ECONOMIC, ENVIRONMENTAL, AND DESIGN ASPECTS OF LARGE-SCALE PRT NETWORKS

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A parametric study of system variables of large-scale personal rapid transit (PRT) networks is presented. An idealized urban area having uniformly distributed population (trip) origins and destinations serves as the trip model, and a square mesh pattern serves as the PRT network model. Independent variables in the analysis are population (trip) density, PRT operating and fixed costs, mesh spacing, automobile speed, perceived automobile cost per mile, and PRT speed and fare. Dependent variables are modal split (patronage), reduced automobile emissions, cost and subsidy per mile, benefit-cost ratio, electrical power requirements, fleet size, and needed guideway and station capacity. The analysis identifies ranges of population (trip) densities and PRT system performances and costs for which PRT is either economically feasible or a benefit to society. Quantified societal benefits include reduced automobile costs, reduced travel time and pollution, and increased safety. The results provide useful guidelines for system designers, urban planners, and decision-makers.

EVERY urban area is faced with a transportation problem. The problem lies not so much in how people might be transported 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. Most American cities are characterized by low-density residential areas and a dissolving central core, and thus trip origins and destinations are widely dispersed. Because 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 who do not have access to an automobile) and those whose origins and destinations are in the areas that can be served well by transit. 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 urban area'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 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 to 6 passengers) and operate individually under automatic control. Trips are nonstop from origin to destination—high capacity is achieved by operating at close headways. Its auto-like characteristics (privacy, comfort, speed) make it a potentially viable competitor with the auto. In its completed

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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), Frieberg (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 has also been reported (7).

This paper presents a parametric study of PRT design and cost variables. An urban area is idealized by assuming a uniformly distributed population, i.e., a uniformly distributed transportation demand model. Two population (trip) densities are assumed, one representing residential areas, the other representing major activity centers (MAC)—e.g., employment, shopping, and educational centers. The PRT network of lines serving the idealized city is one having a square grid. Residential areas have a larger mesh spacing than the major activity centers. The analysis uses aggregate information on auto travel time, trip distance, and income that happens to characterize the Twin Cities of Minneapolis-St. Paul, Minnesota, but also represents many of America's larger urban areas. The study was performed concurrently with our study of real-city networks for the Twin Cities and Duluth. The motivation for the idealized 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. A Monte Carlo procedure (2) 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, revenue, 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.

SYSTEM MODELS

Trip and Trip-Maker Characteristics

The idealization of a real urban area by simply modeling only two population densities—i.e., residential areas and major activity centers—provides a sensible level of abstraction for parametric analysis and a convenient point of departure for a transportation study. A substantial amount of compiled statistics describing trips and trip-makers is available on which to build. Major activity centers include schools, shopping centers, employment centers, and, more generally, all trip destinations except residences. Figures 1b, trip length distribution, and 1f, trip purpose distribution, show some trip characteristics of the Twin Cities. Both figures are based on information from the TCAT study (8). Figure 1b illustrates the predominance of shorter trips. Figure 1f indicates that about 80 percent 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 percent of the total. As indicated in Table 1, residents average about 3 trips daily and 0.3 trips during each of the 4 peak hours. Figure 1c, family income distributions, is based on 1970 income data supplied by the Metropolitan Council.

PRT Network Design Parameters

The Twin Cities street layout is largely rectangular, as is typical of many American cities. The simplest geometric PRT 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. This paper considers a square network, which is thought to be appropriate when modeling 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 longest walk distances (L/2) and the average (L/3). Stations serve an area within the dashed line shown in Figure 2. If a uniform trip generation density over the station attraction area is assumed, the walk distance distribution is as shown in Figure 1a. For this network design it follows that

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

where M is the route 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 substantive effect on network design; they are nominal line speed, jerk, and acceleration. Switch and acceleration (deceleration) lane lengths are estimated respectevely from

$$\begin{aligned} L_s &= 47.04V\ (h/J)^{1/3} \\ L_a &= 1.08V^2/a + 1.47\ (Va/J) \end{aligned} \tag{2}$$

