot{x}_1)_{max} = 10g$ corresponds to an overload ratio of 40 to 1. Even for a very short period this is probably excessive. A 10 to 1 overload would give $(\ddot{x}_1)_{max} = 2.5g$ and in this case eq. (19) gives, for $\delta_M = 0.5$ m,

$$\Delta V \leq \sqrt{\delta_M (3.2) g} \simeq 4 \text{ m/s}$$

Comparing with the previous case, a value $\Delta V = 5.6$ m/s would have produced a $V_c = \frac{1}{2}(5.6) = 2.8$ m/s if $L = 0.29\delta_M$ or $V_c = .73(5.6) = 4.1$ m/s if $L = 0.58\delta_M$. With a non-active padded dashboard, the later figure is probably more practical. The value of V_c it produces is equivalent to dropping an object from a height of 86 cm. This may be marginally satisfactory but lower values would be desirable. Application of a maximum thrust of 10 times normal deceleration would limit the deceleration of vehicle 2 to A_2, the emergency deceleration rate, and would prevent the passengers in this vehicle from being thrown against the padded dashboard. Therefore this type of active collision safety device appears worthy of developing. With this type of device, when the emergency brakes are applied to the rear car, an unsupported body would hit the padded dashboard with a velocity $V_c = \sqrt{2A_2 L}$. For $A_2 = \frac{1}{2}g$ and $L = \frac{1}{2}$ meter, $V_c \simeq 2.2$ m/s. With seats designed to permit normal braking of $\frac{1}{4}g$ to be comfortable, V_c would in practice be considerably less.

We conclude therefore that if we can limit collisions to $\Delta V \leq 5$ m/s, very little if any discomfort will be caused. A good design compromise may be to modify equation (16) to

$$f_2(\delta) = f_2(0) - \beta k \delta \qquad (22)$$

in which $0 < \beta < 1$. This will mean that the required overload on the motor is decreased at the expense of a sensation of increased deceleration by the passengers in vehicle 2.

As a matter of interest, the time required to reach maximum spring deflection δ_M from the moment of collision is

$$t = \frac{\pi}{2\omega} = \frac{\pi \delta_M}{2\Delta V} \qquad (23)$$

in which the simplified form of (11) has been used. Assuming $\delta_M = 0.5$ meter and $\Delta V = 5$ m/s, $t \simeq 0.15$ sec. Overloading of the motors would occur over a small fraction of this time.

Using (11) for computation of ω the spring constant would be

$$k = m_1 \omega_1{}^2 = m_1 \Delta V^2/\delta_M{}^2 \qquad (24)$$

Assuming $m_1 = 1000$ kg,

$$k = 10^5 \text{ Newtons/meter}$$
$$= 560 \text{ lbf/in}$$

The Kinematics of Emergency Operations

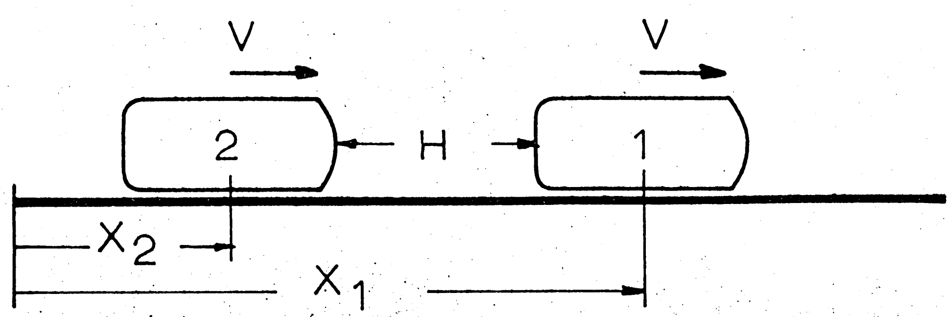


Figure 2. Vehicles traveling at line velocity V and headway H.

In this section we begin with two vehicles in a string of vehicles all traveling at line velocity V and with nose to tail headway H. At time $t = 0$, the lead vehicle is assumed to be subjected to a highly improbable but drastic failure such as a locked axle in the case of a wheeled vehicle, or delevitation in the case of an air-suspended vehicle. The failure deceleration is assumed to build up to a maximum value a_f at a constant rate J_f. After a time delay t_D required to activate the emergency control system of vehicle 2, its brakes are applied in such a way that vehicle 2 deceleration builds up to a maximum value a_e at a constant rate J_e. These deceleration profiles are approximations of actual conditions, but experience has shown that they provide sufficient accuracy, i.e., inclusion of the jerks J_e, J_f is not insignificant, but higher order rates need not be considered.

The objective of this section is to relate the headway H to the collision velocity ΔV for various values of a_e, a_f, J_e, J_f and t_D. This information is needed in the next section to determine the frequency of collisions at various values of ΔV and hence the reliability of the PRT system. In this section, the vehicles can be treated as rigid bodies.

During the constant jerk phase, the motion of the failed vehicle is given by the equations

$$\dddot{x}_1 = - J_f \tag{25}$$

$$\ddot{x}_1 = - J_f t \tag{26}$$

$$\dot{x}_1 = V - \tfrac{1}{2} J_f t^2 \tag{27}$$

$$x_1 = H + Vt - \frac{1}{6} J_f t^3 \tag{28}$$

This motion continues until $\ddot{x}_1 = - a_f$ at which point $t = a_f/J_f$. At this moment

$$\dot{x}_1 = V - a_f^2/2J_f \tag{29}$$

$$x_1 = H + Va_f/J_f - a_f^3/6J_f^2 \tag{30}$$

Let

$$t^* = t - a_f/J_f \tag{31}$$

Then the motion of vehicle 1 for $t > a_f/J_f$ is given by

$$\ddot{x}_1 = - a_f \tag{32}$$

$$\dot{x}_1 = - a_f t^* + V - a_f^2/2J_f \tag{33}$$

$$x_1 = -a_f t^{*2}/2 + (V - a_f^2/2J_f)t^* + H + Va_f/J_f - a_f^3/6J_f^2 \quad (34)$$

This motion continues until vehicle 2 collides with vehicle 1 or until $\dot{x}_1 = 0$. At the later moment,

$$t = V/a_f + a_f/2J_f \quad (35)$$

and

$$x_1 = H + Va_f/2J_f + V^2/2a_f - a_f^3/24J_f^2 \quad (36)$$

Vehicle 2 continues at velocity V until $t = t_D$. If $\bar{t} = t - t_D$, its motion during the constant jerk phase is given by

$$\dddot{x}_2 = -J_e \quad (37)$$

$$\ddot{x}_2 = -J_e\bar{t} \quad (38)$$

$$\dot{x}_2 = V - \tfrac{1}{2}J_e\bar{t}^2 \quad (39)$$

$$x_2 = V(\bar{t} + t_D) - J_e(\bar{t}^3 + t_D^3)/6 \quad (40)$$

Eq. (40) satisfies the condition $x_2 = 0$ when $t = 0$, thus placing the nose of vehicle 2 at a distance H behind the tail of vehicle 1 at $t = 0$.

This motion continues until $\ddot{x}_2 = -a_e$, at which point $\bar{t} = a_e/J_e$. At this moment

$$\dot{x}_2 = V - a_e^2/2J_e \quad (41)$$

and

$$x_2 = V(t_D + a_e/J_e) - J_e(a_e^3/J_e^3 + t_D^3)/6 \quad (42)$$

Let

$$t^{**} = \bar{t} - a_e/J_e \quad (43)$$

Then the motion of vehicle 2 for $\bar{t} > a_e/J_e$ is given by

$$\ddot{x}_2 = -a_e \quad (44)$$

$$\dot{x}_2 = -a_e t^{**} + V - a_e^2/2J_e \quad (45)$$

$$x_2 = -a_e t^{**2}/2 + (V - a_e^2/2J_e)t^{**} + V(t_D + a_e/J_e) - a_e^3/6J_e^2 - J_e t_D^3/6 \quad (46)$$

This motion continues until collision or until $\dot{x}_2 = 0$. At the later moment,

$$t = t_D + V/a_e + a_e/2J_e \quad (47)$$

and

$$x_2 = V(t_D + a_e/2J_e) + V^2/2a_e - a_e^3/24J_e^2 - J_e t_D^3/6 \quad (48)$$

If no collision is to occur, the minimum headway is obtained by equating equations (48) and (36). Then

$$H_{nc} = Vt_D + V(a_e/2J_e - a_f/2J_f) + \tfrac{1}{2}V^2(a_f - a_e)/a_f a_e + \frac{1}{24}(a_f^3/J_f^2 - a_e^3/J_e^2) - \frac{1}{6}J_e t_D^3 \quad (49)$$

Consider the magnitudes of these terms. A typical line velocity is in the range of 20 m/s. System analysis shows that time headways in the order of one half second are needed during rush hoursat critical points in the network. This gives nose to nose spacings at 20 m/s of 10 m. With vehicles 3 m long, this gives $H = 7$ m. Experience with modern control systems indicates that values of t_D in the range of 0.1 sec are not unreasonable. Then $Vt_D \simeq 2$ m. The second term depends upon the ratio a_e/J_e which can be controlled and a_f/J_f which cannot. Comfort values of a/J are in the range of one second. In emergencies, if necessary, brakes can be applied more quickly and a value $a_e/J_e = 0.2$ is not unreasonable. Then $Va_e/2J_e \simeq 2$ m. The slower the failure deceleration can build up, the shorter a headway can be tolerated because $Va_f/2J_f$ has a negative sign. For example, if $a_f/J_f = 1$ sec, $Va_f/2J_f = 10$ m and, from the point of view of this term, arbitrarily short headway would be possible. In the worst case, J_f is infinite and this term vanishes. Practically, it appears unlikely that it would exceed the value possible in emergency braking, thus the second term appears to be unimportant.

The third term in (49) is usually considered the most important. Clearly, however, if by design we make the most severe emergency braking such that $a_e = a_f$ for the locked-wheel case, the third term can be made to vanish. Suppose, however, a_e is smaller than a_f by about 0.1g. Then, if $a_f = 0.7g$ and $a_e = 0.6g$, $\frac{1}{2}V^2(1/a_e - 1/a_f) \simeq 4.8$ m. Adding this to the value $Vt_D \simeq 2$ m we are slightly below the required value H = 7 m for half second headway. Using the estimates given above, it will be seen that the fourth and fifth terms of (49) are well under one meter and hence can be neglected.

Now consider the possibility that H is so small that a collision does occur. Then there are two cases: In the first, the collision occurs after the failed vehicle has stopped. In the second, the collision occurs before the failed vehicle has stopped.

Consider the first case. Then collision occurs when $x_1 = x_2$ in which x_1 is given by (36) and x_2 by (46). The collision velocity $\Delta V = \dot{x}_2$ is given by (45) in which t^{**} is determined by the condition $x_1(t^{**}) = x_2(t^{**})$. At collision, (45) gives

$$t^{**} = (V - \Delta V - a_e^2/2J_e)/a_e \qquad (50)$$

Substituting (50) into the appropriate form of the equation $x_1 = x_2$, we obtain

$$H = H_{nc} - \Delta V^2/2a_e \qquad (51)$$

in which H_{nc} is the headway in the no-collision case and is given by (49). Using the value of $\Delta V = 5$ m/s estimated above, and $a_e = 0.6g$, $\Delta V^2/2a_e \simeq 2$ m. This term is seen to be sufficient to cancel the effect of a one-second time delay at V = 20 m/s and reduces the permissible nose to tail headway at one-half-second time headway by almost 30%.

At a line speed of 10 m/s, the collision term in (51) is even more significant. Thus the third term of (49) under the above assumption reduces to one fourth the above value, i.e., to 1.2 m. The term Vt_D becomes 1 m giving a combined effect of 2.2 m. The collision term almost cancels these terms completely, leaving only the third term of (49). Using the above estimate of this term, the time headway between 3 m vehicles becomes (5 + 3)/20 = 0.4 sec. At 10 m/s, the nose-to-tail headway between 3 m vehicles at one-half-second time headway is only 2 m. Thus the collision term in (51) permits arbitrarily short headways, i.e., down to 0.3 sec.

In the next case, the collision occurs before vehicle 1 has stopped. Then the headway equation is obtained by equating $x_1 = x_2$ in which x_1 is given by (34) and x_2 by (46). The collision velocity is given by $\Delta V = \dot{x}_2 - \dot{x}_1$ in which $\dot{x}_2$ is given by (45) and $\dot{x}_1$ by (33). This equation must be solved for both t^* and t^{**}. To do so, note from (43), (31) and the definition of $\bar{t}$, that

$$t^{**} = t^* - t_D + a_f/J_f - a_e/J_e \tag{52}$$

Then, from $\Delta V = \dot{x}_2 - \dot{x}_1$,

$$(a_f - a_e)t^* = \Delta V - a_e t_D - a_f{}^2/2J_f - a_e{}^2/2J_e + a_e a_f/J_f \tag{53}$$

$$(a_f - a_e)t^{**} = \Delta V - a_f t_D + a_f{}^2/2J_f + a_e{}^2/2J_e - a_f a_e/J_e \tag{54}$$

Substituting (53) and (54) into $x_1 = x_2$ gives, after a great deal of algebraic manipulation,

$$H = \frac{\Delta V^2}{2(a_f - a_e)} + \frac{a_f a_e}{2(a_f - a_e)}\left(\frac{a_f}{J_f} - \frac{a_e}{J_e} - t_D\right)t_D - \frac{J_e t_D{}^3}{6} + \frac{1}{6}\left(\frac{a_f{}^3}{J_f{}^2} - \frac{a_e{}^3}{J_e{}^2}\right) - \frac{1}{8(a_f - a_e)}\left(\frac{a_f{}^2}{J_f} - \frac{a_e{}^2}{J_e}\right)^2 \tag{55}$$

Further consideration of the kinematics will be aided by sketching the velocity-time and position - time diagrams for the two vehicles.

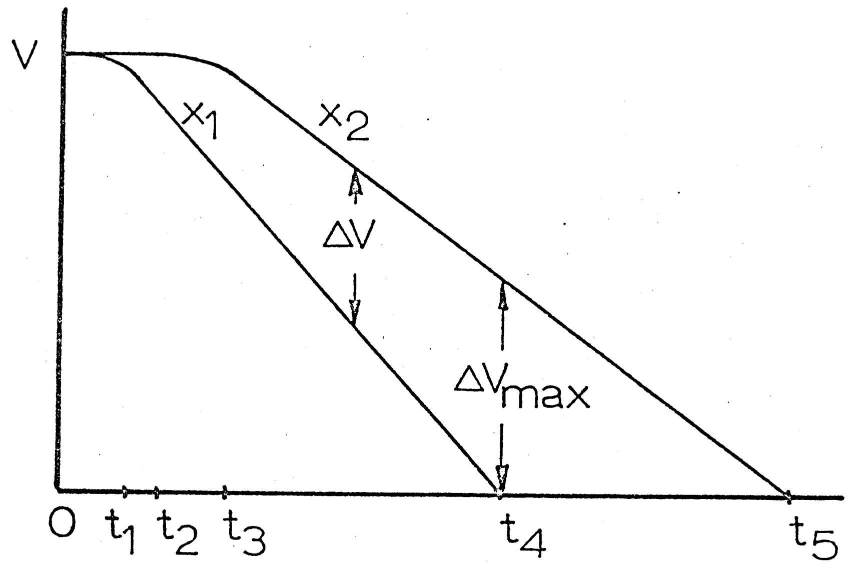


Figure 3. Velocity-time diagrams for two decelerating vehicles.

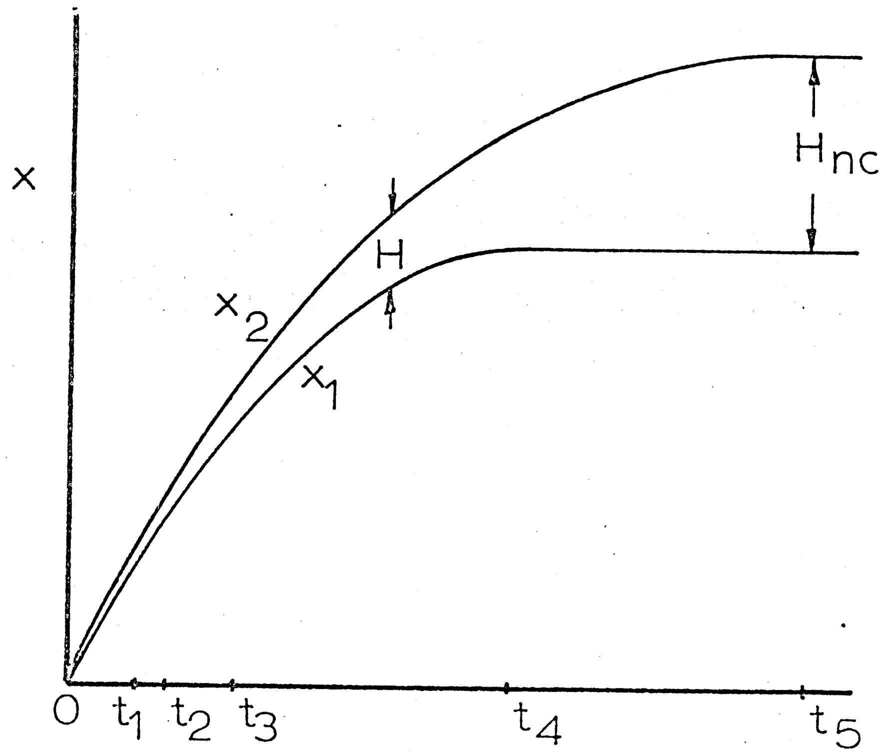


Figure 4. Position-time diagrams for two decelerating vehicles.

In Figures 3 and 4, $t_1 = a_f/J_f$, $t_2 = t_D$, $t_3 = t_D + a_e/J_e$, t_4 is given by (35), and t_5 is given by (47). The figures are drawn under the assumption $t_D > a_f/J_f$ but could have been drawn for the opposite case. Also, we have shown the case $a_e < a_f$ so that the $\dot{x}_1$ and $\dot{x}_2$ curves spread apart as t increases. In this case ΔV increases up to a maximum value $\Delta V_{max} = \dot{x}_2(t_4)$. Substituting (35) into (45)

$$\Delta V_{max} = V\frac{(a_f - a_e)}{a_f} + a_e t_D + \frac{a_e}{2}\left(\frac{a_e}{J_e} - \frac{a_f}{J_f}\right) \qquad (56)$$

Beyond t_4, ΔV decreases to zero at t_5. This means that the collision will be the most severe if H is such that it occurs at t_4. This value of H is given by (51) with $\Delta V = \Delta V_{max}$. For smaller values of H, the collision is less severe. Figure 4 is drawn with $x_1 = x_2$ at $t = 0$. In the actual case $x_1 - x_2 = H$ at $t = 0$, however, by drawing the curves in the former way the separation between the curves at a particular value of t is H if the collision occurs at time t.

The curve obtained by plotting H vs ΔV for given values of t is the fundamental result of this section, but first let us consider the special case $a_e = a_f$. In this case if $t_3 < t < t_4$, ΔV has the constant value obtained by subtracting $\dot{x}_1$ from (33) from $\dot{x}_2$ from (45) for $a_e = a_f$. We obtain

$$\Delta V = \dot{x}_2 - \dot{x}_1 = at_D + \frac{a^2}{2}\left(\frac{1}{J_e} - \frac{1}{J_f}\right) \qquad (57)$$

in which $a = a_e = a_f$. A reasonable value of a for the locked-wheel case may be $a = 0.7g = 7\ m/s^2$. Suppose $J_f = 2J_e = 2(14) = 28\ m/s^3$. Then

$$\Delta V = 7t_D + 7/8$$

To keep $\Delta V < 5$ m/s, as estimated in the previous section, we must have $t_D < 0.6$ sec. With modern sensing and control devices, values of t_D of the order of 0.1 sec should be possible. Therefore there is no need to make a_e as high as a_f.

If we allow $a_e < a_f$ then ΔV will be increased above its value in the case $a_e = a_f$. The maximum value is given by (56). We must keep a_e large enough to keep $\Delta V_{max} < 5$ m/s. If we make $t_D = 0.1$ sec, $a_e t_D \tilde{-} 0.7$ m/s. Also, from the calculation in the preceeding paragraph, the third term in (56) is of the order of one meter. Thus we must make

$$V(a_f - a_e)/a_f < 3 \text{ m/s}$$

If $a_f = 0.7g$ and $V = 20$ m/s, we must have $a_e > 0.6g$ to fulfill the required condition. This would be a design specification for the braking system together with the condition $t_D = 0.1$ sec. If it were necessary to double t_D, a_e would have to go up to 0.63g. By making $a_e = a_f$, t_D could increase to 0.6 sec as shown above.

To compute the frequency of collisions in various ranges of ΔV, the subject of the next section, we need to find the function $H(\Delta V)$. This can be obtained by computing values of H and ΔV at t_1, t_2, ..., t_5 and observing from (51) and (55) that $H(\Delta V)$ is one type of parabola for $t_3 < t < t_4$, and another for $t_4 < t < t_5$. These formulas are as follows:

At t_1, if $t_D > a_f/J_f$, as shown in Figure 3, the results are derived from (27), (28) and $\dot{x}_2 = V$, $x_2 = Vt_1$.
Thus

$$\Delta V = a_f^2/2J_f \quad \text{and} \quad H = a_f^3/6J_f^2 \tag{58}$$

If $t_D < a_f/J_f$, the more usual case,

$$\Delta V = \tfrac{1}{2}J_f t_D^2 \quad \text{and} \quad H = \frac{1}{6}J_f t_D^3 \tag{59}$$

At $t_2 > t_1$, if $t_D > a_f/J_f$, the motion of vehicle 1 is obtained from (33), (34) and $\dot{x}_2 = V$, $x_2 = Vt_D$. We obtain

$$\Delta V = a_f t_D - a_f^2/2J_f$$

$$H = \tfrac{1}{2}a_f t_D^2 + \frac{a_f}{2J_f}\left(\frac{a_f^2}{3J_f} - t_D\right) \tag{60}$$

If $t_D < a_f/J_f$, $\dot{x}_1$, x_1 come from (29), (30); and $\dot{x}_2$, x_2 from (39), (40). We obtain

$$\Delta V = \frac{a_f^{\,2}}{2J_f} - \frac{J_e}{2}\left(\frac{a_f}{J_f} - t_D\right)^2$$

$$H = \frac{a_f^{\,3}}{6J_f^{\,2}} - \frac{J_e}{6}\left[\left(\frac{a_f}{J_f} - t_D\right)^3 + t_D^{\,3}\right] \qquad (61)$$

At t_3; $\dot{x}_1$, x_1 are obtained from (33), (34); and $\dot{x}_2$, x_2 from (41), (42). The results are

$$\Delta V = a_f a_e/J_e - a_e^{\,2}/2J_e - a_f^{\,2}/2J_f + a_f t_D$$

$$H = -\frac{1}{6}J_e t_D^{\,3} + \frac{1}{6}\left(\frac{a_f^{\,3}}{J_f^{\,2}} - \frac{a_e^{\,3}}{J_e^{\,2}}\right) - \frac{a_f a_e}{2J_e}\left(\frac{a_f}{J_f} - \frac{a_e}{J_e}\right) \qquad (62)$$

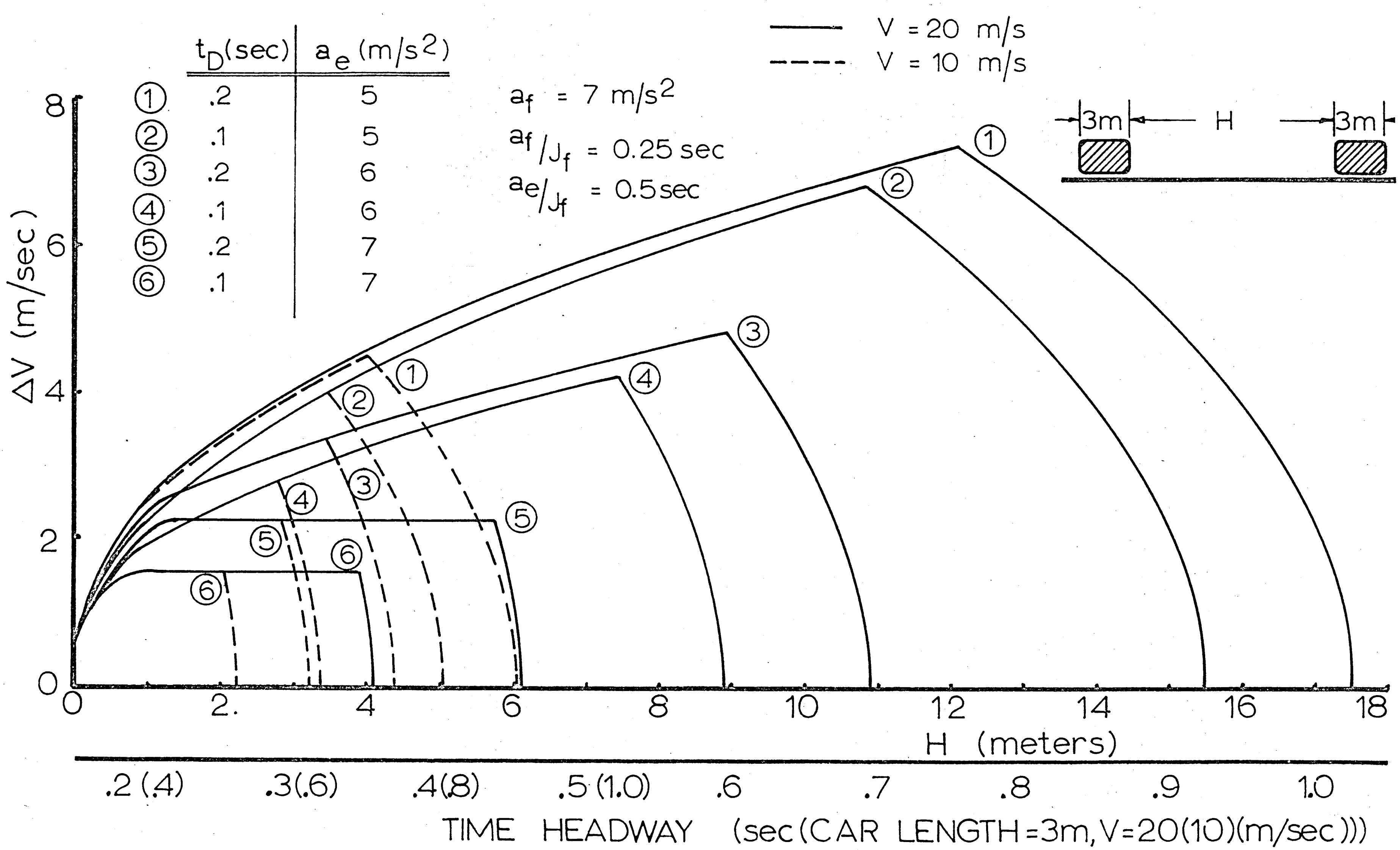
$$+ \frac{a_f}{2}t_D^{\,2} - a_f t_D\left(\frac{a_f}{2J_f} - \frac{a_e}{J_e}\right)$$

In the range $t_3 < t < t_4$, $H(\Delta V)$ is given by (55). At $t = t_4$, $\Delta V = \Delta V_{max}$ is given by (56) and H may be calculated by substituting this value in either (55) or (51). In the range $t_4 < t < t_5$, $H(\Delta V)$ is given by (51) and at t_5, $\Delta V = 0$ and $H = H_{nc}$, where H_{nc} is given by (49).

The function $H(\Delta V)$ is plotted for several cases in Figure 5. The choice of $a_f/J_f = 0.25$ sec is arbitrary. In the most sudden failure possible $a_f/J_f = 0$. Examination of (49) shows that this would have increased H_{nc} by $0.125\ V$ over the value shown, and (55) shows that ΔV_{max} would have increased by $0.125\ a_e$. Examination of the equations shows that the choice of a_e/J_e should relate to the probable value of a_f/J_f. For the sake of minimum discomfort during an emergency, a_e/J_e should be kept as large as possible. Since the comfort level is $a_e/J_e \simeq 1$ sec, the value $a_e/J_e = 0.5$ sec is not unreasonably small.

The value $a_f = 7\ m/s^2$ is representative of an upper-limit value for the locked-wheel or delevatation case. If linear motors are used for braking, a_f could be made smaller by lowering the coefficient of friction between the tires and the readway in wheeled PRT vehicles or between the skids and the roadway in air-suspended PRT vehicles. Since

Figure 5. The Collision Velocity Under Extreme Conditions



a_f in g's is equal to the coefficient of friction, experience shows that values in the neighborhood $0.2g < a_f < 0.5g$ are entirely possible. In this case the condition $a_e = a_f$ is readily attained. Reducing the coefficient of friction and hence a_f is advantageous because the smoother contact surfaces would generate less noise.

For the sake of both safety and noise it would be desirable to reduce the coefficient of friction enough to make a_f say 0.25g, the normal level for deceleration into stations and merge points. Then let $a_e = 0.25g$, the normal braking level. Assume also that $J_f = J_e$. In this case equation (56) reduces to

$$\Delta V_{max} = a_e t_D \qquad (63)$$

and equation (49) to

$$H_{nc} = V t_D \qquad (64)$$

in which the term $J_e t_D^3/6$ is of no importance.

With $t_D = 0.2$ sec, we have $\Delta V_{max} = 0.5$ m/s and $H_{nc} = 0.2$ V. If $V = 20$ m/s, $H_{nc} = 4$ m. With 3 m cars, this gives a time headway of $7/20 = 0.35$ sec. With $V = 10$ m/s, $H_{nc} = 2$ m and the time headway is 0.5 sec. Thus, by proper design, the effects of collisions can be reduced to a wholly acceptable level. As an illustration, a velocity of one meter/sec is the value attained if an object is dropped from a height of 10 centimeters.

The no-collision headway given by equation (49) can be made to vanish by making $a_e > a_f$. If we consider the case $a_e/J_e = a_f/J_f$, a_e is found from the equation

$$V t_D + \tfrac{1}{2} V^2 (a_f - a_e)/a_f a_e = 0 \qquad (65)$$

thus

$$a_e = a_f/(1 - 2 t_D a_f/V) \qquad (66)$$

Suppose $t_D = 0.2$ sec, $a_f = 3$ m/s^2, $V = 10$ m/s. Then $2 t_D a_f/V = 0.12$. Thus the required increase in a_e over a_f, to avoid collisions completely, is trivial if $t_D = 0.2$ sec and should be used.

If there is a failure in the sensing system so that t_D increases too much, it is not possible to make $H_{nc} = 0$. If an upper limit on

a_e were say $10a_f$ (attained by overloading the thrust motor for a short period), we see from (66) that $2t_D a_f/V = 0.9$ so that the limit value of t_D is $t_D = 0.45V/a_f$. In the example used above, $t_D = (0.45)(10)/3 = 1.5$ sec. By designing the system so that $t_D = 0.1$ sec normally, we have a margin of safety of 15. It is interesting to note that this limit doubles if V doubles.

In the case $a_e > a_f$ Figure 3 shows that the maximum value of ΔV is no longer given by (56) but rather is close to the value given by ΔV in (62). The first three terms of this equation roughly cancel one another leaving $\Delta V_{max} \simeq a_f t_D$. Thus, in the above extreme case, $\Delta V_{max} \simeq (3)(1.5) = 4.5$ m/s. This is clearly of concern but can be handled safely by the safety design described in the previous section. It should be emphasized that such a situation requires the simultaneous occurance of two very improbable events.

Another improbable occurance is the simultaneous locking of the wheels of one car together with the failure of the braking system of the following car. In this case $\Delta V = V$ if the collision occurs as or after the lead vehicle stops. ΔV decreases progressively as H reduces below H_{nc}. Numerical values of $\Delta V(H)$ can be obtained by observing for this case that $\dot{x}_2 = V$ and $x_2 = Vt$. Then, using (33) and (34), we find that

$$H = \frac{a_f^{\,3}}{24J_f^{\,2}} + \frac{a_f}{2J_f}\Delta V + \frac{\Delta V^2}{2a_f} \qquad (67)$$

If we set $\Delta V = V = 20$ m/s, $a_f = 3$ m/s and $J_f = 4a_f$, $H = 69$ m and the time headway for 3 m cars is 3.6 sec. If the time headway is 0.5 sec; $H = 7$ m, and $\Delta V = 6.5$ m/s. The interior padding of the vehicle needs to be designed so that in the case of this very improbable type of failure, the occupants will not be injured.

Failures During Merging Operations

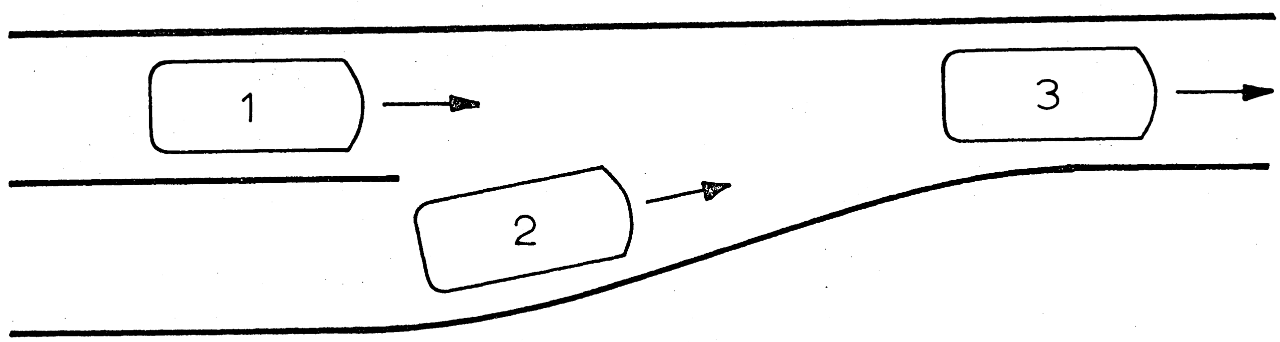


Figure 6. Vehicles at a Merge Point.

The type of failure considered in the previous section could occur during the merging operation. Considering Figure 6, only a failure of vehicle 2 or 3 is a special case. In either case, the emergency control mechanism goes into operation just as if vehicle 2 were in the main line.

We need to consider the possibility of failure of either vehicle 2 or 3 at any point along the merging track. As shown by Figure 3, the worst case occurs when the lead vehicle has just stopped at the moment of collision. Then, if vehicle 3 stops at the worst point, vehicle 2 could collide with the side of vehicle 3 and wedge it in the track. Or if vehicle 2 stops at the worst point, the collision of vehicle 1 with vehicle 2 would similarily wedge the vehicles together and produce an abrupt stop. These types of collisions have a much lower probability of occuring than an on-line collision at an arbitrary point in the track; in fact, lower by the ratio of the length of track for critical collisions to the average distance between merge points. Thus they could be treated differently than normal on-line collisions. The way they should be handled is based upon the fact that ΔV decreases very rapidly as $a_e \to a_f$. In fact if $a_e > a_f$ the collision velocity, if there is a collision, is very small so that the trailing vehicle, in a glancing collision would overtake the lead vehicle by only a small fraction of a meter.

