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OVER THE PAST 75 YEARS vehicles powered by the internal combustion engine have developed to become the dominant forms of urban transportation throughout the world. The engine's small size and packaged fuel supply has permitted its application to personal-sized privately-owned vehicles that provide unparalleled mobility in terms of on-demand service 24-hours a day at potentially high speed between most origins and destinations. The most successful of these vehicles, the automobile, has also introduced numerous social and environmental disadvantages to the urban environment. Among them are: a demand for more land, highways and parking; air and noise pollution; deaths and injuries; and a dominant consumer of limited petroleum reserves.[1-4] Perhaps more significant in most American cities is that the overwhelming success of the automobile has caused the near complete elimination of public urban transportation. Because large segments of the urban society does not have access to automobile transportation, especially the poor and the old, a large division in mobility has resulted.

In an attempt to develop a public transit system that would provide auto-like services to all segments of the urban population, considerable effort in the United States, Japan, and Europe has been focused on the development of Personal Rapid Transit (PRT). PRT is a new class of fixed-guideway transit consisting of small (2-6 passenger) automatically-controlled vehicles that operate at short headways. Off-line stations on an interconnected network provide non-stop origin to destination service. In area-wide applications auto-like vehicles operating on an exclusive guideway network interconnecting many closely-spaced stations would provide auto-like origin to destination service to potentially a much larger segment of urban residents than is presently being served by the automobile. Present controversies on the viability of PRT are focused on three fundamental issues: economics, system capacities and demand forecasting. This paper reviews reported hardware development, the state of planning software for PRT, and some area-wide PRT applications and presents a simplified analysis of a "break-even" design of PRT area-wide network.

STATE OF PRT DEVELOPMENT

PRT has been reinvented numerous times. Present planning fundamentals for PRT were formulated in the so-called HUD studies of 1968[2] and England's Royal Aircraft Establishment's Cabtrack study.[7] The first comprehensive exchange of information occurred at the First International Conference on PRT held in Minneapolis, Minnesota, November 1971. The book, **Personal Rapid Transit**,[8] is a widely distributed collection of the papers presented at that conference. A second conference was held in May 1973, and other transportation conferences are devoting more of their programs to PRT. Present hardware developments had origins with Mr. William Alden developer of the Alden StaRRcar, a research group at General Motors which has developed into the Transportation Technology Inc./Otis system and a group at Varo Inc. that developed into the Rhor/Monocab system. First (and at present only) implementation of a PRT-type system is the Alden-Bendix-Boeing system at Morgantown, West Virginia;[9] however, a demonstration and six month testing of two large-vehicle and two small-vehicle PRT systems was held in conjunction with Transpo '72 in Washington, D.C., June 1972.[10]

Fundamental hardware requirements for area-wide application of PRT are:

(1) Fast-acting on-board switching mechanism. This permits headway to be independent of the switching function and makes feasible network and off-line station operation.

(2) A small (2-6 passenger) vehicle that does not allow standees. This provides personalized service by high performance vehicles operating on smaller, cheaper, and more easily constructed guideways than is possible with larger vehicles.

(3) Safe and reliable operation at headways that satisfy capacity and economic constraints.

At present a number of manufacturers have perfected the switching mechanism on small vehicles, e.g. TTI and Monocab, but the short-headway operation has not been demonstrated. The shortest headway yet demonstrated was 8 seconds by Ford and Rhor/Monocab.[10] An order of magnitude reduction in headway is considered necessary for area-wide application. This is a severe technological challenge in that it requires the violation of the classical minimum safe-headway constraint.[3] At present Germany,[14] Japan,[15] and Switzerland,[16] are developing short-headway PRT hardware and the U.S. Department of Transportation/Urban Mass Transportation Administration is organizing a research and development program in short-headway PRT.[17]

Planning. Planning methodology for area-wide PRT is in its infancy. PRT's network capability requires a 2-dimensional area-wide transit planning concept rather than a 1-dimensional corridor concept that dominate present transit and highway planning processes.