These equations are derived elsewhere (9). V is the nominal speed in miles per hour, h is the distance in feet between ramps and guideways, a is acceleration in ft/sec^2, and J is jerk in ft/sec^3. A station ramp consists of 2 switches, an acceleration lane, a deceleration lane, and 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. For the nominal values of acceleration (8 ft/sec^2) and jerk (8 ft/sec^3), both acceptable for seated passengers, and velocity (35 mph), the minimum mesh spacing is 0.3 mile.

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 that involve travel time and out-of-pocket expenses. A trip is assigned to auto or PRT according to which mode offers the lower cost. A large number (1,000) 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 levels of these attributes similar to if not better than the automobile.

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

$$t_{ss} = X/V + V/a + 2L/V \tag{3}$$

where X is the trip distance, V is the PRT line speed, a is acceleration, and L is mesh space. The second term on the right 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

$$C_{PRT} = FX/1.3 + fW\ (t_{as} + 2t_{proc} + 2X_W/V_X) \tag{4}$$

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 trip-maker places on his time, t_{proc} is the station process time at each trip end, X_W is the combined walk distance at the 2 trip ends, and V_X is the walk speed. Nominal values chosen for these quantities are given in Table 1. The formula assumes an occupied vehicle occupancy of 1.3 passengers/vehicle. Attitudinal studies indicate that walk times and station process times are considered as "nuisance" times, and consequently they are weighted twice as seriously as in-vehicle travel time.

Auto Trip Description

An auto trip is modeled 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

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

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 1d and 1e. Both figures represent the authors' best guess. The 10-cent mean of Figure 1d 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 $\frac{1}{10}$-mile walk was assumed at all MAC ends. Equation 5 assumes an auto occupancy of 1.3 passengers per vehicle.

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 1,000 trips. The passenger-mile modal split 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 by auto for the 1,000 trips. The trip modal splits are shown in Figure 4. Also plotted is the percentage reduction of auto emissions, which is equivalent to the passenger-mile modal split.

Determination of the modal split permits the easy computation of other system parameters, as shown in Figure 4. The formulas are presented in this section, but their derivations are given in the Appendix. The peak-hour station demand in passengers per hour is directly proportional to TMS and is obtainable from

$$D_s = 150\ \text{TMS}\ L^2 \tag{6}$$

where D_s is the station demand per 1,000 people per square mile. Several more quantities are directly proportional to the passenger-mile modal split. The important ones are N_v, the fleet size per million people; P_e, the number of gigawatt plants required per million people; and C_v, the peak-hour guideway capacity requirement, which is plotted on a per hour per 1,000 people per square mile basis. These respective quantities are obtained from the formulas

$$C_v = 0.2\ LX_{PRT} \tag{7}$$

$$P_e = \begin{cases} 0.000054\ X_{PRT}\ \text{(without regenerative braking)} \\ 0.000041\ X_{PRT}\ \text{(with regenerative braking)} \end{cases} \tag{8}$$

Figure 1. Trip models.

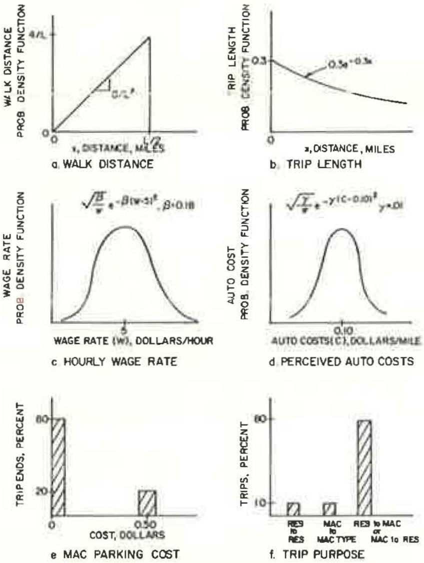


Figure 2. Idealized square mesh PRT network of one-way interchangeable lines.