As indicated in the previous section, we could cause $a_e > a_f$ if linear electric motors are used merely by overloading the motor 20%

or 30% more than in an on-line emergency stop. This could, in principal be affected by causing the failure sensors in the merge point to emit a larger signal than in other parts of the track. The system would be designed so that such a signal would cause a higher than normal emergency-braking rate. This problem has been discussed by Aerospace Corporation in Reference 1.

The Probability of Collisions

The objective of this section is to derive a formula for estimation of the frequency of collisions of various levels of severity in an operational PRT network. This formula will be given in terms of the mean time between failures (MTBF) for a single vehicle and will provide a means for determining the required MTBF.

We first consider the probability of collisions between vehicles on the main line in which ΔV lies between a given value and ΔV_{max}. From Figure 5, such collisions can take place in cases in which the vehicle behind the failed vehicle follows at a distance which lies between a pair of values say H_1 and H_2. Then, given a particular minimum ΔV, Figure 5 yields a set of points H_1 and H_2 such that for $\Delta V > \Delta V_{min}$, $H_1 < H < H_2$.

From an operational simulation of a given network at a given time of day, one can compute the number of vehicles for which the vehicle behind trails at an H in the range $H_1 < H < H_2$. Let this number be $N(H_1, H_2, t)$, which is a function of the time of day t. We will assume that N is cyclical with a period of one day. Different N could be calculated for non-working days.

Next we assume failures occur at random times. Most failures will involve non-operation of the propulsion system and would cause the vehicle to coast at a very low value of a_f. Such failures can be handled by braking the trailing vehicle at a low value of a_e in order to engage the failed vehicle at a low value of ΔV. As described in Reference 1, the failed vehicle is then pushed into the nearest station or to a maintenance shop. We are only concerned with the smaller class of highly improbable failures in which the vehicle decelerates at some maximum rate. With modern automobiles, this type of failure almost never occurs.

Assume, however, that the mean time between such failures can be estimated from tests on a large number of vehicles. Call this value $MTBF_v$. Then if there are N_T vehicles in the system, the mean time between failures anywhere in the system is

$$MTBF_s = (MTBF_v)/N_T \tag{68}$$

If T_d is one day (24 hours), the probability of a failure occuring on a particular day is $T_d/MTBF_s$. During the particular day on which a failure occurs, we assume it occurs with equal probability at any time during the 24-hour period. Thus the probability that it occurs within the time interval t to $t + dt$ is dt/T_d.

The probability that the failure occurs when $\Delta V > \Delta V_{min}$ is $N(H_1,H_2,t)/N_T$. Then using the law of multiplication for the probability of simultaneous occurance of independent events, the probability that a failure for which $\Delta V > \Delta V_{min}$ occurs in t to $t + dt$ is

$$\frac{T_d}{MTBF_s} \cdot \frac{dt}{T_d} \cdot \frac{N(H_1,H_2,t)}{N_T} \tag{69}$$

Now let $MTBF(\Delta V_{min})$ be the mean time between collisions in which $\Delta V > \Delta V_{min}$. Then $MTBF(\Delta V_{min})$ is determined by using the sum law of probabilities and is determined from

$$\frac{1}{MTBF_s}\int_0^{MTBF(\Delta V_{min})} \frac{N(H_1,H_2,t)}{N_T}dt = 1 \tag{70}$$

Using (68) and accounting for the fact that the function $N(H_1,H_2,t)$ has a period of one day (neglecting special days), (70) can be written in the form

$$\frac{MTBF_v}{MTBF(\Delta V_{min})} = \int_0^{T_d} N(H_1,H_2,t)\frac{dt}{T_d} \tag{71}$$

The integral is the average number of vehicles for which $\Delta V_{min} < \Delta V < \Delta V_{max}$ over a period of one day. The larger this value, the larger must be the ratio of MTBF for a vehicle to the MTBF for important nuisance failures in the system. With a quasi-synchronous control system in which the slots are at 0.5 sec headway, the theory of the previous section shows that $N(H_1,H_2,t)$ is the number of vehicles for which the slot behind is filled.

Normally a specification would be placed on $MTBF(\Delta V_{min})$. Then after the integral is computed from a simulation, the required $MTBF_v$ can be calculated. Knowing this value, one can determine from reliability testing on vehicles and components the required frequency of maintenance and the required redundancy in critical components. The mean time between failures at merge points is simply $MTBF(\Delta V_{min})(L_m/\Delta L)$, in which L_m is the average distance between merge points and ΔL is the critical length in which glancing collisions are possible.

Conclusions

The theory of this chapter leads to several specifications for safe design of PRT systems. First, the coefficient of friction between the vehicle and the track in the locked-wheel or delevitation type of failure must be as low as possible. By making the coefficient of friction of the order of 0.25, the failure acceleration becomes 0.25g. By making a_e about 10% higher, collisions can be avoided for arbitrarily close headway. This assumes that the time delay for sensing the failure and applying the brakes is no more than a few tenths of a second, a value easily achieved, and that all vehicles behind the failed vehicle receive signals to decellerate simultaneously.

Using the above specifications, serious failures occur only upon the simultaneous occurence of two improbable types of failure, each of which can be rendered more improbable by use of redundancy in design, and by frequent maintenance, inspection and critical-component replacement. If the wheels lock, the failure-control system requires (1) that the system for sensing such a failure function, i.e., that the time delay before the emergency brakes are applied be of the order of 0.1 sec, and (2) that the emergency braking system on the trailing vehicle be operative. Redundancy can be built into both of these systems. In the case of multiple failures, damage to the vehicles can be avoided by use of a suitably designed padded dashboard placed as close to the occupants as possible. The success of such a padded interior depends upon the use of forward-facing seats only.

Allowable specifications for the frequency of various types of failures in a system can be estimated from the theory given above. Since failures which can produce injury can be made extremely improbable by proper design, attention must be drawn to the type of failures which will delay the patrons. Types of multiple failure which would cause delay need to be analyzed to determine the time that would be required to clear a certain section of track. Obviously a great deal of attention needs to be paid to types of failures that may block the track in order to design around these difficulties. One measure of the severity of nuisance failure would be measured in terms of the number of vehicle-hours of delay produced. By careful analysis of all possible failure modes, designs need to be developed in which the probability of track blockage is extremely low.

Reference

1. H. Bernstein and A. Schmitt, "Emergency Strategies for Safe Close-Headway Operation of PRT Vehicles," pp. 351-360, of Personal Rapid Transit, edited by Professors J. Edward Anderson, Jack L. Dais, William L. Garrard, and Alain L. Kornhauser.

Chapter 9

Computerized Vehicle Management and Control

9.1 Introduction

Although the physical characteristics of PRT systems vary considerably, the basic problems of vehicle management and control are common to all systems. In order to achieve high capacity, the minimum separation between adjacent vehicles must be short (5 to 15 feet). In addition, vehicles must have the capability of merging into tightly packed strings moving at speeds comparable to those of automobile traffic. These requirements can be safely achieved only if the vehicles are automatically controlled.

Control systems must maintain proper spacing between vehicles without causing passenger discomfort, be reasonably economical to implement, be adaptable to merging and demerging from off-line stations and maneuvering at interchanges, be simple enough to insure reliability, and be suitable for use in emergency situations. The PRT concept envisions an extended network of inter-connected guideways with many stations. It is necessary to move large numbers of vehicles through this network without congestion and delays. Thus computer control and coordination of the overall operations of the system is necessary (Hadju *et*.*al*.)*

Vehicle management and control functions common to all PRT systems are the following:

Control Functions

The control of headway and speed of vehicles on the main line. These vehicles operate at essentially constant speed and predetermined separation.

* References are listed in the appendix in alphabetical order.

The control of merging and demerging from the mainline at stations and interchanges. This includes maneuvering of vehicles to avoid conflicts.

The control of vehicles in stations including stopping, unloading, loading, and starting.

Vehicle Management Functions

Automatic routing to move vehicles from origin to destination stations by the shortest available path.

Empty vehicle shuttling to move empty vehicles from carbarns and stations in which there are excess vehicles to stations in which there are excess demands for service.

Batch processing of vehicles at stations.

There are of course a number of ways in which these functions can be performed; however, three basic philosophies for network operation have evolved. These are synchronous, quasi-synchronous, and asynchronous operation. Quasi-synchronous operation is favored by PRT experts in the United States and Great Britain and in the remainder of this chapter quasi-synchronous operation is assumed. Asynchronous operation is used by the Messerschmidt-Demag Consortium in West Germany (Hesse). Synchronous, quasi-synchronous, and asynchronous operation are described in the next section.

Hierarchical control is discussed in Section 9.3 and operation of stations is covered in 9.4. A computer simulation of a PRT network is presented in Section 9.5 and logitudinal control systems are discussed in 9.6. Finally, an overview of emergency operations is given in Section 9.7.

9.2 Synchronous, Quasi-Synchronous, and Asynchronous Operation

Synchronous Operation

The main idea of both synchronous and quasisynchronous operation is that vehicles follow hypothetical slots moving along the guideway at the nominal line velocity. The slot lengths are uniform and are equal to the length of the vehicle plus the minimum allowable nose to tail separation between adjacent vehicles. Vehicles do not communicate directly with one another and the position of the vehicle is determined with respect to the guideway rather than with respect to the other vehicles in the system. Thus system operation depends upon coordinating the movement of the slots so that no conflicts at merge points and intersections can occur. A conflict at an intersection or merge point is a situation in which two vehicles traveling on intersecting lines would arrive at the intersection of these lines at the same time. An unresolved conflict would lead to a collision; therefore, the control system must resolve conflicts at merge points and intersections.

In purely synchronous operation, a vehicle is assigned a specific slot which it follows from origin to destination. Once en route, the travel time between origin and destination is completely predetermined. Prior to the departure of a vehicle from a station, an empty slot which will allow the vehicle to travel from its origin to its destination with no possibility of conflicts at intersections or merge points must be found and reserved. A vehicle is not allowed to leave an origin station until it can travel to the destination station with no conflicts at intersections. Slot reservations are handled by a reservation computer.

Due to other traffic on the network, it may take some time until a slot is available for a particular trip. Considerable passenger queueing may occur, first-come, first-served operation may not be possible and full utilization of potential guideway capacity is impossible if the system is operated synchronously. Since slots must be reserved in advance of a trip, the reservation computer must be aware of reservations made for all trips presently on or waiting to enter the network. For large networks this imposes considerable memory requirements on the reservation computer. Emergency situations also pose serious problems for purely synchronous operation of large networks. For example if a vehicle stops or slips from its assigned slot due to loss or reduction of propulsive force, serious difficulties can arise. This is because other vehicles are either on or en route to the line on which the failed vehicle has stopped or may have a reservation for the slot into which the failing vehicle has slipped. Thus it is necessary to reassign slot reservations in order to avoid collisions. If this reassignment cannot be performed rapidly, it will be necessary to stop traffic on all or a sizeable part of the network until reservations can be reassigned. Emergency situations shatter the rigid structure of purely synchronous operation and can easily disrupt the operation of the entire system (Munson).

Many of the disadvantages of purely synchronous operation can be overcome by use of cycles of N adjacent slots (there are usually five to ten slots per cycle). The cycle rather than the slot is considered the unit for purposes of space reservation (Boyd and Lukas). Space in a specific cycle is reserved for each vehicle before it enters the system, and the vehicle remains in that cycle during its trip through the network. A specific slot within a cycle is not reserved for the vehicle, and vehicles can be maneuvered from slot to slot within a cycle. For example, if two cycles of N slots each merge at an intersection, the reservation computer assigns no more than a total of N vehicles to both cycles. Upstream of the merging point a local controller rearranges the positions of the vehicles in the merging cycles so that no more than one vehicle is located in each pair of merging slots. Compared with purely synchronous operation, the use of cycles makes system operation more flexible and reduces reservation-computer memory requirements and passenger waiting times at stations.

Quasi-Synchronous Operation

It is recognized that Quasi-synchronous operation represents another method for overcoming the disadvantages inherent in purely synchronous operation. As in synchronous operation, vehicles follow hypothetical slots which are routed through the system from origin to destination; however, quasi-synchronous systems have the capability of maneuvering vehicles from one slot position to another in order to resolve conflicts at merge points and intersections. Since vehicles may be called upon to execute manuevers en route, the travel time between origin and destination is never precisely predetermined. The system has the capability of re-routing vehicles which are in transit; consequently, emergency situations may be handled without shutting down the operation of the entire network (Munson).

In quasi-synchronous operation, traffic management at stations, merge points, and intersections is under the control of local computers. For example the local computer for an intersection has tubular routing data which, depending upon vehicle destination and direction of entry into the intersection, indicates whether a vehicle should turn or go straight at that intersection. Wayside sensors determine whether the slots entering the intersection are occupied and interrogate the vehicles as to their destination. If a vehicle wishes to turn and the slot into which it would merge is occupied the intersection computer can manuever (move vehicles from one slot to another) the vehicles on either or both lines in such a way as to attempt to resolve the conflict. In some cases it may be impossible to resolve the conflict by maneuvers and in these cases a turn would not be allowed. Computer simulations and analytical studies indicate that in a properly designed system, the percentage of missed turns (aborts) is small. Those vehicles which miss their turns can of course be re-routed to their destinations. Merging at stations and interchanges will be discussed in more detail later in this chapter.

It is necessary to be able to change the routing instructions in the local computers in order to accomodate variations in network flows (the characteristics of peak-hour traffic flows are different from those encountered during off-peak hours) and for re-routing during emergency situations. During manuevering vehicles must follow predetermined acceleration-deceleration profiles; consequently the on-board control system must be capable of executing precisely controlled maneuvers. Design of such a control system is discussed in Section 9.8.

Asynchronous Operation. Asynchronous operation is based upon direct communication between vehicles and hence is conceptually very different from synchronous and quasi-synchronous operation. Each vehicle automatically travels at some nominal velocity when it is distant from other vehicles in the system. When it comes near other vehicles it adjusts its velocity and position in such a manner as to maintain some minimum separation relative to the nearest downstream vehicle (Fenton et. al., Hesse). Purely asynchronous operation is essentially unstructured, and the travel time and velocity of a vehicle depends upon its random interactions with other vehicles in the system.

One of the primary difficulties associated with purely asynchronous operation occurs during merging at high line densities. In order to insure that proper spacing is maintained between merging vehicles, there must be direct communication between the strings of vehicles approaching the merge point along the two intersecting lines. If congestion and delays at intersections are to be avoided, a complex intervehicular communication network appears necessary. Also during emergency operations some vehicles must be directed to perform manuevers such as pushing a stalled vehicle onto an emergency siding. Implementation of these manuevers requires some sort of external centralized control. Also centralized control is required for routing vehicles in order to avoid congestion. No high-capacity large-scale system can operate in a purely asynchronous manner. However a modified form of asynchronous operation in which many system control functions are performed by centralized control computers is feasible (Hesse).

9.3 Hierarchical Control

For large-scale systems, control functions must be performed at several levels. At the first level is the control system which maintains proper speed and position of the vehicles. This is commonly called the longitudinal or headway control system and will be discussed in detail later in this chapter. The second level of control is performed by a central computer which controls wayside computers in such a manner as to implement routing and empty vehicle shuttling policies. This central computer may control the PRT network for an entire city provided the network is small; however, it is more likely that the central computer will control a zone in the network and will in turn be controlled by a large computer which coordinates inter-zonal activities. This division of responsibilities provides considerable redundancy and makes operation of the system independent of a single computer. Any division of responsibility is by no means unique and there are undoubtedly many possible plans which could be developed. It is anticipated that further research will produce many alternatives for evaluation.

9.4 Capacity Estimates of Stations

In the present report we consider only stations with a single vehicle ramp as shown in Fig. 1. It will be shown that a single-ramp station can result in high capacity, where capacity is measured in terms of vehicles per hour or passengers per hour. High-capacity operation requires processing vehicles in batches in station. The batch processing mode of operation has been studied previously (Royal Aircraft Establishment), (Meserschmidt-Demag), (Dais). The present discussion will borrow ideas from these works and derive some capacity estimates for PRT stations. Two station designs will be considered. One uses the same platform for loading and unloading vehicles. The other uses separate platforms.

Fig. 1 shows an off-line station as well as a main traffic lane. Vehicles which are directed to access the station would leave the main line via the demerge switch. Vehicles not accessing the station would remain on the main line and resume the line speed. Vehicles accessing the station would travel at line speed until passing through the demerge switch. They would then slow down in the deceleration lane and do any necessary maneuvers in the queue area. Motion in the switches, deceleration and acceleration lanes, and stations is synchronous. The vehicle queue area acts as a "buffer" which couples components of the system that have different throughout rates . Fig. 2a shows a station design with N berths and a combined unload-load platform. The unload-load operation would be performed simultaneously

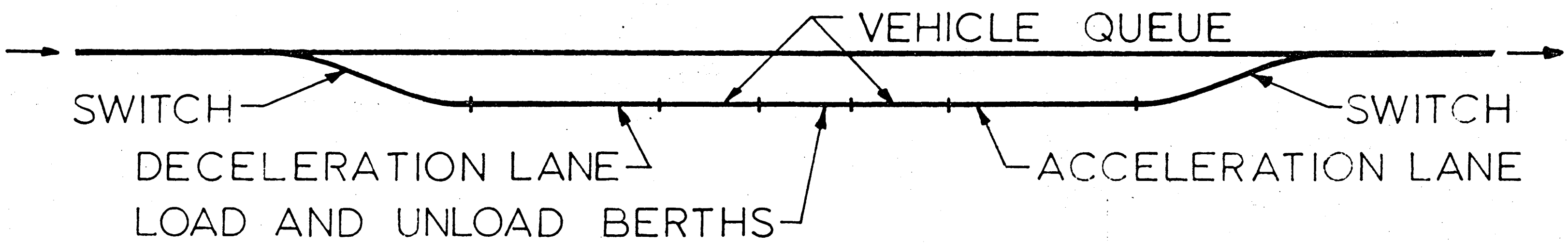


Fig 1 Off-line Station, Plan View

on a specified number N of vehicles. When the operation is complete, the vehicles would simultaneously exit and enter the queue area, where they would do any necessary waiting for open slots for merging to the main line. Vehicles would leave the station only if they are occupied or if it were necessary to make room for entering vehicles to be unloaded. If there are several vehicles in the station and fewer demands during that cycle, then only the front-most vehicles would leave during that cycle. The other vehicles would simply pass to the front of the station and wait to be boarded in some other cycle. Vehicles accessing the station would wait in the queue area until the next cycle. In the next cycle, the front N vehicles in the queue would enter the station, provided that N or more vehicles are present. If less than N vehicles are present, all vehicles would enter. A question as of yet unanswered is - how many vehicle spaces must be allowed in the queue area? If the queue area is filled and a vehicle is scheduled to enter the station, it would have to bypass the station and then be rerouted back. This is called an abort, and the queue area must be large enough to keep abort rates acceptably low. Estimates of abort rate as a function of queue size can be attained via computer simulations. This remains an important problem which merits further study.

The station shown in Fig. 2b has separate unload and load platforms. This station handles batches of up to N/2 vehicles simultaneously. Batches would enter the unload area, be unloaded, shift to the load area, be loaded, and then enter the queue area and queue for merging to the main line.

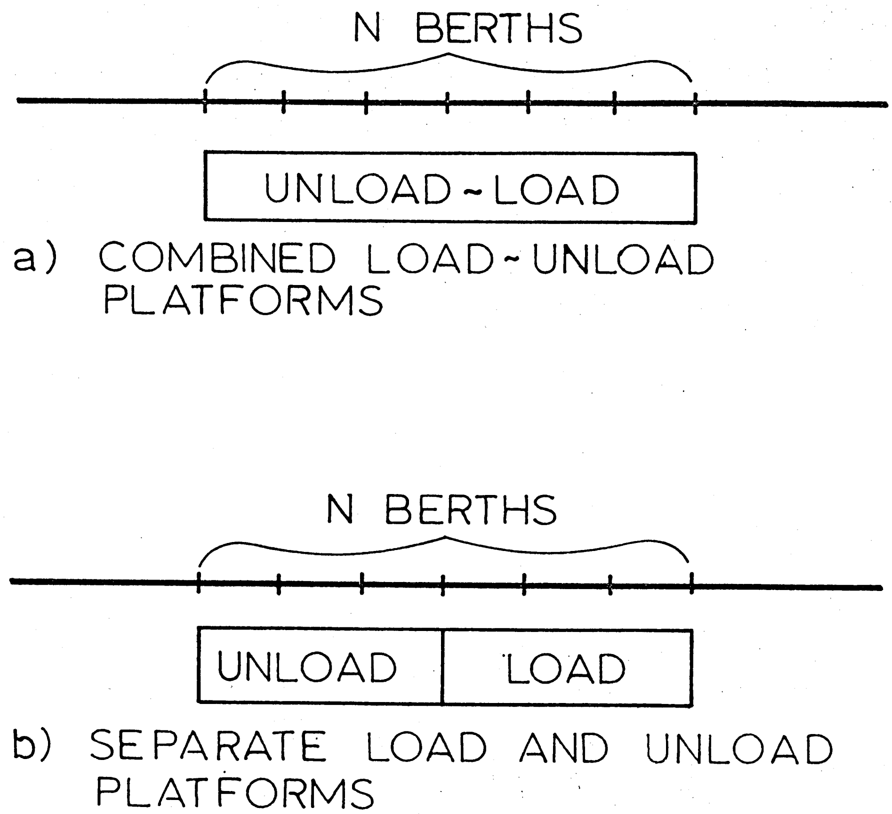


Fig 2 Alternative Station Configurations

To obtain an estimate for the vehicle capacity of the station, it is necessary to consider the time for the vehicle shift process as well as the unload and load precesses. If the vehicles follow the maneuver mode of Figure 3, then it follows that the time T_s required for the shift process is

$$T_s = a/J + \sqrt{a^2/J^2 + 4\hat{N}\ell/a},$$

where

$$\hat{N} = N \text{ for combined unload-load platform}$$
$$\hat{N} = N/2 \text{ for separate unload-load platform}$$

and a is allowable acceleration, J is allowable jerk and ℓ is the nose to nose separation of vehicles. As has been discussed elsewhere in this report, $a = 8$ ft/sec^2 and $J = 8$ ft/sec^3 will be chosen. A conservative estimate of capacity will be obtained by taking $\ell = 16$ feet. It follows then that

$$T_s = 1 + \sqrt{1 + 8\hat{N}} .$$

University of Minnesota students have made numerous observations of people boarding and disembarking from elevators. Based on their observations, it appears that 7 seconds is ample time for loading or unloading from separate platforms and that 15 seconds is appropriate from a combined platform. It follows then that the capacities for PRT stations are

$$C = 3600\ N/(16 + \sqrt{1 + 8N}) \quad \text{combined platform}$$
$$C = 1800\ N/(8 + \sqrt{1 + 4N}) \quad \text{separate platform}.$$

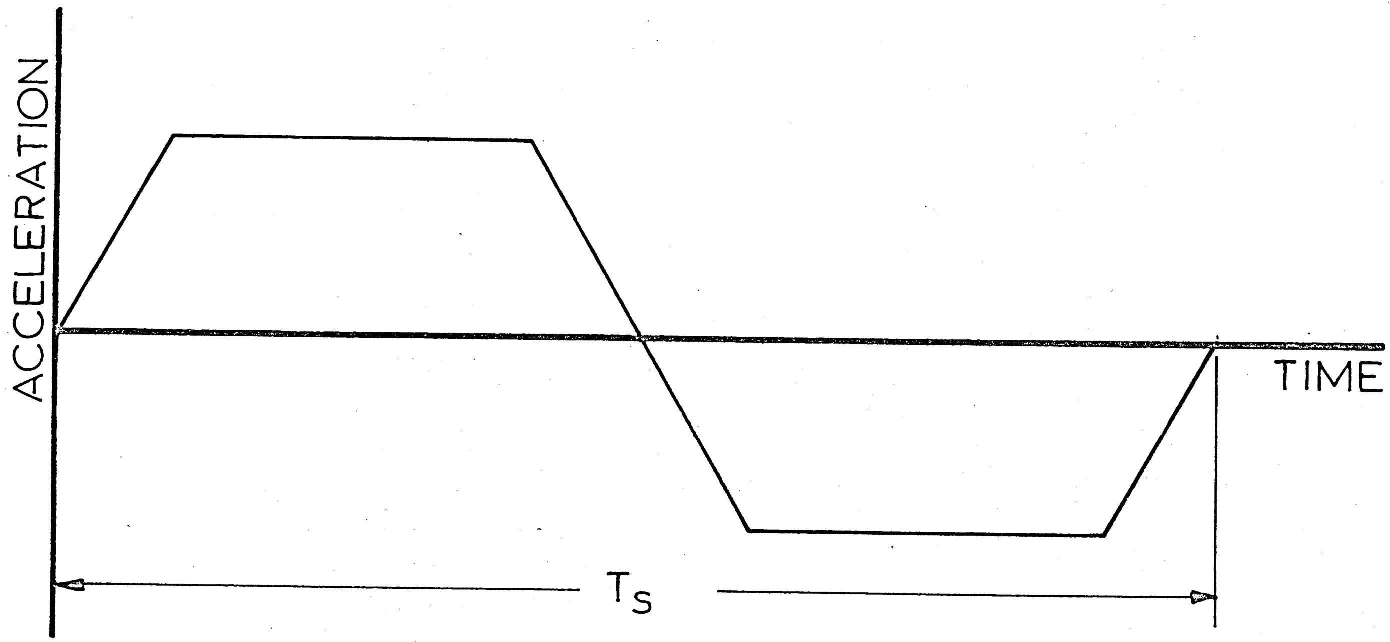


Fig 3 Vehicle Maneuver Profile

These equations have been tabulated for N = 1 through 6 in Table 1. N greater than 6 would provide even more capacity should any application require more.

Table 1 Station Capacity Estimates

C - Vehicles/Hour

N	Combined Load-Unload Platforms	Separate Load-Unload Platforms
1	190	-
2	360	327
3	515	-
4	660	593
5	810	-
6	950	831

9.5 Simulation

In this section, the detailed computer simulation of a PRT system operating under a quasi-synchronous control scheme will be described. The computer simulation was developed to model the detailed operation of a PRT network system, and to determine the effects of random passenger arrivals on system performance. The simulation demonstrates the feasibility of managing the network flow volumes of the magnitude predicted in the Minneapolis and Duluth studies described elsewhere in this report. The network system being modeled is assumed to operate under a quasi-synchronous control with slot-slipping performed on the interchange and station ramps. Each section of the guideway is divided into slots of one headway length. For example, if the nominal line velocity of the system is 12 meters per second, and the vehicles travel with minimum headway of one second, then each slot on the main line is 12 meters long. Each slot on the main network lines as well as those on the interchange and station ramps are assigned storage locations in the computer. Each station in the system is identified by a number. Each storage location contains the destination-station number of the vehicle which occupies the corresponding slot in the network at a given time. If the slot is unoccupied, a zero is assigned to the storage location corresponding to the slot.

At time increments of one headway time, the whole system is updated. The updating involves shifting or otherwise modifying the contents of the storage locations representing the guideway slots to simulate the movements of vehicles through the system. At each time step, demands for vehicles at stations are also simulated using a Monte-Carlo method. In the example described later, a headway and update time of one second is used.

The updating of vehicle positions on the main lines of the network is performed by a sequence of logical operations which can be enumerated as follows:

(1) If the vehicle is on a slot which does not contain a demerge switch, it is advanced a slot on the main line.

(2) If an interchange demerge switch slot is occupied, the vehicle destination is interrogated. The destination number is then checked with a minimum-path table to determine whether the vehicle should proceed on the main line or be placed on the interchange ramp.

(3) If the vehicle is located in a station demerge switch slot, its destination is interrogated. If that destination corresponds to the appropriate station number, the vehicle is placed on the station-entrance ramp. Otherwise, the vehicle is moved one slot forward on the main line.

In a quasi-synchronous control scheme, vehicle maneuvering takes place on interchange and station ramps. Interchange ramps may be divided into three sections consisting of a deceleration ramp, a maneuvering section, and an acceleration ramp. On both the acceleration and deceleration ramps, the vehicle operates in a synchonous manner; this means that the vehicle always maintains a specified speed profile. In the maneuvering section, the vehicle may adhere to a constant-speed profile, which is normally lower than the main-line speed, or it may "slip" slots by a combination of acceleration and deceleration maneuvers. The slot-slipping procedure might entail bringing the vehicle to rest on the maneuvering section of the guideway to wait for an open slot on the main line.

When a vehicle enters an interchange ramp, it undergoes a specified deceleration profile until it reaches the maneuvering section. From this point, the vehicle requires a certain number, J_{min}, of time increments to reach the merge switch on the main line. Since vehicles on the main line move in a synchronous mode, vacant unreserved slots on the main line which represent possible future merges will lie between the previous upstream merge point and J_{min} slots upstream of the interchange merge switch. By considering only vacant slots downstream of previous merge points, all intersections are able to function independently. The merging vehicle selects the empty slot which will permit it to pass through the interchange with the smallest delay, and determines the number of slots which will have to be slipped to complete the merge. The vacant slot is then reserved for the vehicle.

The logical operations by which the interchanges are updated at each time step can be enumerated as follows:

(1) If the lead slot of the maneuvering section is unoccupied, all vehicles in this section are advanced one slot.

(2) If the lead slot is occupied and there will be an open slot for this vehicle on the main line for the merge, the vehicle is placed in the first slot of the synchronous acceleration ramp, and all vehicles behind it are advanced one slot.

(3) If the lead slot is occupied and there would not be an open slot on the main line for the merge, the vehicle must slip a slot in the maneuvering section. All vehicles behind this vehicle, up to the first vacant slot, must also slip a slot.

(4) A vehicle is permitted onto the interchange ramp if there is room for the vehicle in the maneuvering section. In the simulation, only a specified number of vehicles are allowed to slip slots simultaneously on the maneuvering section. In the example network which will be described later, up to ten vehicles were permitted to slip slots at any time. There will be space for a vehicle on the maneuvering section if fewer than the specified maximum number of vehicles are simultaneously slipping slots there. If no vacant slot is available, the vehicle desiring to turn is instead advanced forward on the main line.

The vehicle will then be routed to the destination station via the best route from its current position downstream of the demerge switch. A vehicle denied access to an interchange ramp is said to have been <u>aborted</u>. Each abort is recorded by the computer.

In the case of a T-intersection, such as ramp number 15 on the test network shown in Figure 4, the line from Station 8 to Station 10 is run synchronously. Slot slipping is permitted downstream of the merge from Station 9.

If all slots on the line downstream of Station 9 are filled, only vehicles going to Station 9 are allowed to enter the line upstream of Station 9. All other vehicles are rerouted at the interchange upstream from Station 9. These vehicles are con-

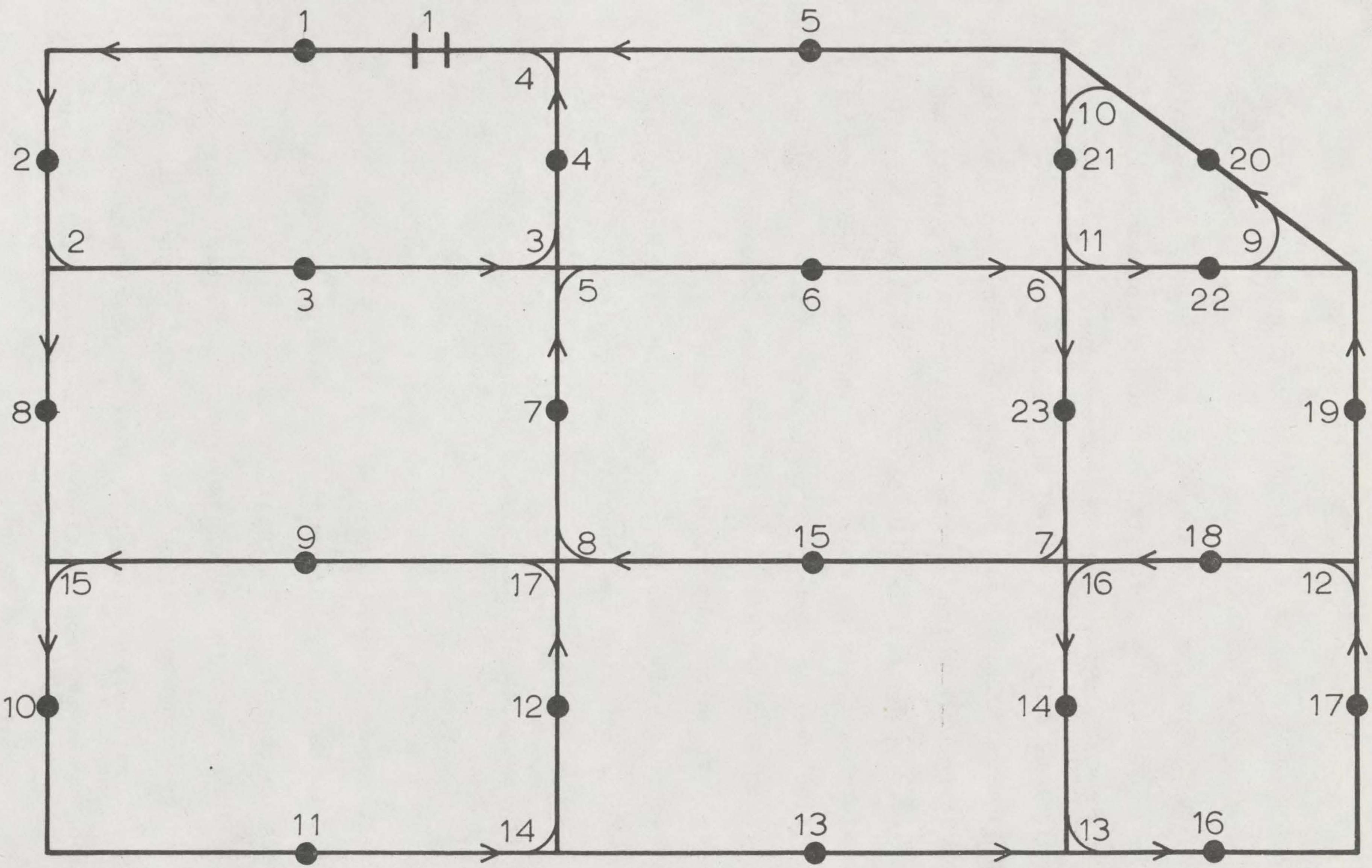


Fig. 4 Test Network

sidered to be aborted, and the number of aborts at T-intersections are recorded.

