AN ECONOMIC PERSPECTIVE ON PRT NETWORKS

Michael B. Godfrey
Department of Civil Engineering
The Ohio State University

Nigel H. M. Wilson
Warren M. Yamamoto
Department of Civil Engineering
Massachusetts Institute of Technology

This paper estimates the costs and benefits of PRT networks designed to service non-work and off-peak trip-making, then compares them with the costs and benefits of the following alternative public transport technologies:

- bus-on-street,
- bus-on-guideway,
- small-bus-on-street,
- small-bus-on-guideway,
- automated guideways using bus-size vehicles, and
- dial-a-bus.

PRT, in this paper, refers to an automated, demand-responsive, small-vehicle (4-6 seats) system offering point-to-point service (no shared riding) on fixed guideways. Minimum headways are assumed to be no smaller than 3 seconds.

Modal comparisons are nothing new. Early 1900's systems analysts occupied themselves demonstrating the existence of significant cost, service, and environmental advantages for the automobile over the horse. Of late, the issue of busways versus rail transit has been the subject of several technical analyses (2,3), conventional bus and dial-a-bus have been compared (4), and PRT and other automated guideway modes have come in for a considerable amount of attention with respect to cost and benefit comparisons(5-22). Against this background, the present paper is offered with the hope that the incorporation of a supply-demand equilibrium approach, plus a true measure of benefit, will result in a useful sharpening of the complex issues which underlie the comparison of alternative urban public transport modes and the evaluation of PRT. It is recognized, of course, that the economic analyses presented here are by no means the final judgment on modal choice. But they are a necessary first step, and are presented as such.

PROBLEM ORIENTATION

This introductory section first defines the cost and benefit framework upon which are based the economic analyses to follow. Second, the two types of analysis offered here are briefly introduced. Third, the orientation of the principal analysis of this paper to non-work trips, rather than to work trips, is stated and explained.

System costs include the costs of providing the fixed network and the vehicles which operate on it, including costs for initial investment and for continuing operation, maintenance, and replacement. In addition, the value of travelers' journey times is included as an element of cost. Fare payments are not included in the cost calculations, because they represent a transfer payment from the passenger to the operator which is internal to the "system" under analysis.

System benefits encompass direct benefits to travelers, both measurable and non-measurable. Measurable benefits are often equated to the value of travel time savings; this entry, however, appears in the analysis as a negative cost increment, rather than as a positive benefit. It is properly considered as a cost saving, not a benefit, since time, like land, labor, and capital, is a resource. Non-measurable passenger benefits are equated to the totality of the differences between the maximum "price" a traveler would be willing to pay and the "price" actually paid. This totality of received--but not paid for-- benefits is the "consumers' surplus," a standard concept in microeconomics (1). Cf. Fig. 1. There are two problems in using the consumers' surplus. First, the demand function must be known. Second, there are implicit distributional inequities when dealing with diverse income groups, because the equivalent dollar value of non-monetary price components (such as travel

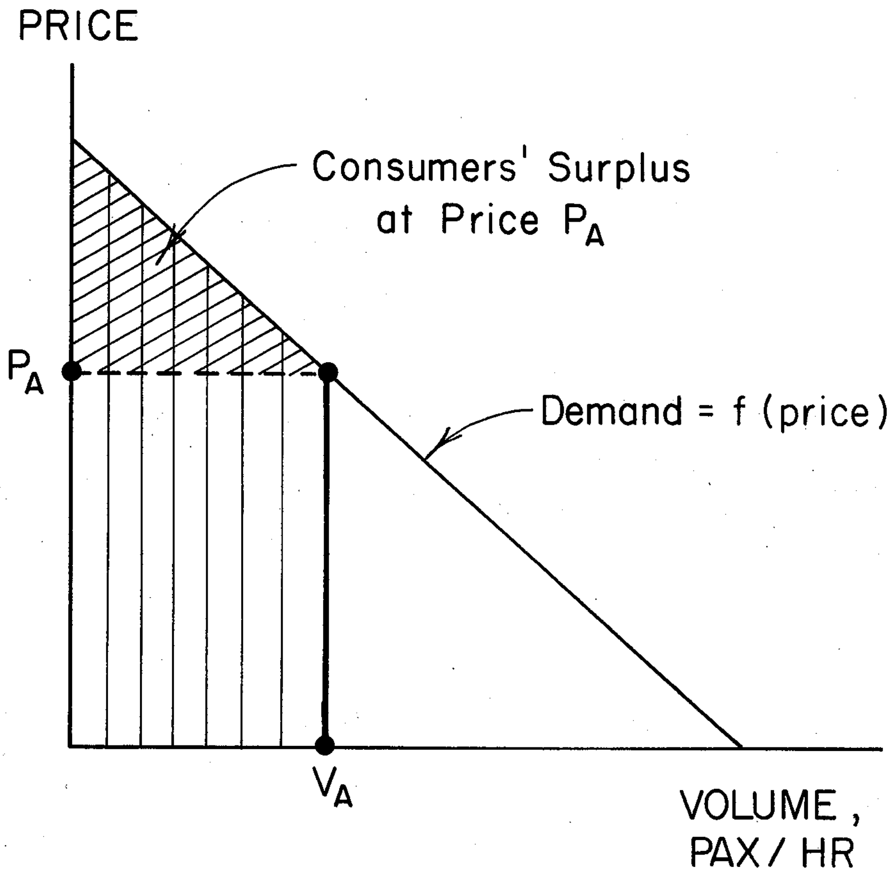


FIGURE 1

time) depends on the
Thus, the same pric
time) will be valued
income groups. Th
cussed briefly at a l

We are also concern
accruing to the publ
result of the transpo
profits are not a pro
since they result fro
passengers to opera
status of an operato
tance and will be co

The analysis consid
the proper frame o
municipality or a p
orientation seems r
time; most foresee
heavily dependent u
federal government
decisions are matte
not just municipal
this means that all
for, including gove
of capital or match
dependence on gove
that an opportunit
the relevant intere
cepted that an inte
to 10% is therefore
exact value has lon
discussion. This

While the selected
analyst to "conside
ever they may acc
not allow this. Th
values are not plac
ty impact or on ot
short-range or lon
exceed direct bene
determine the mag
necessary either t
show it as the bes
tives.

Two types of anal
ing a description
parative hourly co
sentative mile of
assumed demand
provides a simple
comparing altern
identifying param
that there are se
alternatives whic
antithetical choic

time) depends on the income of the traveler Thus, the same price difference (e.g. travel time) will be valued more (in dollars) by higher income groups. These problems will be discussed briefly at a later point.

We are also concerned with profits (if any) accruing to the public transport operator as a result of the transportation system. While such profits are not a proper measure of benefit, since they result from internal transfers from passengers to operators, the profit or subsidy status of an operator is clearly of great importance and will be computed.

The analysis considers society at large to be the proper frame of reference, rather than a municipality or a private corporation. This orientation seems reasonable at this point in time; most foreseeable PRT networks will be heavily dependent upon capital grants from the federal government, so that the relevant funding decisions are matters of national public policy, not just municipal concerns. Operationally, this means that all costs are to be accounted for, including government-subsidy contributions of capital or matching grants. Further, the dependence on government funding requires that an opportunity cost of capital be used as the relevant interest rate. It is generally accepted that an interest rate in the range of 6% to 10% is therefore appropriate, although its exact value has long been a matter of active discussion. This paper uses a value of 8%.

While the selected reference frame directs the analyst to "consider all benefits, to whomsoever they may accrue," the state of the art does not allow this. Thus, in this work, economic values are not placed on measures of community impact or on other externalities, whether short-range or long-range. However, if costs exceed direct benefits, it is at least possible to determine the magnitude of the indirect benefits necessary either to justify the project or to show it as the best choice of several alternatives.

Two types of analyses are carried out. Following a description of the alternative modes, comparative hourly costs are estimated for a representative mile of network as functions of an assumed demand level. This cost analysis provides a simple, but limited, procedure for comparing alternatives. Further, it assists in identifying parameters and highlights the fact that there are several technological and service alternatives which fall in between the simple antithetical choices of bus-on-street and PRT.

Following the prototype modal cost analysis for fixed demand, an analytical framework for comparing modal alternatives in the more realistic case of elastic demand is defined. The major elements of a set of demand, supply, and cost models are described, then employed in a modal cost and benefit analysis which compares alternative network technologies designed to service an area of uniform population density. Dial-a-bus is considered only in this analysis; it is not included in the fixed-demand prototype analysis.

The analysis is directed to a network service which is designed to serve relatively short trips (i.e., less than 3 or 4 miles), principally during off-peak periods for non-work purposes. Access to a fixed network under such circumstances will be largely by foot, and the network must therefore be relatively dense if it is to serve its intended purpose. This sort of application was chosen for several reasons. First, it considers a market which is often not well served by public transportation, except taxis, particularly in low-income areas of cities. Second, it is one kind of application for which several aspects of PRT service may uniquely suit it, namely the aspects of area-wide, rather than linear single-line service, and of point-to-point responsive service, rather than pre-scheduled and shared-vehicle service, which requires transfers. Third, we believe that rush-hour congestion problems are often relatively over-emphasized.

Thus, in contrast to most transportation system analyses, we are providing a service explicitly designed for non-work and off-peak trips, in preference to the usual orientation to peak-hour travel. The reasons for this departure from standard practice are explained in the following paragraphs.