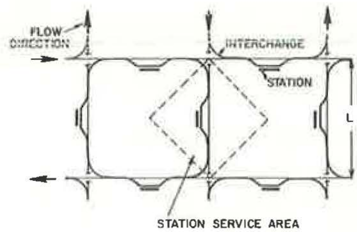


Figure 3. Auto trip time.

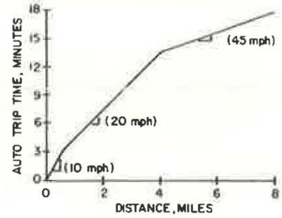
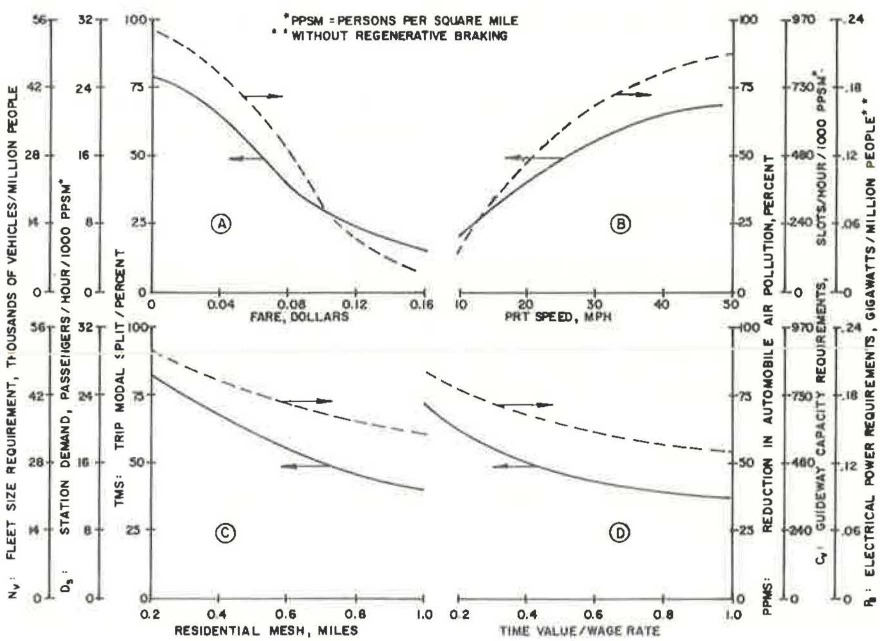


Table 1. Nominal values and range of variation of parameters.

Symbol	Name	Nominal Value	Range of Variation
V_x	Walk speed	3 mph	—
L	Residential mesh spacing	0.5 mile	0.2 to 1.0 mile
	MAC mesh spacing	0.2 mile	—
V	PRT speed	35 mph	10 to 50 mph
F	PRT fare	\$0.05/occupied-vehicle-mile	\$0 to \$0.20
f	Time value/wage rate	0.25	0.2 to 1.0
	Interest rate	6 percent	—
	Amortization time for fixed facilities	30 years	—
	Amortization time for vehicle	5 years	—
t_{proc}	Station process time	1 minute	—
	Daily trip generation rate	3 trips/person	—
	Peak-hour trip generation rate	0.3 trips/person	—
a	Vehicle acceleration	8 ft/sec^2	—
J	Vehicle jerk (maximum)	8 ft/sec^3	—

Figure 4. Modal split and PRT system requirements.



$$N_v = (2{,}000/L/V)\ C_v \tag{9}$$

and are plotted in Figure 4.

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 this paper; however, possible sources, some controversial, include federal capital grants, property taxes, general funds, and highway user taxes. Furthermore, studies by Lea (4) and Smith (11) indicate that goods movement should be investigated as a potential source of significant revenue and better system utilization.