The rerouting of aborted vehicles is easily managed by the computer, on the basis of a minimum-path table. At each intersection, the destination of the vehicle is interrogated, and the appropriate entry in the minimum-path table is examined. The minimum-path table is an N x N array, where N is the number of stations in the network. The element located in row i and column j of the indexed array is the number of the next station which should be passed on the minimum path from station i to station j. Each interchange is associated with the station just upstream from it, so that the minimum path is determined directly from the vehicles present location and its destination.

At each system update, demands for service are also generated. These demands, while random in nature, have a mean value which corresponds to specified input data. The actual demand arrivals are generated by a Monte-Carlo process. Because of the nature of PRT, passenger demands probably will not occur as a Poisson distribution. Passengers will arrive at a station in small groups with the intention of riding together. Each group, however, represents a vehicle demand, and it is reasonable to assume that the arrival of each group representing a vehicle demand is a Poisson process.

A table of average vehicle demands per hour from each origin station to every destination station is specified apriori as an input to the simulation program. The actual demand arrival pattern is a Poisson distribution with a mean equal to the given average demand. Additional inputs to the simulation program are generated at this time using the average vehicle-demand matrix and some of the computational procedures described in Chapter 10. One of these inputs consists of a table of average empty-vehicle demands, which will be referred to as e_{ij}, representing the average flow of empty vehicles from station i to station j per hour. This input is obtained using an optimization procedure which minimizes the average total empty-vehicle-trip mileage per hour while ensuring that the average waiting time at each station in the network is less than a specified value. An estimated necessary vehicle-fleet size is also computed for the system. The fleet size is determined by the formula

$$FS = \sum_{j=1}^{N} \sum_{i=1}^{N} t_{ij}(d_{ij} + e_{ij})$$

where t_{ij} is the minimum-path travel time between station i and station j, and d_{ij} and e_{ij} are the full and empty vehicle demands per hour from station i to station j, respectively. Vehicle shuttling requirements, and in turn the fleet size, are influenced by two station parameters, the number of berths in the station, and the upper bound on the average passenger waiting time. For example, the fleet size requirements will increase for a fixed vehicle demand matrix, if the specified average waiting time at stations is decreased, since this will require an increase in empty-vehicle shuttling activity. In the present computer model, "waiting time" includes only the time spent waiting for an empty vehicle. Passenger boarding time and intra-station vehicle movement times have not been included. The inclusion of these effects into the computer model awaits further research which would include more details of station design and vehicle management.

Vehicle demands at each station are generated by a two-stage Monte Carlo process. The first stage of the process determines whether a vehicle demand has occurred at a station during the update time interval. For each station, the average vehicle demand per update time, which is given by the formula

$$(DPU)_i = \frac{\sum_{j=1}^{N} d_{ij}}{(UPH)}$$

where (UPH), the number of update intervals in one hour, is known. The update time is assumed to be small enough so that

$$(DPU)_i \ll 1 .$$

This insures that the probability of a multiple-vehicle demand in the time interval is very small. If this condition is not satisfied, a time interval smaller than the update time should be used to generate individual demand arrivals. In stage one of the Monte Carlo process, a random number between zero and one is generated for each station. If the random number, R_i, is less than $(DPU)_i$, then a vehicle demand has occurred, and the queue of vehicle demands is increased by one. If R_i is greater than $(DPU)_i$, then no vehicle demand has occurred.

The destination of a full or empty vehicle departing from a station is determined by the second stage of the Monte Carlo process. This stage requires the use of two matrices, $f_{i,j}$ and $g_{i,j}$, which are defined by the expressions

$$f_{i,j} = \frac{\sum_{\ell=1}^{J} d_{i\ell}}{\sum_{\ell=1}^{N} d_{ij}}$$

$$g_{i,j} = \frac{\sum_{\ell=1}^{J} e_{i\ell}}{\sum_{\ell=1}^{N} e_{i\ell}}$$

The elements d_{ij} and e_{ij} are the full and empty vehicle demands per hour, which, it will be recalled, are inputs to the simulation program. Vehicle dispatching proceeds in the following way at each update time:

(1) If there is a vehicle-demand queue and an empty vehicle is in the station, that vehicle is dispatched by generating a random number, R_i. The vehicles destination is the station number, k, which satisfies the inequality

$$f_{i,k-1} < R_i \leq f_{i,k} .$$

(2) If there is no demand queue, and there is an excess empty vehicle in the station, the vehicle is dispatched according to the empty-vehicle demand matrix by generating a random number, R_i. The vehicle destination is the station number, k, which satisfies the inequality

$$g_{i,k-1} < R_i \leq g_{i,k} .$$

The simulation program was written in FORTRAN and was designed to run on the CDC 6400 time sharing facility at the University of Minnesota. Running time and storage requirements were significantly reduced by using word packing on an extensive scale. Each slot on the guideway was represented by six bits of a sixty bit computer word. Thus one computer word represents ten slots of guideway. At each time step, the sixty-bit word is shifted six bits to the right, with the right-hand six bits transferred to the left end of the next word. Since the largest six-digit binary number is 63, the network is limited to 63 possible stations using this representation. A network with more stations would require more storage than six bits per guideway slot. One problem in computer simulation is that the simulation must be run long enough so that transients caused by the initial state of the system do not greatly affect the final results. This difficulty was overcome to some extent by storing the final network state after each run, and then using it as the initial state for the next run.

Several indicators of system performance are listed at the end of each computer run. These are:

(1) The number of passengers waiting at each station at the end of a given time period.

(2) The average passenger waiting time at each station during the run.

(3) The number of aborts encountered at each interchange in the network.

(4) The total vehicle flows on all links in the network.

(5) The average time delay per vehicle at each interchange in the system.

These are some of the more important measures of system performance which can be obtained from the simulation program. Information as to maximum waits and delays may also be obtained.

Numerical Example

A laboratory network of 23 stations and 17 interchanges was set up to examine some of the command and control problems associated with demand-activated transit networks, and to demonstrate that a high-capacity PRT network could operate effectively under a quasi-synchronous control scheme at high-demand rates. A scale drawing of the network is shown in Fig. 4. The empty-vehicle shuttling algorithm described in Chapter 10 was also implemented here so that its effectiveness could be determined in an operating situation under random passenger demands. It was felt that this demonstration would support the feasibility of managing the network flow volumes predicted in the Duluth and Minneapolis studies described in Chapter 10.

In order to test a high-demand situation, a vehicle-demand level which would require about fifty percent of the total slots on the main line to be occupied was considered. At one-second headways, this represented a fleet size of about 1100 vehicles operating on the network of Figure 4. To simplify the construction of input data, station-to-station vehicle demands were taken to be randomly distributed around a given mean value. A sequence of average flow calculations of the same type used in the network flow analysis described in Chapter 10 was performed. The calculations showed that a predicted fleet size requirement of 1100 vehicles would be acheived with a randomly-distributed origin-destination input matrix having a mean value of about 18 station-to-station vehicle demands per hour. This figure represents an average station demand for the system of about 400 vehicle demands per station per hour. The calculations were done assuming stations with 3 berths. It was shown previously that 3-berth stations can handle more than 400 vehicles per hour. The origin-destination vehicle demand matrix used as the input to the simulation program is given in Table 2.

The average empty-vehicle demand matrix was computed from the origin-destination demand matrix using an upper bound of a one-minute average wait at each station. The optimization procedures used to compute this matrix are described in Chapter 10. The empty-vehicle origin-destination matrix for the input given in Table 2 is presented in Table 3. This matrix also serves as an input to the simulation program. Other inputs to the simulation program include the minimum-path table and other network-description arrays.

The network of Fig. 4 was initialized by loading every other slot on the main line with a vehicle whose destination was chosen at random. The simulation was then run for 10,000 time steps and the system state at the end of the run was saved for later retreival. The purpose of this run was to remove the transient effects due to the particular initial conditions used. A large number of aborts at interchanges were encountered during the first

Table 2 ORIGIN-DESTINATION MATRIX FULL VEHICLES

DESTINATION \ ORIGIN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0	14	32	6	29	31	24	15	35	18	15	28	11	27	10	9	4	31	28	0	8	29	18
2	8	0	33	33	16	14	20	12	32	26	30	13	32	13	14	3	28	5	1	0	16	4	12
3	20	0	0	19	23	23	11	20	26	24	15	19	22	33	0	31	32	34	13	10	2	17	8
4	34	9	31	0	22	33	23	11	30	1	35	17	13	18	12	25	19	31	7	23	32	30	0
5	7	12	28	6	0	15	3	25	29	32	25	30	2	1	17	22	20	20	7	15	22	26	30
6	22	7	32	13	10	0	16	11	0	6	17	25	9	1	4	13	4	33	1	18	22	3	14
7	4	2	29	3	6	3	0	12	13	14	30	8	34	18	8	19	20	3	2	13	21	14	14
8	12	29	20	27	16	8	5	0	22	25	27	0	4	7	34	12	29	13	33	10	29	11	32
9	0	16	33	8	33	24	21	14	0	6	3	15	34	25	5	13	33	6	30	10	10	11	34
10	28	34	17	17	27	0	15	21	26	0	19	24	11	29	33	11	8	31	14	32	15	26	30
11	2	16	6	9	13	3	33	10	29	27	0	16	2	5	27	31	28	31	28	32	12	19	24
12	26	17	12	34	7	3	10	34	29	10	16	0	8	32	27	13	21	0	34	35	9	15	9
13	28	30	34	10	17	34	7	1	21	2	0	28	0	19	13	34	7	15	8	20	3	14	27
14	7	10	34	20	31	5	14	16	0	12	24	20	17	0	4	28	17	22	29	22	18	28	9
15	16	26	35	3	7	27	16	6	27	20	27	12	10	32	0	29	2	30	0	10	14	29	10
16	28	27	7	2	3	15	17	33	11	8	30	30	34	26	29	0	15	9	29	4	14	19	21
17	18	0	7	29	2	5	22	27	25	25	19	10	14	35	16	33	0	15	5	32	15	26	5
18	32	24	13	14	31	10	24	32	4	23	5	18	29	34	14	20	14	0	23	20	34	20	0
19	2	7	0	1	23	1	30	32	25	23	35	18	16	29	26	2	27	19	0	29	21	2	25
20	30	19	11	10	18	11	4	32	1	4	35	34	20	30	25	25	31	35	14	0	9	5	9
21	27	14	32	0	28	33	2	26	13	17	13	4	35	16	21	8	15	33	10	5	0	2	5
22	6	13	11	25	12	34	18	19	4	16	2	23	35	29	0	34	32	16	12	1	8	0	28
23	0	6	32	19	0	26	0	4	14	26	8	12	0	23	20	30	17	9	1	17	11	18	0

Table 3 ORIGIN-DESTINATION MATRIX EMPTY VEHICLES

DESTINATION \ ORIGIN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	52	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	70	0
7	0	0	0	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	60	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	61	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	33	27	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	20	39	0	0	0	0	0	0	0	0	0	0
12	0	0	0	44	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27	0	16	15	0	0	0	0
14	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	49	0	38	0	0
15	0	0	0	15	0	0	0	0	29	13	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19	41	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	57	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	61	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	58	0	0	0
20	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	36	0	0
21	5	18	0	0	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	0	0	0
23	0	13	0	0	0	0	0	0	0	22	0	8	0	0	25	0	0	0	0	0	0	0	0

few-hundred time-steps of this run. This was due primarily to the initial state of the system: only three aborts were encountered in the system during the remainder of the run after the first 1000 time-steps.

After this initial run, a two-hour simulation (7200 time-steps) was run using the final state of the previous run as the initial state. The origin-destination matrix of Table 2 was again used as the input. Link flows for this demand level, based on average flow calculations, are given in Table 4. Several of the link flows in this table are in the range of eighty percent of the theoretical line capacity of 3600 vehicles per hour, assuming one-second headways. Results of the two-hour simulation run are presented in Table 5. Average passenger waiting times are given for each station. These waiting times are computed over the full two-hour period. The times appear to be well within the specified one-minute maximum average wait. A certain fluctuation around the one-minute average wait is encountered - for example, station 19 has an average wait of 88 seconds- but these deviations seem consistent with the random fluctuations in passenger demands. The very low average waiting times experienced at some of the stations - for example station 16 has an average wait of 24 seconds - are not random affects. At these stations, the arrival of full vehicles is significantly higher than the vehicle demand rate at the station. The vehicle-shuttling procedure is designed to assure that no station will have a theoretical average wait, under steady-state conditions, which will exceed one minute. Lower average waits are possible at

Table 4 LINK FLOWS DERIVED FROM AVERAGE FLOW CALCULATIONS

LINKS		AVERAGE LINK FLOW (VEHICLES PER HR)
ORIGIN STATION	TERMINATING STATION	
1	2	2817
2	8	1691
3	6	817
5	1	1490
6	22	839
7	4	1015
8	10	1691
10	11	2866
11	13	1527
12	7	987
13	16	1526
15	9	822
16	17	2748
17	19	1445
18	15	960
19	20	1446
20	5	1489
21	23	796
23	14	880
2	3	1127
3	4	310
4	1	1326
6	23	761
7	6	784
9	10	1173
11	12	1338
12	9	351
14	16	1222
15	7	812
17	18	1303
18	14	344
20	21	1075
21	22	279
22	20	1118
23	15	675

Table 5 WAITING TIMES IN STATIONS AND INTERCHANGES

AVERAGE WAITING TIME IN STATIONS

STATION	AVERAGE WAIT IN SECONDS
1	57
2	83
3	39
4	41
5	66
6	42
7	47
8	51
9	30
10	56
11	52
12	46
13	50
14	32
15	36
16	24
17	31
18	26
19	88
20	65
21	84
22	56
23	58

AVERAGE DELAY THROUGH INTERCHANGES

INTERCHANGE	AVERAGE DELAY IN HEADWAY TIMES
1	0.0
2	0.0
3	0.5
4	2.1
5	0.5
6	0.4
7	0.7
8	0.6
9	1.6
10	0.0
11	0.4
12	0.0
13	1.8
14	0.0
15	3.2
16	0.4
17	0.4

stations where full-vehicle arrivals exceed service demands, as this example demonstrates.

Average delays through each interchange in the network are also given in Table 5. These represent the average number of slots slipped per vehicle on each interchange. The largest delay was encountered at the T-intersection of ramp 15. The average flow downstream of this interchange was 80 percent of capacity, and the average number of slots slipped per vehicle was 3.2 over the two-hour running time. These figures indicate that delays due to merging in a quasi-synchronous system are quite modest as long as average line flows downstream of the intersection remain below about 80 percent of theoretical capacity. This result is consistent with analytical predictions obtained elsewhere (Royal Aircraft Establishment).

The problem of aborts is quite significant in the quasi-synchronous mode since each abort represents a considerable increase in the vehicle's travel time. The abort rate for a given flow through an interchange is dependent on the permissible queue length of vehicles on the interchange ramp. In this simulation, as previously stated, no more than ten vehicles were allowed to slip slots simultaneously on the maneuvering section. High flow volumes were encountered at interchanges 15 and 4, which are T-intersections. At interchange 15, the flow on the main line downstream from Station 8 was about 47 percent of capacity and the flow downstream from Station 9 was about 34 percent of capacity, producing a total flow past Station 10 of 81 percent of theoretical capacity. The probability of an abort may be determined analytically by using the relation

$$P_A = \frac{\lambda(1-\lambda)(p^N-\lambda^N)}{(1-\lambda^{N+1})(p-\lambda)} \qquad (\lambda = \frac{pq}{(1-p)(1-q)})$$

where N is the number of vehicles which can slip slots simultaneously, p is the flow rate as a fraction of theoretical capacity on the interchange and q is the flow rate as a fraction of theoretical capacity on the main line upstream of the interchange. This relation was obtained by observing that merging vehicles are of two type - queued vehicles, and vehicles which are technically not yet in the queue, but which occupy space on the merge ramp.

Using this relation, an abort probability of .0008 was obtained for vehicles entering interchange 15 if a total of ten vehicles were allowed to slip slots simultaneously. While the probability of an individual vehicle being aborted is quite small, the expected number of aborts per hour may not be small, since a large number of vehicles will pass through the interchange. In fact, for this particular example, the probability that at least one abort will occur in a one-hour period is

$$1 - (1-P_A)^{3600P} = .62$$

For this reason, at the T-interactions 15 and 4, slot slipping was permitted on the main line upstream of the interchange ramp. In these cases, up to thirty vehicles were permitted to slip slots simultaneously upstream of the intersection merge switch.

If this limit is exceeded, only vehicles whose destination station is located on this section of guideway are allowed to enter it. All other vehicles are rerouted around the congestion point.

Using this procedure, no aborts were encountered at any of the interchanges. The provision for slot-slipping on the main line at T-intersections 15 and 4 was necessary to acheive this level of performance. When the simulation was rerun with the usual ten vehicles slipping slots simultaneously, a total of twenty aborts occurred at these intersections in a two-hour run.

With the input data given in Table 2 and a fleet size of 1100 vehicles, the system clearly operated in a steady-state manner. Vehicle demand queues at the end of a two-hour simulation averaged 5.5 demands per station. This figure remained relatively constant at various sampling times during the run. In another set of runs, the fleet size was kept constant at 1100 vehicles and all vehicle demands were scaled up by various factors. A small increase in the overall demand rate of about 10 percent caused average waiting times to increase to about 75 seconds per station, but the system still operated in a steady-state. When the overall demand rate was increased by 40 percent, however, the system did not operate in a steady-state, and the average demand queues at stations increased monotonically with time. At some stations, queues of over 100 vehicle demands were experienced at the end of a two-hour run. Even in this saturated state, however, no aborts were experienced at any of the interchange or station ramps in the system, and average delays through interchanges corresponded quite closely with those given in Table 5.

This result is easily explained. For a given distribution of demand, the maximum number of total demands per hour which can be satisfied by a given fleet size can be estimated. The fixed fleet size thus has the effect of metering the flow in the system.

By using the procedures described here, it is possible to simulate a PRT network of nearly any size. The basic constraint for large networks is computer time. For the laboratory network described here, with 23 stations and 17 interchanges, about 12.5 seconds of CDC 6400 time was required for every 1000 real-time steps. A two-hour simulated run with one-second headways required about 1.5 minutes of computer time. From the type of operations performed in the simulation, it is anticipated that running time should increase linearly with the number of stations in the system.

9.6 Design of Longitudinal Control Systems

Asynchronous Systems

Control systems designed for asynchronous operation differ substantially from those designed for synchronous or quasi-synchronous operation. The first portion of this section is concerned with longitudinal controllers for asynchronous operation and the remainder is concerned with controllers for synchronous or quasi-synchronous operation.

The simplest form of controller for headway maintenance for asynchronous operation depends upon the measurement of the actual velocity of the vehicle and the position of the vehicle relative to the preceding vehicle (provided the vehicles are near one another). These measurements are converted to electrical signals by sensors of which a number of types are available (Chestnut *et al*). The velocity measurement is compared to the desired velocity and the difference is the velocity error. The spacing between the two vehicles is compared to the desired spacing and the difference is the spacing error.

The spacing and velocity errors are appropriately scaled, added, and amplified and resulting signal controls the propulsion and braking system. If, for example, the spacing error is positive (the following vehicle is closing upon the leading vehicle) the brakes are applied. The system gains (the values by which the errors are scaled) play a large role in determining the dynamic response of the system. Proper selection of these gains can result in a system in which relatively large motions of the leading vehicle can be attenuated by the control system in such a manner that the resulting motions of the following vehicles are quite small. Selection of system gains for asynchronous control is discussed by Hadju et al.

Quasi-Synchronous Systems

During normal mainline operation, vehicles follow hypothetical slots moving along the guideway at the nominal mainline velocity. During merging and demerging, maneuvering to avoid conflicts at intersections or to push failing vehicles, or stopping for emergencies, the vehicles follow one of a set of fixed acceleration profiles as commanded by the wayside computers. There is no direct intervehicular communication during quasi-synchronous operation. The longitudinal control system must be capable of holding a vehicle within its alloted slot under the action of headwinds and other disturbances. It must be capable of closely following commanded acceleration profiles, and it must perform these functions without causing passenger discomfort.

In this section, optimization theory is applied to design of longitudinal control systems for high-capacity, quasi-synchronous PRT systems. Optimization theory has found wide usage in the design of control systems for spacecraft, high-performance aircraft and other applications in which stringent performance specifications must be satisfied. In using optimization theory, the system to be controlled is modelled by a set of ordinary differential equations. In control of a PRT vehicle, these are the equations describing the dynamics of the vehicle and the propulsion system. The variables included in this model are the state variables and the control variables. For a PRT vehicle driven by a linear electric motor the position and velocity of the vehicle could be considered as state variables and voltage input to the motor could be considered as the control variable. The control variables determine the dynamic response of the system, for example, increasing the voltage input to the motor causes the velocity of the PRT vehicle to increase.

The designer must select the form of the control variables in such a way as to satisfy specified performance requirements. For example the control system for PRT vehicles must maintain a given spacing between vehicles without causing passenger discomfort. In applying optimization theory, a mathematical measure of system performance, the performance index, must be formulated. The control variables may then be selected in such a manner as to minimize or maximize this performance index. If the problem is formulated properly, the control variables can be determined as functions of the state variables and a feedback or closed-loop controller will result. In the case of PRT vehicles, errors in position and velocity are sensed and used to control the input to the propulsion or braking system. These systems then apply forces which accelerate or decelerate the vehicle in such a manner as to reduce errors in position and velocity to zero. During normal operation, these forces must be applied in such a way as to maintain passenger comfort. Thus the performance specifications on the control system are that errors in position and velocity must be kept small without compromising passenger comfort. Optimization theory provides a systematic approach for the design of such a control system. The resulting feedback controller provides excellent dynamic response for mainline operation with headwinds three times the nominal vehicle velocity; for merging and demerging from off-line stations; for maneuvering at interchanges; and for emergency control. It is shown that by use of the optimal control, nose to nose headways of one-half second at nominal line velocities of 50 feet/second are attainable with no passenger discomfort. The remainder of this section is concerned with the details of the design of an optimal control system for PRT vehicles.

Vehicle Dynamics and the Control System Model

The differential equation describing the longitudinal motion of the PRT vehicle is

$$M\frac{dV}{dt} = -F_D(V,V_W) + F - Mg \sin \theta - F_M \tag{1}$$

where:

M = mass of the vehicle

V = velocity of the vehicle

V_W = velocity of the wind (positive for a head wind)

F = propulsive force

g = gravitational acceleration

θ = slope of the guideway

F_D = aerodynamic drag

F_M = mechanical resistance

The aerodynamic drag is

$$F_D = C_D(V + V_W)^2 \tag{2}$$

where C_D is a drag coefficient. Furthermore, the propulsive force is assumed to be governed by

$$\frac{dF}{dt} = -(\frac{1}{\tau})F + Gi \qquad (3)$$

where:

τ = time constant of the propulsion system

i = control input to the propulsion system

G = gain constant of the propulsion system

That is, the propulsion system as modeled as a first-order lag. The error, e, is defined as

$$e = X - X_c \qquad (4)$$

where

X = actual position of the vehicle

X_c = the desired or command position of the vehicle.

Since $V = \dot{X}$, (1) can be re-written in terms of the error as

$$\frac{d^2e}{dt^2} = -\frac{C_D}{M}(\frac{de}{dt} + \frac{dXc}{dt} + V_W)^2 + \frac{F}{M} - g \sin \theta - \frac{d^2X_c}{dt^2} - \frac{F_M}{M} \qquad (5)$$

For purposes of generality, the system equations will be non-dimensionalized. The following non-dimensional variables will be used:

$v = \frac{T^2 Gi}{MV_N}$, non-dimensional control input to the propulsion system

$w = \frac{Vw}{V_N}$, non-dimensional headwind velocity

$y = \frac{e}{H}$, non-dimensional error

$y_c = \frac{X_c}{H}$, non-dimensional command position

$\sigma = \frac{t}{T}$, non-dimensional time

$f = \frac{TF}{MV_N}$, non-dimensional propulsive force

$\cdot = \frac{d}{d\sigma}$, derivative with respect to non-dimensional time

where:

V_N = nominal velocity of the vehicles on the main guideway

H = nominal nose to nose distance between vehicles on the main guideway

T = nominal time headway between vehicles, $T = \frac{H}{V_N}$.

The resulting system equations are

$$\ddot{y} = -\left(\frac{C_D}{M}\right) H(\dot{y} + \dot{y}_c + w)^2 + f - \frac{Tg \sin \Theta}{V_N} - \ddot{y}_c - \frac{F_M T}{MV_N} \quad (6)$$

$$\dot{f} = -\frac{T}{\tau} f + v \quad (7)$$

During normal mainline operation the vehicle will operate at near nominal velocity, and linearization of (6) and (7) is legitimate. Furthermore $\ddot{y}_c$, the commanded acceleration, will be zero, and $\dot{y}_c$, the commanded velocity, will be unity. The resulting linearized equations of motion are

$$\ddot{y} = -\left(\frac{2C_D}{M}\right) H\,(1 + w)\dot{y} + f - d$$

$$\dot{f} = -\frac{T}{\tau} f + v \qquad (8)$$

$$d = \frac{Tg \sin \theta}{V_N} + \frac{F_M T}{V_N M} + \left(\frac{C_D H}{M}\right)(w + 1)^2,$$ the non-dimensional disturbance force.

The velocity of the headwind is not known a priori; however, its average value will in general be zero. Thus the coefficient of $\dot{y}$ in (8) will be approximated by its average value $\frac{2C_D H}{M}$. As will be shown subsequently, a feedback controller designed on the basis of the above assumptions provides excellent dynamic response for mainline operation with headwinds three times the nominal vehicle velocity; for merging and demerging from off-line stations; for maneuvering at interchanges; and for emergency control.

Synthesis of the Optimal Feedback Control System

The vehicle and propulsion system have been modeled by a set of linear differential equations with constant coefficients. If the state variables are selected properly, it is possible to use optimization theory to design a feedback control system which will keep headway and velocity errors small without causing passenger discomfort (Athans, 1971). The appropriate state variables for this problem are headway error, velocity error, acceleration error, and rate of change of propulsive force. Headway and velocity error are obvious choices for state variables; however, acceleration error and rate of change of propulsive force are less obvious candidates. The reasons for selecting these two quantities as state variables will be discussed in detail below.

The state variables are $x_1 = y$, the non-dimensional headway error; $x_2 = \dot{y}$, the non-dimensional velocity error; $x_3 = \ddot{y}$, the non-dimensional acceleration error; and $x_4 = \dot{f}$, the rate of change of the non-dimensional propulsive force. The control variable is $u = \dot{v}$, the rate of change of the non-dimensional input to the propulsion system. For purposes of control system design, the non-dimensional disturbance force, d, is assumed constant (the headwind is constant or the vehicle is ascending or descending a constant slope). Using these definitions and assumptions, the equations of motion of the vehicle can be written in vector-matrix form as

$$\dot{\underline{x}} = A\underline{x} + \underline{b}u \tag{9}$$

where

$$\underline{X}^T = [x_1\ x_2\ x_3\ x_4],$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -\frac{2C_DH}{M} & 1 \\ 0 & 0 & 0 & -\frac{T}{\tau} \end{bmatrix},$$

and

$$\underline{b}^T = [0\ \ 0\ \ 0\ \ 1].$$

The control u will be selected in such a manner as to drive the state variables to zero. The state variables x_1 and x_2 represent the position and velocity errors and the necessity of driving these quantities to zero is clear. The state variables x_3 and x_4 represent the acceleration error and the rate of change of propulsive force. The acceleration error must be zero if the position and velocity errors are to remain zero; furthermore, in order to achieve zero acceleration error, the propulsive force must equal the disturbance force. Since the disturbance force is assumed to be constant, the propulsive force must also approach a constant value, and the derivative of the propulsive force, x_4, must approach zero.

The error equations have been formulated in the standard notation of optimal control theory; however, in order to apply this theory a mathematical criterion for the measurement of system performance is necessary. A quadratic performance index is proposed. This index is

$$J = \frac{1}{2} \int_o^\infty (q_1 x_1^2 + q_2 x_2^2 + q_3 x_3^2 + q_4 x_4^2 + ru^2)\ dt \qquad (10)$$

The optimal feedback control problem is to determine the control, u, as a function of the state variables in such a manner as to minimize J. It can easily be shown that the control which minimizes J drives the state variables to zero (Lee and Markus, 1967).

The performance index J is the integral of the weighted sum of the position error, velocity error, acceleration error, derivative of the propulsive force, and the control effort. Since the drag coefficient is small, the derivative of the propulsive force is very nearly proportional to the jerk. The performance index penalizes large position and velocity errors and the control which minimizes J should result in a system in which these errors are kept small. The performance index also penalizes large acceleration errors and jerks. These two variables affect passenger comfort and the control which minimizes J should also result in a system which is comfortable to ride. The rate of change of the control input to the propulsion system, u, must be included in the performance index in order to obtain the optimal control in feedback form.

It is of course possible to formulate many other performance indices which include system error and passenger comfort; however, use of a quadratic performance index as given in (10) permits determination of the optimal control in feedback form. This is one of the few classes of optimization problems in which the optimal feedback control can be found (Lee and Markus, 1967). In addition the optimal feedback control is linear with constant gains. Such a controller is easy to implement.

The feedback control which minimizes J is

$$u = -r^{-1} \underline{b}^T K \underline{x} \tag{11}$$

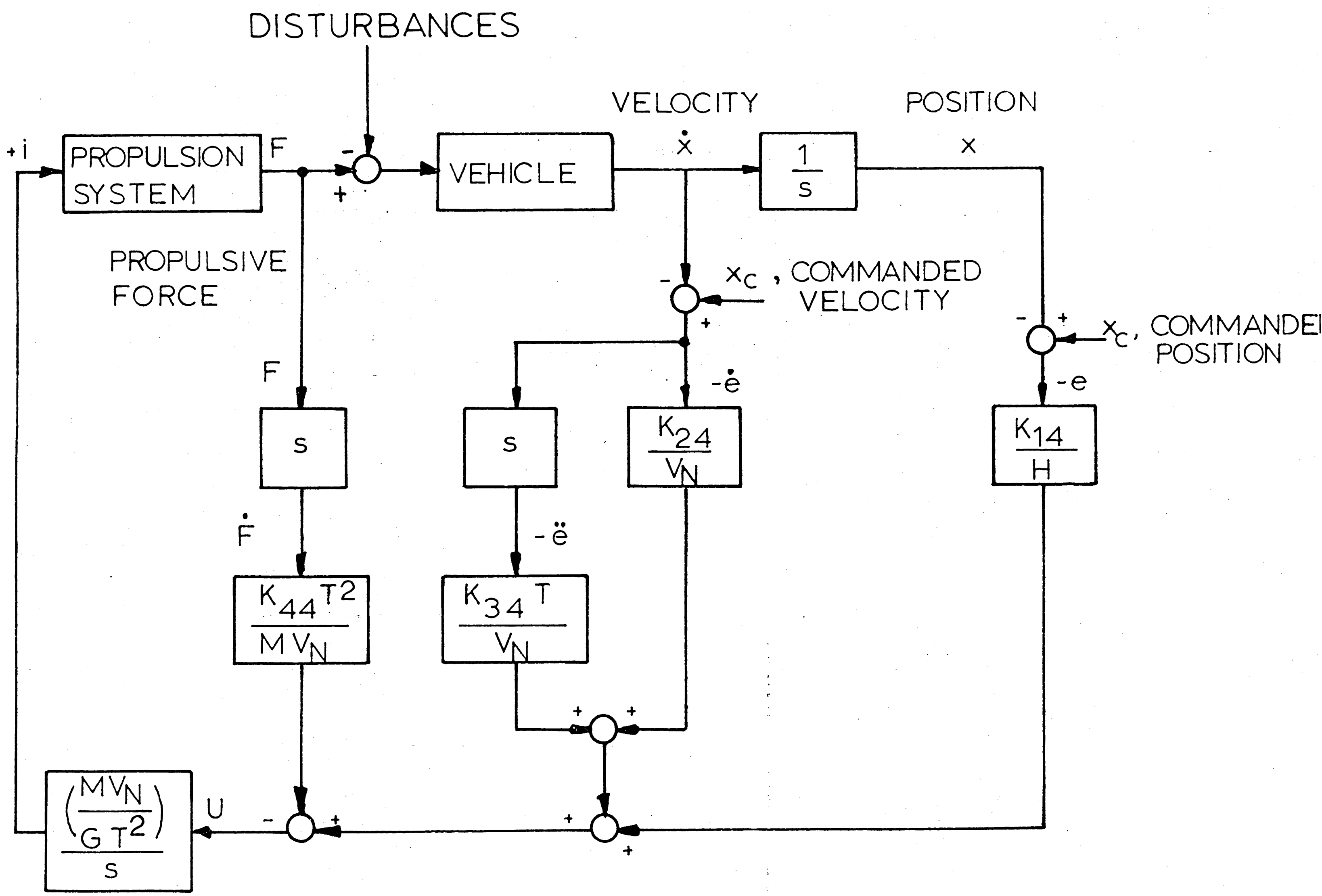


Fig. 5 Block Diagram of Vehicle, Propulsion System, and Feedback Controller

where K, the optimal gain matrix, is the symmetric, positive-definite solution of the matrix Ricatti equation

$$KA + A^TK - K\underline{b}^Tr^{-1}\underline{b}K + Q = 0 \tag{12}$$

where

$$Q = \begin{bmatrix} q_1 & 0 & 0 & 0 \\ 0 & q_2 & 0 & 0 \\ 0 & 0 & q_3 & 0 \\ 0 & 0 & 0 & q_4 \end{bmatrix}$$

Iterative methods for the solution of (12) allow rapid determination of the optimal gain matrix by use of a high-speed digital computer (Kleinman, 1968).

From (12) the optimal control in terms of the actual error variables is

$$u = -\frac{K_{14}e}{H} - \frac{K_{24}\dot{e}}{V_N} - \frac{K_{34}T\ddot{e}}{V_N} - \frac{K_{44}T^2}{MV_N}\dot{F} \tag{13}$$

where the K_{ij}'s are the elements of the optimal gain matrix K. A block diagram of the vehicle and control system is shown in Fig. 5*. It can be seen that the input totthe propulsion system is proportional to the headway error, the derivative of the headway error, the integral of the headway error, and the propulsive force. The optimal control (13) is similar to the control derived by Whitney and Tomizuka (1972) using classical techniques and by Wilkie (1970) and Larson (1971) using optimization theory. However, in neither of these studies was the dynamics of propulsion system considered. It should be noted that in all of these systems,

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* The symbol "s" denotes the Laplace operator.

steady-state errors due to constant biases in the measurements of velocity errors, acceleration errors, and the rate of change of propulsive force are zero.