The urban transportation problem of highest urgency is the lack of inexpensive and reliable transportation to the large segments of our urban population composed of individuals who either cannot--or may not--drive, or who do not have an automobile available for their use. Some transport needs of this group are met by taxis and other forms of urban public transport. But, since these individuals are generally dependent on public transport modes, many of their transport needs are simply not met. This transit-dependent group has been continually less well served by public transit during the last two decades, as urban dispersion has resulted inevitably in the sequence of decreasing patronage, increasing fares, and increasing service. Since the relatively most severe loss in transit patronage has occurred during weekend and off-peak periods, the non-rush-hour traveler has experienced the most serious decreases in service and in accessibility, by public transit, to urban activities. Not only is the non-work, non-peak-hour traveler less well served by transit, but also less well served by auto, to the extent that, in single-auto households, auto-use priority tends to be given to work trips and, in zero-auto and non-car-saturated households (i.e., fewer autos than workers), car pools for work trips would seem to be easier to arrange than car pools for non-work trips. A dense PRT network may be capable of serving the needs of that group of individuals who presently have few choices other than walking or taking taxis for off-peak and non-work travel.

Not only are the most pressing needs for new transportation service principally related to non-work and off-peak travel, but it can also be stated that many, if not most, urban transportation problems having to do with the provision of adequate rush-hour capacity have been solved. The Interstate program, for example, has succeeded in removing much through traffic from center-city streets and in raising travel speeds. It can, in fact, be argued that, in some cities, too much urban highway capacity has been built, in the sense that some of the funds could have been better spent on other public projects. Despite the continued existence of rush-hour congestion, the durations of rush hours have often been decreased, and previously off-peak trips have been able to relocate to the rush-hour. The continued existence of rush hours is based on the concentration of trip-making in space and in time and on the increasing lengths of work trips as cities disperse. The most effective strategy for dealing with rush-hour congestion would seem to be one which places heavy emphasis on operational and other low-cost improvements, such as staggered work hours, in order to use existing facilities at lower social costs.

DESCRIPTIONS OF MODES

Fixed-route bus services currently account for approximately two-thirds of all urban transit passengers, a percentage that has been increasing slightly over the past twenty years. However, the total number of bus passengers has been declining by 5 to 10 percent per year. The reasons for this decline have been documented elsewhere; suffice it to say here that two important factors have been fare increases (50 percent in the past five years), resulting from rapidly rising costs, and a failure to improve the service offered. As a result of declining ridership and increasing costs, the amount of service provided has also been declining. Several approaches have been taken to improve transit's competitive and financial position: the use of smaller vehicles, operation on reserved rights-of-way, demand-responsive operations (dial-a-bus), and automated-vehicle operation.

Minibuses, or small buses having fewer than 30 seats, have been used in various new fixed-route services over the past several years. The principal arguments for their use are that:

1) In areas of low transit demand, there is no need for a larger vehicle; since minibuses have lower capital costs, in these locations they are preferable.
2) In newly developed suburban areas having complex street patterns, a smaller vehicle has better maneuverability, thus increasing point-to-point speeds.
3) Smaller vehicles are more compatible with suburban areas and are less likely to trigger community opposition to public transit service innovations.
4) A more personal atmosphere in the vehicles may encourage new ridership.

The number of these buses in operation is increasing, but the design experience to date has not been sufficient to produce the operating cost reductions that were expected. As this experience accumulates, greater operating cost reductions should be obtainable.

Over the past few years, numerous fixed-route bus services have benefitted from schemes giving priority to transit vehicles over general highway traffic. The fullest embodiment of this approach is to provide a reserved right of way for the exclusive use of transit vehicles. This provides a travel-time advantage for transit over highway and represents a low-volume rapid transit system still under manual control. Clearly this concept is most useful where there is significant highway congestion and where additional rights of way are readily available. In a network of exclusive bus rights of way, bus stops would be on the guideway (i.e., on-line stations) and intersections would be at-grade with allowance for change of direction. A further refinement of this concept which results in dramatic reductions in labor costs is the personal rapid transit (PRT) concept, to be described later in this section.

Dial-a-bus (DAB
proach to the pr
compete with the
DAB systems pr
groups of indivic
origin-destinatio
is a critical func
performed on a
manual or comp
DAB systems ha
in the past few y
10 vehicles in o
tems operate in
make fixed-rout
feasible. The h
support higher f
with slightly hig

DAB is designed
of-vehicle acces
door service. C
hand, are desig
time by increasi
being on a right
traffic, street c
speeds are not u
strained by curv
ings, and by saf
tion consideratio
automation. Au
monly considere
"people-movers
speeds and, it w
through vehicle
the kind of servi
route, fixed-sch
quality of that s
block speed, ho
frequency of sta
crease stop spac
more difficult, a
replace large ve
thereby elimina
This is the esse
small vehicles c
tively short hea
to individual pas

It is important t
least four separ
issues subsume
trast between bu
issues are the f
1) Small
2) Grade
opera
3) Point
servi
accep
4) Auton

Dial-a-bus (DAB) represents a different approach to the problem of transit's failure to compete with the auto in low-density markets. DAB systems provide door-to-door service for groups of individuals with similar, but different origin-destination points. Dispatching, which is a critical function in this type of system, is performed on a real-time basis under either manual or computer control. More than twenty DAB systems have been implemented in the U.S. in the past few years (23, 24), the largest having 10 vehicles in operation. Many of these systems operate in areas with densities too low to make fixed-route bus services economically feasible. The higher quality DAB service can support higher fares than fixed-route services with slightly higher costs.

DAB is designed to reduce or eliminate the out-of-vehicle access time by providing door-to-door service. Guideway modes, on the other hand, are designed to reduce in-vehicle travel time by increasing average vehicle speeds. By being on a right of way separated from street traffic, street congestion is avoided. Maximum speeds are not unlimited, of course, being constrained by curves and grades, by station spacings, and by safety, noise, and power consumption considerations. The next step is that of automation. Automated guideway modes, commonly considered as falling into the class of "people-movers," were designed to raise speeds and, it was hoped, to reduce labor costs through vehicle automation. Fundamentally, the kind of service offered is the same as fixed-route, fixed-schedule bus service, although the quality of that service may be better. The block speed, however, is still limited by the frequency of station stops. Rather than increase stop spacings and make station access more difficult, an alternative approach is to replace large vehicles with small vehicles, and thereby eliminate intermediate stops altogether. This is the essence of the PRT concept. The small vehicles can be pre-scheduled (at relatively short headways) or dispatched in response to individual passengers' requests for service.

It is important to recognize that there are at least four separate, and somewhat independent, issues subsumed in the apparently clearcut contrast between bus-on-street and PRT. These issues are the following:

1) Small versus large vehicles;
2) Grade separation versus on-street operation;
3) Point-to-point service versus serving all intermediate stops, and accepting the need for transfers; and
4) Automatic versus manual control.

At the very least, it would appear that most of the service-related advantages of PRT over bus could be obtained without automation, and perhaps at lower cost. That is, the provision of small vehicles offering point-to-point service on grade-separated rights of way can be achieved without automation. The principal benefits sought from automation are related to the capability of running vehicles at short headways, potential reductions in operating costs and in vehicle maintenance costs, decreased vulnerability of service to labor disputes, potential reductions in land requirements with respect to the auto mode, and increased vehicle reliability. It is one of the purposes of this paper to investigate the cost aspects of the anticipated benefits of automation, in comparison with non-automated modes which nonetheless offer some of PRT's potential service advantages.

MODAL COST DATA

This section gives the lifetimes and unit costs for the various modes to be evaluated. Seven modes are evaluated in the fixed-demand analyses; six of the nine modes are evaluated in the elastic-demand analyses. The network costs quoted include all costs, except the right of way. A basic assumption is that it is possible to construct an elevated guideway network without severely compromising or utterly destroying the urban fabric which the network is intended to serve. The cost data are based on standard unit costs, where available, supplemented by an amalgam of costs developed for past studies by transportation planning agencies and their consultants. Specific references cannot be cited for these latter costs, because the authors were provided most of this information in confidence. Data which are not given below, such as station locations, are provided below in the section on supply models. All guideway modes have guideways at half-mile intervals.

Standard Bus on Street (BUS)

The network cost per two-way route-mile is $50,000, covering the costs of bus bays, passenger shelters, and signs. The lifetime of this capital equipment is set at ten years. The purchase price of a new bus is $45,000, with a lifetime of ten years (the industry standard) and an operating cost of $12 per vehicle-hour. This cost assumes that operator costs (including fringe benefits) are $8 per hour and represent 65% of the total hourly cost. Buses seat 45 passengers and have block speeds of

12 mph, which includes delays at bus stops.

Small Bus on Street (SBUS)

The purchase price of a 25-passenger bus, of high quality, is $30,000. Its lifetime is ten years, and its operating cost is $11.50 per vehicle-hour. All other data are the same as for the standard bus-on-street mode.

Standard Bus on Reserved, Elevated Guideway (BGWY)

The network cost is $7,500,000 per two-way route-mile, including the costs of two stations (@ $300,000) and two network intersections (@ $250,000). The facility lifetime is thirty years. The block speed is 16 mph, and the operating cost is $13 per hour, reflecting the higher speed. The vehicle lifetime is unchanged, its being assumed that the decreased wear and tear resulting from guideway operation is compensated by the increase in yearly mileage. For all guideway modes, the cruising speed is assumed to be 20 mph.

Small Bus on Reserved, Elevated Guideway (SBGY)

Vehicle data are the same as for SBUS above, except that the operating cost is $12.50 per vehicle-hour. Network data are the same as for BGWY above.

Scheduled Small Bus on Guideway, Point-to-Point Service (SSBGY)

Off-line stations are now required, but only a one-way guideway is needed, because service is point-to-point and there is no need for passengers to transfer. The network cost per one-way route mile is $5,000,000, including the costs of two off-line stations (@ $450,000) and two network interchanges (@ $250,000). The block speed is 18 mph, raising the operating cost to $13.50 per hour. Vehicle lifetime is still ten years.

Dial-a-Bus (DAB)

All data are the same as for SBUS above, except that the vehicle operating cost is raised to $13 per hour to include an estimated DAB control cost of $1.50 per vehicle-hour. Maximum vehicle productivity in many-to-many service is fixed at 10 passengers per hour. Dial-a-Bus is considered only in the elastic-demand analyses.