Systems Costs

Cost estimates for this paper are given in Table 2. The estimates are in line with those used elsewhere (2, 3, 12). The most substantial departure from these works is to assume a higher price for vehicle storage, namely $3,000 per vehicle. This estimate is based on the assumption that guideway ramps costing $1.5 million per mile would be used for the storage; $3,000 would then buy about 10 ft of ramp. Interest rates are assumed to be 6 percent (Table 1). Fixed facilities are assumed to be amortized over 30 years. Vehicles are amortized over a lifetime of 5 years. The 3 cents-per-mile operating cost includes the computer facility and personnel costs, electricity, maintenance, and cleaning. All ramp lengths were computed from Eq. 2 with $a = 8\ \text{ft/sec}^2$ and $J = 8\ \text{ft/sec}^3$. Equation 1 provides an estimate for the number of stations and interchange ramps.

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, obtained from the modal-split analysis. The variable cost per passenger-mile, C_v, is found by converting the variable costs to a per-vehicle-mile basis. With an assumed 1.3 passengers per vehicle and with total vehicle mileage equal to an assumed 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 shown in Figure 5 for a wide range of system parameters.

Benefit-Cost Ratio

The benefit-cost method of economic analysis obtains a parameter BCR, termed the benefit-cost ratio, defined by the equation

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

The present analysis identifies three benefits that 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. Auto-cost savings include parking fares not encountered plus a mileage cost, taken to be 10 cents per mile (intermediate between total cost and variable cost). Pollution and safety benefits can be estimated from the RECATS report (13), where it is estimated that by 1976 automobiles will incur 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 cent per mile; 2 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 travelers for two reasons: First, most of the trips taken by PRT are faster than by auto, and second, 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 4 peak hours, therefore affecting only about 35 percent of the daily trips. It seems reasonable to assume a form

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

where T is the auto trip time at demand level D and 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 two-thirds 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 shown in Figure 6. The benefit-cost ratio is plotted in Figure 7 for a range of parameters.

DISCUSSION OF NUMERICAL RESULTS

Output of the patronage and economic model of large-scale PRT systems is shown in Figures 4, 5, and 7. The data are presented in the form of network performance indices (patronage, Fig. 4; cost/mile, Fig. 5; 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 given in Table 1. They are initial values for a base-line Twin Cities PRT system. The mesh spacing (0.5 mile) provides reasonable access by walking and the speed (35 mph) and fare (5 cents per vehicle-mile) are competitive with the automobile. Our model predicts that this nominal PRT system would attract about 60 percent of the trips, which represents 75 percent of the passenger-miles. This 75 percent diversion of automobile trip miles to transit implies among numerous things a 75 percent reduction in auto air pollution and a reduced dependence on scarce petroleum reserves. For a city of 1 million people a 0.15-gigawatt power plant would be needed to power a PRT system requiring a fleet of 35,000 vehicles at the peak hour (assuming no regenerative braking). Regenerative braking could reduce the power requirements by approximately 25 percent. The 24-hour average power requirement is about 40 percent 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 per hour and guideway capacity at 35 mph would require 0.5-sec headways.

It is of interest to compare the energy requirement of PRT travel with that of the automobile. If a reasonable power plant efficiency of 40 percent is assumed, it follows from Eq. 8 that PRT without regenerative braking requires 1,500 Btu per vehicle-mile (equal to assumed average passenger-miles). For auto travel 9,000 Btu per passenger-mile are required, assuming 12 miles per gallon and 1.3 passengers per auto. It follows that a PRT system that attracts 75 percent of the passenger-miles from the auto could effect an urban transportation energy reduction of roughly 60 percent.

Figure 5 shows 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 as follows:

1. 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, whereas at high fares only few (and shorter) trips are by PRT.
2. Patronage is very sensitive to PRT speed at its lower values. At speeds of 35 to 40 mph, PRT has captured most of the market, and a point of diminishing return is reached.

Figure 5. Cost and subsidy per passenger-mile.