Assessing Area-Wide Personal Rapid Transit

by

*Alain L. Kornhauser**
*Jack L. Dais***

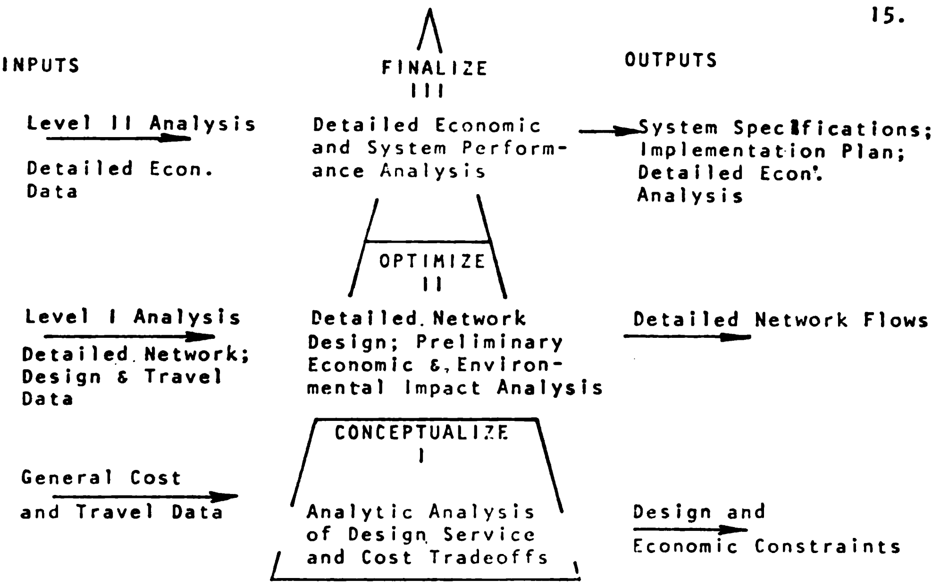

Figure 1. Stratified Planning Methodology

The large number of possible guideway and station locations possible with PRT and, at best, a very vague definition of optimality in network design make it imperative for both the planner and the policy maker that various levels of design exist. These levels should be structured from the very simple analytic system-model that provides fundamental concepts on the relation between cost and service variables, to detailed simulation of network operation, as is depicted in Figure 1. The number of discrete levels is debatable but the lowest level should require only "back-of-the-envelope" calculation and provide "quick-and-duty" estimates for large variations in the values of the parameters. The last analysis requires an extensive computer facility manipulating a detailed data base. The large computational cost associated with the final analysis limits its versatility and permits only small adjustments in network design parameters. The purpose of the intervening levels is to sequentially refine and improve the network design parameter to be used by the next higher level of analysis. Interest is often focused on the top level; however, the bottom level is as important because it provides intuition that assists in the comprehension of the results of the higher levels.

The authors have developed computer software for the two lowest levels of analysis[18, 19] and York[20] and Wade[21] have developed detailed network simulations of passenger/vehicular flows that would be a small part of a level III analysis (a detailed economic and performance analysis that would yield detailed design and cost specifications has

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not been developed). Further efforts to improve on the level I analysis are presented in Section III.

Implementation. Actual implementation of small-vehicle PRT an urban setting has yet to be realized, although the Morgantown project represents a giant step by demonstrating wholly automatic control of a fleet of medium-size vehicles having on-board switching capabilities and a guideway having off-line stations. Minimum headway is 15 seconds at 30 mph. A potentially significant step in the implementation process of small-vehicle PRT could result if the Rohr/Monocab system is chosen for implementation in Las Vegas, Nevada. At one time it was widely suspected that Denver, Colorado would be awarded a grant that would be the first step in an area-wide implementation of small-vehicle PRT; however, at present the recommendation for implementation is expected to be for a medium-sized ($\cong$ 20 passenger) vehicle system,[22] rather than an auto-sized vehicle system.