The weighting factors q_1, q_2, q_3, q_4 and r affect the values of the elements of K, the gain matrix*. The values of the elements of the gain matrix in turn affect the dynamic response of the system. The relationship between the weighting factors and the dynamic response of the vehicle cannot be analytically determined. If the weighting factors on headway and velocity error are chosen to be large relative to the weighting factors on the acceleration errors and jerk (rate of change of propulsive force) a system which zeros errors rapidly but which gives an uncomfortable ride will result. On the other hand, if the weighting factors on acceleration error and jerk are chosen to be large relative to the weighting factors on headway and velocity error, the ride will be comfortable but the system will be rather sluggish in reducing the headway error to zero. Thus the designer must determine how the weighting factors affect the dynamic response in order to obtain the proper trade-off between ride quality and adequate control of headway error.

Figs. 6-15 illustrate various system performance characteristics as functions of the weighting factors. Preliminary

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* It can be shown that $K_{14} = \sqrt{q_1}$; the other gains must be determined numerically, however.

computations indicated that the velocity error should be weighted ten times the position error ($q_2 = 10q_1$). This resulted in tighter headway control as well as a more comfortable ride than could be obtained by weighting the position error the same as or greater than the velocity error. Since the performance index can be multiplied by a constant without changing the value of the optimal-gain matrix, any one of the weighting factors can be arbitrarily set equal to unity. Thus the weighting factor on the control was chosen to be one. The weighting factor on acceleration error, q_3, was set at ten, and the values of the other state-variable weighting factors were varied with respect to q_3. The coefficient $\frac{2C_D H}{M}$ was set at .025, a value typical of vehicles in many PRT and dual-mode systems (Whitney and Tomizuka, 1972, Wilkie, 1970).

The headway error, acceleration, jerk, maximum power, and the time to reduce the headway error to ten percent of its initial value were plotted versus the ratio of q_1 to q_3. The maximum acceleration and jerk were determined for an initial headway error of ten percent and zero headwind. The maximum headway error and maximum power were determined for zero initial headway error and a headwind three times the nominal velocity of the vehicle. The information presented in Figs. 6 - 15 is applicable to a wide variety of systems since the quantities plotted are non-dimensional. An example using specific values of V and H is presented later. In Figs. 6 - 10 the time constant of the propulsion system was assumed to be one-tenth of the

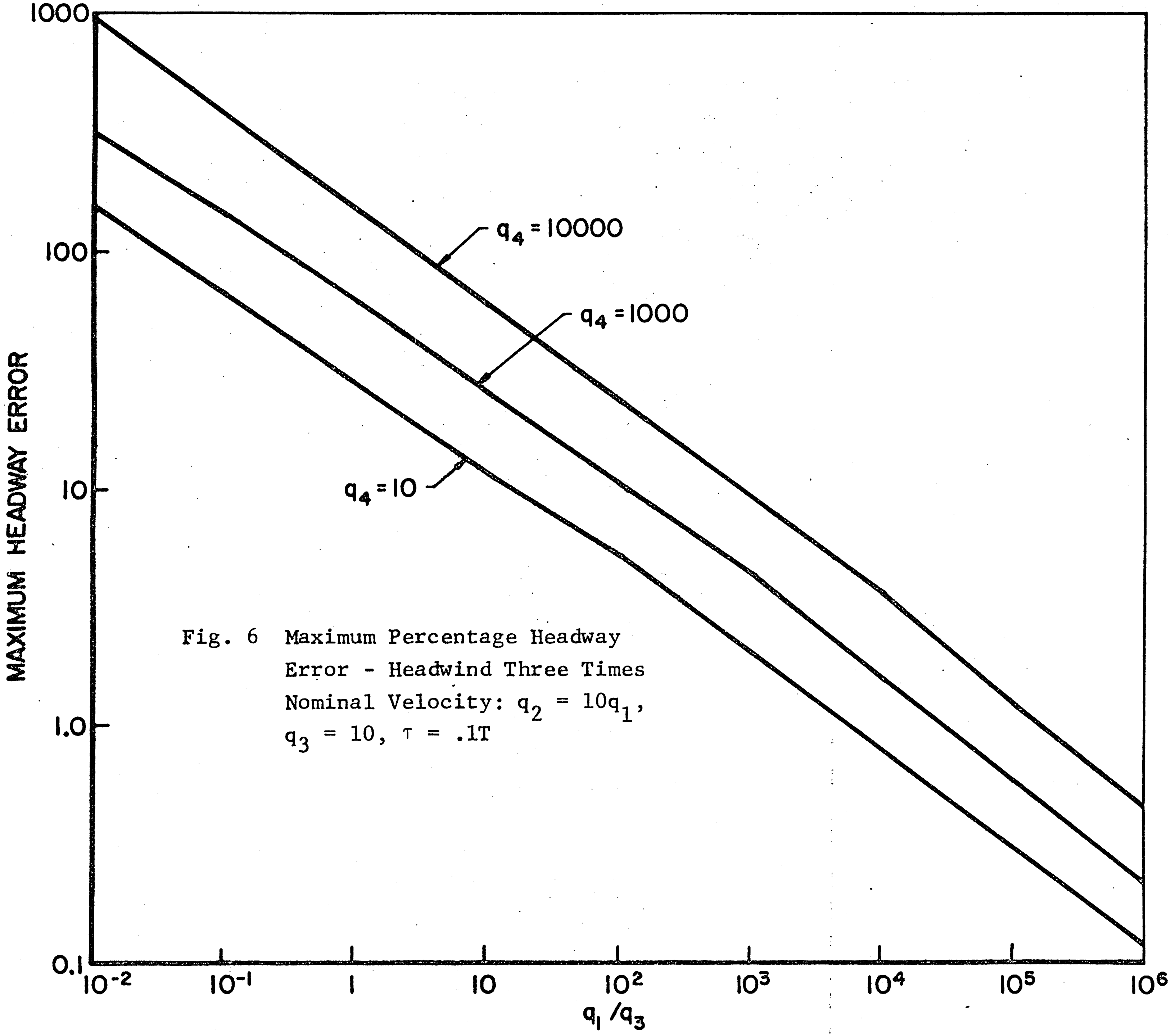


Fig. 6 Maximum Percentage Headway Error - Headwind Three Times Nominal Velocity: $q_2 = 10q_1$, $q_3 = 10$, $\tau = .1T$

minimum headway time and weighting factors of ten, one thousand, and ten thousand were placed on the jerk.

It is interesting to note in Fig. 6 that in order to obtain maximum headway errors of less than fifty percent, it is necessary to weight the headway error at least ten times the acceleration error. In Fig. 9 it can be seen that for values of the weighting factor on headway error greater than ten, the time to reduce a headway error to ten percent of its initial value is, for all practical purposes, constant and does not depend on the weighting factor associated with the jerk. As would be expected, Figs. 7 and 8 indicate that acceleration and jerk increase as the ratio of headway error to acceleration error increases. Furthermore, the jerk increases at a faster rate than the acceleration and has larger numerical values than the acceleration. Thus jerk, rather than acceleration is the limiting factor in obtaining tight control. Fig. 10 illustrates the maximum power requirements for various values of the weighting factors. The maximum power required is smaller for large values of the weighting factor on the headway error than for small values and is sensitive to the value of the weighting factor on jerk. It can be seen that acceptable performance is obtained for ratios of q_1 to q_3 between one and ten thousand. Unacceptable large headway errors result if q_1/q_3 is less than one and excessive jerk results if q_1/q_3 is greater than ten thousand. Also peak power requirements are not excessive for q_1/q_3 between one and ten thousand.

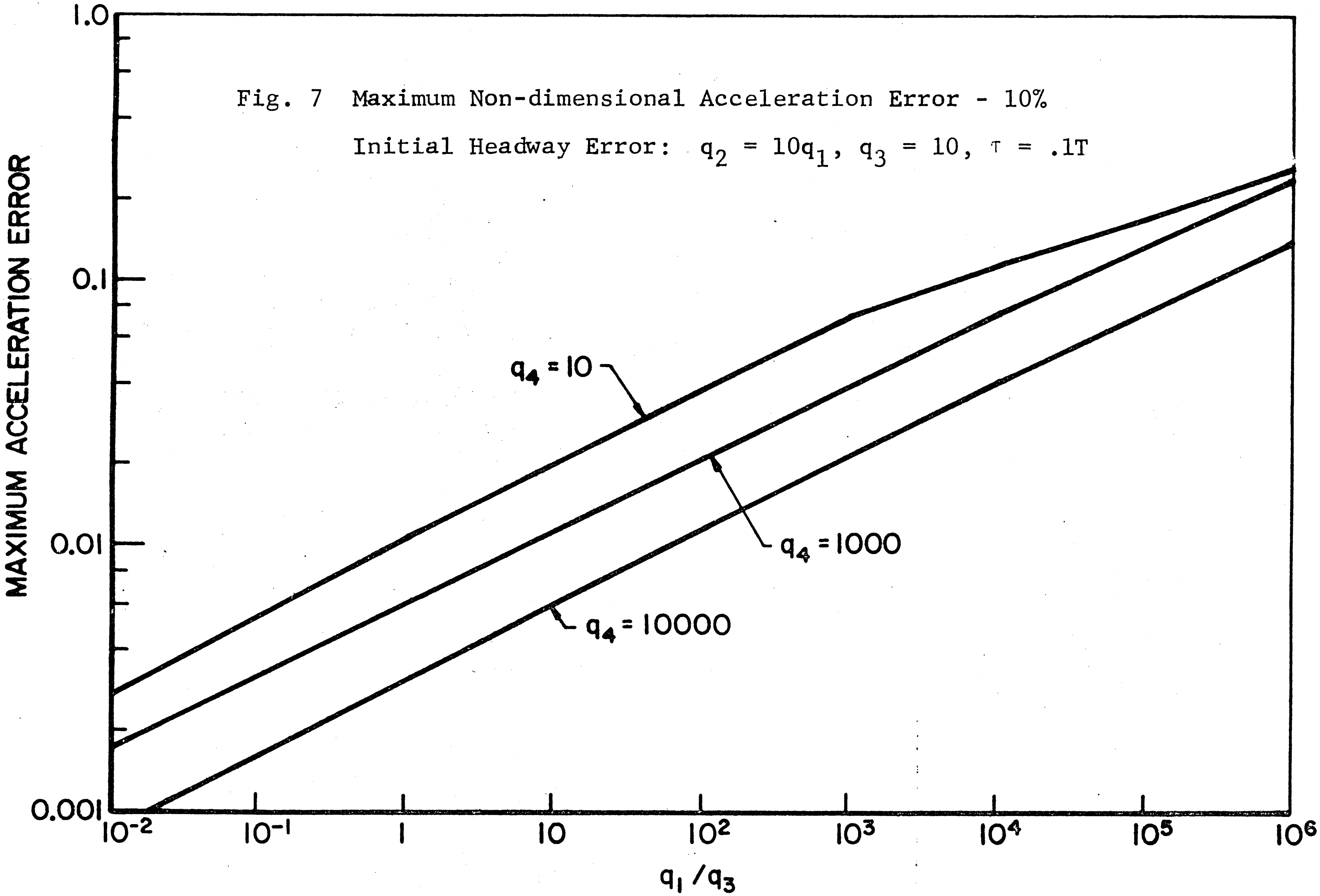


Fig. 7 Maximum Non-dimensional Acceleration Error - 10% Initial Headway Error: $q_2 = 10q_1$, $q_3 = 10$, $\tau = .1T$

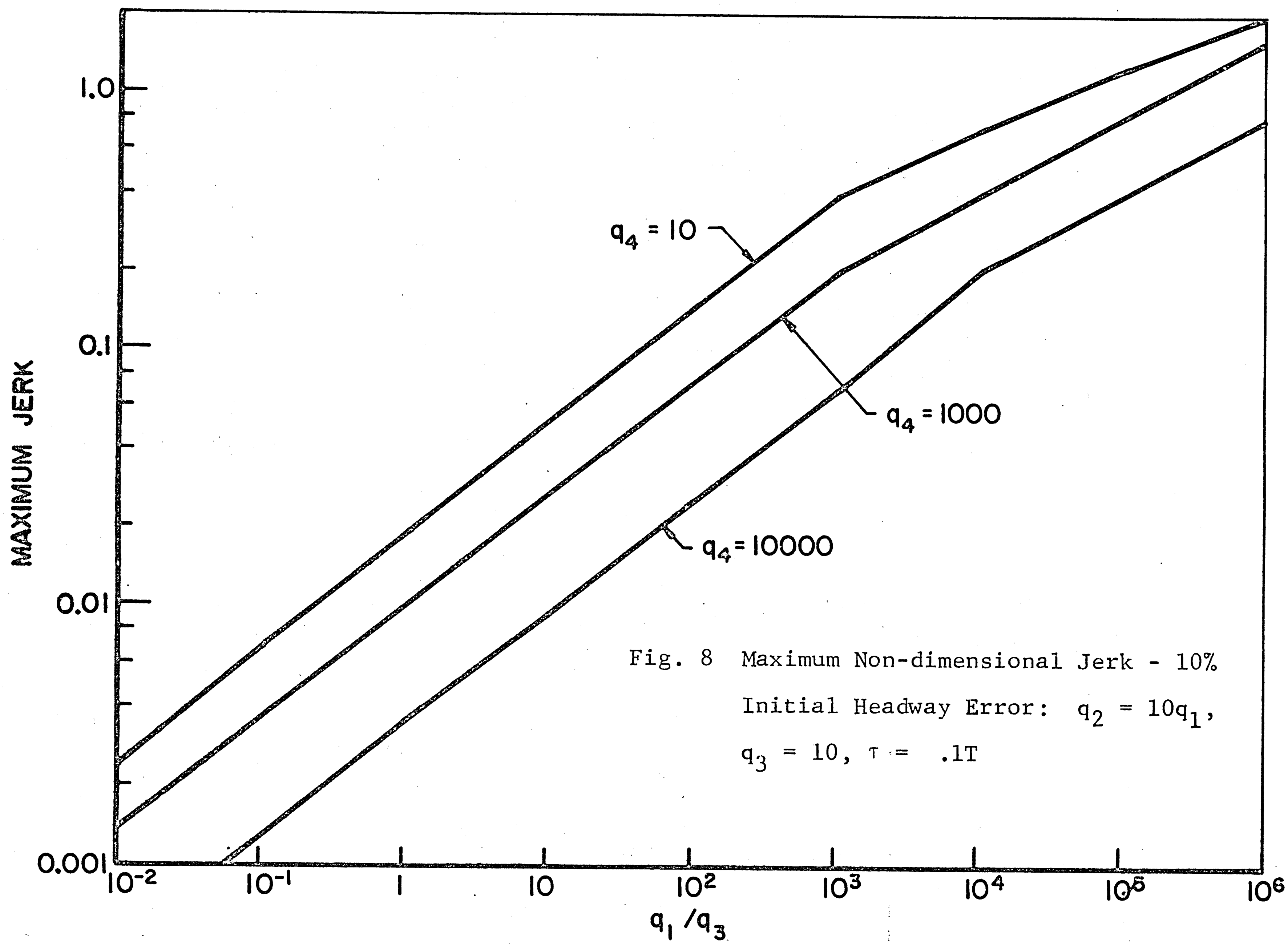


Fig. 8 Maximum Non-dimensional Jerk - 10% Initial Headway Error: $q_2 = 10q_1$, $q_3 = 10$, $\tau = .1T$

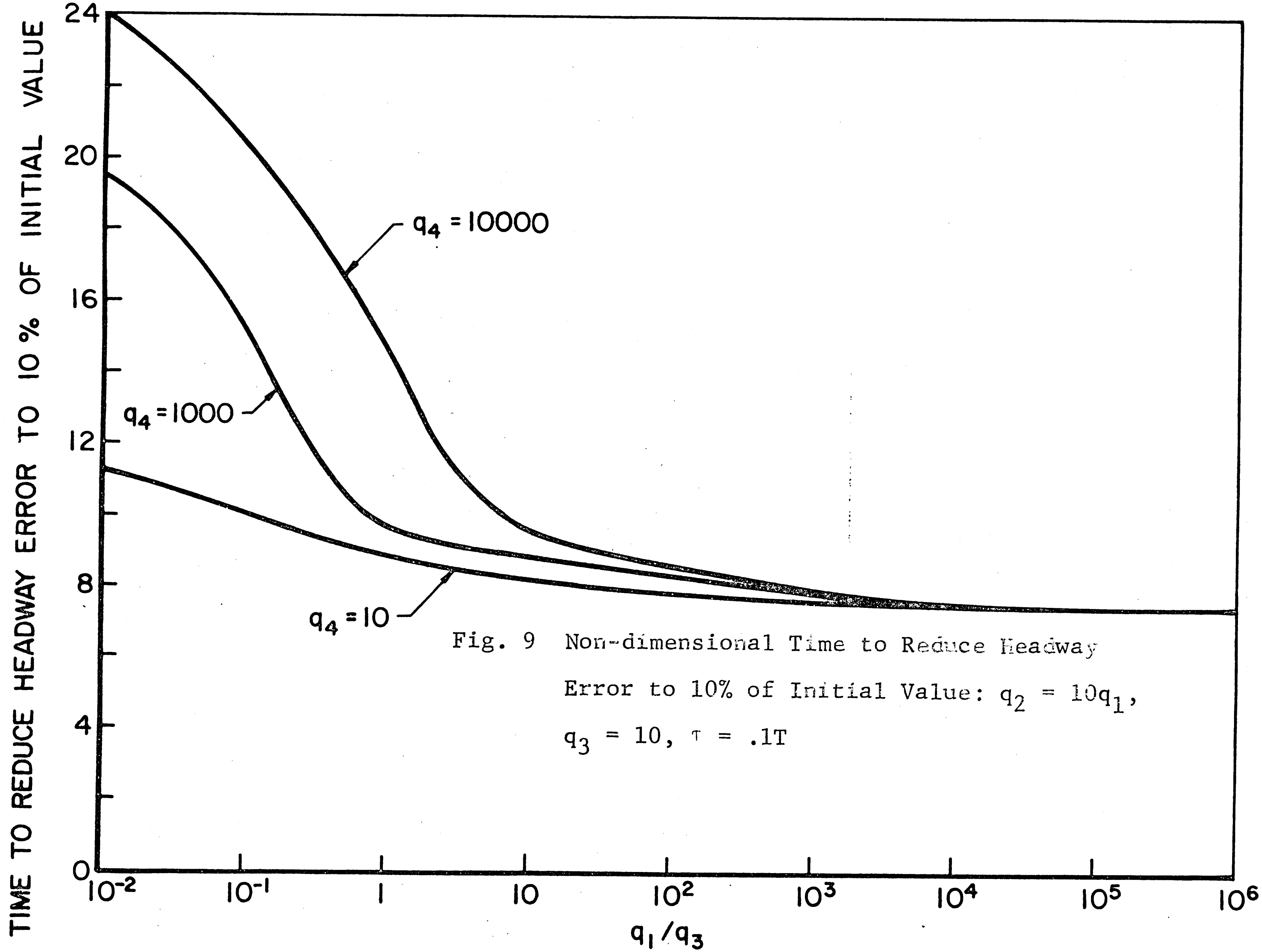


Fig. 9 Non-dimensional Time to Reduce Headway Error to 10% of Initial Value: $q_2 = 10q_1$, $q_3 = 10$, $\tau = .1T$

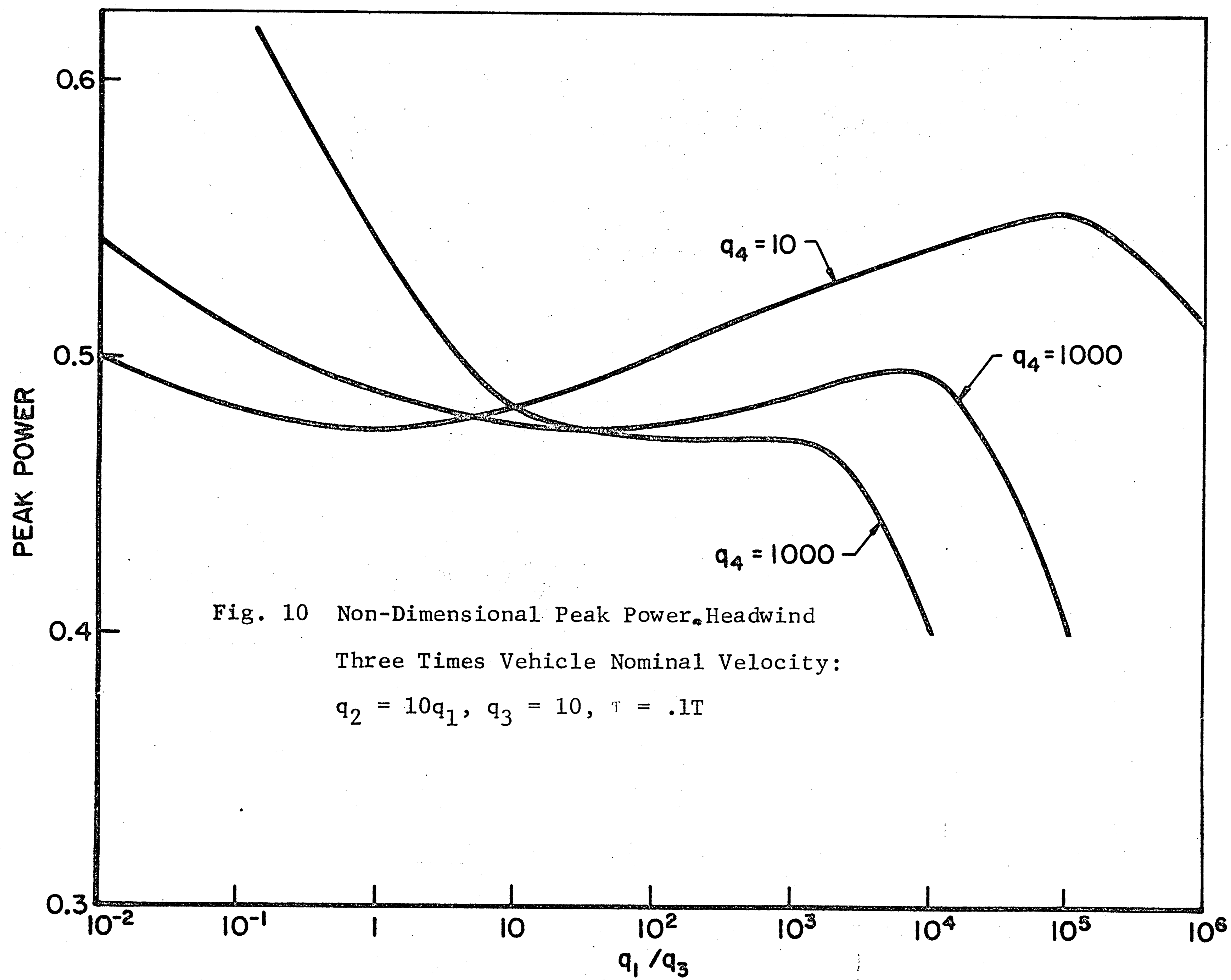


Fig. 10 Non-Dimensional Peak Power, Headwind Three Times Vehicle Nominal Velocity: $q_2 = 10q_1$, $q_3 = 10$, $\tau = .1T$

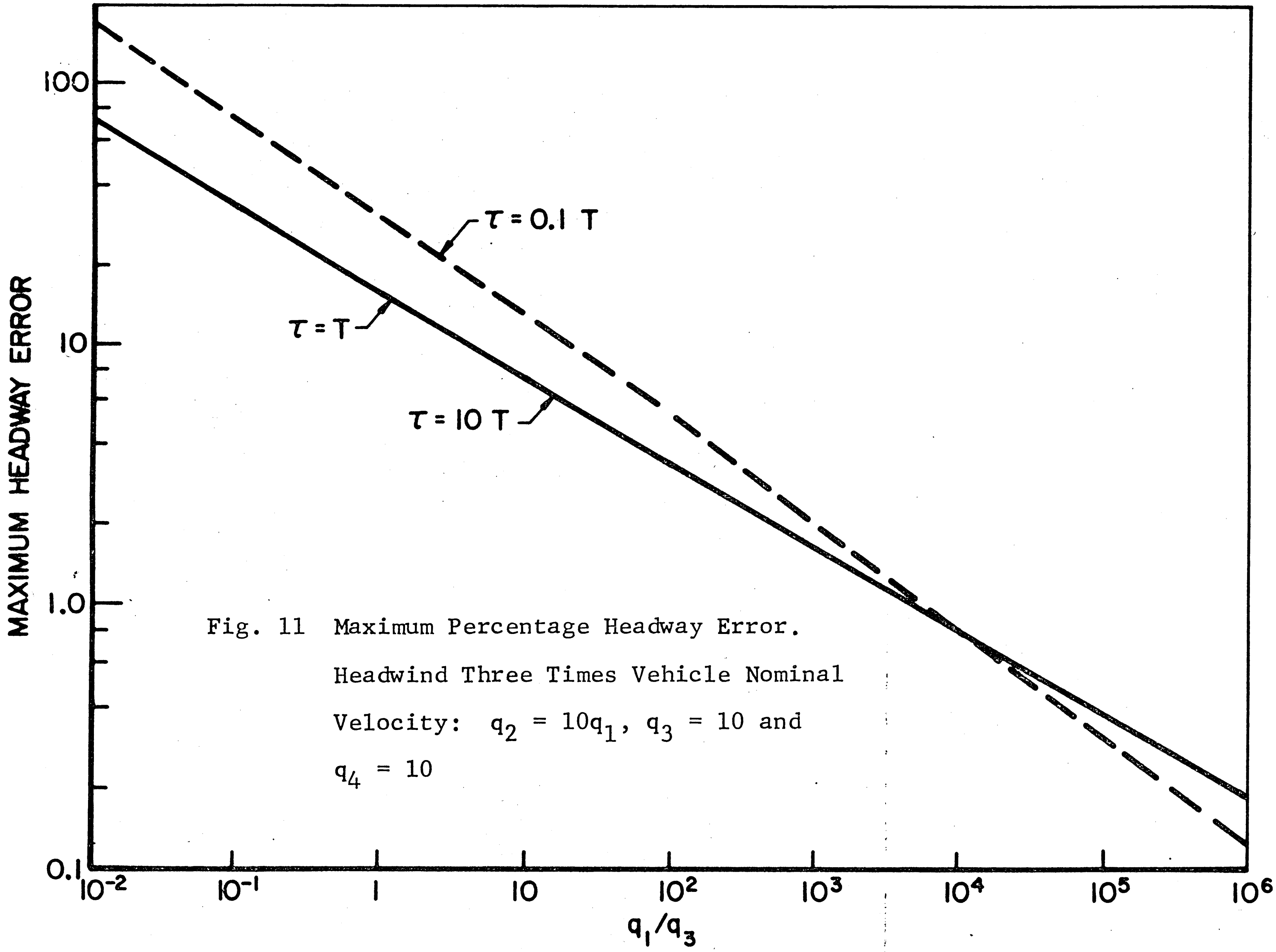


Fig. 11 Maximum Percentage Headway Error. Headwind Three Times Vehicle Nominal Velocity: $q_2 = 10q_1$, $q_3 = 10$ and $q_4 = 10$

The time constant of the propulsion system is an important parameter in the design of the longitudinal control system. If proper consideration is given to propulsion system dynamics oscillatory or unstable responses can be avoided even for large values of the propulsion-system time constant. The system model used in this study includes propulsion system dynamics and the optimal control compensates for time lags introduced by the propulsion system. This illustrated in Figs. 11-15. The dynamic response characteristics of the optimally controlled vehicle are shown for propulsion system time constants equal to the minimum headway time, one-tenth the minimum headway time, and ten times the minimum headway time.

The response characteristics of the vehicle for $\tau = T$ and $\tau = 10T$ are almost indistinguishable. This can be explained by referring to Table 6. The gains for position, velocity, and acceleration errors are almost identical for both values of the propulsion system time constant. The gains for the derivative of propulsive force are different. However, if the natural coefficient of the propulsive force, $\frac{T}{\tau}$, is added to the gain for the derivative of the propulsive force is almost the same for $\tau = T$ and $\tau = 10T$. Thus the dynamic response of the optimally controlled vehicle is for all practical purposes invariant for large values of the time constant of the propulsion system.

It is interesting to note that for the same value of q_1/q_3 tighter headway control was maintained with large propulsion system time constants than with small. However, the accelerations, jerks and peak power were also larger. The time required to

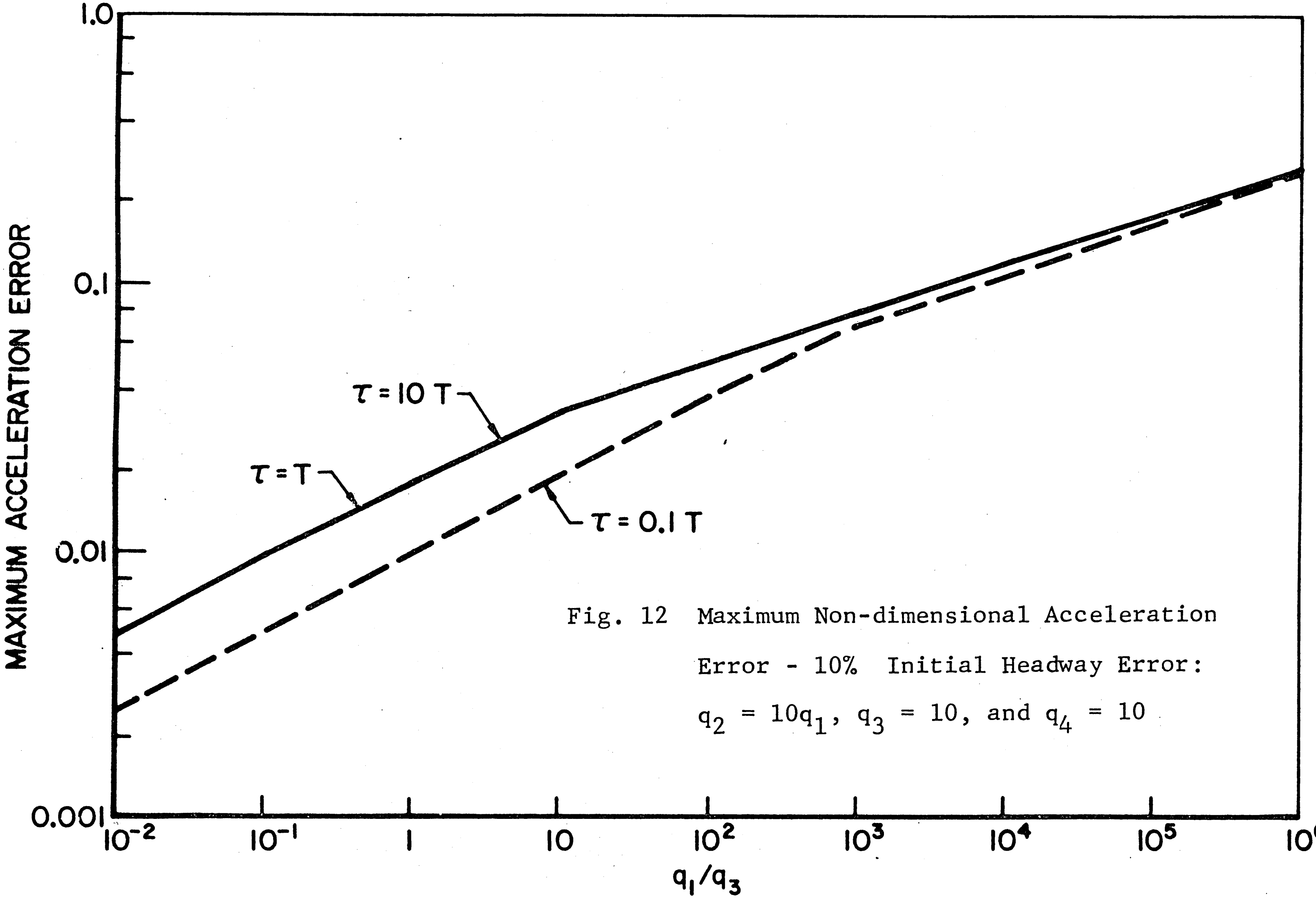


Fig. 12 Maximum Non-dimensional Acceleration Error - 10% Initial Headway Error: $q_2 = 10q_1$, $q_3 = 10$, and $q_4 = 10$

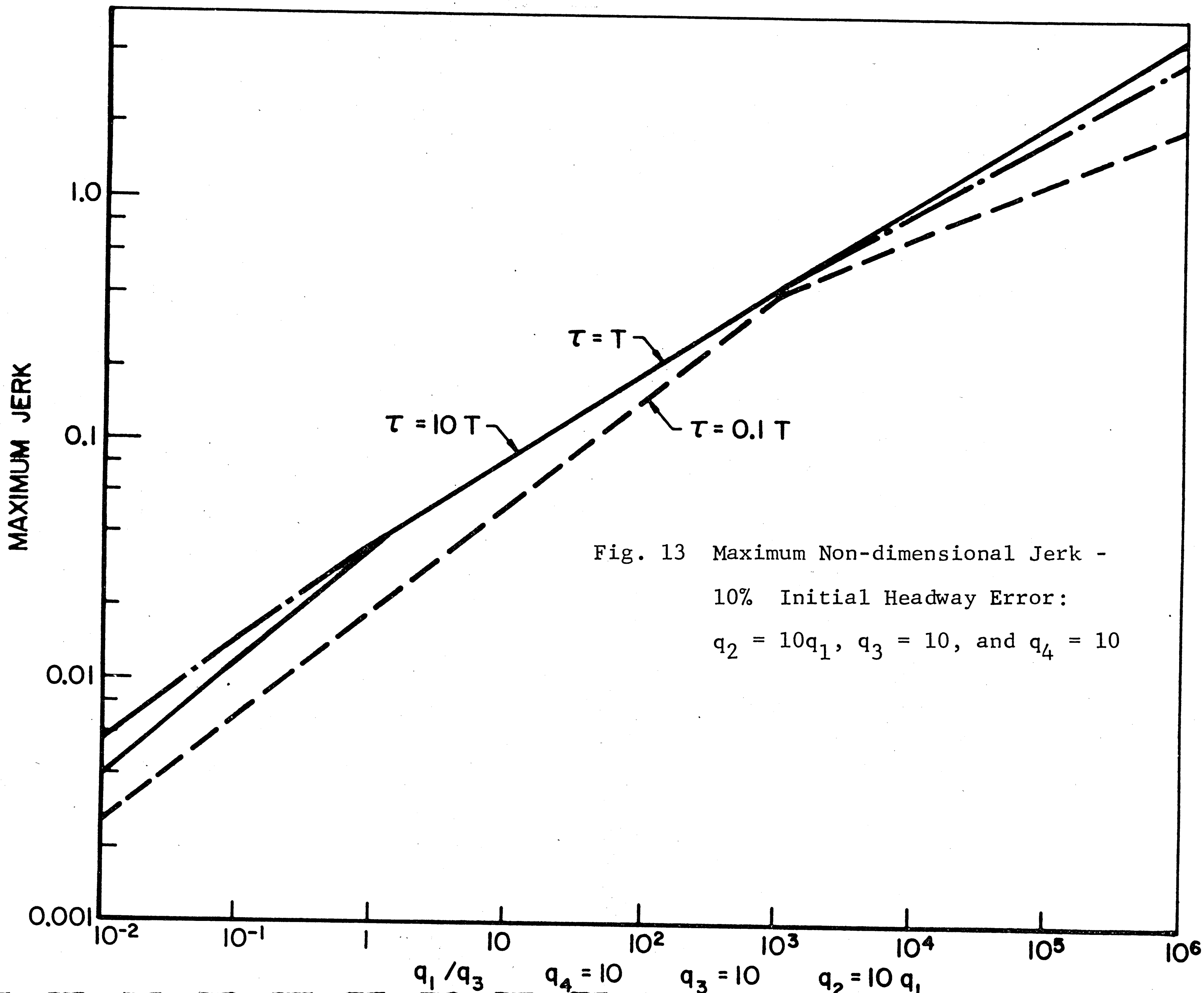


Fig. 13 Maximum Non-dimensional Jerk - 10% Initial Headway Error: $q_2 = 10q_1$, $q_3 = 10$, and $q_4 = 10$