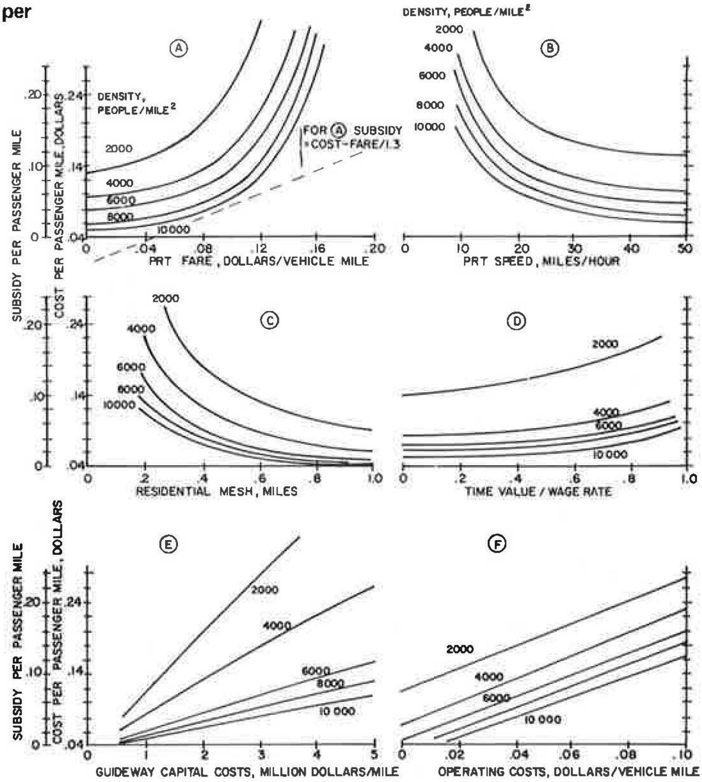


Table 2. Cost estimates.

	Fixed Costs		Variable Costs	
Item	Capital	Other	Capital	Other
Guideway, right-of-way support, electrification	$1.5 million per mile	Maintenance, 1 percent[a]	–	–
Stations				
Ramps	$1.5 million per mile	Maintenance, 1 percent	–	–
Buildings and controls	$200,000	Maintenance, 1 percent	–	–
Interchange				
Ramps	$1.5 million per mile	Maintenance, 1 percent	–	–
Queue area and controls	$100,000	Maintenance, 1 percent	–	–
Maintenance garage	–	–	$100/vehicle	Maintenance, 1 percent
Carbarn	–	–	$3,000/vehicle	Maintenance, 1 percent
Vehicle	–	–	$4,000/vehicle	Operating, 3 cents/mile

[a]Maintenance cost refers to annual cost equal to 1 percent of capital cost.

Figure 6. Travel time versus congestion.