PHASE I—DESIGN ANALYSIS

A simple parametric analysis,[18] of basic PRT design and cost variable recently appeared in the **Highway Research Record No. 427.** The analysis idealizes the network and service area so that computations can be performed on a per unit area (density) basis. The results, presented in parametric form, are convenient for preliminary network design, costs, and patronage estimates. The analysis is weakened by the inclusion of a modal split model that, a.) masks some fundamental relationships between network capacity and cost, and b.) is highly sensitive to small variations in the value of assumed parameters (perceived auto costs). The theoretical basis for modal split models is microeconomic disutility theory; however, a quantitative comparison of travel modes is extremely difficult because some utilities such as comfort are essentially unquantifiable and the weighting matrix that attempts to convert various attributes into a single utility is, at best, unreliable. Experience and models based on a comparison of conventional transit with the automobile are of little value because of the vast difference in service offered by PRT as compared to conventional transit. Claims that PRT has the potential to attract a large percentage of all urban trips can be substantiated by the continued success of transit in areas where the automobile is not superior to transit, e.g. New York City, and by the Dial-a-Ride experience.

Capacity - Constrained, "Break-Even" Analysis. What follows is a Level I analysis of area-wide PRT based on the idealized-city model. The idealized-city model normalized the network to a per unit area basis and presents feasible values for network design parameters given averaged data on trip making characteristics for that unit area. For a "city" having uniform travel demand the ideal network would be a square grid of oneway lines with stations located at mid-points between interchanges.[7] An appropriate unit size for consideration should be as small as possible but larger than the line spacing squared—say a square mile or square kilometer.

For such networks, the one-way guideway route mile, M; the number of stations, N_s; and the number of interchanges, N_I; per unit area are given as follows in terms of line spacing, L:

$$M = 2/L;\ N_s = 2/L^2;\ N = 1/L^2 \qquad (1)$$

Because stations and interchanges require switches and acceleration/deceleration lanes, the actual guideway mileage required is substantially more than the route mileage. A good approximation to the additional length of guideway required per unit area for stations and interchanges can be obtained from Reference 23 to be $0.6/L^2$,[4] giving a total one-way guideway requirement per unit area, N_g, of

$$N_g = 2/L + 0.6/L^2 \qquad (2)$$

The theoretical minimum guideway capacity requirement, C_{min}, is given by

$$C_{min} = \frac{D^v{}_{ph}\varphi}{M} \qquad (3)$$

where $D^v{}_{ph}$ is the peak-hour vehicle demand and φ is the average trip length Equation (3) assumes an unrealistic uniform distribution of demand on the guideway. Because peak-hour demand is directional and near capacity utilization of the guideway should be avoided to avoid congestion and its related reduction in service we define a practical design guideway capacity $C = C_{min}/\eta$, where η is a realistic guideway utilization efficiency. A reasonable peak-hour value is 0.5.

Peak-hour person trips, $D^p{}_{ph}$, is related to $D^v{}_{ph}$ via an average vehicle occupancy, ξ, $D^p{}_{ph} = D^v{}_{ph}\xi$. For private auto-like PRT service values of $\xi \cong 1.0$ are commensurate with low auto occupancy for work trips and the need for vehicle shuttling to satisfy the skewed peak-hour demand.

From Equation (3) the preferred vehicle design capacity measure-minimum time-headway, $t_h = 3600/C$ (seconds), is

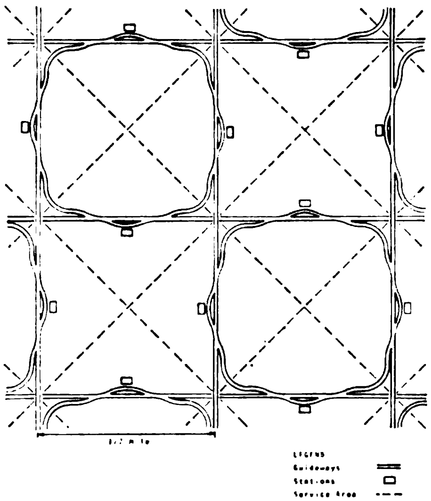

Figure 2. Idealized PRT Network

found to be inversely proportional to person trip demand rate, trip length and line-spacing.