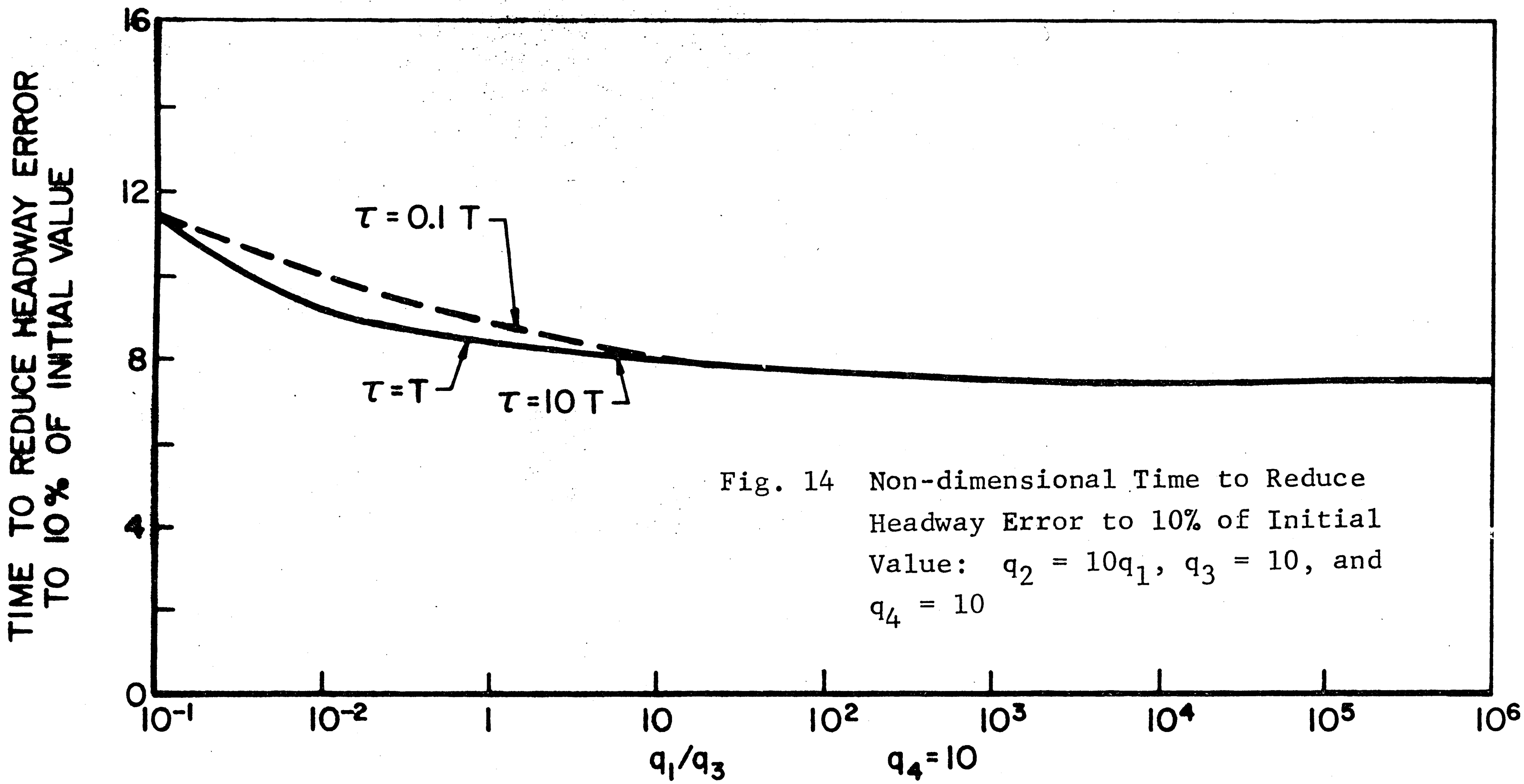


Fig. 14 Non-dimensional Time to Reduce Headway Error to 10% of Initial Value: $q_2 = 10q_1$, $q_3 = 10$, and $q_4 = 10$

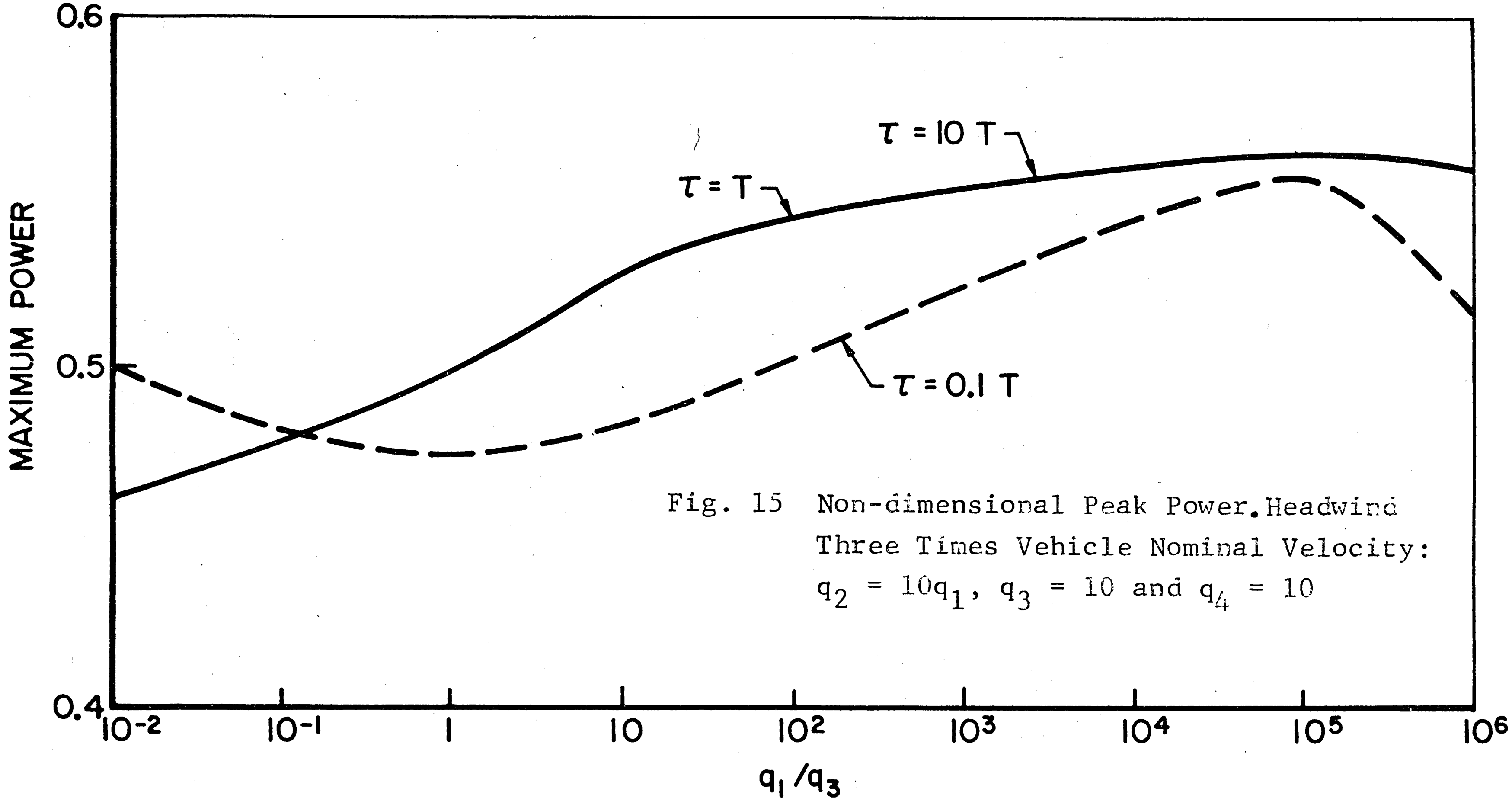


Fig. 15 Non-dimensional Peak Power. Headwind Three Times Vehicle Nominal Velocity: $q_2 = 10q_1$, $q_3 = 10$ and $q_4 = 10$

q_1/q_3	$\tau = .1T, \quad q_2 = 10q_1, \quad q_4 = 10, \quad q_3 = 10$			
	K_{14}	K_{24}	K_{34}	K_{44}
10^{-2}	0.316	2.469	7.776	1.205
10^{-1}	1.000	5.823	11.665	1.547
1	3.162	14.866	18.824	2.151
10	10.000	40.664	32.340	3.217
10^2	31.624	117.204	58.687	5.079
10^3	100.000	349.970	111.879	8.270
10^4	316.243	1068.284	222.545	13.563
10^5	1000.000	3304.094	457.215	22.012
10^6	3162.434	10299.756	959.351	35.050

q_1/q_3	$\tau = 10T, \quad q_2 = 10q_1, \quad q_4 = 10, \quad q_3 = 10$			
	K_{14}	K_{24}	K_{34}	K_{44}
10^{-2}	0.316	2.090	5.214	4.420
10^{-1}	1.000	5.030	7.534	4.908
1	3.162	13.458	12.674	5.846
10	10.000	38.474	23.816	7.493
10^2	31.624	114.159	47.669	10.165
10^3	100.000	346.134	98.628	14.300
10^4	316.243	1063.84	207.650	20.529
10^5	1000.000	3299.276	441.348	29.787
10^6	3162.434	10294.722	942.977	43.457

Table 6 - Non-Dimensional Gains for Various Values of Propulsion System Time Constants

q_1/q_3	$\tau = T$,	$q_2 = 10q_1$,	$q_4 = 10$,	$q_3 = 10$
	K_{14}	K_{24}	K_{34}	K_{44}
10^{-2}	0.316	2.098	5.265	3.640
10^{-1}	1.000	5.049	7.617	4.122
1	3.162	13.486	12.792	5.049
10	10.000	38.512	23.960	6.670
10^2	31.624	114.203	47.827	9.329
10^3	100.000	346.182	98.794	13.446
10^4	316.243	1063.896	207.825	19.661
10^5	1000.000	3299.327	441.516	28.909
10^6	3162.434	10294.773	943.164	42.572

Table 6 (cont.) - Non-Dimensional Gains for Various Values of Propulsion System Time Constants reduce a headway error to ten percent of its initial value did not vary a great deal with the various values of the propulsive system time constant.

Figs. 6 - 15 and Table 6 will be of considerable use in the design of optimal feedback control systems for automated vehicles as the proper values of the weighting factors for a given set of specifications can be easily selected from the figures. Once the weighting factors have been selected, the proper non-dimensional gains can be found in Table 6 , and the dimensionalized gains can then be determined from (13). Thus a systematic procedure is presented for the design a longitudinal control system which maintains tight headway control without causing passenger discomfort.

Implementation of the Optimal Controller

Implementation of the optimal feedback controller necessitates measurement of all state variables - the position error, velocity error, acceleration error, and rate of change of propulsive force. In actual practice, it is inconvenient and expensive to measure accurately the acceleration error and rate of change of propulsive force. However it is possible, to estimate or reconstruct the values of these variables from measurements of the position and velocity errors. This estimation can be accurately performed by using the theory of observers (Luenberger, 1971). The resulting estimator appears to be relatively economical to implement and the dynamic response of the vehicle is very close to the optimal.

For design purposes, the vehicle and propulsion system is modeled by (9), and the optimal control is

$$u = -\underline{k}^T\underline{x} \tag{14}$$

Where from (11), $\underline{k}^T = r^{-1}\underline{b}^T K$. The measurable output of the system is defined as a vector, $\underline{y}$, of dimensionality $p \leq 4$. This vector is given by

$$\underline{y} = C\underline{x} \tag{15}$$

where C is a matrix of dimensionality p x 4.

In order to implement the optimal control, $\underline{x}$ must be reconstructed from $\underline{y}$. This is possible if and only if the 4 x 4p matrix

$$\left[C^T \,\vdots\, A^T C^T \,\vdots\, (A^T)^2 C^T \,\vdots\, (A^T)^3\ C^T\right]$$

has rank 4 (Lee and Markus, 1967). If this condition is satisfied, the system is said to be completely observable. It can easily be shown that the position error of the vehicle must be measured in order to guarantee observability. The velocity error, acceleration error, and derivative of propulsive force can be reconstructed from the position error alone. However, it is relatively simple to measure velocity error; therefore, the matrix C is assumed to be

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{16}$$

That is, both position and velocity errors are measured.

The theory of observers can be used to synthesize a network the output of which is a suitable approximation of the state of the vehicle. An observer is a dynamical system which operates on the output of another dynamical system in order to provide an estimate of the state of that system (Luenberger, 1971). The estimate of the state of the original system is denoted as $\hat{\underline{x}}$, and the state of the observer is defined as $\underline{z}$ where

$$\underline{z} = T\,\hat{\underline{x}} \tag{17}$$

and

$$\dot{\underline{z}} = F\underline{z} + G\underline{y} + T\underline{b}u \tag{18}$$

with

$$TA - FT = GC \tag{19}$$

In the longitudinal control problem as formulated in this study, $\underline{z}$ is of dimensionality two, and

$$\hat{\underline{x}} = \begin{bmatrix} C \\ \hline T \end{bmatrix}^{-1} \begin{bmatrix} y \\ \hline \underline{z} \end{bmatrix} \tag{20}$$

The matrixes F and G are 2 x 2 and the matrix T is 2 x 4. Thus sixteen matrix elements have been introduced. Matrix equation (19) represents eight algebraic equations relating the elements of F, G and T, thus eight of the matrix elements can be chosen arbitrarily. These elements will be selected in such a manner as to result in a simple, efficient observer.

First the matrix F is selected as

$$F = \begin{bmatrix} \lambda_1 & \beta \\ 0 & \lambda_2 \end{bmatrix} \tag{21}$$

The reasons for selecting F in this form will be given later. Substitution of (21) into (19) yields

$$\lambda_1 t_{11} - \beta t_{21} = g_{11} \tag{22a}$$

$$- \lambda_2 t_{21} = g_{21} \tag{22b}$$

If $g_{11} = g_{21} = 0$, $t_{11} = t_{21} = 0$ and the structure of the observer is simplified with no apparent degradation of performance. After making this simplification, the remaining equations resulting from the substitution of (21) into (19) are

$$- \lambda_1 t_{12} - t_{22} = g_{12} \tag{23a}$$

$$- \lambda_2 t_{22} = g_{22} \tag{23b}$$

$$t_{12} + (\ell - \lambda_1) t_{13} - \beta t_{23} = 0 \tag{23c}$$

$$t_{22} + (\ell-\lambda_2)t_{23} = 0 \qquad (23d)$$

$$t_{13} + (m-\lambda_1)t_{12} - \beta t_{24} = 0 \qquad (23e)$$

$$t_{24} + (m-\lambda_2)t_{24} = 0 \qquad (23f)$$

where $\ell = \frac{-2C_DH}{M}$ and $m = \frac{-\tau}{T}$.

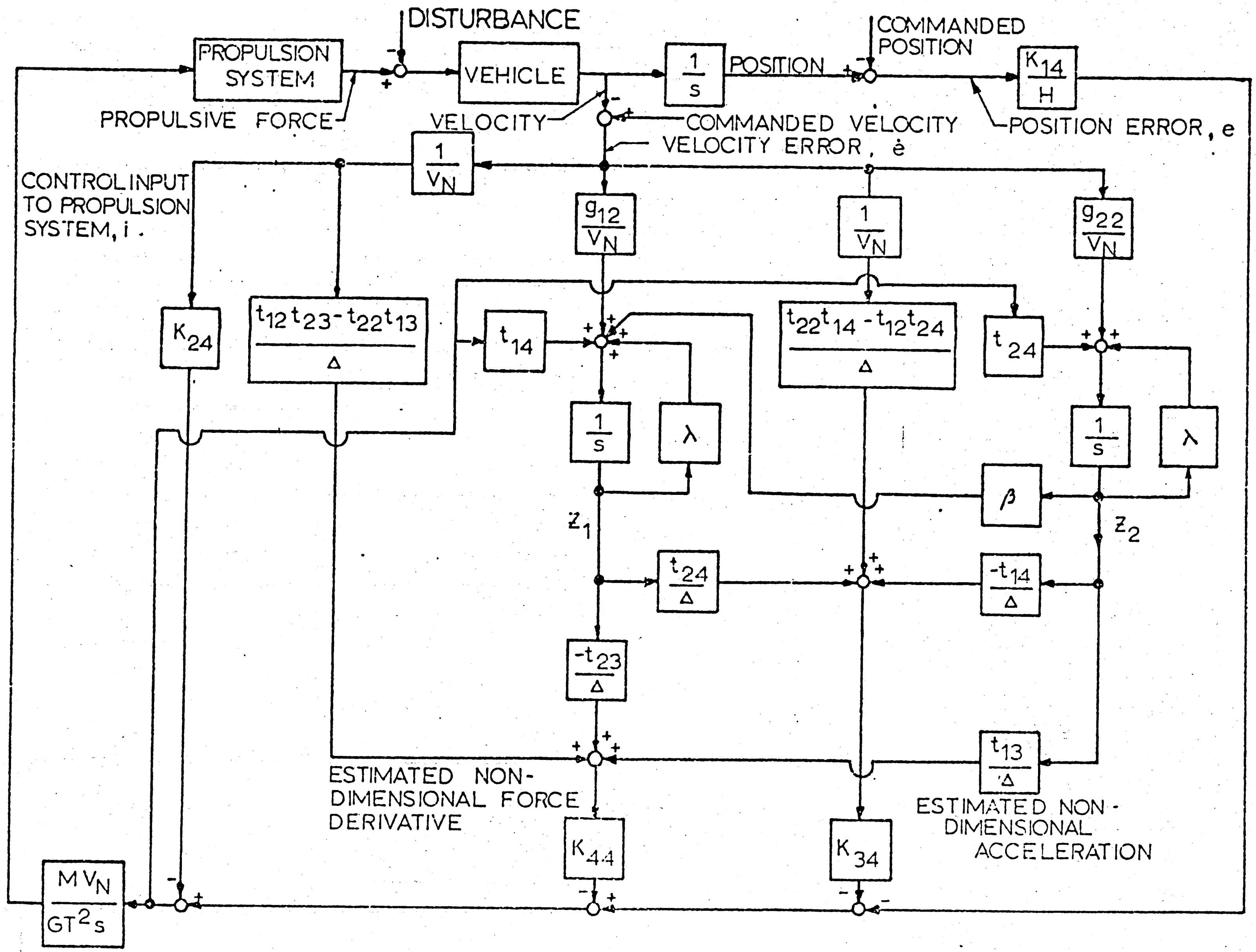
Now

$$\left[-\frac{C}{T}-\right]^{-1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & \frac{t_{22}t_{14}-t_{12}t_{24}}{\Delta} & \frac{t_{24}}{\Delta} & \frac{-t_{14}}{\Delta} \\ 0 & \frac{t_{12}t_{23}-t_{22}t_{13}}{\Delta} & \frac{-t_{23}}{\Delta} & \frac{t_{13}}{\Delta} \end{bmatrix} \qquad (24)$$

where $\Delta = \beta t_{24}^2$. Obviously $\beta \neq 0$. It can also be shown that $t_{24} = 0$ if $g_{22} = 0$; therefore, $g_{22} \neq 0$. A block diagram of the observer, vehicle and propulsion system is shown in Fig. 16.

It can be shown that an observer does not change the eigenvalues of the original system but simply adjoins its eigenvalues to those of the original system (Luenberger 1971). Thus if the original system is stable and the eigenvalues of the observer are chosen to have negative real parts, the resulting system will also be stable. If the eigenvalues of the observer are chosen to be large, the estimate of the state will approach the actual value of the state extremely rapidly; however, the resulting system is extremely sensitive to high-frequency disturbances. On the other hand, if the eigenvalues of the observer are small, the estimate of the state approaches the actual value of the state very slowly and the overall performance of the system is substantially degraded. In practice the eigenvalues of the observer are selected to be slightly larger than the largest eigenvalues of the original system. From (21), the eigenvalues of the observer are λ_1 and λ_2. There appears to be no reason for having λ_1 differ from λ_2; therefore, λ_1 and λ_2 were set equal to one

Fig. 16 Block Diagram of Optimal System with Observer



another and were made slightly larger than the largest eigenvalue of the original system. The values of the constants β, g_{12}, and g_{22} have no affect on the dynamic response of the observer and hence were arbitrarily set equal to one.

The response of the vehicle with the observer was determined as a function of q_1/q_3 for zero initial headway error and a headwind three times the vehicle nominal velocity and for an initial headway error of ten percent and zero headwind. The response to an initial headway error was graphically indistinguishable from the response obtained with all states sensed (Figs. 7-9). Only a small increase in maximum headway error and peak power resulted from use of the observer to estimate the acceleration and rate of change of propulsion force. (Figs. 17, 18).

Design of an Optimal Longitudinal Feedback Control System for a High-Capacity PRT System

A longitudinal control system was designed for a PRT system with the following specifications:

Nominal Mainline Velocity = 50 ft/sec

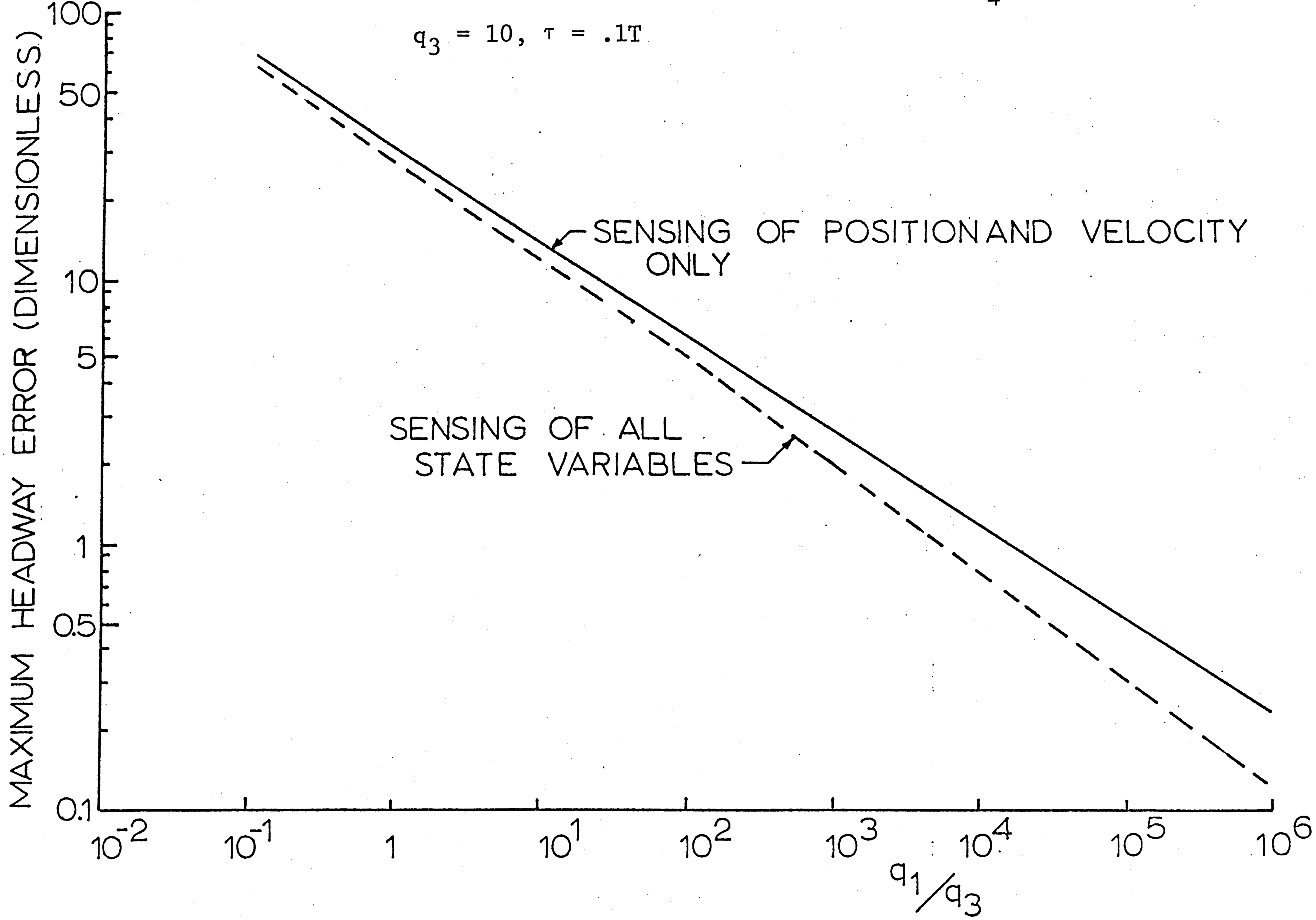
Minimum Headway Time = 0.5 sec

Vehicle and Passenger Weight = 3200 lbs

Vehicle Length = 10 ft

Maximum Acceleration in Mainline Operation = 4 ft/sec^2

Fig. 17 Maximum Dimensionless Headway Error - Headwind Three Times Nominal Mainline Velocity, $q_4 = 10$, $q_3 = 10$, $\tau = .1T$



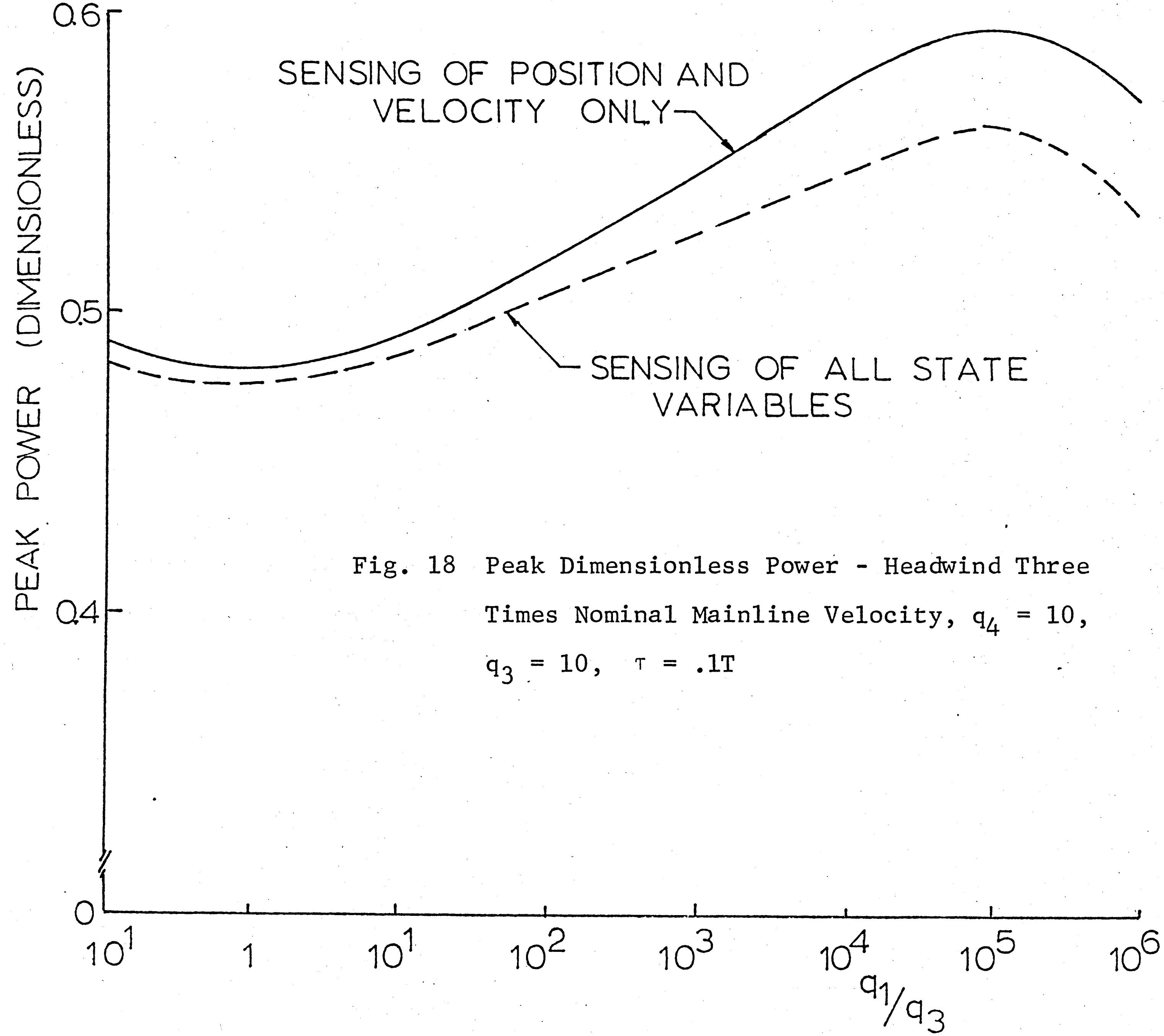


Fig. 18 Peak Dimensionless Power - Headwind Three Times Nominal Mainline Velocity, $q_4 = 10$, $q_3 = 10$, $\tau = .1T$

Maximum Acceleration for Merging and Manuevering = 8 ft/sec^2

Maximum Emergency Deceleration = 25 ft/sec^2

Maximum Jerk in Mainline Operation = 4 ft/sec^3

Maximum Jerk in Merging and Manuevering = 8 ft/sec^3

Maximum Headway Error = 7.5 ft

Propulsion System Time Constant = 0.05 sec

The above specifications are typical of many proposed high-capacity PRT systems and result in a system with a mainline capacity of 7200 vehicles/hr. The minimum nominal separation between adjacent vehicles is 15 feet, thus even in the case in which the leading vehicle encounters a sudden gust of 150 ft/sec, the minimum separation between the leading and following vehicle is 7.5 feet.

The nominal headway for the system is 25 ft., thus a maximum headway error of thirty percent is allowed. From Fig. 17 it can be seen that this criterion will be satisfied for q_1/q_2 greater than or equal to one. The maximum allowable jerk in mainline operation is 4 ft/sec^3 and from Fig. 8*, q_1/q_3, must be less than or equal to one. From Fig. 7 it can be seen that the acceleration criterion of 4 ft/sec^2 is also satisfied

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* Non-dimensional jerk is obtained by multiplying dimensional jerk by T^2/V and non-dimensional acceleration is obtained by multiplying dimensional acceleration by T/V.

for q_1/q_2 less than or equal to one. Thus passenger, comfort and headway control requirements are satisfied for q_1/q_2 equal to one. The non-dimensional feedback gains for this case are given in Table 6. The most negative eigenvalue for this system is -10.48; therefore, the eigenvalues of the observers were set at -12.