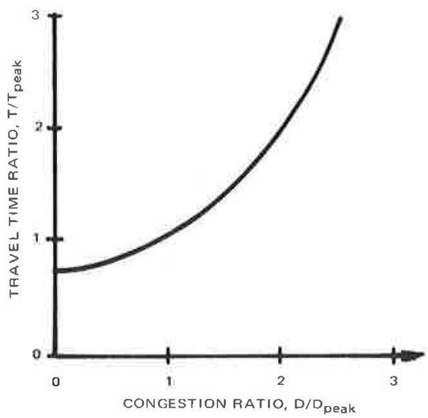
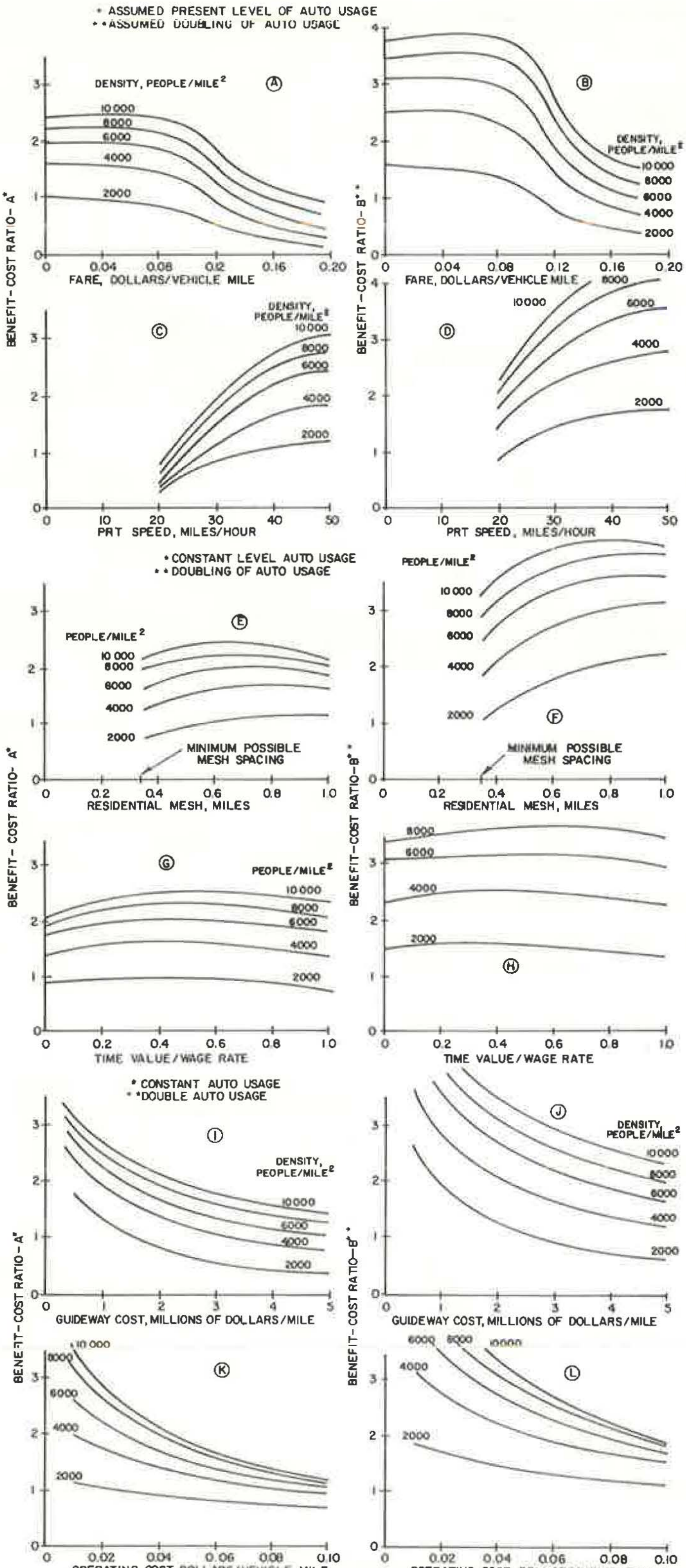


Figure 7. Benefit-cost ratio.



3. A steady decrease in patronage results from increased residential mesh size.

Perhaps the most significant result of Figure 5 is that the total cost (including full capital costs) per PRT passenger-mile is less than 10 cents for cities of 9,000 ppsm or more. This means that PRT travel costs are competitive with travel costs by auto, buses, and dial-a-ride. Figure 5 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 equals 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 cents to 9 cents. 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. Figure 5 shows that the cost per ride is largely insensitive to variations in the time value per wage rate ratio, particularly in high-density areas. In another computer run it was assumed that the actual ridership was only half of that predicted. For 10,000 ppsm, the cost per mile then jumped from 7 cents to only 8 cents; for 2,000 ppsm, the cost per mile jumped from 17 cents to 27 cents. At high densities a large percentage of the cost is variable. This makes the cost per passenger-mile rather insensitive to ridership and fixed-cost estimation errors.