Scheduled Automated Guideway Transit (AGT)

Since this mode looks like a bus service, except for the added feature of automation, it requires a two-way guideway; stations are on-line. The network cost per two-way route mile is $9,500,000, including two stations (@ $500,000) and two network interchanges (@ $500,000). Facility lifetimes are thirty years. Vehicles cost $100,000 and hold a maximum of 25 passengers. Assuming that vehicle design is based on the use of automotive technology, the lifetime is estimated at fifteen years. The block speed is 16 mph and the operating cost is set at $6 per vehicle-hour.

Scheduled PRT, Point-to-Point Service (SPRT)

One-way guideways and off-line stations result in an estimated network cost of $6,600,000 per one-way route-mile, including two off-line stations (@ $750,000) and two network intersections (@ $300,000). Vehicles cost $50,000 and carry a maximum of 6 - 10 passengers. The vehicle lifetime is fifteen years. Block speed is 18 mph and the operating cost is $4 per vehicle-hour.

Demand-Responsive PRT (PRT)

All data are the same as in the preceding paragraph. Note, however, that the elastic demand analyses to be discussed subsequently will determine the minimum necessary station size and will utilize appropriate unit costs for station bays.

PROTOTYPE MODAL COST ANALYSES FOR FIXED DEMAND

The purpose of this section is to carry out, in somewhat simplified form, a standard comparative cost analysis in which demand is assumed to be fixed and benefits are not considered. The simplicity of such an analysis makes its assumptions apparent and its results comprehensible; the impacts of specific parameters are readily discerned. Only the seven scheduled modal alternatives are included; DAB and demand-responsive PRT are not analyzed until the next section. Average hourly costs are estimated for a representative mile of network.

The analyses set forth in this section assume that all unit costs remain constant, on a relative basis, into the future, that any economies of scale are implicit to the analysis, rather than explicit, and that the installed network will continue to operate into the foreseeable future. Systematic increases in the real costs of operation and in values of time can be incorporated by manipulating the value of the capital recovery factor. The basic cost model is as follows:

Network costs:

cost/mile-hour =

(fixed cost/mile) x (capital recovery factor) x (hours of operation/year)$^{-1}$

$= C_{net}\ crf_{net}\ (hours_{net})^{-1}$

Vehicle costs:

fixed cost/mile-hour =

(fixed cost/vehicle) x (capital recovery factor) x (vehicles/network-mile) x (hours of operation/year)$^{-1}$

$= C_{veh}\ crf_{veh}\ 2(f \times \bar{t})\ (hours_{net})^{-1}$

variable cost/mile-hour =

(cost/vehicle-hour) x (frequency of service) x (travel time/mile) x 2

$= 2f\bar{t}\,C_{op}$

Travel time costs:

total value of travel time/mile-hour =

(average trip length) x (travel time per mile - 4.0 minutes/mile) x (passenger-boardings/mile-hour) x (in-vehicle value of time)

\+ (average passenger waiting time) x (passenger-boardings/mile-hour) x (out-of-vehicle value of time) x (1.0 + transfer fraction)

$= \bar{d}(\bar{t} - 4.0)\ q\ V + (k_w/f)\ q\ (2V)\ (1.0 + P_c)$

The factors of two in the equations for vehicle costs are for the case of two-way routes; they must be deleted for one-way routes. The quantity $f \times \bar{t}$ is the number of vehicles per one-way network mile, where f is the frequency of service in a single direction. The number of passenger trip origins per mile per hour, q, is a two-directional total; it represents all boardings, regardless of direction of travel. The factor $(\bar{t} - 4.0)$ represents the difference between the average travel time per mile and a standard travel time corresponding to an average speed of 15 miles per hour. The reason for this is that the 15 mph speed represents the travel time that travelers expect to invest, based on auto travel speeds, whether or not an auto is available. It has no effect on the relative costs between modes. The quantity k_w/f is the average passenger waiting time when the service frequency is f; k_w reflects the effect of schedule variability. When the schedule is regular, $k_w = 0.5$; as the variability in headways increases, k_w approaches unity. In this analysis, k_w is assumed to be independent of q, although this is not in general a necessary restriction. For point-to-point service, where only every n-th vehicle on the guideway is available to serve a particular pair of stations, the value of k_w must be multiplied by n in order to obtain the mean waiting time. The incidence of transfers between routes is reflected by P_c, the average number of transfers per trip. The value of 0.67 for P_c, in networks not having point-to-point service, is based on an approximate model of tripmaking and is in agreement with data on transfers in Boston's transit network. The value of waiting time is taken as twice the value of in-vehicle time, in accord with the results of numerous investigations of the value of time.

An important issue arises when one attempts to assign a value to V. The issue is whether V is to be based on an income-based classification of travelers in order to reflect the fact that travel time seems to be valued proportionately with income. Following this approach leads to an analysis which is biased toward investments which benefit the higher-income groups. In order to avoid this bias, a common value of time is used for all travelers. This is to be interpreted simply as a device for converting travel time to an approximate dollar equivalent. The value selected is $2.00 per hour, which is valid for work trips, but too high for non-work trips. But its use will tend to bias the analysis toward SPRT and PRT, which are the modes with the highest levels of service.

The cost equations given above can be generalized to reflect the impacts of peaking and of systematic weekly and monthly usage cycles (i.e. q and $\bar{d}$ are functions of time) and of schedule patterns (i.e. k_w, f, and $\bar{t}$ are functions of time). For purposes of illustration, these time dependencies are ignored. Setting the frequency of service f on the basis of a desired vehicle occupancy (i.e. 0.8 x no. of seats), and using the unit costs developed in the preceding section, the cost equations for the scheduled modes are obtained; the only free parameter is q. The values of all cost and operating parameters are listed in Table 1, and the resulting cost equations are listed in Table 2, and plotted in Figs. 2 and 3.

The seven cost equations in Table 2 illustrate the issues which can be addressed using this methodology, namely:

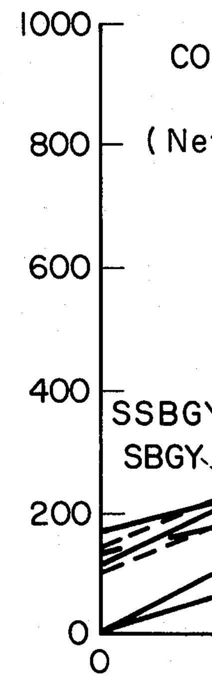
- vehicle size and load factor (large vs. small vehicles);
- vehicle utilization, which is a function of block speed (street vs. guideway; all stops vs. point-to-point);

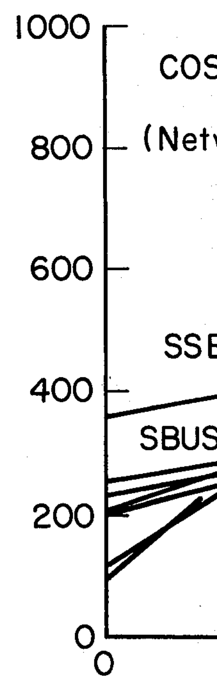
Table 1. Parameter Values for Prototype Cost Analysis of Scheduled Modes

Vehicle Guideway Service type	Bus Street All stops	Bus Guideway All stops	Small bus Street All stops	Small bus Guideway All stops	Small bus Guideway Point-to-point	AGT Guideway All stops	PRT Guideway Point-to-point
C_{net}	\$ 50,000	\$7,500,000	\$50,000	\$7,500,000	\$5,000,000	\$9,500,000	\$6,600,000
lifetime (yrs) .	10	30	10	30	30	30	30
crf_{net}	.1490	.0888	.1490	.0888	.0888	.0888	.0888
$hours_{net}$	5000	5000	5000	5000	5000	5000	5000
C_{veh}	\$ 45,000	\$ 45,000	\$30,000	\$ 30,000	\$ 30,000	\$ 100,000	\$ 50,000
lifetime (yrs) .	12	12	10	10	10	15	15
crf_{veh}	.1327	.1327	.1490	.1490	.1490	.1168	.1168
C_{op}	\$ 12.00	\$ 13.00	\$ 11.50	\$ 12.50	\$ 13.50	\$ 6.00	\$ 4.00
block speed .. (mph)	12	16	12	16	18	16	18
pax. cap'y ...	45	45	25	25	25	25	8
veh. occ'y ...	36	36	20	20	20	20	6
f	$q\bar{d}/72$	$q\bar{d}/72$	$q\bar{d}/40$	$q\bar{d}/40$	$q\bar{d}/20$	$q\bar{d}/40$	$q\bar{d}/6$
min. frequency	6	6	6	6	12	6	12
$\bar{d}$(miles)	2	2	2	2	2	2	2
k_w	.7	.5	.7	.5	.5x8	.5	.5x8
P_c	.67	.67	.67	.67	0.0	.67	0.0
V	\$ 2.00	\$ 2.00	\$ 2.00	\$ 2.00	\$2.00	\$ 2.00	\$2.00

Table 2. Cost Equations for the Prototype Cost Analysis

Mode (min. hdwy; route cap'y)	Passengers per vehicle	Cost/mile-hour = (without time costs)	 (with time costs)
1. Bus-on-street (BUS) (40 sec; 6500 pax/hr)	36	1.49 + .0610q	119.50 + .1276q
2. Small-bus-on-street (SBUS) (40 sec; 3600)	20	1.49 + .1032q	94.82 + .1698q
3. Bus-on-guideway (BGWY) (30 sec; 8600)	36	133. + .0493q	253.25 + .0326q
4. Small-bus-on-guideway (SBGY) (30 sec; 4800)	20	133. + .0837q	199.90 + .0670q
5. Small-bus-on-guideway, scheduled (SSBGY) (point-to-point) (30 sec; 4300)	20	89. + .0800q	355.50 + .0356q
6. AGT, scheduled (all stops) (AGT) (10 sec; 14400)	20	169. + .0521q	235.50 + .0354q
7. PRT, scheduled (point-to-point) (SPRT) (3 sec; 7200)	6	117. + .0957q	197.25 + .0513q