The nonlinear vehicle dynamics (6), the dynamics of the propulsion system (7), and the observer (18) were simulated on a digital computer. The following situations are illustrated:

1. Mainline operation with a suddenly applied headwind of 50 ft/sec (Figs 19 and 20)
2. Mainline operation with an initial headway error of 2.5 ft (Fig. 21)
3. An emergency stop with a constant deceleration of 25 ft/sec (Figs 22 and 23)
4. Merging from an off-line station following a trapezoidal acceleration profile (Fig 24)

In Fig. 19 it can be seen that the maximum headway error due to a suddenly applied wind gust of 50 ft/sec is 1.5 ft and the maximum velocity error is 1.8 ft/sec. The response of the vehicle with only position and velocity measured is very near the response with all states sensed. The rapidity with which the

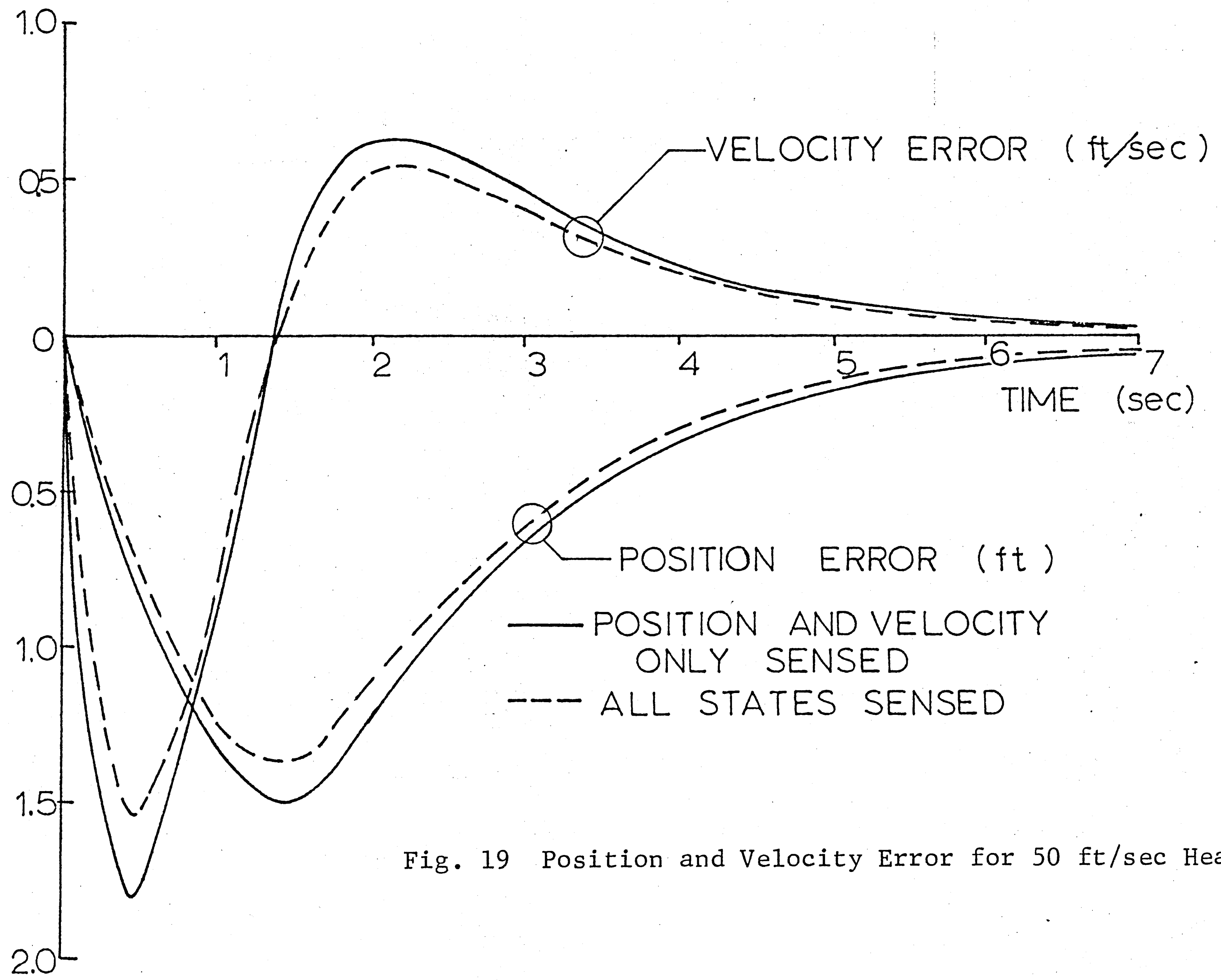

Fig. 19 Position and Velocity Error for 50 ft/sec Headwind

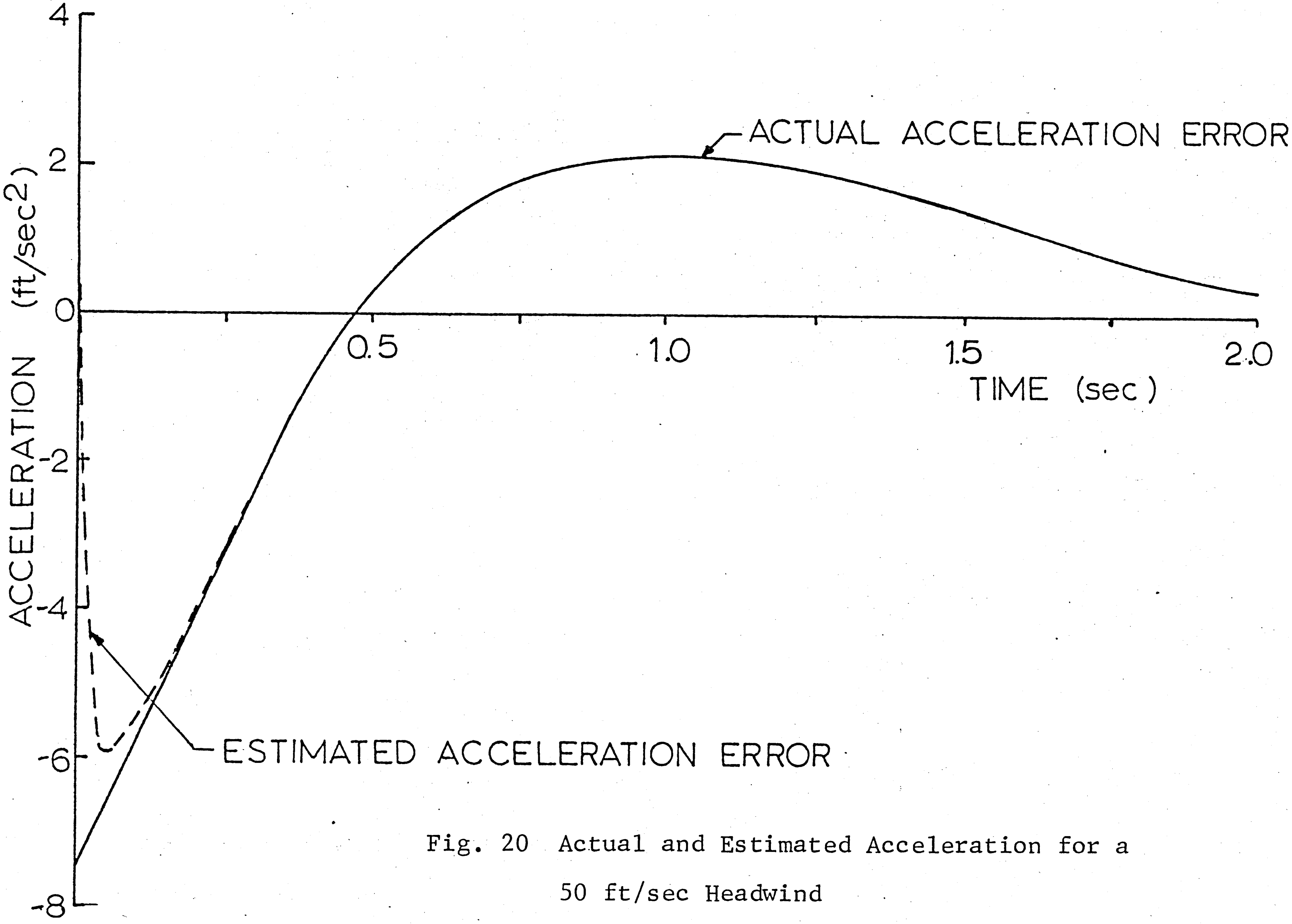

Fig. 20 Actual and Estimated Acceleration for a 50 ft/sec Headwind

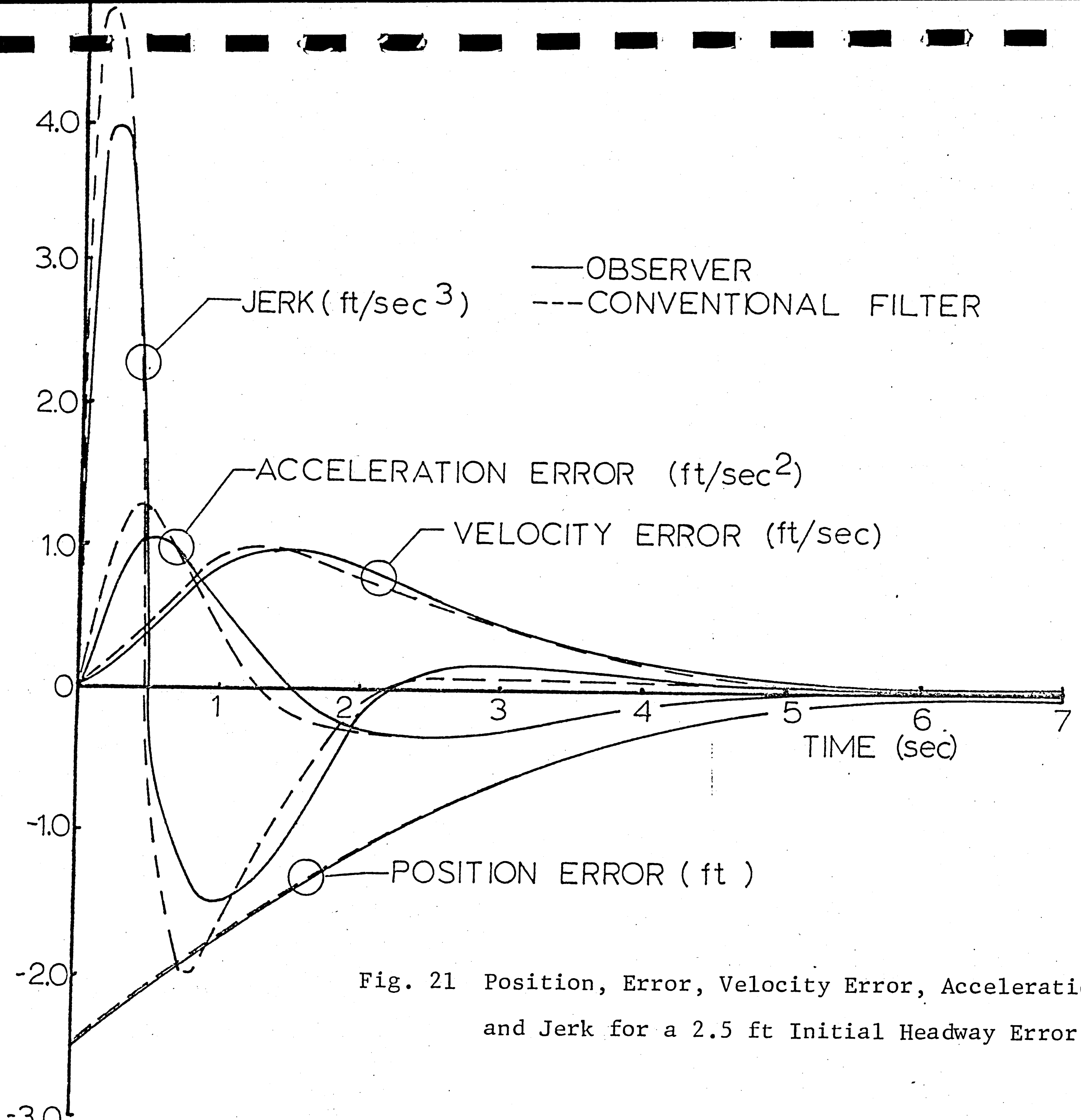

Fig. 21 Position, Error, Velocity Error, Acceleration, and Jerk for a 2.5 ft Initial Headway Error

estimated acceleration approaches the actual acceleration is illustrated in Fig. 20. As shown in Fig. 21, the maximum jerk for an initial error of 2.5 is 4 ft/sec^3, and the maximum acceleration is 0.75 ft/sec^2, thus the resulting ride is not uncomfortable. In this case the difference between the response of the vehicle with all states sensed and the response with only position and velocity are indistinguishable. These results are to be expected since the design was based on mainline operating conditions.

During merging, emergency stopping, and manuevering the vehicle is not operating at mainline conditions. For example, during merging the vehicle starts with zero velocity and accelerates to line velocity following a commanded acceleration profile as shown in Fig. 24. The differential equations describing the state of the system during merging, emergency stopping, and manuevering are nonlinear with time-varying coefficients. The control system in this study was designed on the basis of state equations which were linear with constant coefficients. However as can be seen from an examination of Figs. 22-24, the resulting controller follows the desired profiles very well even though the conditions are vastly different from those encountered during mainline operation. There is little difference in the dynamic response for the system with the observer and the system in which all states are sensed.

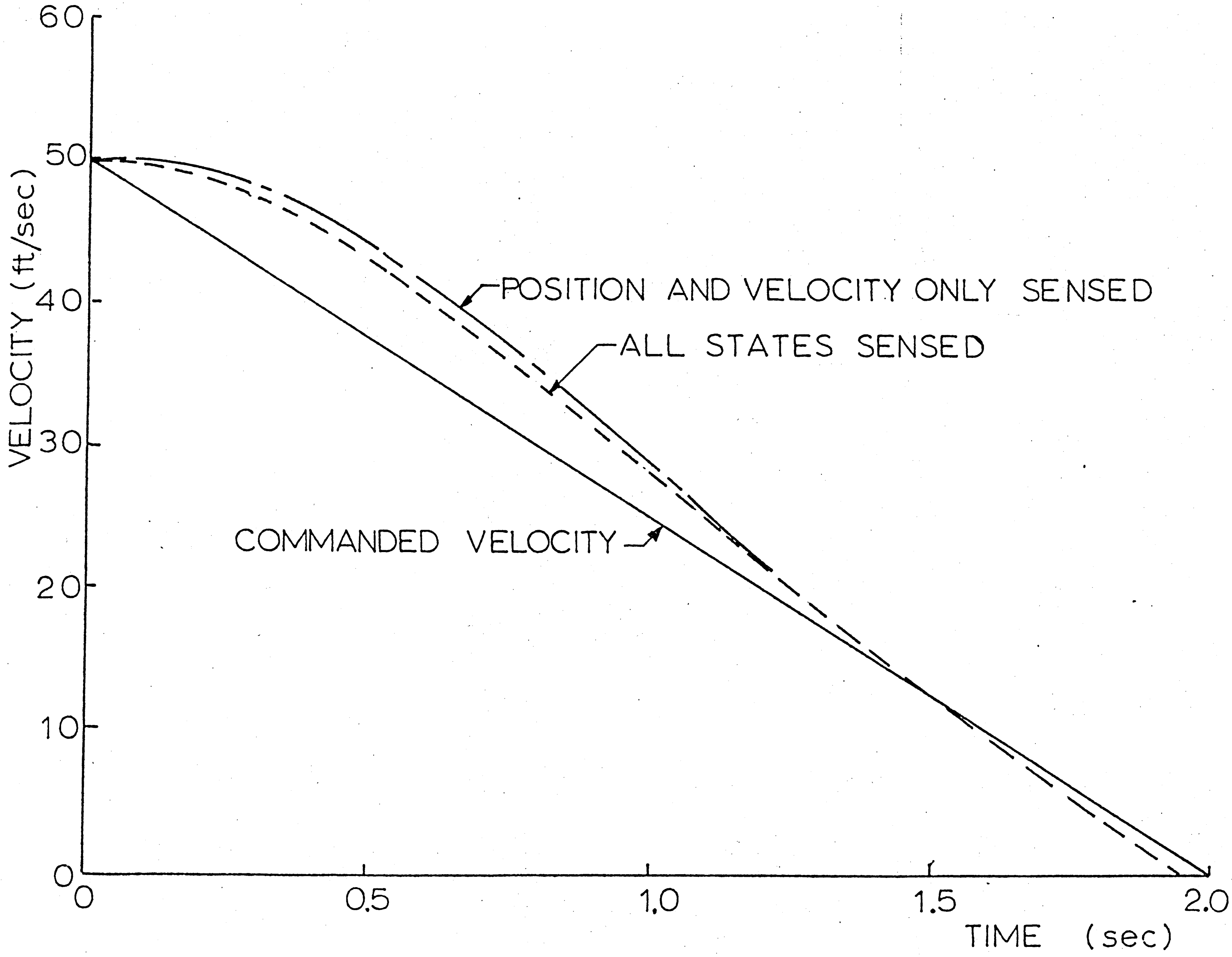

Fig. 22 Velocity-Emergency Stopping

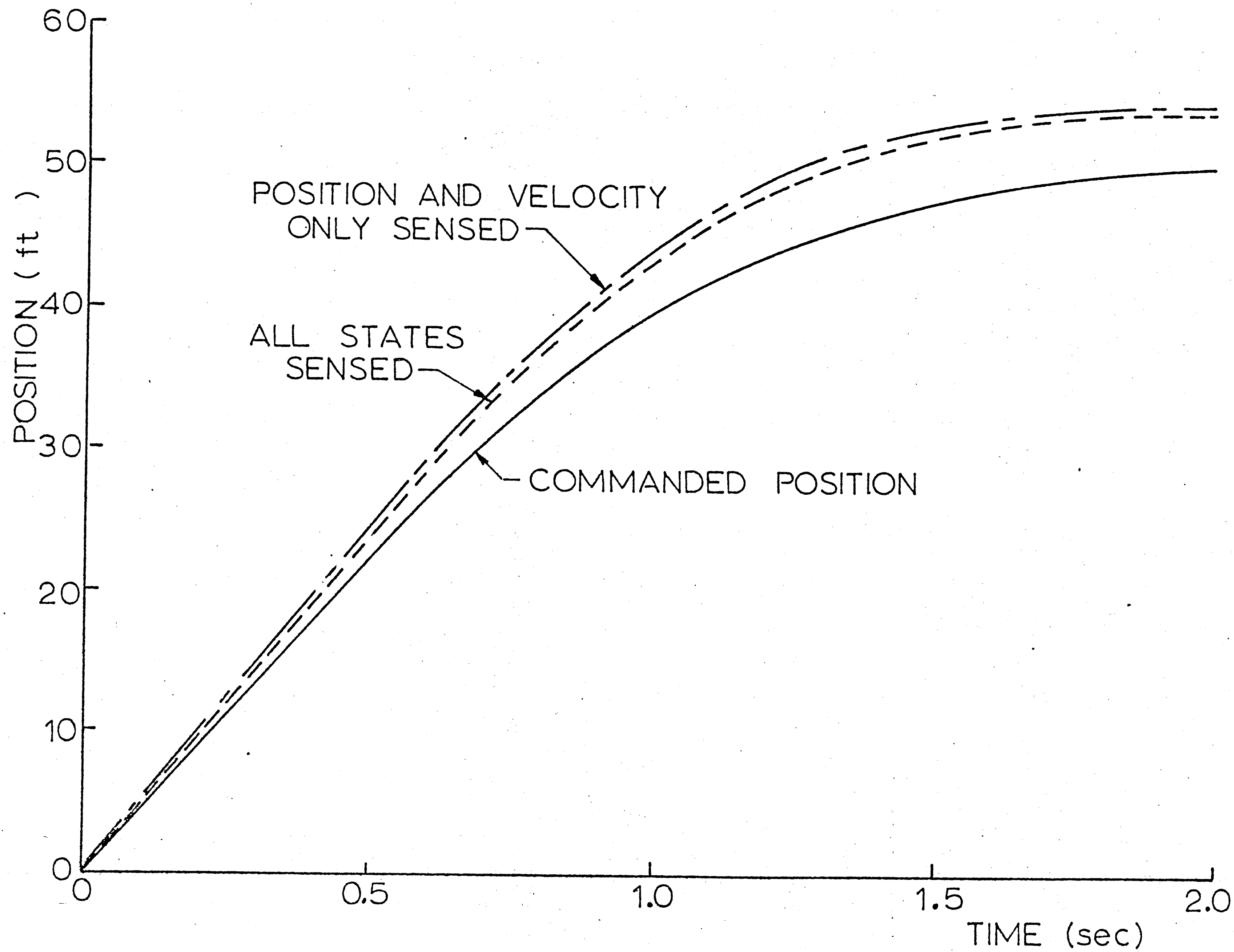

Fig. 23 Position-Emergency Stopping

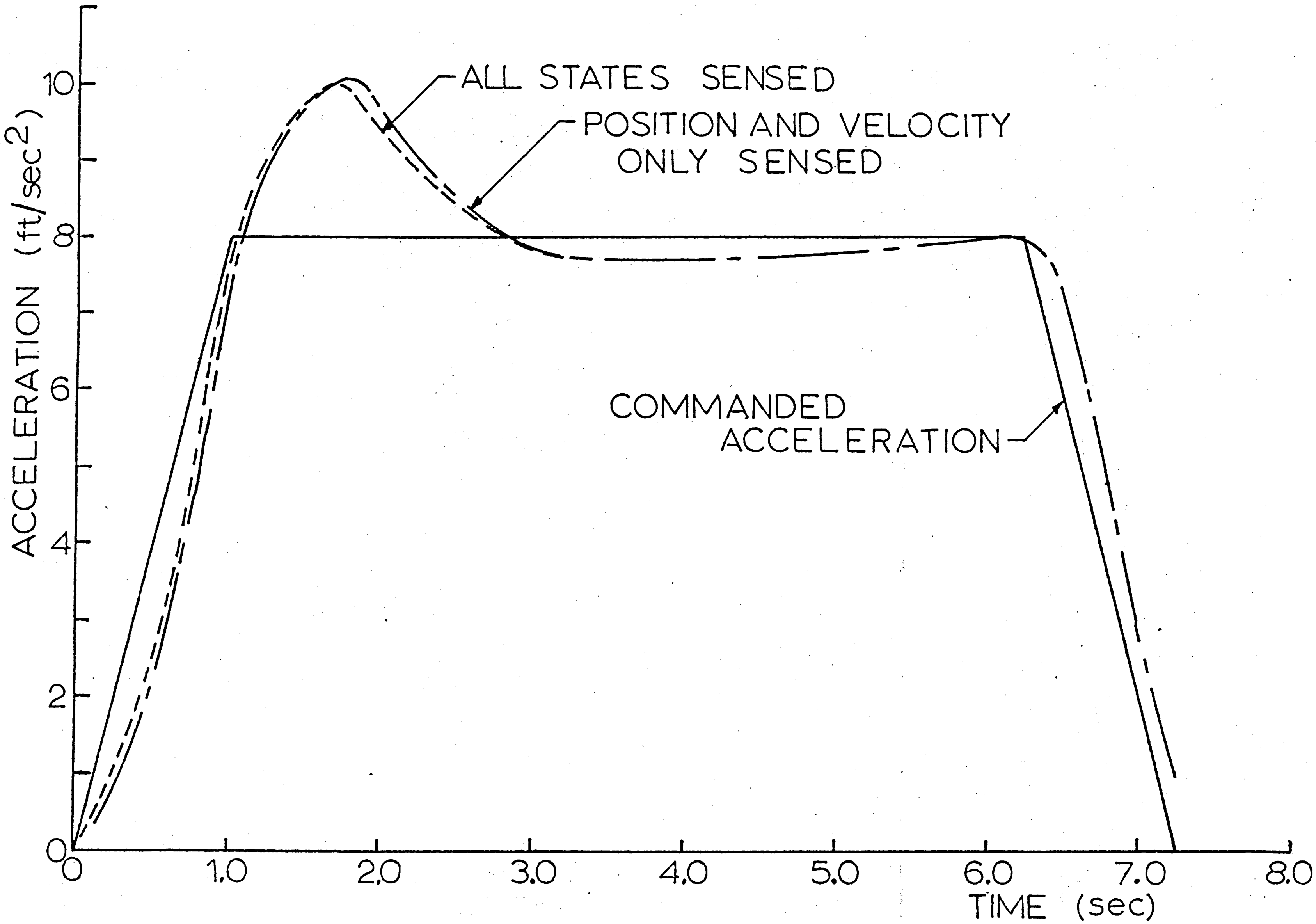

Fig. 24 Acceleration - Merging from Off-Line Station

Thus a controller designed for mainline operation can also be used for other operations such as emergency stopping, merging and manuevering. This is important since it shows that a linear controller with fixed gains is sufficient for all control operations and thus the complexity of the control system is minimal.

The velocity of the vehicle can easily be measured continuously by use of a tachometer; however, it appears that position can only be determined at discrete intervals by means of sensors imbedded in the guideway. The effects of sampling of position on the dynamic response of the system was determined for sensors placed at five-foot intervals on the guideway. At a nominal time velocity of 50 ft/sec, this corresponds to a sampling time of one-tenth of a second. Of course when the vehicle is traveling at less than line velocity, for example during merging or emergency stopping, the sampling rate decreases.

A typical example of vehicle response with sensors placed at five-foot intervals is shown in Figs. 25-28. It can be seen that sampling does not significantly degrade performance. Emergency stopping and response to suddenly applied headwinds were also considered and the vehicle response did not differ significantly from that obtained with continuous position measurement. The results for merging and emergency stopping are summarized in Table 7.

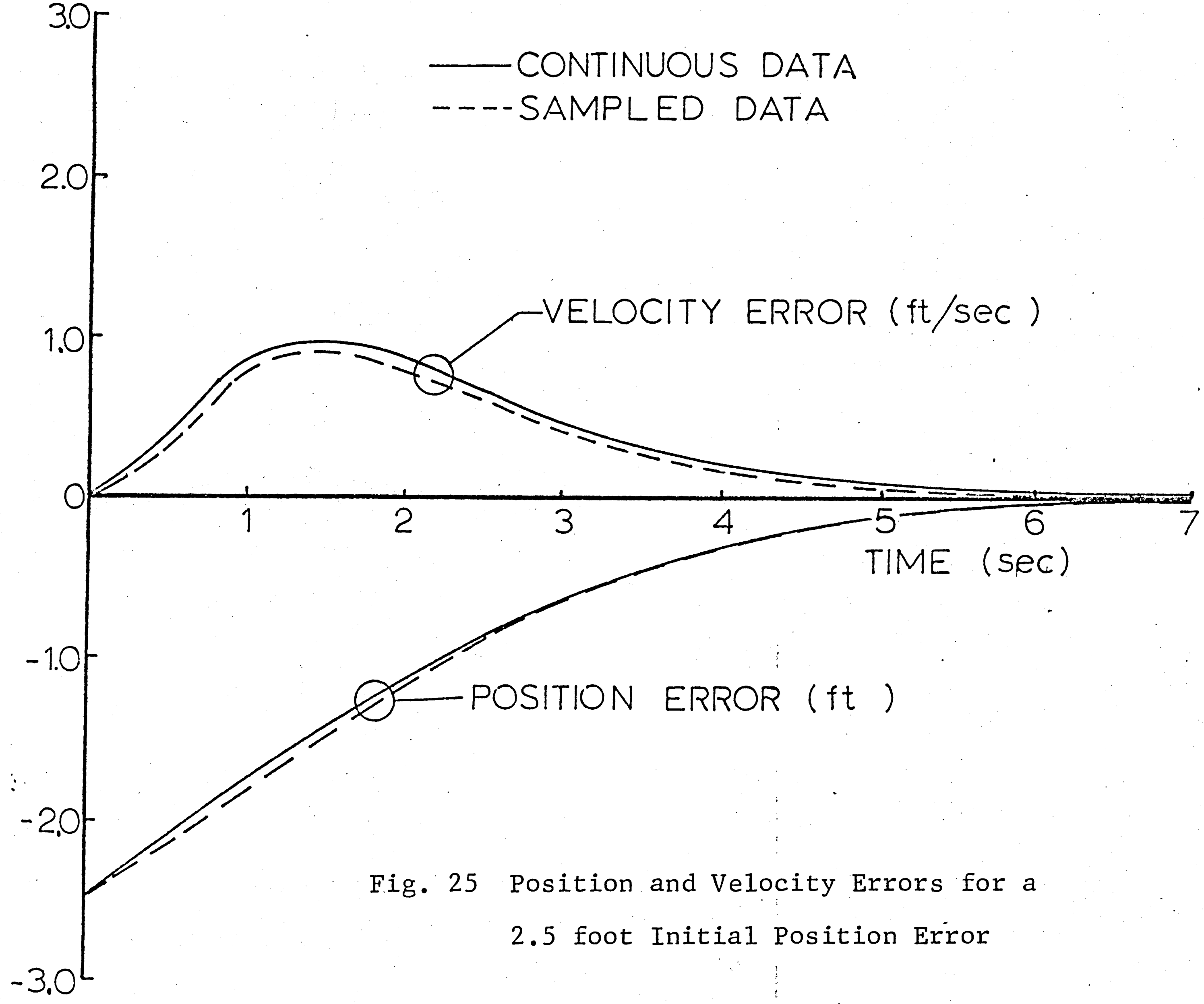

Fig. 25 Position and Velocity Errors for a 2.5 foot Initial Position Error

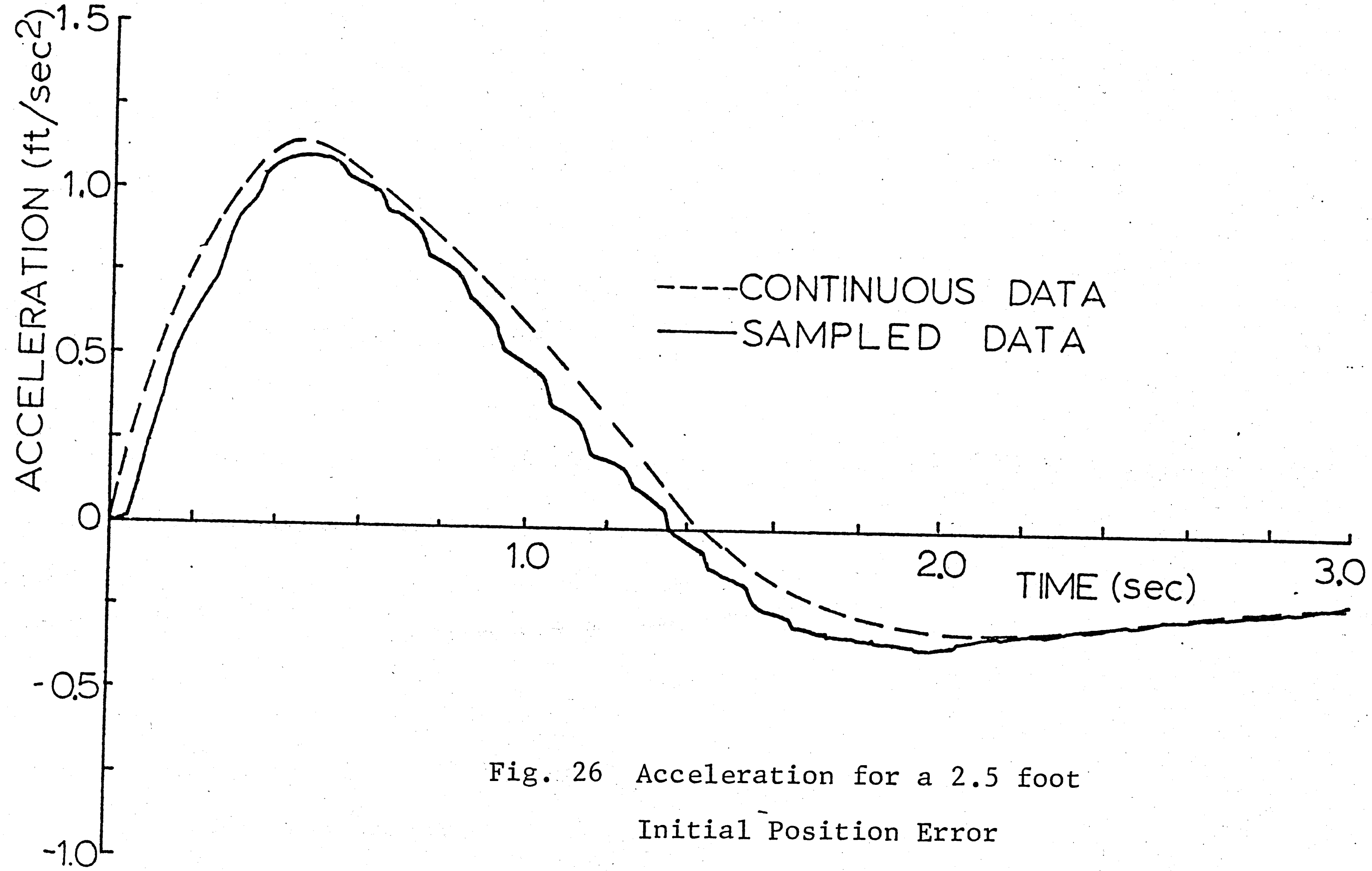

Fig. 26 Acceleration for a 2.5 foot Initial Position Error

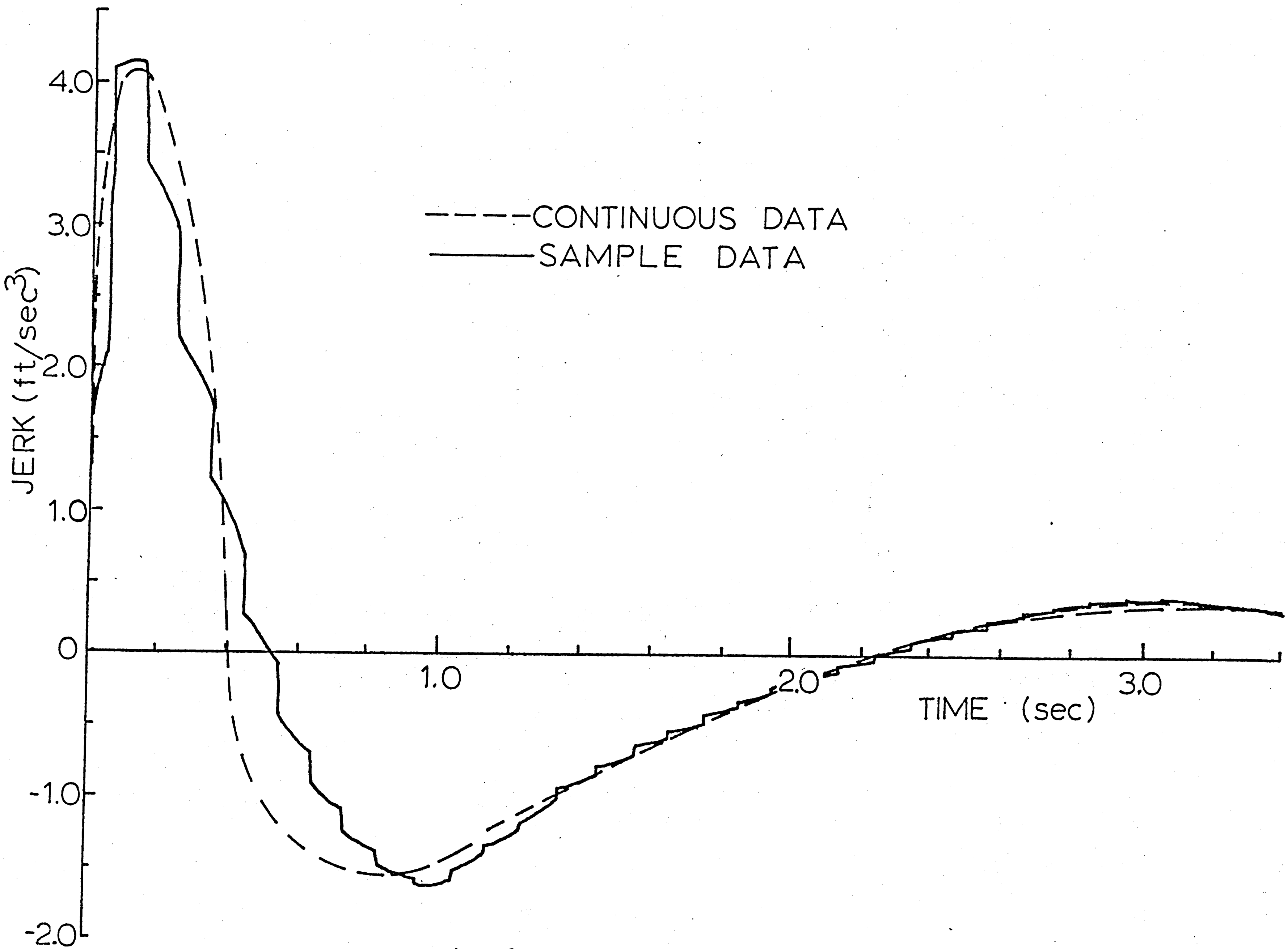

Fig. 27 Jerk for a 2.5 Foot Initial Position Error

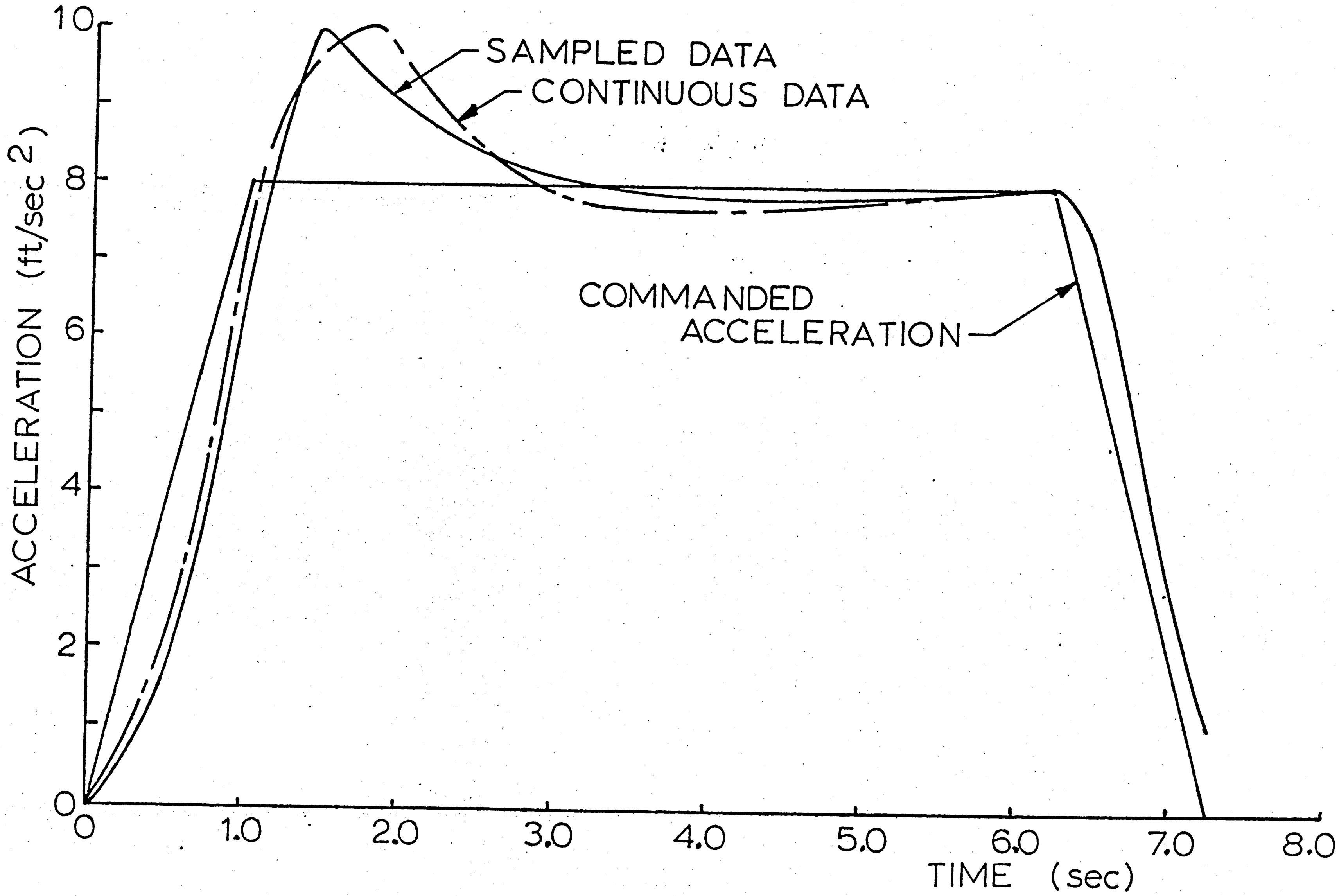

Fig. 28 Acceleration - Merging from Off-Line Station

Merging						Emergency Stop
Final Headway Error			Final Velocity Error		Maximum Jerk	Final Headway Error
	per cent	ft.	per cent	ft/sec	ft/sec^3	ft.
All States Sensed	1.70	0.425	2.69	1.35	10.40	4.25
Position and Velocity Only Sensed	1.91	0.475	2.95	1.45	10.66	4.70
Position and Velocity Only Sensed-Position Sampled	2.00	0.500	3.00	1.50	10.48	4.80

Table 7 Comparison of System Errors for All States Sensed, Position and Velocity Only Sensed, and Position and Velocity Only Sensed-Position Sampled.