$$t_n = \frac{7200\,\eta\xi}{Dp_{ph}\,\varphi\,L} \tag{4}$$

t_h is also linear with average vehicle occupancy, ξ; however, ξ is a characteristic of the travel demand and cannot be considered a design variable in the same way average auto-occupancy is not a highway design variable. Therefore, Equation (4) exhibits the tradeoff between only two design variables, t_h and L. Actually the demand is a monotonically decreasing function of L (through the impercise modal split model) which tends to place a lower bound on t_h. Costs impose the upper bound on t_h. Service requirements, in terms of walk distance to a station, indicate that the line spacings should be not much larger than 0.62 mi. (1km) to 0.5 mi. An estimate of the population density required to generate the peak-hour demand at headways of 1, 2, 4 and 8 seconds is presented in Table 1. Assumed is that 50% of the average 0.3 person trips during the peak-hour take the PRT system having $L = \frac{1}{2}$. The relationship between population and average trip length are ideal for real cities because high-density residents tend to have shorter work trips than low-density suburban residents.

TABLE 1
POPULATION REQUIRED TO SUPPORT PEAK-HOUR CAPACITY OPERATION

Population (/mi.^{2})	Ave. Trip Length (mi.)	Headway (sec.)
16,000	3	1
8,000	6	1
4,000	12	1
4,000	6	2
2,000	6	4
1,000	6	8

Costs. The costs per unit area of the above network can be divided into three categories: operating, maintenance, and capital costs. For Level I analysis maintenance costs can be incorporated into operating ($\cong$\$0.01/vehicle mile) and capital cost (1% added to the annual cost equivalent).

Annual capital costs per unit area for the system, $\$_c$, can be expressed in terms of unit costs, α, as

$$\$_c = \alpha_v\,CRF_v\,N_v + \alpha_s\,CRF_s\,N_s + \alpha_g\,CRF_g\,N_g \tag{5}$$

where the capital recovery factor, CRF,[5] converts total capital costs to an annual basis and the subscripts v, s, and g indicate vehicles, stations and guideways, respectively. The peak-hour fleet-size requirement, N_v, is a product of the peak-hour guideway utilization efficiency, ζ, and the guideway slots available per unit area, or

$$N_v = \frac{7200\,\eta}{t_h\,VL} = \frac{Dp_{ph}\,\varphi}{\xi} \tag{6}$$

where V = mainline velocity. Using (4), and (6), Equation (5) becomes

$$\$_c = \alpha_v\,CRF_v\,\eta\,7200/(t_n\,V\,L) + \alpha_s\,CRF_s\,2/L^2 + \alpha_g\,CRF_g\,(2/L + 0.6/L^2)^6$$

The relative impact on capital costs of the various system components is available from Equation (7). For example, if we consider V = 35 mph, $t_h = 1$ sec., L = 0.5 mi. and amortize the vehicles for 10 years and the guideways and stations for 30 years at 6% interest (conservative interest for municipal bonds) then $CRF_v \cong 2\,CRF_{s,g} = .0726 = CRF$ and

$$\$_c = 4CRF\,\{\,1.6\,\alpha_g + 2\alpha_s + 100\alpha_v\,\}$$

For a proportionate distribution of capital costs the station and guideway costs should be of the same order of magnitude, while vehicle cost should be 2 orders of magnitude smaller. Indeed some of the widely-quoted target costs for PRT systems have this distribution, i.e. $\alpha_g \cong$ \$1.5M/mile, $\alpha_s \cong$ \$400,000/station and $\alpha_v \cong$ \$5,000-\$10,000/vehicle. Table 2 lists the distribution of annual capital costs for the above assumptions.