PRT
Guideway
Point-to-point

$6,600,000
30
.0888
5000

$ 50,000
15
.1168

$ 4.00
18

8
6
qd̄/6
12
2
.5x8
0.0
$2.00

me costs)

+ .1276q

+ .1698q

+ .0326q

+ .0670q

+ .0356q

+ .0354q

+ .0513q

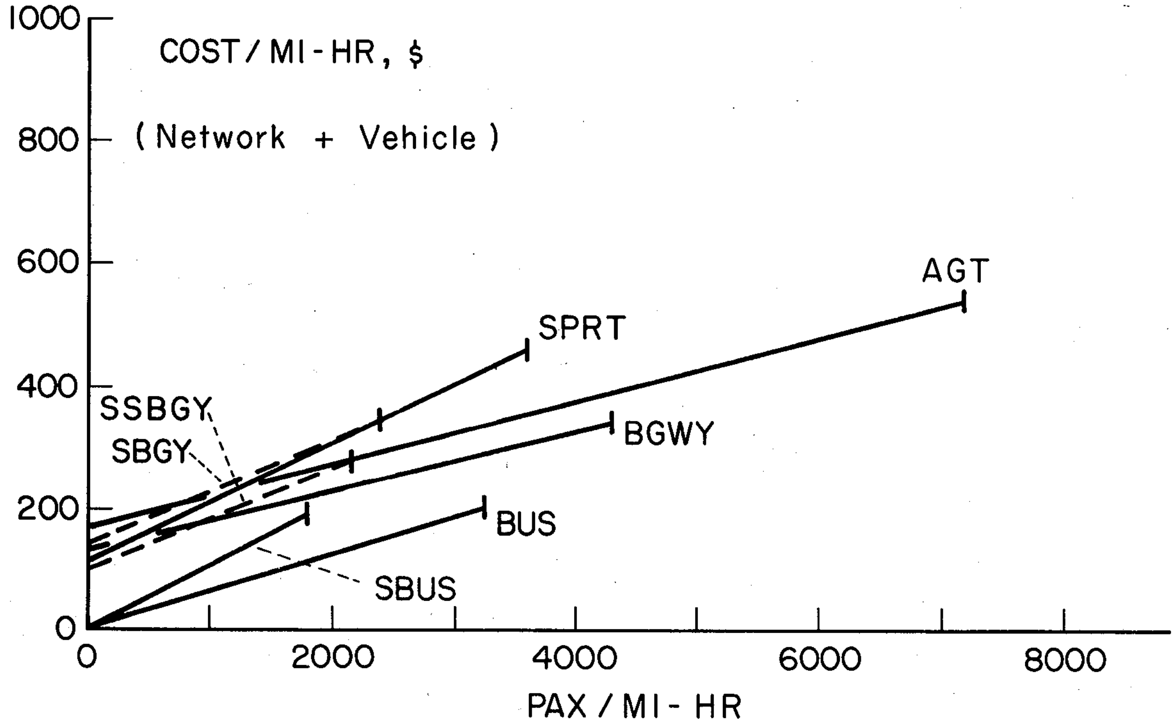


FIGURE 2

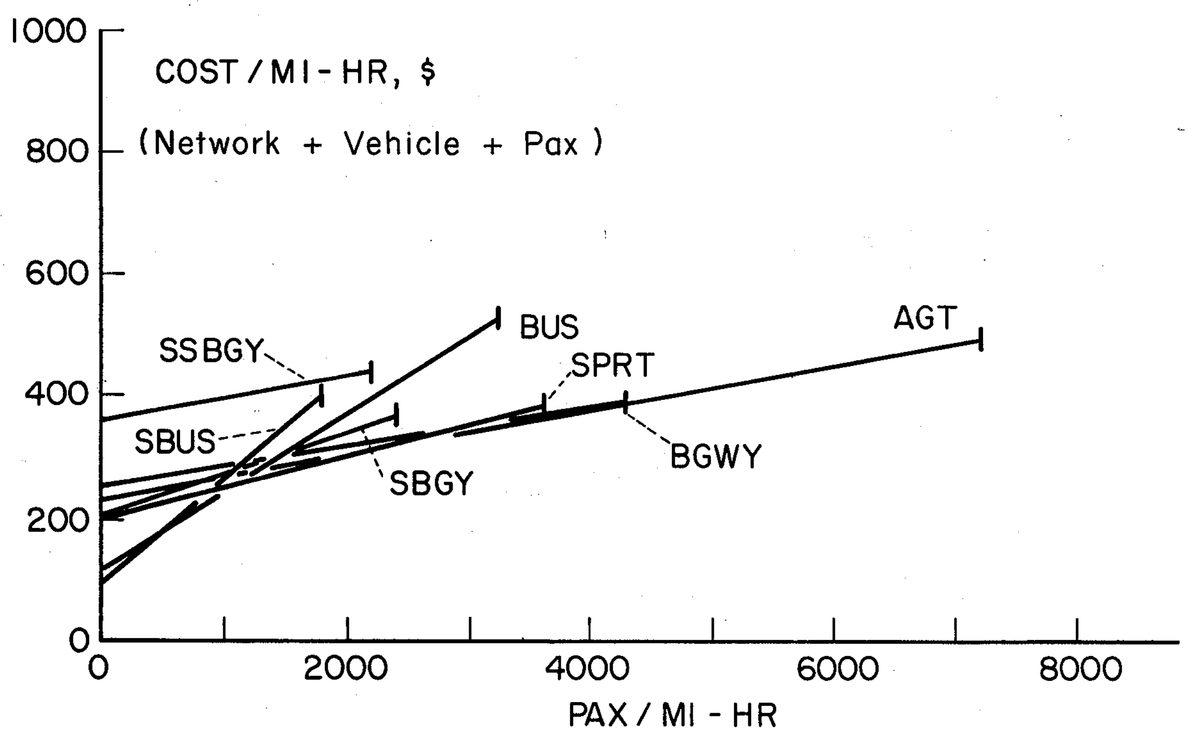


FIGURE 3

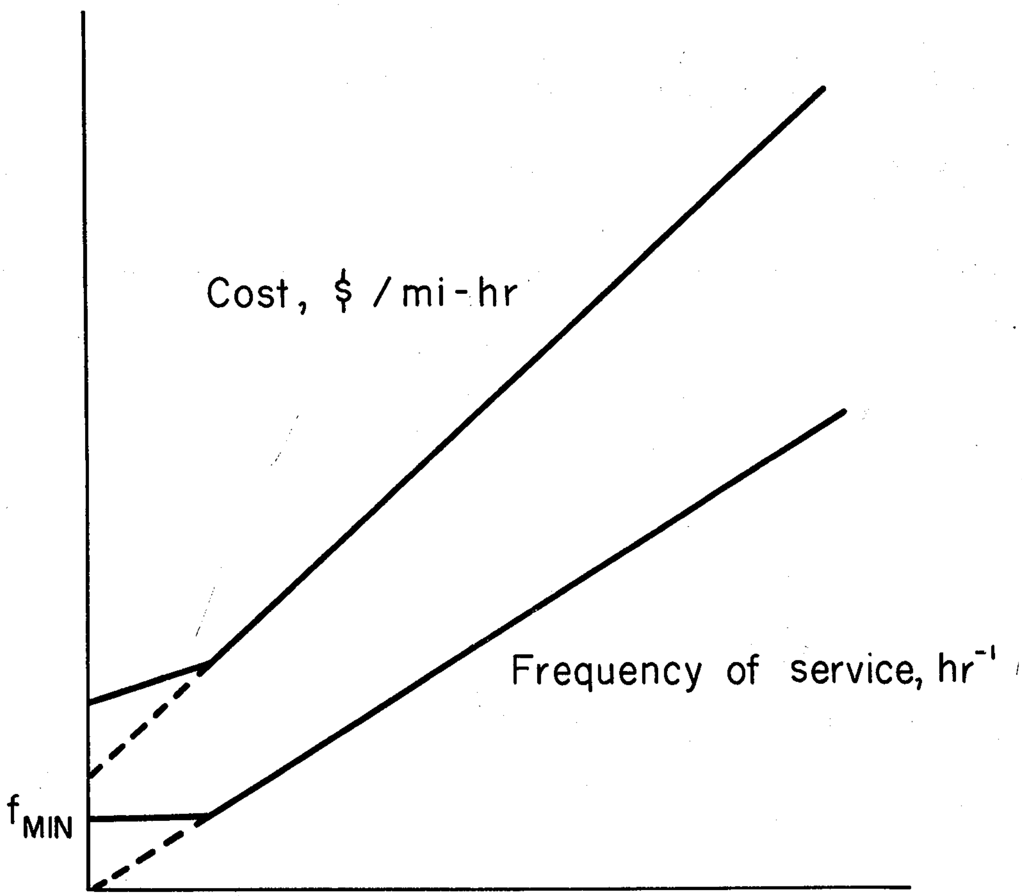


FIGURE 4

conventio
stop at
must tr
routing
transfe
value of ti

Those cost mode
ated with passeng
time show that S
as the most costl
cluded in this ana
of the SPRT cost
other slopes exce
tion. This is a r
and station costs
a vehicle. Buses
mately $1000 per
over $6000 per a
speed simply can
where the high ve
equally high prod
$0.037 per passe
ating costs per p
load factor of .8,
BGWY, and AGT
small-bus modes
.75 - .80 is assu

The cost models
expected result;
service tends to
guideway modes,
standard referen
slopes of their c
guideway modes
ever, because of
on-street modes
modes for q<110
to 2200 passenge
SPRT is the min
and BGWY being
value q = 2200.
preferred is, of
cost assumptions
time. It is also
shown by this an
high capacities,
capacity mode.
becomes the pre
all other modes
pacity. At low v
sis should impos
service (cf. Tab
tion of the resul
Fig. 4.