Conclusions

From the results presented above, it appears that optimal control theory can be usefully applied to the design of longitudinal control systems for PRT systems with a wide variety of characteristics. The resulting control systems keep headway and velocity errors small without causing passenger discomfort, and excellent dynamic response is achieved during mainline operation, merging and demerging, maneuvering and emergency stopping. The controllers are linear with constant gains and should be relatively economical to implement and simple enough to insure reliability. Since the data presented the results are applicable to a wide variety of systems, the designer should find these data useful in selecting the appropriate feedback gains for various system specifications. It is shown that by use of the optimal control system one-half second nose-to-nose headways are attainable at nominal line speeds of 34 miles/hr (50 ft/sec) without causing passenger discomfort. The resulting system would have the capacity for carrying 7200 vehicles/hr.

9.7 Emergency Operations

The kinematics and dynamics of vehicles during emergency operations is discussed in Chapter 8; consequently, only the vehicle management aspects of emergency operations are discussed below.

The operation of a high capacity PRT system in emergency situations has been studied in considerable detail by the staff of the Aerospace Corporation. The results of these studies are available elsewhere (Bernstein and Schnitt); consequently this section contains only brief overview of these results.

Various types of failures can cause a vehicle to deviate from its assigned position and velocity; however, the types of failures can be divided into two classes - those in which the failed vehicle can be pushed and those which render the failed vehicle unpushable. For example, ordinary loss of propulsive power would not render a vehicle unpushable whereas a broken axle would. Most failures would be of the type in which the failed vehicle would be pushable.

In such cases vehicle decelerations would in general be low and a failure would be detected when wayside sensors ascertain that the velocity and position of the vehicle deviate appreciably from their nominal values. The local-control computer would then order the following vehicle to move forward and push the failing vehicle to an emergency siding where the passengers could disembark, board another vehicle, and continue their trip. The velocity of the pushing vehicle would be controlled in such a way that upon contact, the relative velocity between vehicles would be very small. In addition shock absorbing bumpers would be used, and passenger discomfort during contact would be minimal.

In cases in which the failing vehicle is unpushable, its deceleration rate would ordinarily be large. In such cases an accelerometer on board the failing vehicle would signal the failure to the local control computer which would in turn command the vehicles following the failing vehicle to perform an emergency stop. This would temporarily block the section of line upon which the failed vehicle is stopped. However, vehicles which were not on this section of line could be re-routed around the blocked line. Those non-failed vehicles which were stopped could simply be backed up to the nearest intersection, fed into lateral lines, and re-routed to their destinations. Computer simulations have shown that even if eighty per cent of the available slots on both the blocked and lateral lines are filled, only ten minutes are required to clear the blocked lines. The unpushable failed vehicle could be removed by a special service vehicle.

Emergency control during merges is very important because a collision at a merge between two vehicles on intersecting lines could wedge vehicles into the guideway. The possibility of a collision at a merge point could occur if (1) maneuver commands are improperly commanded or executed or (2) one or both of the vehicles entering a merge point fail.

The possibility of a collision at a merge point can be avoided by properly controlling the merging vehicles. Improperly commanded maneuvers can be avoided by having several separate intersection control computers simultaneously and independently perform the maneuver computations for each intersection. If the results of these computations did not agree, no turns would be permitted and all vehicles would be routed through the intersection. Failure to properly execute manuevers could be detected by wayside sensors located downstream of the maneuver zone. If a potential conflict appears, emergency stopping would be instituted. If the vehicle or vehicles approaching the merge point fail, either pushing or emergency stopping could be used depending upon whether the failed vehicles are pushable or not. Redundancy in critical subsystems, regular maintenance, and monitoring of critical hardware for signs of potential failure would be used to insure that failure rates are very low.

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Chapter 10

Computerized Network Evaluation

Summary: This chapter describes a computer-based methodology for evaluating PRT networks. The methodology consists of a set of computer subroutines which require inputs consisting of a data base of travel demands and auto travel times, a specified transit network and associated performance parameters, and provide the following outputs:

<u>Ridership</u>

Percent of trips by PRT

Percent of passenger miles by PRT

<u>Economics</u>

Fixed cost per trip, per occupied-vehicle mile, and per passenger mile

Variable cost per trip, per occupied-vehicle mile, and per passenger mile

Total cost per trip, per occupied-vehicle mile, and per passenger mile.

Annual farebox revenue

Annual fixed costs

Annual variable costs

Total annual costs

Annual benefit from reduced auto usage

Annual safety and pollution benefit

Annual time savings benefit

Total annual benefits quantified in dollars

Benefit-cost ratio

Total capital cost

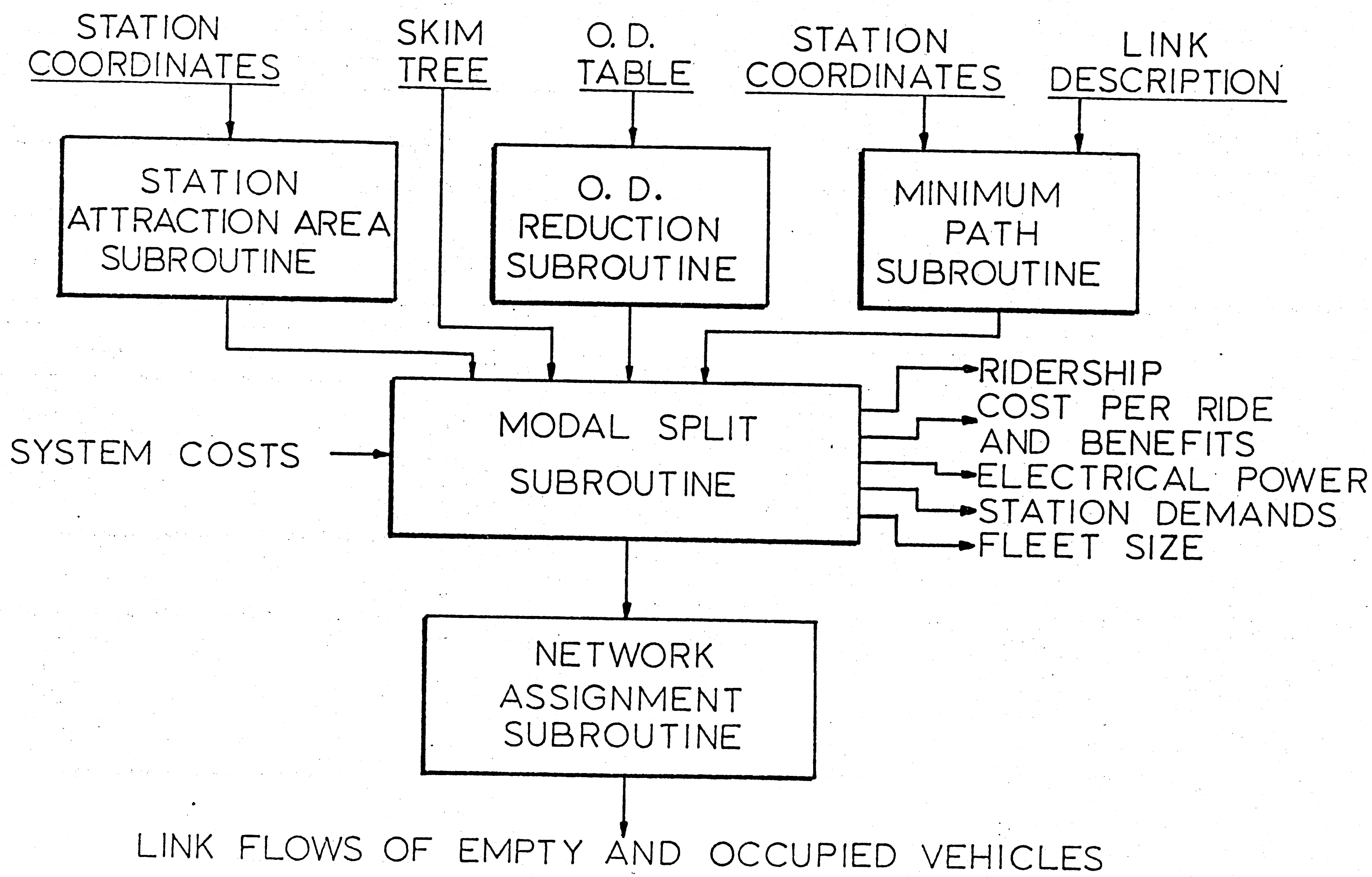

Figure 1. Computerized Network Evaluation Methodology

Annual capital cost

Annual operating cost

Environmental considerations

Peak-hour and 24-hour average electrical power requirement

Automotive air-emission reductions

Transportation energy requirements

Design data

Guideway capacity requirements (peak hour)

Station capacity requirements (peak hour)

Vehicle fleet size

Empty vehicle shuttling requirement

The computer subroutines, inputs, and outputs, are shown schematically in Figure 1. The subroutines will be described in detail in the following sections. The inputs will be described briefly here, however. Origin-destination (O.D.) demand tables and skim trees have been prepared by governmental agencies for many urban areas. Both provide information about travel between the many (1187 for the Twin Cities, 202 for Duluth) traffic assignment zones (TAZ's) in the study area. The skim tree gives the auto travel time between every zone pair. The O.D. tables give the total number of trips between TAZ's. Daily-trip tables have been mainly used in the present study although work-trip tables are useful in testing empty-vehicle shuttling routines. The Minnesota Highway Department has provided us with O.D. tables for both the Twin Cities and Duluth as well as a Twin Cities skim tree. The network information required by the subroutines are station coordinates and a link description. In our study, the station coordinates were obtained by placing the network map on an electronic flat-bed digitizer. By placing a cross-hair at a station location and pressing a button, the coordinates are obtained. Links connect station pairs and are classified into two categories - straight and turn. The necessary link description for each type consists simply of identifying the stations at each end of each link by number.

The computerized network evaluation procedure entailed a substantial effort in formulation and programming. The subroutines perform efficiently, as can be seen from the following CDC 6600 computer times to do a 128-station, 80-mile network for the City of Duluth:

Station Attraction Area Subroutine:	10 seconds
O.D. Reduction Subroutine:	30 seconds
Minimum Path Subroutine:	4 seconds
Modal Split Subroutine:	30 seconds
Network Assignment Subroutine:	80 seconds
Total:	154 seconds

Networks of substantially larger size can be handled without added difficulties, although more machine time is required. The major personnel time is devoted to converting input data into required forms or in adapting the program to handle different forms of input data.

Minimum Path Subroutine

The minimum path subroutine computes the shortest route from each origin to each destination in the network. The minimum-path algorithm we used was a modification of the procedure described in Ref. [1]. Inputs to the subroutine include a list of station coordinates and a "link deck" which describes the network. The main output of the subroutine is the minimum-path travel distance between each pair of stations. This data is stored on magnetic tape for use by other programs in the program set.

A link in the network is a connected path between two adjacent stations. Each interchange ramp is identified by a separate link called a turn link. A path connecting two adjacent stations which does not use an interchange ramp is called a straight link. Each link is identified by its start and end nodes. Thus a direction is also associated with each link. In our coding procedure, all nodes are stations, and the nodes are enumerated to correspond with the station numbering scheme. An example of the coding procedure for an interchange is given below.

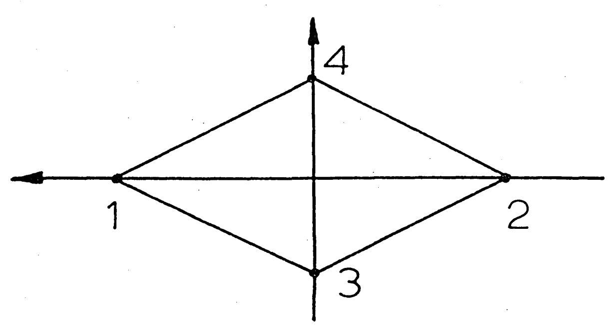

Figure 2 Coding of an interchange

	Start	End
Turn-Link 1	3	1
Straight-Link 2	2	1
Straight-Link 3	3	4
Turn-Link 4	2	4

[1] The Computer Journal, Vol 10, Nov. 1967, p. 307.

Data on station coordinates is used to find the length of each link in the system. The length of the straight links is found by taking the Euclidean distance between its start and end nodes. The length of the turn lengths is approximated by assuming that the through-links at the interchange intersect perpendicularly, and that the start and end nodes are equidistant from the intersection. Thus the turn-link length is approximated by $D\sqrt{2}$, where D is the straight-line distance between the start and end nodes. Some error may be introduced here in cases where lines do not intersect at right angles or the start and end nodes are not equidistant from the intersection. In most instances these errors should not greatly influence travel-time computations, since most paths are made up of several links. In cases where large errors would result from computing turn link distances on this formula, additional "dummy" nodes, which do not correspond to stations may be added to improve accuracy. By coding the straight and turn links separately, a "penalty" can be placed on the turn links by adding a suitable constant to its computed length. In this way, paths involving excessive turns and merges are eliminated. In our studies we used a constant equivalent to .1 mile distance. At forty miles per hour, a .1 mile distance would correspond to a nine-second time delay through an interchange. This would be the expected delay through an interchange .1 mile long with a velocity profile averaging 20 miles per hour.

In a large network, the possibility of human error in compiling the link deck is great, so diagnostics are provided in the subroutine for checking the input data. A check is made to ensure that each station is accessible to all other stations in the network, and unconnected paths are listed in the output. As a further diagnostic aid, the link list from selected origin stations to all destination stations in the network is printed out. This enables a check of selected routes in the network for errors. Often a coding error will produce some routes which are obviously circuitous, and easily detected.

Origin-Destination Table Reduction Subroutine: This subroutine inputs an area-wide O.D. matrix and reduces it to a smaller matrix for entry into the Modal Split Subroutine. For example, the Duluth-Superior area had 290 traffic assignment zones or (TAZ's). However, in our network layout only 93 of these zones contained stations and so the modal split subroutine requires only a 73 x 73 matrix instead of a 290 x 290. In this case the 290 x 290 matrix was entered and the 73 x 73 matrix output was written on magnetic tape. In addition, the program computes the total trips in the 290 x 290 and prints this on paper. The program accomplishes the reduction by reading in the i-th origin-zone vector, and then scanning a list of zones containing stations for zone i. This list is an additional required input of the program. If zone i is not found, vector i is erased and vector i + 1 is read in. If vector i is found on the list, then a similar scanning process takes place for each destination element in vector i. Each destination element whose zone number is found on the list is placed in a new origin-zone vector. The program continues in this fashion until all origin-zone vectors have been checked. The 290 x 290 matrix for the Duluth Study was reduced to a new 73 x 73 matrix, resulting in considerable savings in machine time and core space in the modal-split program. The program also outputs a list containing the new zone numbers of every station.

Station-Attraction-Area Subroutine: This subroutine provides a digital characterization of all station attraction areas. The procedure is to work with small (1/24 mile x 1/24 mile) unit cells. The routine requires the x, y coordinates of all stations as an input. The x, y coordinates are obtained by placing a network map on a flat bed digitizer, placing a set of cross-hairs at a station location, and pressing a button. The principal output of the program is a walk-distance distribution for every station. Figure 3 shows some typical walk-distance distributions. The distributions show the number of cells at walk distance increments of 1/24 miles. It is tacitly assumed that people will not walk more than 10/24 mile to a station. The distributions are obtained by considering every unit cell in the entire urban area individually. A search is performed over all stations, and the cell is assigned to the station at the shortest walk distance. This means that a traveller is assumed to always walk to the nearest station. The total area of a station attraction area is obtained by finding the total number of cells. The walk-distance-determination

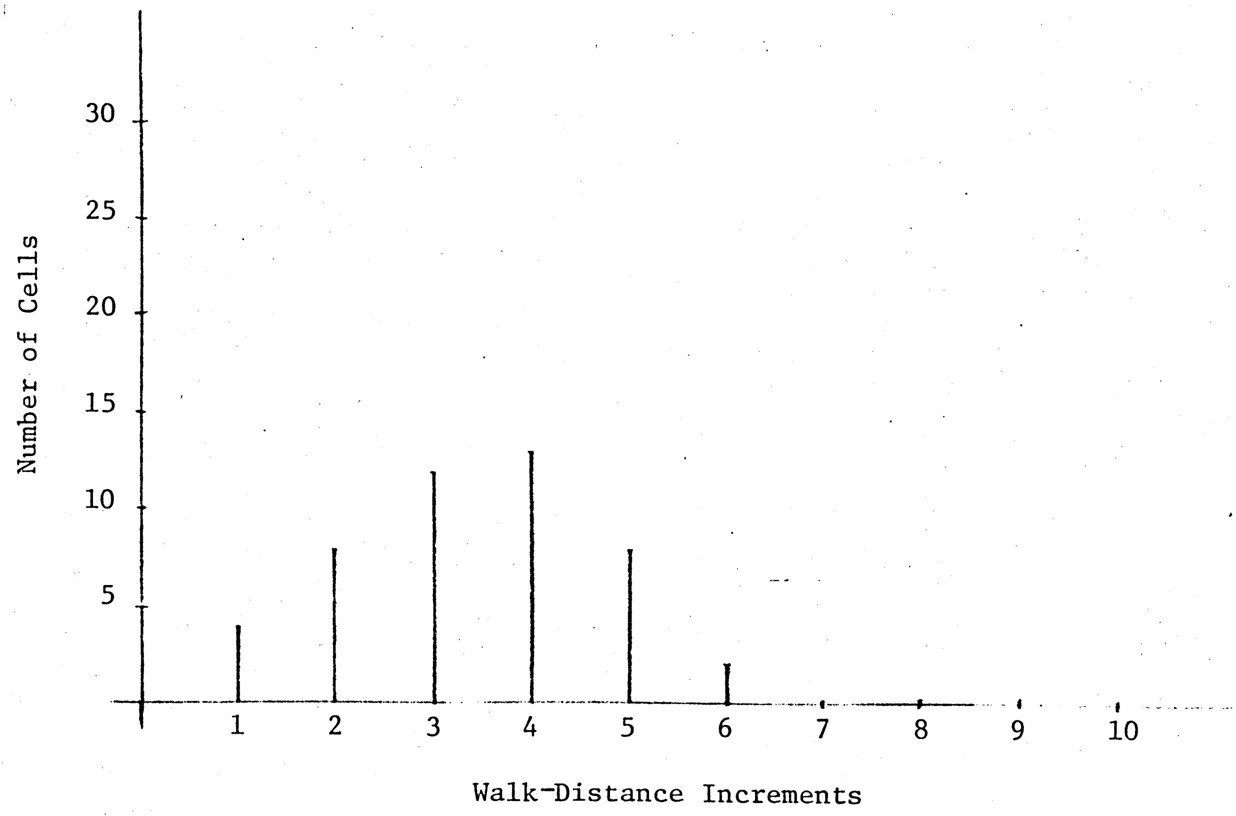

Figure 3a. Station with several nearby stations

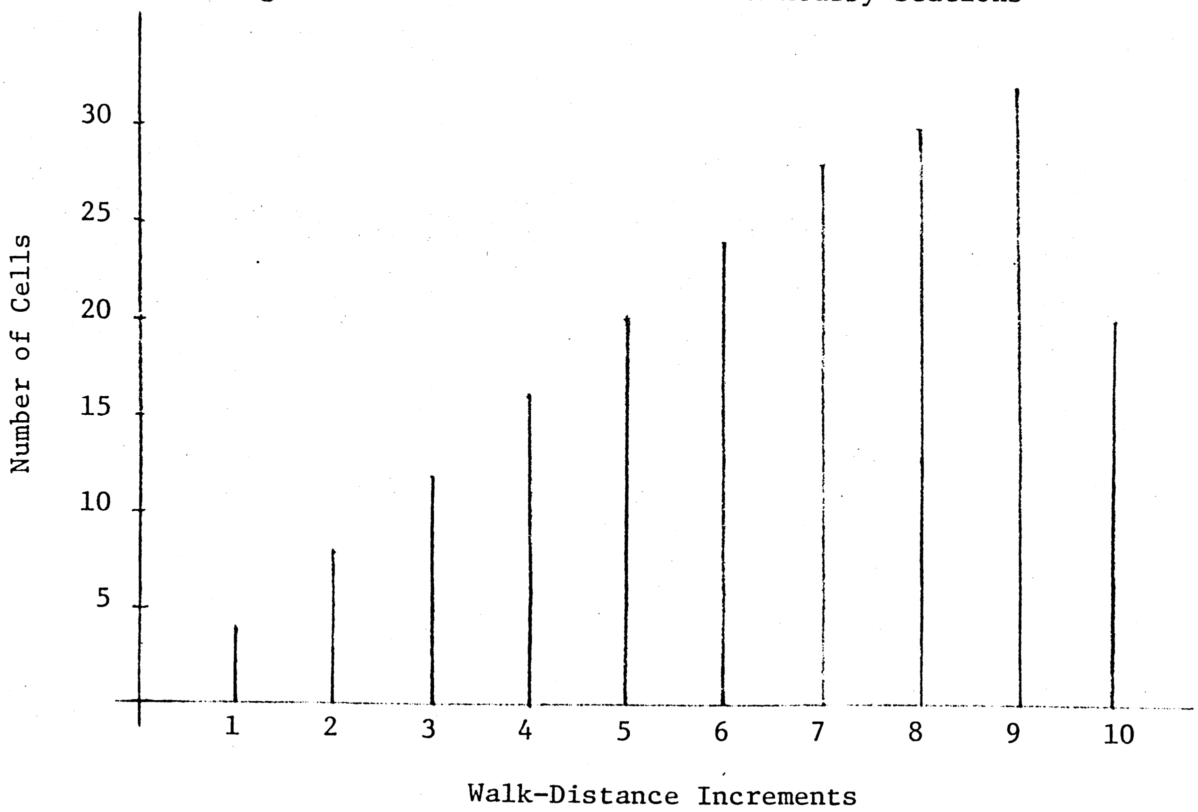

Figure 3b. Station with no nearby stations

Figure 3. Typical Walk-Distance Distributions

routine assumes that the traveller will walk along existing sidewalks and so the formula

$$W = |x - x_s| + |y - y_s|$$

is used for the walk distance. (x,y) are the coordinates of the unit cell and (x_s, y_s) are the station coordinates.

Modal Split Subroutine: This subroutine inputs information on the PRT system, the traffic assignment zones (TAZ), user characteristics and cost parameters as shown in Table 1. The routine outputs information on ridership, costs and subsidies, benefits and the environment as shown in Table 2. The procedure used is to first do computations on daily ridership, PRT passenger mileage, auto passenger mileage, PRT passenger time, auto passenger time, station capacity requirements, operating costs and electrical energy individually for each station pair. Then by considering all station pairs, the totals can be obtained for the entire network. The central item is the estimate of ridership, and the rest of this paragraph as well as the next is concerned with the estimation scheme used in the subroutine. The problem is broken into two parts. First, the total trip demand between the two station-attraction areas is estimated (station attraction areas were defined in the discussion of the Station Attraction Area subroutine). Second, the percentage of tripmakers using each mode between the two station-attraction areas is determined. The total trip demand S from station i to station j, was estimated from the most appropriate of three

Table 1 Program Input

Classification	Item	Form
PRT System Information	Number of Stations	Frotran Statement
	Number of Interchanges	Fortran Statement
	Miles of Guideway	Fortran Statement
	PRT Speed	Fortran Statement
	Interstation travel times*	Mag. Tape
	Station Attraction Area Description**	Mag. Tape
	TAZ of each station	Mag. Tape
	Fare	Fortran Statement
TAZ information	O.D. Daily Trip Matrix***	Mag. Tape
	Skim Tree	Mag. Tape
	Park cost and Auto Walk time	Cards
	Number of TAZ's	Fortran Statement
	TAZ area***	Mag. Tape
User Characteristics	Average Walk Speed	Fortran Statement
	Average Annual Income	Fortran Statement
Cost Parameters	Guideway Cost per Mile	Fortran Statement
	Station Cost	Fortran Statement
	Interchange Cost	Fortran Statement
	Interest Rate	Fortran Statement
	Fixed Installation Amortization period	Fortran Statement
	Vehicle Amortization period	Fortran Statement
	Perceived Mileage cost for auto travel	Fortran Statement
	Vehicle Cost, Carbarn Cost	Fortran Statement

* Output of the Minimum Path Subroutine

** Output of the Station Attraction area Subroutine

*** Output of the O.D. Subroutine

Table 2 Program Output

Classification	Item	Form
Ridership	Trip Modal Split	Print
	Passenger Mile Modal Split	Print
	Total Daily Trips by PRT	Print
	Fleet Size Station to Station O.D. PRT trip table	Mag. Tape
	Peak hour Station Demands	Print
Costs and Subsidies	Annual farebox revenue	Print
	Annual variable cost	Print
	Annual fixed cost	Print
	Total annual cost	Print
	Fixed Cost per trip area occupied vehicle mile	Print
	Variable cost per trip and occupied vehicle mile	Print
	Total cost per trip and occupied vehicle mile	Print
Benefits	Annual auto cost reduction	Print
	Annual safety and pollution savings	Print
	Annual travel time savings	Print
	Total annual benefits	Print
	Benefit Cost Ratio	Print
Environmental Outputs	Peak hour electricity required	Print
	Transportation Energy Reduction	Print
	Air Pollution Reduction	Print

formulas:

Case 1. (Uniform trip distribution at both ends)

$$S_{ij} = Z_{ij} \times A_{si}/A_{zi} \times A_{sj}/A_{zj} \quad (1)$$

Case 2. (Point attraction or production source at each end)

$$S_{ij} = Z_{ij} \times f_i \times f_j \quad (2)$$

Case 3. (Uniform distribution at one end, point source at other)

$$S_{ij} = Z_{ij} \times A_{si}/A_{zi} \times f_j \; . \quad (3)$$

In the formula, Z_{ij} is the demand from the TAZ containing station i to the TAZ containing station j, A_{si} is the area of the i-th station attraction area, A_{zi} is the i-th TAZ arca, and f_i is the estimated fraction of zonal trips associated with the point source at station i. Equation (1) assumes that trip generation is uniform throughout the TAZ at each end of the trip. Equation (2) assumes that trip generation occurs nearby the PRT station on both ends. Equation (3) has one end uniform and the other a point source. Examples of uniformly distributed situations are CBD's and residential areas. A point source could be a shopping center, school or industrial park. In (2) and (3), f_i and f_j are simply the planners' best estimate of the fraction of zonal trips nearby respectively stations i and j.

The PRT ridership between the two station-attraction areas is obtained by multiplying the trip demand S by the fraction of trips by PRT, otherwise termed the modal split to PRT. The modal split is determined by comparing automobile travel and PRT travel on the basis of travel time and cost. The present study considers that stations are reached only by walking. However, a more thorough study would also consider kiss-and-ride, park-and-ride and dial-a-ride access. The procedure uses a cost function where vehicle travel time is weighted at one quarter of the wage rate, and walk and station process times at one half the wage rate. The credibility of this assumption is discussed in Chapter 6. In this way one can determine a maximum distance W that a person would walk to take PRT. The combined walk distance at both ends of the trip must be less than W for the person to take PRT. The formula is

$$W = (T_{car} \times w/4 + C_{op} + E - T_{PRT} \times w/4 - T_{proc} \times w/2 - F)$$

$$\times V_{walk}/w*.5$$

$$W = \frac{V_{walk}}{2w}\left(\frac{1}{4}w\ T_{car} + C_{op} + E - \frac{1}{4}w\ T_{PRT} - \frac{1}{2}w\ T_{proc} - F\right)$$

where T_{car} and T_{auto} are respectively the auto and PRT travel times, w is wage rate, C_{op} is auto operating trips (10¢/mile was assumed), E includes parking costs (50¢ at all CBD TAZ's)* plus a 1/10 mile auto trip walk cost at major activity centers. T_{proc} (1 minute was assumed) is PRT station process time, F is PRT fare and V_{walk} (3MPH was assumed) is walk speed. T_{proc} was taken as one minute which would include time for empties

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*In the Twin Cities study, a parking charge of 50¢ was attributed to trip origins <u>and</u> destinations in the CBD. In the Duluth study, 50¢ was attributed to trip origins only.

to arrive at stations when they are not already available there. The program determines the fraction of the trips between the station attraction areas at walk distances less than W, and assigns these to PRT. This is done by determining the number of unit cell combinations (see Station Attraction Area Subroutine) at the origin and destination which would result in a walk less than W. The procedure considers the number N_o (i) of cells at distance* i ($1 \le i \le 10$) from the origin and the number N_d(j) of cells at distance* j from the destination. The PRT trip fraction denoted as frac, is then computed from the following formulas, which correspond to the cases 1, 2, and 3:

Case 1. (**Uniform** trip distribution at both ends)

$$\text{frac} = \sum_{i=1}^{10} \sum_{i=1}^{10} \hat{N}_{ij} / (M_o \times M_d) \qquad (4)$$

Case 2. (Point attraction or production source at each end)

$$\text{frac} = f_o \times f_d \text{ if } W > 0$$
$$\text{frac} = 0 \text{ if } W \le 0 \qquad (5)$$

where f_o and f_d are respectively the planners' best estimate of the fraction of zonal trips nearby the origin and destination stations.

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*Distance units are 1/24 mile.

Case 3. (Uniform distribution at one end, point source at other)

$$\text{frac} = f_d \sum_{i=1}^{10} \hat{N}_o(i)/M_o \quad \text{(point source at destination)}$$

(6)

$$\text{frac} = f_o \sum_{i=1}^{10} \hat{N}_d(i)/M_d \quad \text{(point source at origin)}$$

where

$$\hat{N}_{ij} = N_o(i) \times N_d(j) \quad \text{if } i+j < 24W$$

$$\hat{N}_{ij} = 0 \quad \text{if } i+j \geq 24W$$

$$M_o = \sum_{i=1}^{10} N_o(i)$$

$$M_d = \sum_{i=1}^{10} N_d(i)$$

$$\hat{N}_o(i) = N_o(i) \text{ if } i < 24W$$

$$\hat{N}_o(i) = 0 \text{ if } i \geq 24W$$

$$\hat{N}_d(i) = N_d(i) \text{ if } i < 24W$$

$$\hat{N}_d(i) = 0 \text{ if } i \geq 24W$$

Once the ridership between two stations is known, several other quantities can be calculated. The <u>trip modal split</u> is the number of daily trips by PRT divided by the total daily trips. For any station, daily passenger demands are computed by summing the trips to every other station. Peak hour demands are assumed to be 10% of the daily demand and calculated accordingly. The number of PRT passenger miles travelled is equal the number of PRT trips times the trip distance. In the program it is assumed that the average vehicle occupancy is 1.3 people (average automobile occupancy) and that due to shuttling empties, the total number of vehicle miles is 1.3 times the number of occupied vehicle miles. So the total number of vehicle miles is the same as the total number of passenger miles. The passenger mile modal split is the daily passenger miles by PRT divided by the total daily passenger mile. If X_{ij} is the total daily number of passenger miles travelled by PRT between the stations i and j, then the corresponding daily revenue Rev_{ij}, daily electrical energy E_{ij} and daily operating costs C_{ij} computed from the formulas

$$Rev_{ij} = F \times X_{ij}/1.3 \tag{8}$$

$$E_{ij} \doteq .3X_{ij} \text{ (without regenerative braking)}$$
$$E_{ij} = .12X_{ij} \text{ (with regenerative braking)} \tag{9}$$

$$C_{ij} = OP \times X_{ij} \tag{10}$$

where F is the fare in dollars per occupied vehicle mile, E_{ij} is the daily electrical requirement in kilowatt hours and OP is an assumed operating cost in dollars per vehicle mile. Equation (9) was derived in Chapter 6. Equations (8), (9) and (10) can be converted to a network-wide basis by summing over all station pairs in the network. Relations (8) and (10) are annualized by multiplying by 300. The peak hour power requirement in megawatts can be estimated by dividing the daily energy requirement in megawatt hours by 10.