Figure 7 shows that the benefit-cost ratios 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. Most metropolitan master plans for the future are based on predicted large increases in transport demands resulting from population growth and increased per capita trip-making. Consequently the second benefit-cost ratio, BCR-B, assumes a doubling of the total demand. The BCR curves indicate that the fare should be less than 10 cents per vehicle-mile, and an optimum is actually attained between 4 and 6 cents per vehicle-mile. Coupling these data with those of Figure 5 indicates that a fare of 8 cents per vehicle-mile would minimize the subsidy requirement and provide an excellent BCR for a wide range of population densities. In areas having 7,000 ppsm or more, this fare would cover operating costs of 4 cents per occupied-vehicle-mile plus enough for the capital cost to permit completion of the financing of a one-third local share of a capital grant program. The benefit-cost curves also yield optimum values of residential mesh size (0.6 to 0.8 mile) and PRT speed (~50 mph).

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 approximately 4,000 ppsm, PRT offers attractive benefit-cost ratios and costs per passenger-mile. At somewhat higher densities, the financing of a PRT system is possible with farebox revenues and two-thirds federal capital grants. Furthermore, at these higher densities, moderate estimation errors in fixed costs and ridership do not significantly distort the favorable system economics. On the environmental side, about 0.15 gigawatt of electrical power would be required to serve 1 million people if the PRT system does not have regenerative braking; somewhat less would be needed if regenerative braking is used. The trade-offs would be large reductions in auto emissions and petroleum requirements as well as a significant overall reduction in the total urban transportation energy requirement.

ACKNOWLEDGMENT

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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 1,000 people per square mile. The demands at other densities are higher by a proportional amount. Assuming a trip generation of 0.3 trip 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, Eq. 6 follows immediately.

Electrical Power Requirements

A frequently used formula for automobile motion resistance R is

$$R = (7.6 + 0.09V + C_g)W + C_c V^2$$

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 thousands 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 2,000 lb. 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

$$R = (15.2 + 18V) + 0.022V^2$$

It follows further that the energy required to travel 5,280 ft at 35 mph is 256,000 ft-lb. If an average of 3 accelerations in a 4-mile trip at 0.25 g for 190 ft is assumed, 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 ft per mile, requiring an additional 50,000 ft-lb. The total energy requirement per vehicle-mile is 386,000 ft-lb. If it is assumed that regenerative braking can recover 80 percent of the energy used in accelerating and climbing, then the requirement would be 289,000 ft-lb per mile. If it is assumed that there are 1.3 people per 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 kW-h per passenger-mile, the respective figures are 0.145 and 0.108. Assuming a 10 percent transmission line loss and 90 percent motor efficiency, the requirements are respectively 0.18 and 0.135. For 1 million people and 0.3 peak-hour trip 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 requirements in kilowatts are respectively 54 X_{PRT} and 41 X_{PRT}. This is Eq. 8 of the text.

Guideway Capacity

Studies (1, 15) indicate that merging can be handled with a relatively low abort rate, even if more than 80 percent of the guideway slots are occupied. Our capacity calculations are made on the assumption that 70 percent 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 1,000 people per square mile.

The number of passenger-miles of travel generated by 1,000 ppsm is 0.3 X_{PRT}. The number of guideway miles on that square mile is 2/L, and so the passenger flow requirement is 0.15 X_{PRT} L/0.7, which approximates Eq. 7. The time headway T can then be computed from the formula $T = 3{,}600/C_V$.

Fleet Size

The vehicle fleet includes the vehicles on the guideway plus those being processed in stations, stored in carbarns, maintained, and repaired. The fleet requirement for the guideway would be 70 percent of the slots. It is assumed that the remaining fleet would fill up the remaining slots. Thus, the fleet requirement per square mile (assuming 1,000 ppsm) is 2/L/ (V T/3,600 = $2C_V$/ (L/V), which if multiplied by 1,000 gives Eq. 9.