This analysis ha
nique for carryi
ses. The result

conventional route structure (vehicles stop at all stops and most passengers must transfer) vs. point-to-point routing (no intermediate stops, no transfers);

value of time.

Those cost models excluding the costs associated with passenger waiting time and travel time show that SPRT quickly establishes itself as the most costly of the scheduled modes included in this analysis. In addition, the slope of the SPRT cost function is greater than all other slopes except that of the SBUS cost function. This is a result, not of the fixed network and station costs, but rather of the high cost of a vehicle. Buses, for example, cost approximately $1000 per available seat; SPRT costs over $6000 per available seat, and the block speed simply cannot be increased to the point where the high vehicle cost is balanced by an equally high productivity. Furthermore, at $0.037 per passenger-mile, SPRT direct operating costs per passenger-mile, assuming a load factor of .8, are higher than those of BUS, BGWY, and AGT, although lower than the three small-bus modes. Note that a load factor of .75 - .80 is assumed.

The cost models including time costs show the expected result; SPRT's relatively high level of service tends to balance its high costs. The guideway modes, having speeds higher than the standard reference speed of 15 mph, reduce the slopes of their cost functions, while the non-guideway modes increase their slopes. However, because of their lower capital costs, the on-street modes are preferable to the guideway modes for $q<1100$. For q in the range of 1100 to 2200 passengers per hour, per route-mile, SPRT is the minimum-cost mode, with AGT and BGWY being interchangeable above the value $q = 2200$. The region in which SPRT is preferred is, of course, quite sensitive to the cost assumptions, particularly the value of time. It is also noteworthy that SPRT is not shown by this analysis to be a mode suited to high capacities, but rather a low to medium capacity mode. For q greater than 8600, AGT becomes the preferred mode by default, since all other modes would be operating above capacity. At low volumes, a more careful analysis should impose minimum frequencies of service (cf. Table 1); a schematic representation of the resulting cost function is shown in Fig. 4.

This analysis has illustrated a simplified technique for carrying out comparative cost analyses. The results presented here are meant to be illustrative and to provide a relatively uncomplicated context in which to introduce the cost elements to be included in the benefit and cost analysis to follow. The technique, while allowing only tentative conclusions to be drawn from the results of the very much simplified analysis just presented, can be improved upon without great difficulty. It can then provide a quick and inexpensive initial comparison of modal alternatives, in order to eliminate obviously inferior choices. A far more detailed analysis can then focus on the remaining alternatives.

THE ANALYSIS FRAMEWORK FOR ELASTIC DEMAND

The remainder of this paper deals with an area of uniform population density served by one of the network technologies listed previously. This section explains the demand, supply, and cost models which form the framework for analysis. As explained in the introduction, this analysis is directed to a network service which is designed to serve relatively short trips (i.e. less than 3 or 4 miles) by persons not having ready access to automobiles, principally during off-peak periods for non-work purposes. Thus, the facility is to be designed for the relatively lower levels of off-peak travel, and its costs are to be allocated to non-work travelers. Any extra investment required for adequate peak-hour service is charged to peak-hour work trips. By modeling the demand for travel in response to level-of-service variables, an equilibrium state of network flow is obtained, from which it is possible to estimate costs and benefits. Costs are computed using the same cost elements developed previously, while net benefits (consumers' surplus) are computed directly from the demand equation. Costs and benefits are both functions of the equilibrium state of network flows and travel times. The purposes of the analysis are, first, to compare alternatives within a single mode, such as route spacings and headways, and, second, to compare alternative modes. It may be of interest to note that the approach taken here was sparked by the well-known work of the Chicago Area Transportation Study on least-cost arterial and freeway spacings (25).

A Prototype Demand Model

A critical input to this analysis is the demand function. Unfortunately, there are no data from PRT networks operating in an intensive, small-area service environment. Nor, in fact, are there calibrated demand functions for existing bus networks. Furthermore, previously calibrated demand functions--when they exist--cannot simply be transferred from one mode to another, because abstract-mode representations are known to be seriously deficient. A demand function must therefore be assumed, but, in the face of significant uncertainties, it will be treated parametrically.

The demand function selected is linear in all parameters and makes use of the well known result that out-of-vehicle time (walking + waiting) is more critical to traveler decision-making than in-vehicle time and fare. This linear form has three virtues: it exhibits intuitively plausible behavior, it is simple, and it has convenient analytical properties.

The demand function is as follows:

$$T_p = F_p\, a\left(1 - \frac{Z}{2VE_{max}}\right)$$

where

- T_p = public transit trips/person-day, by purpose
- F_p = trip generation factor (trips/person-day, by purpose)
- a = a constant, the maximum fraction of daily trips which can be made by public transit
- V = in-vehicle value of time
- $2V$ = out-of-vehicle value of time
- E_{max} = excess time at which a traveler will cease using the mode (set at 40 minutes for the reported analyses)
- $\bar{d}$ = average trip length
- Z = generalized price of trip (i.e. the level of service)
  = fare + 2V (walking time + waiting time) + $V\bar{d}$ (enroute delay, relative to automobile travel @ 15 mph, per mile)

This demand equation is used to determine how many travelers use the service offered, given specific values of the frequency of service, the route spacing, the average stop spacing, and the average trip length. It is not intended to be a modal split model in an explicit sense. In particular, it is not intended to model a choice between the private auto mode and a public transit mode; this would violate the problem definition. The issue here is not whether PRT or some other transit mode can attract auto travelers to transit; rather, the issue is that of which modes are appropriate for serving non-auto users. The reason for the enroute-delay term is simply to reflect the different block speeds of different modes. The travel alternatives implicit in the demand function are those of traveling at a different time of day, when perhaps an auto or a ride is available, making the trip by foot, making fewer trips with more purposes per trip, fulfilling the need which motivated the trip in some other way, or simply not satisfying the need at all and neither traveling nor finding a substitute.

The demand function and the consumers' surplus must be dealt with by integrating them over the area served by a transit stop, since the generalized price of tripmaking is a function of the distance from a transit stop. In order to carry out this computation, it is assumed that travelers use the nearest transit stop. The details of this computation are reported in detail by Yamamoto (26). Dial-a-bus demand is far easier to compute, because of the homogeneous and ubiquitous nature of DAB service.

Stops are spaced at 1/4-mile intervals for the non-point-to-point modes, regardless of line spacing, such that stops are located at all route intersections in order to permit transfers. Point-to-point service removes the constraint that stops be located at route intersections, thereby permitting network grid spacing and stop spacing to be increased, even while maintaining the same maximum access distance to the nearest stop. Thus, PRT stops can be located at 1/2-mile intervals between network intersections; however, the computer program for this analysis was written using 1/4-mile station spacings. Network costs were thereby increased by no more than 10%, which should have little impact on the overall conclusions to be drawn from the analysis.

Despite the focus on non-work and off-peak tripmaking, the nature of peak-hour tripmaking must still be accounted for. This is done by defining a day as consisting of sixteen hours of system operation, of which four are peak hours and twelve are off-peak hours. The trip generation factor F_p is assigned values of 0.5 and 2.0 for the number of work trips and non-work trips, respectively, per person per day. Work trips average six miles in length; non-work trips average two miles in length. The work trips are divided evenly among the four peak hours, the non-work trips evenly among sixteen hours. The resulting numbers of work trips and non-work trips during the peak hour are equal, although the longer lengths of work-trips mean that there are three times as many work travelers per vehicle as there are non-work travelers. During peak hours, the consumers' surplus calculations are designed to account only for the benefits to non-work travelers. The total benefits for an entire day can thus be computed for non-work trips.

Supply Models

This section describes how vehicle requirements are determined for the different modes. The various modes fall into three categories, each of which has a different supply model. The unit of analysis is one square mile of an urban area served by the mode in question. Modal cost data conform closely to Table 1. The major differences are that C_{net} fo bus and small-bus-on-street was set to zero, and there are 4800, not 5000 hours of network operation per year.

Fixed-Route, Scheduled Transit Model

As a first cut, vehicle requirements are estimated from the route spacing and the scheduled headways, independently of the as yet unknown patronage. The model assumes:

1. All routes are evenly spaced, forming a square-grid network.
2. Headways on all routes are identical.

In light traffic and/or on automated guideways, the mean waiting time is normally half of the headway (assumed to be fixed). In congested traffic, however, the variance of the headway increases to the point where the mean waiting time becomes approximately equal to the mean headway. Thus, specifying the headway, H, for a particular route also specifies the mean waiting time for passengers and, with the block speed v, the number of vehicles needed per route-mile, the latter being 1/(Hv). If the route spacing is Y miles, there are 2/Y two-way route-miles per square mile, or 4/Y one-way route-miles, resulting in a total of 4/(HvY) vehicles per square mile. Note that independence of H and patronage allows a direct calculation of the resulting demand.

PRT Model

Unlike the fixed-route, scheduled transit model, the demand responsive nature of PRT requires an iterative process to determine, simultaneously, vehicle requirements, level of service, and patronage. To be determined are: the average passenger waiting time in a station; the average time for a vehicle to wait for an available route (a slot reservation scheme is assumed to be the network operating strategy); the demand; and the number of vehicles per square mile. The results are derived by specifying a value of the ratio of loaded vehicles to total vehicles, this ratio remaining fixed during the iterative process. Empirical relationships for estimating average passenger waiting times in stations, and average waiting times for available routes were derived from results reported by Sirbu (27).