Annual Revenues. An estimate on the annual patronage based on the peak-hour demand is available by estimating daily demands in terms of peak-hour demands,

TABLE 2

DISTRIBUTION OF ANNUAL CAPITAL COSTS PER SQUARE MILE

	Total	Annual	% Of Annual Capital Costs		
	Capital Costs	Capital Costs	Vehicles	Stations	Guideways
$\alpha_v = 5{,}000$	\$13.8M	\$1.07M	13.5%	21.5%	65%
$\alpha_v = 10{,}000$	\$14.8M	\$1.22M	24%	19%	57%

Assumed: $L = 0.5$, $\eta = 0.5$, $\xi = 1.0$, $\alpha_g = \$1.5M/mi.$, $\alpha_s = \$0.4M/$, $V = 35mph$.

$\varphi_{ph} Dp_{ph} = 5 \varphi_d Dp_d$, and the equivalent number of transit days per year. For conventional transit peak-hour ridership represents 15-20% of total daily ridership. Experience from the Haddonfield, N.J. Dial-a-Ride experiment indicates that demand-responsive transit has a larger demand for service during off-peak hours than conventional transit and therefore, a smaller percentage of total daily trips are taken in the peak-hours. This improved demand distribution is somewhat offset because off-peak trips tend to be shorter than peak-hour trips. Consequently a realistic estimate of ζ for PRT seems to be $\zeta \cong 0.15$. The area-wide time-independent service provided by PRT can also be expected to yield more week-end patronage than conventional transit. Assuming non-business day ridership to be 10% of business day ridership gives about 265 transit days per year.

Considering a per passenger mile fare, F, the yearly revenue per unit area, $\$_r$,

$$\$_r = 265\, F\, \varphi\, Dp_{ph}/\zeta \tag{8}$$

By equating the yearly revenue to cost, interesting tradeoffs between system costs parameters and service variables are discovered. Equating Equation (8) to Equation (7) (modified to include maintenance and operating costs) express the "break-even" fare in terms of system design and cost variables as

$$F = 0.03 + 1.05x10^{-6}\, t_h \zeta (CRF + 0.01) \{ 7200 \eta \alpha_v / t_h / V + \alpha_g + (\alpha_s + 0.3\alpha_g)/L \} / (\eta \xi) \tag{9}$$

Using assumed values for CRF, V, ζ, ξ, and η, Equation (9) reduces to

$$F = 0.03 + 2.59x10^{-8} \{ 100\alpha_v + t_h \alpha_g + (\alpha_s + 0.3\alpha_g) t_h \eta \} \tag{10}$$

Equation (10) exhibits the sensity of the "breakeven" fare to the unit capital cost element under the patronage assumptions stated above. Figures 3-5 present parametrically fare required to pay for each element of the capital cost. Note that the cost of amortizing the fleet of vehicles is independent of either demand or network design parameters (except V). Also noted on Figure 5 is the minimum practical population density, ρ, that corresponds to the paired values of t_h and L. Table 3 below summarizes the "break-even" fare components for the nominal values of the cost parameter.

A parametric analysis of the guideway portion of the "break-even" fare, F_g, as a function of demand at constant vehicle technology, say $t_h = 1$ sec., indicates a linear increase with demand which can be used to

$$F_g = 2.59x10^{-8}\, \alpha_g t_h \left\{ 1 + \frac{.3\, Dp_{ph}\, \varphi\, t_h}{7200\, \eta \xi} \right\} \tag{11}$$

define upper limits of demand for which PRT is applicable. For example, if F_g max is chosen as \$.10/mile then the practical maximum population would be 21,000 pps for $t_h = 1$; whereas, $F_g < \$.10$ is impossible for $t_h > 2.57$. A similar analysis is possible for the station component for the fare, F_s.