Table 3 summarizes the cost assumptions. Additionally, the analysis assumes a 6% interest rate. Fixed facilities are amortized over 30 years and vehicles over 10 years. The analysis converts the fixed costs and the variable costs to an annual basis and sums to obtain the total annual cost. The difference between the total annual cost and annual revenue is then the annual subsidy. Cost and subsidy per passenger mile is obtained by dividing by the number of passenger miles travelled per year. Cost and subsidy per trip is obtained by dividing by the number of annual trips. To determine the variable costs, it is necessary to know the fleet size. This is estimated by dividing the number of peak-hour miles travelled by the average speed of the vehicle.

The analysis identifies three benefits for quantification in dollar terms. These are reduced auto usage, auto safety and pollution and time savings. Reduced auto-usage costs are computed on the basis of parking costs not paid and 10¢ per mile for auto miles not driven by people using the PRT system instead of the auto. Several studies, one cited in Chapter 6, estimate that in a few years, auto travel will be significantly more expensive to meet existing legislation on air emissions and safety. So the present analysis assumes an additional 2¢

per auto mile not driven as a benefit to PRT. Time savings arise from two sources and are converted to dollars by multiplying by an assumed wage rate of $5 per hour. The first source is that many trips are faster by PRT. Those benefits are all determined individually for every station pair, summed over the entire network, and annualized by multiplying by 300. The second source of time saving is that PRT attracts a significant portion of the auto trips, thereby relieving congestion and enabling the remaining drivers to travel faster. The latter effect is estimated by assuming that peak-hour trips only are affected. This means that only 35% of the trips are considered in the benefit computation. Peak hour trip times are computed on the basis of the formula

$$T/T_{peak} = \frac{2}{3} + \frac{1}{3}\left(\frac{D}{D_{peak}}\right)^2 \qquad (11)$$

where T is the auto trip time at demand level D and T_p is the trip time at the present level of demand D_{peak}. The formula is explained more fully in Chapter 6. D/D_{Peak} is simply one-PMMS, where PMMS is the passenger mile modal split, calculated in the program.

Network Assignment Subroutine

The network assignment subroutine has two Lasic components. The first is an empty-vehicle-shuttling routine which determines the average flow of empty vehicles in the network. Input to this component of the subroutine consists of the origin-destination matrix (output of the Modal Split Subroutine), and the travel time (output of the Minimum Path Subroutine) between each pair of stations in the network. The theoretical basis for the empty-vehicle-shuttling routine, as well as the computational procedures used to execute it will be described next.

A procedure must be established to redistribute empty vehicles in the PRT system. Normally, passenger demands at stations will not be the same as full-vehicle arrivals. Where vehicle arrivals exceed demands at a station, empty vehicles will have to be dispatched from the station. Alternatively, when arrivals of full vehicles are not sufficient to meet passenger demands, empty vehicles must be sent to the station. While the "rush hour", with its large component of trips from residences to work centers, is an extreme example of the necessity to redistribute the empty vehicles, it is expected that some vehicle shuttling will be necessary for almost any type of demand distribution. Storage barns will be required for a large-scale PRT system. When passenger demands in the system increase, vehicles are sent from the storage barns to stations requiring vehicles. In periods of decreasing total demand, vehicles are sent back to the car barn for storage. In this section, we will be concerned with "global" strategy of vehicle shuttling, which assumes that average station demands, on a per-hour basis, are known and that these demands are relatively constant over that period. For this steady-state condition, vehicle storage barns will be neither dispatching or receiving vehicles. Therefore, under constant-demand conditions, storage barns may be decoupled entirely from the system.

In order to properly examine the vehicle shuttling problem, it is necessary to model the operation of a station. In our station model, we assume that vehicle demands, as well as the arrivals of vehicles at the station, are Poisson processes. Figure 4 depicts a simple model of the passenger-vehicle interface at the station. The parameter p represents the vehicle demand per hour, and q represents the arrival rate of vehicles (empty and full) per hour. The vehicle demand rate is assumed to be equal to the passenger arrival rate divided by 1.3, the assumed vehicle occupany. Provision is also made for storing empty vehicles up to the number, X, in the station.

The passenger-vehicle interface is assumed to work in the following way:

(1) If a vehicle arrives at the station and a passenger group is waiting, the vehicle is immediately dispatched to the passenger's destination.

(2) If a vehicle arrives, and no passengers are waiting, the vehicle is stored, provided that the storage capacity, X, is not exceeded. If the capacity is exceeded, an empty vehicle

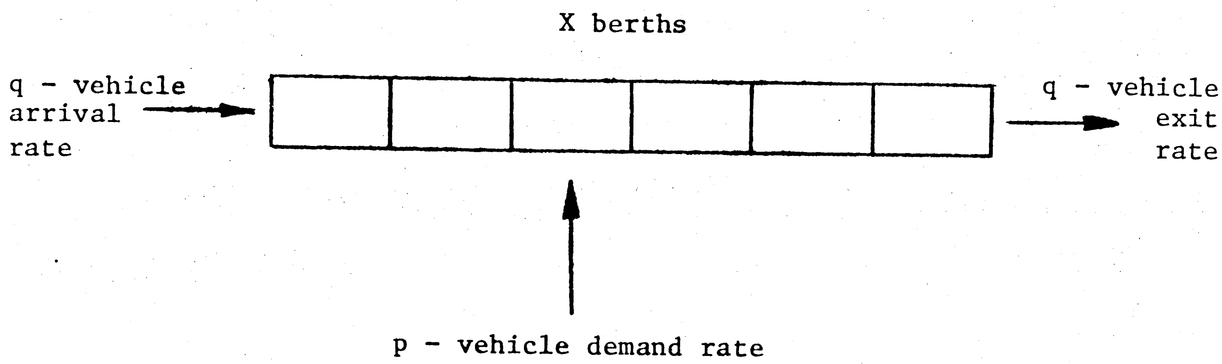


Figure 4 Passenger Vehicle Interface

is dispatched from the station.

(3) If a passenger group arrives at the station, and there is an empty vehicle stored there, that vehicle is immediately dispatched to the passenger's destination.

The possibility of unsatisfied vehicle demands occurred while empty vehicles are stored in the station is excluded in the procedure described above.

If steady state operation of the station is desired and T is the average passenger waiting time, the model described above gives a relation between vehicle demands, p, and the required vehicle inflow, q. This relation is

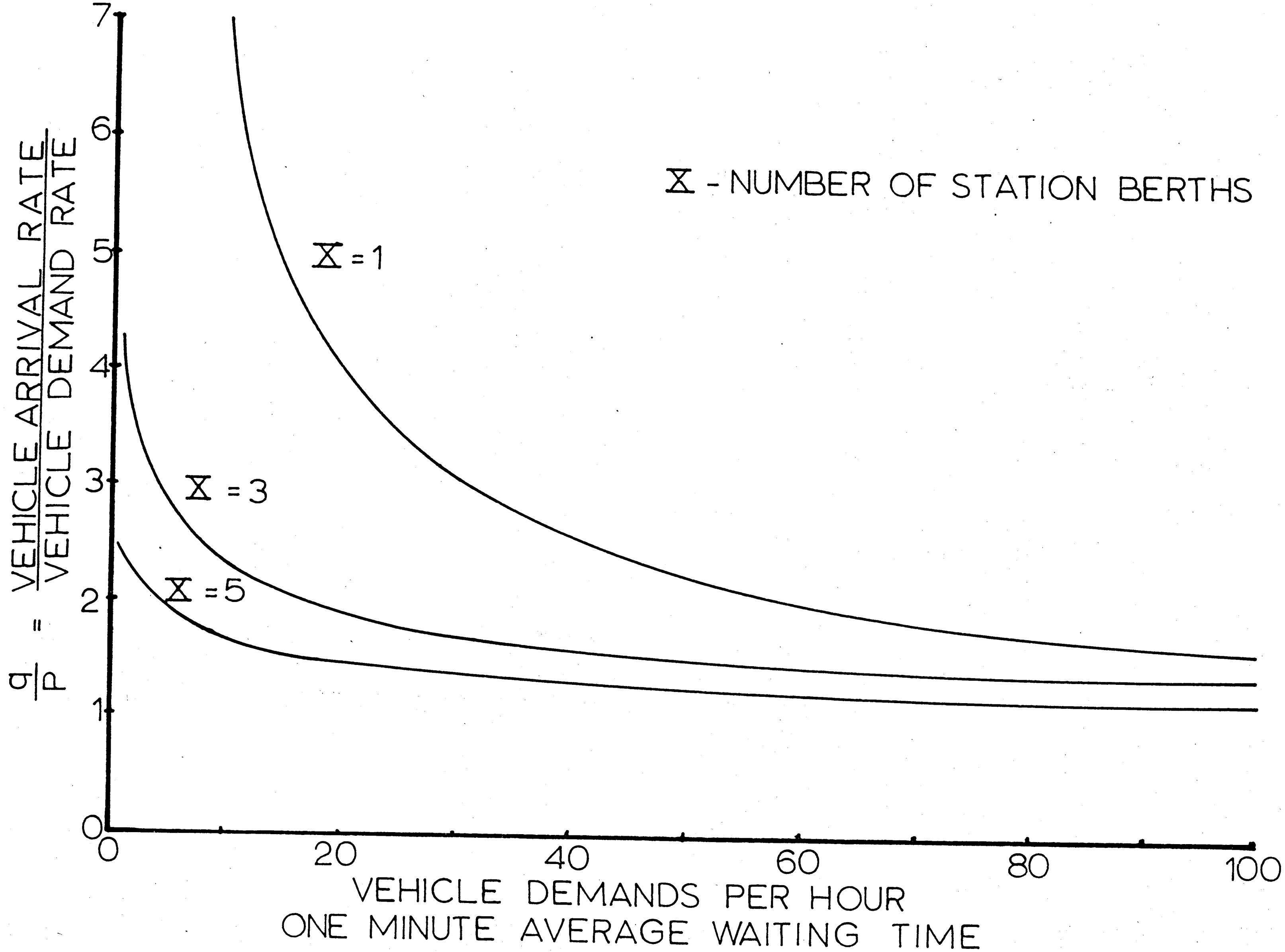
$$pT = \frac{\lambda^{X+1}}{(1-\lambda)} \qquad (12)$$

where $\lambda = p/q$, the ratio of vehicle demands to vehicle arrivals. A plot of $1/\lambda$ versus pT is given in Figure 5 for several values of X. These plots demonstrate that for small values of pT, representing either low vehicle demands or short waiting times, there is a significant saving in vehicle shuttling requirements if several empty vehicles can be stored in the station.

Besides specifying the average waiting time, it may also be desirable to set a "maximum" waiting time which is only exceeded with very small probability. From the model described previously, the probability that a wait will exceed T_M units is given by the relation

$$P(T_M) = \lambda^{x}\exp\{-(\frac{1-\lambda}{\lambda})pT_M\} \quad , \qquad (13)$$

Figure 5. Waiting Time Curves



where $\lambda = p/q$ as before and X is the number of storage berths. If both the average wait and maximum wait are specified, then the value of λ which satisfied both these constraints is used. For example, if an average wait of 1 minute is desired, and a "maximum" wait of 10 minutes should be exceeded only with probability .001, the constraints from equation (12) and (13) which apply to λ are

$$.001 \geq \lambda^X \exp -\left(\frac{1-\lambda}{\lambda}\right) p^*(.16)$$

$$(.016)p \geq \frac{\lambda^{X+1}}{(1-\lambda)} \qquad (14)$$

Here, p is expressed as demands per hour. The smallest value of λ which will satisfy both constraints is used. The vehicle in-flow required is then

$$q = p/\lambda \ , \qquad (15)$$

The constraints (14) may be used to define a function

$$q = Q(p,T,X) \ . \qquad (16)$$

In the program, Newton's method was used in an iteration procedure to solve the constraint (14) for λ.

Once the function has been determined, the vehicle shuttling procedure is basically that described in [2]. All

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[2] W. J. Roesler, M. C. Waddell, B. M. Ford, and E. A. Davis, Operating Strategies for Demand - Actuated ACGV Systems, Volume I - Design and Simulation, Volume II - Evaluation and Comparison, Applied Physics Laboratory of Johns Hopkins University, Silver Spring, Maryland. August 1971 and March 1972.

station demands with specified maximum and average wait times are satisfied by moving empty vehicles in the system. If full-vehicle arrivals to station i, computed from the origin-destination demand matrix, d_{ij}

$$D_i = \sum_{j=1}^{N} d_{ji} \tag{17}$$

are less than the necessary value

$$q_i = Q\ (p_i, T_i, X_i)\ , \tag{18}$$

then empty vehicles must be sent to this station to make up the deficit. This requirement is

$$\sum_{j=1}^{N} e_{ji} = -D_i + Q\ (p_i, T_i, X_i)\ . \tag{19}$$

Here, e_{ij} represents the rate of empty vehicles shuttled from station i to station j. If $A_i > F\ (p_i, T_i, X_i)$ then no empty vehicles need to be sent to station i. By defining the function

$$H(D_i, p_i) = Q\ (p_i, T_i, X_i) - D_i$$

$$H(D_i, p_i) = 0 \tag{20}$$

$$\text{for } Q\ (p_i, T_i, X_i) \le D_i\ ,$$

a relation for the empty vehicles shuttled per hour can be written as

$$\sum_{j=1}^{N} e_{ji} = H(D_i,p_i) \quad . \tag{21}$$

The outflow of empty vehicles is the difference between the inflow and the outflow of full vehicles. The inflow of vehicles is

$$I_i = D_i + H(D_i,p_i) \tag{22}$$

while the outflow of full vehicles is

$$p_i = \sum_{j=1}^{N} d_{ij} \quad . \tag{23}$$

The difference,

$$G(D_i,p_i) = D_i - p_i + H\ (D_i,p_i) \tag{24}$$

is always a positive function.
The outflow of empty vehicles is then given by the relation

$$\sum_{j=1}^{N} e_{ij} + G(D_i,p_i) \quad . \tag{25}$$

The relations (21) and (25) do not completely determine the unknowns e_{ij} for $N > 2$. They may therefore be viewed as constraints for an optimization problem. Any function $Z = Z(e_{ij})$ may be chosen to be minimized. The function

$$Z = \sum_{i=1}^{N} \sum_{j=1}^{N} C_{ij}e_{ij} \tag{26}$$

was used in the subroutine, where C_{ij} represents the minimum path distance from station i to station j. Minimizing Z corresponds to minimizing the total number of empty vehicle miles traveled per hour.

To summarize the procedure, the optimization problem is:

$$\text{minimize} \quad Z = \sum_{j=1}^{N} \sum_{i=1}^{N} C_{ij} e_{ij}$$

under the constraints

$$\sum_{j=1}^{N} e_{ij} = G(D_i, p_i)$$

$$\sum_{j=1}^{N} e_{ji} = H(D_i, p_i)$$

$$e_{ij} \geq 0 \quad i,j, = 1, \ldots N.$$

This problem was solved on the CDC 6600 facility using the Primal-Dual algorithm, a standard algorithm for solving linear programing problems.(3) For the Duluth study with 128 stations, computing time was 67 seconds. Computation time increases quite rapidly, however, as the number of stations is increased. For our Twin Cities study with 506 stations, it was worthwhile decomposing the network into a few large zones, and considering intra-zonal and interzonal shuttling separately. In the intra-zonal problem, sources and sinks are included on the perimeter of the zone. Interzonal routing is accomplished by determining vehicle shuttling between these sources and sinks. This method of vehicle redistribution would correspond physically to a system

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(3) Linear Programming, G. Hadly, Addison-Wesley, Reading, Mass.

which was divided into zones, with each zone serviced by a car barn. If vehicle flow into the zone exceeded outflow, the car barn would receive the excess vehicles. If vehicle outflow exceeded inflow, the car barn would supply vehicles to the stations in the zone. Empty vehicles would be shuttled between the vehicle barns to balance the flows in the network.

The principal output from the vehicle shuttling routine is an origin-destination matrix for empty vehicles. When this is added to the original origin-destination matrix for full vehicles, the total flow of empty and full vehicles in the system can be found using the direct assignment procedure which will next be described. A quantity which measures the efficiency of the system, the ratio of empty to full vehicle trip miles is also computed in this routine. The total number of empty vehicle distance units traveled per hour is given by (26). This quantity is obtained as a by-product of the computational routine.

The direct assignment routine, the second component of the program, determines the vehicle flow on each link in the system. The vehicle flow from each origin-destination pair is assigned to routes computed from the minimum path algorithm. After assignment is completed, each link is checked for overload. A link is assumed to be overloaded if the slot occupancy is greater than 85%. The abort rate on merges under quasi-synchronous operation increases greatly when line flows much exceed this value.

The overloaded links are then assessed with a distance penalty to discourage their use. Minimum paths are then recomputed and the assignment procedure is repeated. The iteration process continues until either all link flows are below the overload value, or an arbitrarily imposed iteration limit is exceeded. For the Twin Cities Study, a limit of 5 iterations was used. In the Duluth simulation, 1 second headways were assumed and no overloads were encountered on the first iteration. Link flows are printed out after the iterative process is complete. Full-vehicle-trip-miles per hour are also computed, as well as the ratio of empty to full vehicle trip miles.

Appendix: In performing the studies on Duluth and the Twin Cities, unavailability of data or peculiarities of data required departures from the procedures previously described. These departures will be discussed in this appendix.

For the Duluth study, a skim tree was not available so that auto travel times had to be estimated by another means. The procedure chosen was to assume an average auto speed of 20 MPH. The number was chosen from interpreting data compiled in a traffic study report on Duluth. Auto travel distances were assumed to be the same as PRT station to station travel distances.

In the Twin Cities study, the skim tree gives TAZ centroid to TAZ centroid travel times. We added two minutes of terminal travel time to each end of auto trips, or a total of four minutes to each auto trip. All PRT links of the Stage 1 network of the Summary report as well as several in Stage 2 (Stage 1 lies primarily in the Minneapolis and St. Paul CBD's) were assigned a speed of 15 MPH. All other network links were assigned a 40 MPH speed. The trip table we used included truck and auto trips. The table was multiplied by a factor .87 to provide auto trips, and then by a second factor 1.52 to provide auto passenger trips. The trip table was based on a 1% sample. Consequently, many of the entries were zeros and the nonzero entries were very large. It was felt that the table was suitable for most purposes of the study but that certain information, such as demands at a particular station are unreliable. For this reason, we computed an average CBD station demand and an average system station demand.

For the Twin Cities study we also computed an average flow on the straight links in the CBD's of Minneapolis and St. Paul. The average flow is reported in the summary report. In the Summary report, the maximum flow requirement was not reported even though it was computed in the study. Corresponding to the Stage 8 network of the Summary report, the maximum flow in vehicles/hour was found to be 5000, including redistributed empties. To accomplish this with a line occupancy of 80%, a flow of about 6250 slots per hour would be required. This is equivalent to a .6 second headway which is less than the minimum 3/4 second headway at 15 MPH found possible from the considerations of Chapter 7. For three reasons it is felt that the requirement of 5000 vehicles per hour found in the study is significantly higher than the requirement that would result from a more detailed study.

1. Due to time and budget limitations, no redesign of the network in the CBD vicinity was attempted.
2. Due to budget limitations on computer expenses, no attempts were made to use the Network Assignment routine to send vehicles over routes with lesser use. All vehicles were sent over routes computed from the minimum time path algorithm.
3. The link flows are computed on the basis of station demands. Because of the trip table difficulty cited in the previous paragraph, some of the station demands were unrealistically high.

Chapter 11

The Process of Implementation

Introduction

By use of data and analysis presented in earlier chapters, we have demonstrated that area-wide personal rapid transit systems would substantially improve the urban environment at a unit cost comparable to other forms of transportation. We have also argued that the present state of technological development is such that personal rapid transit systems with sufficient capacity to serve as the major transit system in an urban area can be made available for deployment within this decade. System development and/or town planning for such systems is now under way in Canada, England, France, Japan, Sweden, Switzerland, West Germany, and the United States.

At present a number of types of personal rapid transit are under development in the United States which are incompatible with one another. Because of the possibility that demonstrations initiated in various areas of the country may eventually be extended sufficiently to enable them to be linked together, and because of the need to minimize costs, it is of fundamental importance that a standard guideway be developed which could accommodate a variety of types of vehicles.

We recommend, therefore, that the first step toward implementation of PRT systems capable of area-wide deployment be to establish a national development program aimed at development of standard guideways and a variety of standard vehicle designs compatible with these guideways. Under this program, all leading PRT systems would be examined and a series of trade-off tests would be performed to determine which of the various alternate ways of implementing PRT would be the most appropriate.

This engineering development program must be conducted in close cooperation with one or more town planning studies aimed at examining all of the problems associated with integration of PRT into the urban environment. Obviously, cities which participate in these planning studies would be the first that could qualify for initial installation of the equipment developed in the standardization program. Thus any city interested in early installation of high-capacity PRT should initiate such a planning program.

In the next section a process for planning for PRT systems in a specific city is discussed. Then in the following section a development program which will build upon work already done is discussed. In both cases many interactions between the city planning process and the development process will become apparent.

The Planning Process

The planning process in a specific city will begin with certain information which can be classified into (1) external factors, and (2) internal factors.

1) External factors
   - A. Present knowledge of characteristics and development status of systems around which the planning process is to occur.
   - B. Availability of resources: energy, materials and capital.
   - C. Knowledge of related federal programs and legislation germane to the transportation program development.

2) Internal factors
   - A. The present and projected population distribution of the city.
   - B. The present and projected travel patterns for both people and goods movement.
   - C. The topographical features of the city.
   - D. The desired development pattern for the city.
   - E. The characteristics of the present transport system including routes and terminals.
   - F. The needs, desires, and priorities of the urban area as determined from community hearings.

Based on the information above, the city planners working with the development team can develop a recommended preliminary set of line and station locations. In developing this preliminary plan, consideration should be given to the possibility of both above and below-ground installations and both goods and people movement. This preliminary network plan will be developed in stages with a subsequent analysis performed for each successive stage.

Flow Calculations

By means of a computer program the patronage attracted to this system is now calculated. Since techniques for calculating patronage are still under development and dispute, part of this process is a research program to improve on the methods for calculating patronage. In order to determine the required system capacity needs, the maximum peak-hour flows must be calculated. In order to determine the total revenue that will be attracted to this system the total number of trips per year must be calculated. These calculations should include trips taken for both people and goods movement and should attempt to estimate induced travel that did not occur before the system was built. In order to satisfy the needs of the impact study the trips attracted to the system must be classified according to the income and other characteristics of the people traveling, the origins and destinations by groups, etc.

System costs are determined based on the preliminary line and station locations by making use of capital and operating cost information available from the developers. With this information, in addition to the annual patronage calculation, the average cost per trip and the annual revenue can be estimated. This calculation produces maximal flows in each link of the network and the required capacities of each station. In order to determine the impact of the system on the required capacity of streets, a total transportation flow analysis should be conducted at this point so that the modal-split calculations can lead to estimates of the required capacity of the street system after the PRT system is installed. These calculations are needed in the studies of the impact of the system on the pattern of auto traffic, air pollution and noise.

These calculations will result in the requirement that some of the lines and stations be relocated. These relocations are performed at this point and the flow calculations are repeated once more.

Impacts

Analysis of impacts of the system on the community can begin at the beginning of the study but once the revised flow calculations are completed as described above the impacts can begin to be quantified. The following types of impact analyses need to be performed:

A. Impacts on the magnitude and distribution of employment as a result of the new system. The number of jobs required to plan, construct and operate the system at each stage is estimated. The jobs which will be induced as a result of increased mobility of certain urban residents will be estimated.

B. Impacts on development. The potential influence of the system at each stage of its development on the construction of new buildings in the community is estimated. Some of this development may be simply relocations of development already planned. Other development may be induced by the system.

C. Impacts on institutions. By analysis of the operations of the medical care system, the educational system, the police system, and so forth, the potential impacts of the system on the institutions will be estimated. This analysis will of course require strong interaction between the development team and the personnel in these institutions.

D. Impacts on individuals. Time-motion studies of the actions people go through in transporting themselves around an urban area at the present time will be compared with similar analyses for individuals using the automated system. By doing these studies on a variety of classes of people not only will information attained be useful in developing behavior models of modal split but the impact of the system on the community will be clarified.

E. Impacts on the environment. The system will have at least four types of major impacts on the environment: 1) Visual impact, 2) Impact on the air quality, 3) Impact on noise, and 4) Impact on transportation land use. The visual impact will be determined initially on the basis of photomontages of the system in various parts of the community and models of the system. The analysis of air quality should go deeper than just estimating a general reduction in air pollution by estimating the number of vehicle miles removed from the road. The analysis should be performed zone by zone in order to determine if regions in which the air pollution is more intense can be reduced. The noise analysis requires design of a community noise model and will investigate the possibility of reduction of speed limits, elimination of truck traffic from the inner part of the urban area, etc. In the latter case the trucks would be required to unload their goods at peripheral terminals from which point the goods would be distributed on the automated system. The land-use impacts are determined on the basis of the reduction in street-capacity need as a result of the automated system and may lead to narrowing of some of the streets in order to create linear parks, convert parking lots to parks or other land uses, etc.

Community Involvement Program

All of the information on the impacts indicated above should be summarized into a form which can be presented to the community in order to determine the reactions of all interested types of community organizations to the system. This community involvement program, which in fact will probably proceed throughout the entire development period, will result in further revisions of the line and station locations, followed by refined calculations as described above. Based on these refinements, the computer models developed to determine each type of impact are re-exercised to determine if the revised impacts will be acceptable. The community involvement program is repeated and the entire process is iterated until the community feels the physical design of the system is satisfactory.

Staging Plan

At this point a plan for time staging of the network will be prepared for approval. At any stage in the process, the lines which would be intended to be implemented first would have been analyzed more thoroughly and, even while the first stage is under construction, analysis of the remainder of the plan should be under continual review up to the time construction is ordered. In addition to the staging plan, the planning process will produce for a given city system specifications on the following items: 1) The minimum headway needed in a particular city; 2) Types of architectural designs of guideways and stations which would be acceptable; 3) The layouts of stations needed to serve the needs of all the people in the community; 4) Refinements on the service characteristics desired in the system; 5) The desired layout and capacity of the vehicles; and 6) Statements as to whether or not the system would be a captive-vehicle PRT, a pallet system, or a dual-mode system.

In the above analysis the interaction between the automated system and other transport systems in the community would be considered.

The Development Program

The resources available to various companies working on development of PRT systems have not been such that these companies have been able to undertake major comparative analyses between various types of hardware by means of developmental testing. Instead, it has been necessary for them to select a set of ideas based upon preliminary analyses, build the hardware, and try to develop the particular set of ideas to the fullest. The status of system developments at the time of writing this report is such that at least a dozen different developers have conceived a dozen different ways of implementing PRT and each developer is able to make a good case why his system is preferable to the others.

There are two ways that a development program could proceed. In the first, each company simply proceeds to develop its hardware and then attempts to market the hardware in open competition with other ideas. In such a program it is never possible for any of the manufacturers to expend the resources needed to fully and completely test the hardware available to them to the point that positive tradeoff decisions between types of hardware can be made. In the second procedure, the United States Department of Transportation would develop a program for systematic testing and tradeoff between the various sub-system components and total systems in order to determine the specifications for a standardized class of PRT systems. The various companies involved would develop capabilities and would receive licenses to manufacture certain components of the systems. If performed properly this approach appears capable of minimizing the direct costs of each system and producing systems that would be compatible as area-wide networks begin to expand and eventually unite. This systematic approach will lead to the most rapid development and deployment of PRT systems. It is also the better alternative because it would give planners in cities throughout the country stronger assurance that the federal government had a commitment to make hardware of personal rapid transit available for deployment. Such a program would also reduce the confusion in the minds of urban planners who are not equipped to make tradeoffs between the dozen or so systems being marketed today.

Review of Present Systems and Technical Developments

The system-development program would begin with a comprehensive review of the characteristics and status of hardware development performed by each of the major PRT system developers. Out of this analysis and the considerable number of preliminary planning studies already performed, initial specifications for a high-capacity PRT system would be developed. At this point these specifications would leave open the question as to whether the system is a captive-vehicle PRT system, a palletized system or a dual-mode system. It would leave open the question to whether the system would be applied above ground or below ground, whether the guideway would be open to the elements or placed in an enclosed tube, or whether the suspension system would be above the vehicle or below the vehicle.

Component and Sub-system Developments

1) System failure analysis.

This activity is listed first because of its primary importance in the development of high-capacity PRT and because such an analysis will lead to specifications for the design of the other system components which may rule out certain types of designs. Under this program detailed analysis of every possible mode of failure of the major high-capacity PRT systems would be undertaken. Where weaknesses are found, either the design would be ruled out or some means would be developed to provide needed redundancy into the system. Failure analysis, continued throughout the development program, will finally lead to designs of fundamental simplicity, redundancy in the system where needed, maintenance and inspection procedures for both the systems and track designed to insure the reliability of the system, and component replacement programs for critical components of finite lifetime.

2) Safety Design.

No mechanical system can be designed to insure that no collision could ever occur; however, the effects of collisions can be minimized as indicated in Chapter 8 by analyzing collision processes. As indicated in Chapter 8, it would be recommended that the process of collision between two vehicles be modeled on the assumption that the vehicles are equipped with shock absorbers, padded interiors and possibly various types of passenger constraint mechanisms. This anlysis will result in recommended layouts for the vehicles and shock mounts.

3) Propulsion and Suspension Systems.

These two areas are considered together because, in several of the designs, they are strongly coupled. In current designs, vehicles are suspended from both above and below, on wheels, air and by magnetic fields. Some proposed systems are propelled by rotary electric motors, others by linear motors. Linear induction motors, linear pulsed DC motors and air motors are being considered. In all, this indicates 24 possible combinations of which about half a dozen are currently being developed. Extensive sub-system testing needs to be made to determine the lifetime, the reliability, weight and power requirements of each type of motor.

4) Pallet versus Whole-Vehicle.

Use of pallets or moving general-purpose platforms possesses obvious advantages for the system but it also increases the weight of the total vehicle because of the need for clamps and some redundancy in the structures. The challenge is to design pallets light enough so that the weight penalty is acceptable. The pallet also introduces problems in system operation discussed below.

5) The Guideway.

The design of the guideway is intimately dependent upon the type of propulsion and suspension systems used, and upon information attained from community planning studies on the acceptable dimensions of guideways. In order to minimize the cost and visual impact of overhead guideways these guideways must be designed to be as light and as small in cross-section as possible. Under these circumstances, aircraft analysis procedures for lateral wind loads and vibrational loads due to the moving vehicles need to be carried out. Also single-post and arch supports need to be analyzed to determine the required sizes of the footings in each case as well as the dimensions of the support.

6) Human Factors

The lengths of acceleration and deceleration ramps and the curvatures of the guideway are dependent upon conditions of human comfort under various combinations of longitudinal and lateral acceleration and jerk. While a great deal of information exists on this subject, little of it relates to the precise conditions which will be encountered in PRT systems or with subjects particularly susceptible to motion discomfort. Therefore, as part of the development program, a comprehensive program of testing to determine human-comfort criteria must be conducted.

7) Power-Distribution Systems.

Most PRT systems require on-board power from electrical leads strung along the guideways. This is expensive and requires moving brushes which are a source of problems. Therefore careful testing needs to be done to determine the best possible designs. Consideration should also be given to the possibility of various types of on-board power systems.

8) Track Sensors.

Sensors need to be placed along the track to determine the position and velocity of the vehicle and to sense emergency conditions. Alternate types of sensors need to be designed, built and tested.

9) Effects of Weather.

If open guideways are used, both the vehicle and the guideway have to be designed together as a system to reduce the effects of weather to an acceptable level. The procedures for operating in adverse weather conditions need to be developed.

10) Stations.

Stations need to be designed for maximum use and minimum abuse. A set of criteria for use of the system by handicapped people is available and should be used in developing layouts and standards for station designs. The station must be designed in such a way that the potential of vandalism is minimized. Alternate fare collection schemes need to be developed usable for both residents of the community as well as visitors. Station layouts for various capacities found to be needed from the planning studies must be considered. In some stations it will be desirable to have TV surveillance. Procedures for handling emergencies should be developed and the possibility of using stations for freight, or the design of special freight stations should be considered.

11) Doors.

Design of highly reliable safe-operating doors for PRT vehicles is not a trivial procedure and will require careful attention.

12) Communication.

The design and test of alternate schemes for providing communication between the vehicles, stations and central computer must be carried out.

13) Tunneling.

The alternative of tunneling part or all of the system needs to be carefully considered in the light of modern low-cost tunneling methods. The best of both overhead and tunneled guideways need to be subject to careful cost analysis to enable community planners to make appropriate tradeoffs.

14) Use for Other Utilities.

The guideway design should be analyzed to determine whether other utility lines such as power lines, telephone lines and gas lines can be run inside the guideway in order to reduce costs for the community.

System Operations, Analysis and Design

The total design program must be led by the team responsible for system operations, analysis and design. In addition, the following system functions need to be refined, and computers need to be developed for performing them.

A. Management of the flow at each intersection.

B. Selection of the minimum-time route.

C. Empty vehicle shuttling for optimizing the motion of empty vehicles around the system.

D. Emergency procedures.

E. Special procedures required if the pallet system is used.

System Testing

While the various subsystems are being designed, tested and compared, plans should be developed for full-scale engineering tests on one or more candidate systems. These tests should be done initially at a remote site in order to remove the pressure for absolute perfection in the early stages of the testing. After this program gets under way plans should be made for testing of the full system in an urban environment. Only cities that would have conducted comprehensive planning for high-capacity PRT could qualify for such a demonstration because of the lead time needed to design a system into a community.

Programs analogous to that indicated above are under way in both Germany and Japan aimed at operation in cities approximately five years from the initiation of the program. If such a systematic development program is undertaken in the United States, it appears quite possible to think in terms of having high-capacity PRT systems available for general area-wide deployment in the last two years of the present decade.

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Copy 2