Dial-a-Bus

Like PRT, the level of service of a dial-a-bus system depends on its patronage. Thus, it too requires an iterative procedure in order to calculate, simultaneously, vehicle requirements, level of service, and patronage. To be determined are: the average waiting time for service; the average travel time per mile; the number of vehicles per square mile; and the demand. The results are derived by specifying a value of vehicle productivity, which remains fixed during the iterative process. Empirical relationships for average waiting times and travel times were derived from a designed experiment consisting of a number of runs of a Dial-a-Bus simulation program developed at the Massachusetts Institute of Technology.

Cost Models

This section describes how costs are calculated for the different modes, and how the appropriate portion of the total cost is allocated to non-work trips.

Fixed-Route, Scheduled Transit Costs

The following network elements are accounted for in the computations for fixed costs: guideways, interchanges, and stations. These costs are allocated equally over all trips, work and non-work, so that the non-work capital burden is determined simply by multiplying the total capital cost by the ratio of non-work trips to total trips. We note that there are many ways in which the work trip vs. non-work trip allocation could be specified; the selected procedure is simple, and probably as arbitrary as any other.

Capital costs and all operating costs (peak and off-peak) for the basic vehicle fleet required for off-peak service are charged to non-work travelers. Capital and operating costs for the added vehicles needed for peak-hour service are charged to work trips.

PRT Costs

With the exception of station costs, the PRT cost model is the same as the fixed-route, scheduled transit cost model. The non-work-trip share of capital costs for stations is determined by the station sizes required for

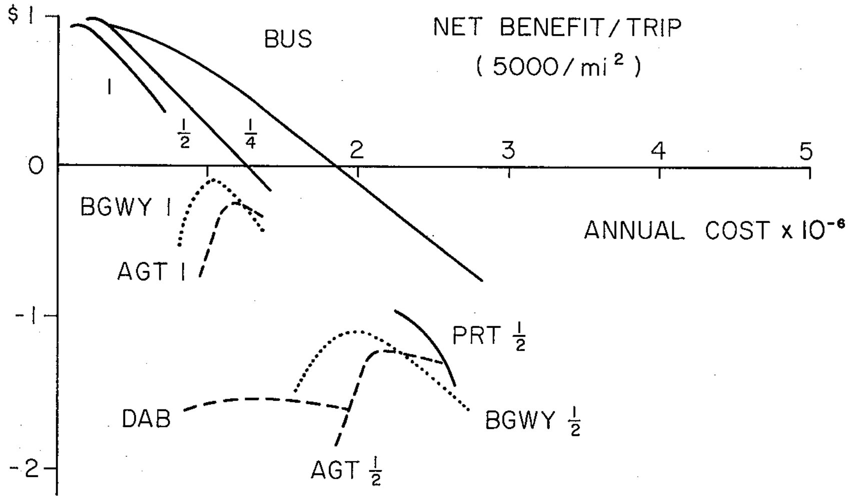


FIGURE 5

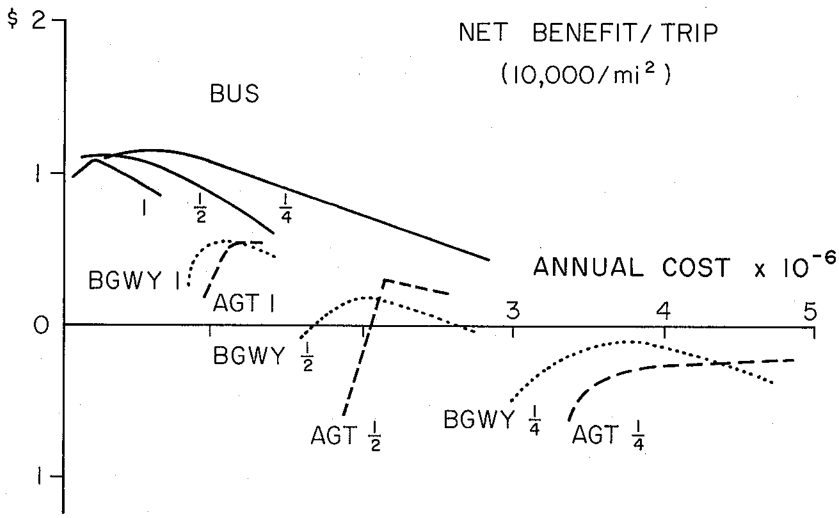


FIGURE 6

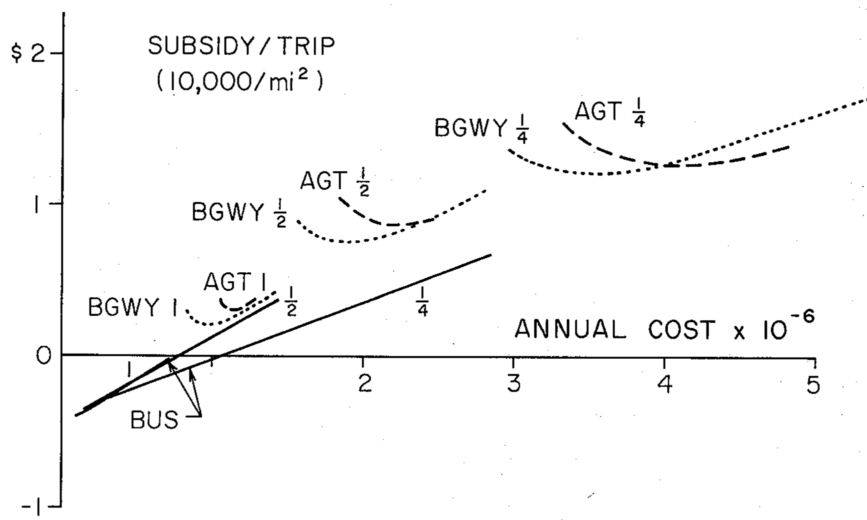


FIGURE 7

off-peak service c
tion costs require
allocated wholly t
cating all network

Dial-a-Bus Costs

Dial-a-bus costs
ly from either bus
posed dial-a-bus
subscription serv
peak hours. In th
vehicles can serv
hours, provided t
ly. It will be ass
same vehicle flee
peak hours, and t
gers is restricted
work passengers
slack during the v
capital cost of veh
the same ratio as
daily passengers.
vehicles is determ
while the peak-ho
the number of DA
productivity, set

Vehicle operating
trips are the sum
pro-rated share c
analysis assumes
gers serviced in t
for non-work purp

The cost model ac
and their equipme
digital dispatching
are charged to off
cause the peak-ho
not make significa

MODAL COST AN
ELASTIC DEMAN

Modal compariso
values of populati
and 20000 peopl
were used: bus o
way (BGWY), sma
a-bus (DAB), sch
vehicles (AGT), a
comparisons are
average requi
average net be
(= av. cons
annual consum
average weekd

The results are p
modes for given l

off-peak service only. That is, the added station costs required for peak-hour work trips are allocated wholly to work trips, rather than allocating all network costs among all users equally.

Dial-a-Bus Costs

Dial-a-bus costs are handled somewhat differently from either bus or PRT. In existing and proposed dial-a-bus systems, a higher-productivity subscription service is usually offered in the peak hours. In this way the same number of vehicles can serve more passengers in the peak hours, provided that demand is served selectively. It will be assumed in this analysis that the same vehicle fleet operates in both peak and off-peak hours, and that service to non-work passengers is restricted during the peak hours, non-work passengers being slipped into any available slack during the vehicle tour. Therefore, the capital cost of vehicles must be apportioned in the same ratio as that of non-work trips to total daily passengers. That is, the number of DAB vehicles is determined by the off-peak patronage, while the peak-hour patronage is determined by the number of DAB vehicles and their peak-hour productivity, set at 16 trips per vehicle hour.

Vehicle operating costs allocated to non-work trips are the sum of all off-peak costs plus a pro-rated share of the peak-hour costs. This analysis assumes that one-eighth of the passengers serviced in the peak hours are traveling for non-work purposes.

The cost model accounts for telephone operators and their equipment, a control computer, and digital dispatching equipment. All of these costs are charged to off-peak, non-work trips, because the peak-hour subscription service does not make significant use of this equipment.

MODAL COST AND BENEFIT ANALYSES FOR ELASTIC DEMAND

Modal comparisons were carried out for four values of population density: 1000, 5000, 10000, and 20000 people per square mile. Six modes were used: bus on street (BUS), bus on guideway (BGWY), small bus on street (SBUS), dial-a-bus (DAB), scheduled 25-passenger automated vehicles (AGT), and PRT (PRT). The modal comparisons are based on the four criteria of:

average required subsidy, per passenger;
average net benefit, per passenger
(= av. consumers' surplus - av. total cost);
annual consumers' surplus; and
average weekday passengers.

The results are presented so as to compare modes for given levels of total annual costs, including all capital costs and all operating costs. It is thus possible to choose the mode that maximizes benefits, or passengers carried, or minimizes subsidy, given a fixed level of cost. For all runs reported, unless indicated otherwise, V = \$2.00/hour, E_{max} = 40 minutes, and a = .5. Only five modal-comparison summaries are presented; cf. Figs. 5 - 9. The major results, however, are outlined below for each of the four population densities. The integer or fraction which labels the curves in these figures is the route or guideway spacing, in miles. The curves themselves are generated by varying the headway and/or fleet size. See Yamamoto (26) for a more detailed discussion of the modal comparisons. Note that PRT appears only in Fig. 5; in Figs. 6 - 9 it is off the graph, because its costs were very high and its net benefits were negative. All fares were \$0.50.

Population Density = 1000 Persons per Square Mile

A. It is difficult to justify any transit system for such a low population density since costs generally exceed benefits.
B. For an annual investment of over \$200,000, dial-a-bus appears to provide more cost-effective service than scheduled bus. For smaller investments than this, a less sophisticated dial-a-bus control system would be required, which was not explicitly modeled in this analysis.
C. For any smaller investment, a scheduled, fixed-route bus with route spacings greater than 1/2 mile and headways longer than 6 minutes appears to be optimal.
D. Small-bus-on-street provides more economical service than BUS, but with the same benefits, since the two modes are running the same schedule, so long as the vehicle capacity of SBUS is not exceeded.