Equation (9) is also in a convenient form to determine the sensitivity of the fare to small changes in the assumed parameters such as the peak-hour ridership index, ζ, maintenance cost, the average vehicle occupancy, ξ, and the guideway utilization, η. Changes in total

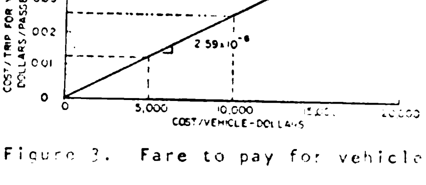

Figure 3. Fare to pay for vehicles.

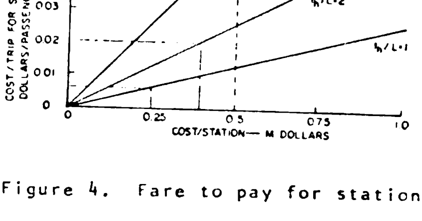

Figure 4. Fare to pay for stations.

TABLE 3
"BREAK-EVEN" FARE COMPONENTS

	Total	Operating	Vehicles	Stations	Guideways
$/Mile	13.9	0.03	0.026	0.021	0.062
Percent		21%	18.7%	15.1%	44.6%

Assumed: $L = 0.5$, $\eta = 0.5$, $\xi = 1.0$, $3 = .15$, $\alpha_g = \$1.5M/mi.$, $\alpha_s = \$0.4M/$, $\alpha_v = \$10{,}000/$, $t_h = 1$, $\varphi = 6mi.$ Required population density: 8,000/mi^2.

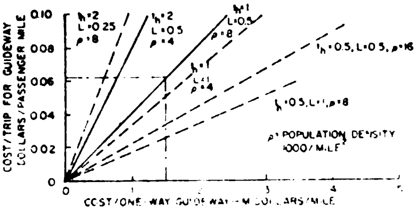

Figure 5. Fare to pay to guideways.

fare due to variations in assumed parameters are listed in Table 4

APPLICATIONS IN SPECIFIC CITIES

Level II analyses of area-wide PRT networks have been conducted in a number of cities. These include Boston, General Research Co.;[5] Birmingham and London, by the Royal Aircraft Establishment;[7] Frieberg, by Messerschmitt-BBG;[14] and Tucson and Los Angeles, by Aerospace Co.[24] As members of a task force at the University of Minnesota the authors developed a Level II computer-based methodology for evaluating area-wide PRT networks. The methodology consists of a set of computer-subroutines which operates on a detailed data base of a standard origin-destination travel demand auto skim trees, a specified PRT network and associated performance parameters.[7] Outputs include:

Ridership: trip and mileage model split

Economics: fixed and variable costs; total costs per trip, capital costs and annual costs; annual farebox revenues; annual benefits from reduced auto usage, safety and pollution; benefit-cost ratio

Environmental: peak-hour and 24-hour average electrical power requirements; automotive emission reductions; transportation energy requirements

Design Data: maximum flows in each link of the network; station capacity requirements; vehicle fleet size; empty vehicle shuttling requirements

The computer subroutines, inputs and outputs are shown schematically in Figure 6. The minimumpath subroutine finds the travel time and best travel route between each station pair of the PRT network. Both one- and two-way links can be accommodated. The station attraction subroutine calculates the distribution of walk-distance to each station from every point in its service area. The O-D reduction subroutine eases the manipulation of large data bases, e.g. O-D data from as many as 1,000 traffic assignment zones.

The modal split model is a binary choice model that assigns each trip between each pair of station service areas to the "cheaper" mode. Cost is taken as a linear combination of the total origin to destination travel time and perceived travel costs. Aggregated data on trip maker and modal characteristics and the walk-distance distributions are used to calculate travel costs via each mode.