Population Density = 5000 Persons per Square Mile (Fig. 5)

A. BUS is the optimal mode with respect to costs and benefits.
   1. A 1/2-mile route spacing is the optimum with respect to average net benefits.
   2. A 1/4-mile route spacing is the optimum if the value of the total net benefits is used as a criterion.
   3. BUS is the only mode to show a positive average net benefit at this population density.
   4. As investment in a BUS network increases, it is more cost-effective to

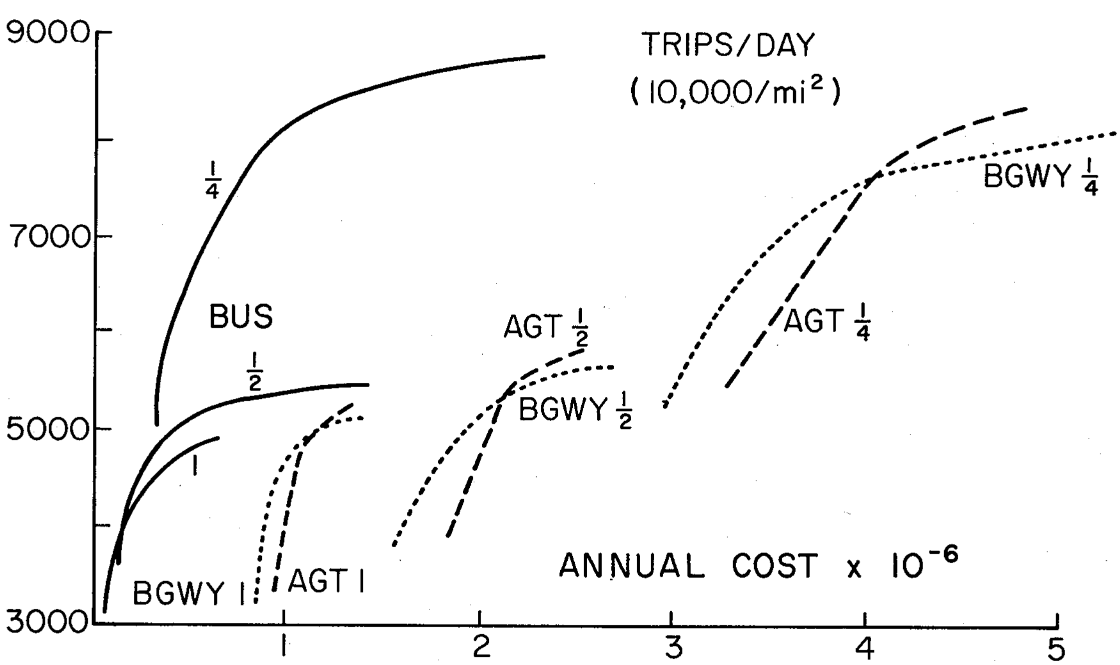


FIGURE 8

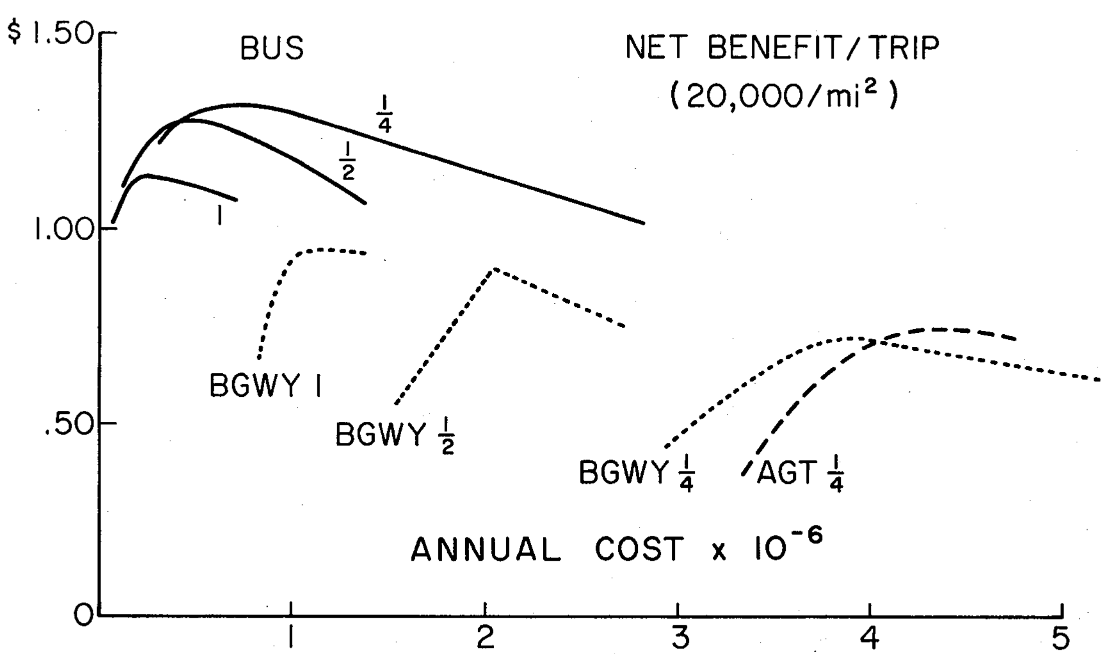


FIGURE 9

decrease
decrease
B. Dial-a-bus an
nated by BUS
1. Dial-a-bu
ty, resul
hicles fo
increasin
ger.
2. The high
sults in h
not enoug
to warra
3. Bus-on-g
cost-effe
C. SBUS provide
than BUS, bu
peak hours.
ered at highe

Population Densit
Square Mile (Figs

A. BUS is again
1. BUS show
ment les
mile, pe
2. A 1/4-mi
both aver
B. BGWY and AG
benefits for o
spacing. AG
similar, with
effective at lo
C. PRT is capac
periods. (Th
seconds.) PI
lower benefit
D. BGWY and AG
consumers' s
except that B
higher speeds
The higher sp
for short trip
sumers' surp
capital expen

Population Densit
Square Mile (Fig.

A. BUS, AGT, a
net benefits a
20,000.
B. BUS dominate
C. AGT is capac
hours for all
D. PRT's benefit
its costs are

decrease route spacing than it is to decrease headways.

B. Dial-a-bus and guideway systems are dominated by BUS and have no net benefits.
   1. Dial-a-bus operates at a low productivity, resulting in a large number of vehicles for each square mile, thereby increasing operating costs per passenger.
   2. The high fixed cost for guideways results in high average costs. There is not enough patronage per square mile to warrant a guideway network.
   3. Bus-on-guideway and AGT provide more cost-effective service than PRT.

C. SBUS provides more economical service than BUS, but is capacity constrained during peak hours. It will therefore not be considered at higher population densities.

Population Density = 10,000 Persons per Square Mile (Figs. 6 - 8)

A. BUS is again the preferred mode.
   1. BUS shows a profit at levels of investment less than $1,000,000 per square mile, per year.
   2. A 1/4-mile route spacing maximizes both average and total net benefits.

B. BGWY and AGT have positive average net benefits for one-half and one-mile guideway spacing. AGT and BGWY appear to be very similar, with AGT proving to be more cost-effective at lower headways.

C. PRT is capacity-constrained during peak periods. (The minimum headway is 3 seconds.) PRT still has higher costs and lower benefits than BGWY or AGT.

D. BGWY and AGT provide about the same consumers' surplus as a BUS system, except that BUS is a little lower due to the higher speeds of the guideway vehicles. The higher speeds do not have a large effect for short trips. The small addition to consumers' surplus is achieved with a large capital expenditure for the guideways.

Population Density = 20,000 Persons per Square Mile (Fig. 9)

A. BUS, AGT, and BGWY all show positive net benefits at a population density of 20,000.

B. BUS dominates BGWY and AGT.

C. AGT is capacity-constrained during peak hours for all spacings greater than 1/4 mile.

D. PRT's benefits are lower than BUS, while its costs are far higher.

SUMMARY AND CONCLUSIONS

The purpose of this work has been to estimate the first-order costs and benefits of a number of alternative urban public transport technology and service combinations. The focus of this benefit and cost analysis has been on an evaluation of PRT in comparison with other alternatives, including medium-sized-vehicle automated networks operating in a scheduled mode. In order to provide a problem-oriented context for this evaluation, considerable thought was given to the selection of a specific aspect of "The urban transportation problem". The problem selected was that of non-work tripmaking by individuals to whom automobile travel was not a readily available option, principally during the off-peak periods of the day. This aspect of urban transportation problems was chosen, first, because it is a serious and widespread problem, particularly in low-income areas of cities; second, because the dispersed pattern of origins and destinations is the kind of travel pattern that an area-wide, responsively operated network, like PRT, is designed to serve; and, third, because it is felt by the authors that rush-hour problems have received more than adequate attention and are very likely over-rated.

The costs encompassed by the analysis include all costs -- exclusive of acquiring the right-of-way -- of providing the fixed network and the vehicles which operate on it, regardless of which segment of society bears those costs. The costs also include the value of travelers' journey times, accounting for all out-of-vehicle times and for all in-vehicle journey time in excess of a standard reference in-vehicle speed of fifteen miles per hour. A paradigmatic cost analysis for fixed demand has been presented in order to highlight the specific cost components which are responsible for modal cost differences. A second analysis, based on supply-demand equilibrium, was carried out as the primary means of comparing and evaluating alternative modes, and net benefits were computed on the basis of the consumers' surplus concept.

The major assumptions of the analysis are now summarized. The area served by the transit network is of uniform population density. It is assumed that a network of elevated guideways can be constructed without destroying the area which is to be served. Weekday non-work trips are uniformly distributed over a sixteen-hour period, including the four hours contained within the morning and afternoon weekday peak periods. Work trips are uniformly over the four peak hours and are a function of the number of non-work trips. The assumed demand function is linear in form and is formulated in terms of a generalized price, which includes the effects of fare, walking time, waiting time, and enroute delay. The value of time for all travelers is set at $2.00 per hour; it is set at a fixed value, independent of income, in order to avoid potential biases in the consumers' surplus calculations. The supply models for the various modes have been derived from a combination of theory and experiment, the experiments being primarily Monte Carlo simulations of dial-a-bus and PRT. The cost figures are based on the best current available information on costs. In particular, PRT costs are not based on an assumed mass production output of hundreds of thousands of units per year. Thus, they reflect the current situation facing planners and politicians, that of being one of the first few cities to adopt PRT or AGT. Costs and benefits are displayed only for non-work travelers; costs and benefits accruing to work trips are deducted from the total cost and benefit values. That is, it is assumed that the network is designed to service non-work trips and is sized accordingly. The cost calculations therefore do not reflect any incremental investments in the network and in the vehicle fleet, which are needed solely to service peak-hour work trips.

The results of the analyses for fixed demand and for elastic demand are consistent: PRT is a relatively costly mode and is outperformed by other modes, notably bus-on-street, bus-on-guideway, and AGT, depending on the patronage level. It would thus appear that, at the present state of PRT technology and hardware costs, PRT offers little or no economic incentive for adoption to serve off-peak and non-work urban trips. If this conclusion has merit, PRT must be selected on non-economic grounds, unless costs--particularly vehicle capital and operating costs--show significant decreases from their present levels. Even non-economic reasons for adopting PRT to serve the travel needs of transit dependent groups may be difficult to find, however. Aside from the technological uncertainties associated with its being a new technology, PRT is often burdened with the stigma of being located on an elevated right-of-way. This presents real problems of compatibility with existing structures, streets, and activity patterns. Furthermore, as pointed out in a paper presented at the first National Conference on Personal Rapid Transit (28), it is unlikely that a PRT network will be able to provide the kind of door-to-door transportation service that is presently sorely lacking in many low-income areas of cities.

The conclusions of the analyses presented here should not be extrapolated beyond the context of the selected problem definition and the many assumptions needed to carry out the analyses. That is, despite these unencouraging results, there do appear to be applications for which PRT and/or AGT are well suited, particularly as internal circulation systems for airports and other activity centers. The principal conclusion to be drawn from the present analysis is that PRT costs must show significant decreases if PRT is to be a serious area-wide transit alternative for those portions of urban areas showing low levels of auto ownership. There is clearly a need for further problem-oriented analyses, which define specific groups of travelers to be served and carry out careful evaluations of service and modal alternatives. Beyond that, the broader issue of public resource allocation must be faced; that is, even if the net benefits from large transportation investments are expected to be positive, there still remains the question of determining the conditions under which transportation is to be favored over other public sectors, such as education, housing, welfare, water and sewer services, administration, and police and fire protection.

ACKNOWLEDGMENT

This work was supported in part by the Urban Mass Transportation Administration, U.S. Department of Transportation, under Grant URT-9, as provided for in Section 11 of the Urban Mass Transportation Act of 1964 as amended, and was directed at M.I.T. by Mr. H. W. Bruck. The responsibility for the opinions and conclusions expressed herein lies solely with the authors.

R

1. R. deNeufville
Analysis for
McGraw-Hi

2. T.B. Deen an
of Bus and
Highway Re
Highway Re
D.C., 1969

3. D.R. Miller,
of Rapid Bu
presented a
the Highway
D.C., Janu

4. A.J. Soolman
mode Public
Manchester
lished Mast
ment of Civ
August, 197

5. "Project MET
tionary Tra
Areas", M.
report of th
project in s
Spring Ter

6. Manchester R
"Study of R
Concepts",
and Partner
O'Heocha a

7. "Systems Ana
tion", Gene
Santa Barba
(PB 178 26

8. E.T. Canty,
plementatio
Research I
gan, Febru

9. C. Henderson
Transporta
Evaluations
Research I
fornia, Ma

10. Royal Aircra
"Cabrack S
taxi Urban
Transport
Farnboroug
68287, Par

f-way. This
npatibility with
and activity
pointed out in a
ational Conference
), it is unlikely
le to provide the
tation service that
many low-income

es presented here
yond the context of
n and the many
out the analyses.
uraging results,
ions for which
ted, particularly
ns for airports
The principal con-
present analysis
significant de-
ious area-wide
portions of urban
uto ownership.
urther problem-
ne specific groups
carry out careful
odal alternatives.
ue of public re-
ed; that is, even
transportation
be positive, there
determining the
portation is to be
ctors, such as edu-
ater and sewer ser-
olice and fire pro-

ENT

part by the Urban
istration, U.S.
on, under Grant
ection 11 of the
Act of 1964 as
at M.I.T. by Mr.
ibility for the opin-
sed herein lies

REFERENCES

1. R. deNeufville and J.H. Stafford, Systems Analysis for Engineers and Managers, McGraw-Hill, New York, 1971.

2. T.B. Deen and D.H. James, "Relative Costs of Bus and Rail Transit Systems", Highway Research Record Number 293, Highway Research Board, Washington, D.C., 1969.

3. D.R. Miller, et. al., "A Cost Comparison of Rapid Busways and Rapid Transit", presented at the 52nd Annual Meeting of the Highway Research Board, Washington, D.C., January 22-26, 1973.

4. A.J. Soolman, "An Analysis of a Multi-mode Public Transportation System for Manchester, New Hampshire", unpublished Master of Science thesis, Department of Civil Engineering, M.I.T., August, 1970.

5. "Project METRAN - An Integrated Evolutionary Transportation System for Urban Areas", M.I.T. Report No. 8 (Formal report of the interdepartmental student project in systems engineering at M.I.T. Spring Term, 1966), M.I.T. Press.

6. Manchester Rapid Transit Study, Vol. 2: "Study of Rapid Transit Systems and Concepts", prepared by: DeLeuw, Cather and Partners - Hennessey, Chadwick, O'Heocha and Partners, August, 1967.

7. "Systems Analysis of Urban Transportation", General Research Corporation, Santa Barbara, California, January, 1968 (PB 178 261).

8. E.T. Canty, et. al., "New Systems Implementation Study", General Motors Research Laboratories, Warren, Michigan, February, 1968 (PB 178 273).

9. C. Henderson, et. al., "Future Urban Transportation Systems: Descriptions, Evaluations, and Programs", Stanford Research Institute, Menlo Park, California, March, 1968 (PB 178 265).

10. Royal Aircraft Establishment (RAE), "Cabrack Studies: Assessment of Autotaxi Urban Transport Systems", Urban Transport Technology Group, RAE, Farnborough, Technical Report No. 68287, Parts 1 and 2, 1969.

11. B.M. Ford, et. al., "Parametric Analysis of Generic Urban Transit Systems", Transportation Programs Report, TPR 001, Applied Physics Laboratory, Silver Spring, Maryland, December, 1969 (PB 188 984).

12. A.J. Sobey and J.W. Cone, "The Case for Personal Rapid Transit", Highway Research Record Number 367, Highway Research Board, Washington, D.C., 1971.

13. D. Brand, "Dual Mode Transportation Systems: Analysis of Demands and Benefits in Urban Areas; and Development of Performance Requirements", Urban Systems Laboratory, Massachusetts Institute of Technology, June, 1970.

14. George Kovatch and George Zames, "Personalized Rapid Transit Systems: A First Analysis", Report No. DOT-TSC-OST-71-11, Transportation Systems Center, Cambridge, Massachusetts, August 1, 1971.

15. N.D. Lea and D.D. Scrafton, "Programmed Module Urban Transport Systems",
16. A.J. Sobey, "Economic Considerations of Personal Rapid Transit",
17. L.R. Bush, "The Economics of High Capacity PRT Systems",
18. R.C. Rand, "Fiscal Policy for Urban Transportation", the above four papers appearing in Personal Rapid Transit, J.E. Anderson, et. al., editors, University of Minnesota, 1972.

19. M.B. Godfrey and Jacob Kolnick, "A Comparison of Automated Guideways and Rail Transit for Tel-Aviv", invited paper presented at the SAE National Meeting, January, 1972.

20. "An Economic Analysis of the Personal Rapid Transit Application at Morgantown, West Virginia", executive summary, The Boeing Company, Seattle, Washington, Revision 4, February, 1972.

21. "Draft Final Report: Development of Vehicle Performance Specifications, Phase III-A-2 of Twin Cities Transportation Planning Program", prepared for the Twin Cities Area Metropolitan Transit Commission by Daniel, Mann, Johnson, & Mendenhall, November 8, 1972.

22. J.L. Dais and A.L. Kornhauser, "Economic, Environmental, and Design Aspects of Large Scale PRT Networks", presented at the 52nd Annual Meeting of the Highway Research Board, Washington, D.C., January 22-26, 1973.

23. "Demand-Actuated Transportation Systems", Special Report 124, Highway Research Board, Washington, D.C., 1971.

24. "Demand-Responsive Transportation Systems", Special Report 136, Highway Research Board, Washington, D.C., 1973.

25. R.L. Creighton, et. al., "Estimating Efficient Spacing for Arterials and Expressways", Highway Research Board Bulletin 253, Highway Research Board, Washington, D.C., 1960.

26. W.M. Yamamoto, "A Comparative Analysis of Transit Alternatives for Non-Work Trips", unpublished Master of Science thesis, Department of Civil Engineering, M.I.T., June, 1973.

27. M.A. Sirbu, Jr., "Station Throughput in Personal Rapid Transit Systems", in this volume.

28. M.B. Godfrey, "Urban Transportation Problems and Automated Transportation Systems", paper presented at the National Conference on Personal Rapid Transit, Minneapolis, November 1-3, 1971.