Network assignment has two basic components. The first is an empty-vehicle-shuttling algorithm that determines the optimum (capacity constrained) vehicle routing to satisfy average and/or maximum wait time constraints at stations. A demand matrix for empty vehicles is constructed solving a classical transportation-type linear programming problem.[20] When the resulting demand for empty vehicles is added to the demand for full vehicles, the total flow of vehicles is assigned to

TABLE 4
SENSITIVITY OF BREAK-EVEN FARE TO VARIATIONS IN PARAMETERS

Variable	Sensitivity	Nominal Value	Range of Variation	Effect On Fare
ζ	0.726	0.15	±0.025	±$0.018
ξ	—0.109	1.0	±0.25	∓$0.027
Maintenance (CRF)	1.319	0.0826	±0.01	±$0.013
η	—.0025	0.5	±0.1	∓$0.00

Note: Variation of single variable, all other variables have assumed values of Table 3.

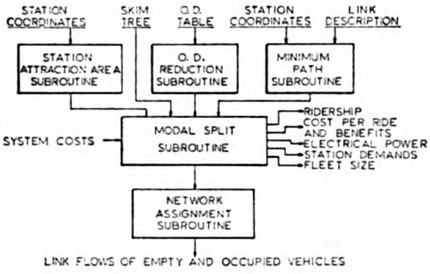

Figure 6. Computerized Network Evaluation Methodology

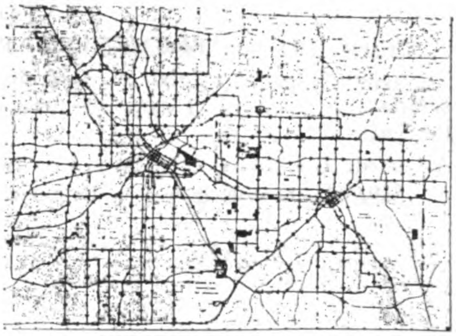

Figure 7 Network evaluated for the Twin Cities--Stage 8

the network while satisfying capacity constraints.

The computer software was used to analyze area-wide PRT networks for the Twin Cities of Minneapolis and St. Paul, Minnesota, and Duluth, Minnesota and is presently being applied in an iterative fashion to progressively improve the design of a PRT network for Trenton, N.J. Figures 7-9 show representative networks for each of these three cities.

The Twin Cities form a rather large metropolitan area. Their combined population is 740,000 and the 7-county SMSA has a population of 1.8 million. Average population density in the cities is less than 5,000/mi^2. For the Twin Cities a sequence of eight networks were analyzed starting with a network consisting of only 21 miles of one-way guideway and serving only the two central business districts. Finally, an area-wide system having 442 miles of one-way guideway and 506 stations, shown in Figure 7 was designed. The effort was to demonstrate how metropolitan area-wide networks can evolve in stages from an initially small network. The networks were developed by Professor J. Edward Anderson using design guidelines dictated by a Level I analysis. Iterative design techniques at Level II were not used to optimize the line and station locations at each stage. A summary of the results of the Stage 1 and Stage 8 networks is presented in Table 5.[8] The statistics show that the system is attracting a high percentage of the trip ends

TABLE 5
COMPARATIVE NETWORK SUMMARIES

	Twin Cities (pop = 740,000)		Duluth (pop = 100,000)	Trenton (pop = 105,000)
Network Statistics	Stage 1	Stage 8		
One-way route miles	21	442	75	29
Number of stations	64	506	128	61
Vehicle fleet size	870	17,600	3,400	2,500
Average station demand (/hr.)	87	88	≅50	—
Ridership Statistics				
PRT/auto modal split	96	34	40	(assumed 50% of 1972 intracity vehicular trips)
Economic Statistics				
Total Capital costs, millions $	87	1,230	177	87
Total annual costs, millions $	12	154	21	10.5
Annual capital costs, millions $	7	93	13	7.9
Annual revenue ($.08/pass. mi. fare)	4	81	—	—
Annual benefits,* millions $	22	133	22	6.7
Total cost per ride, $	.59	.97	.65	.28 (2/3 Fed), .59 (no Fed)
Total cost per passenger-mile, $	.18	.12	.14	.08 (2/3 Fed), .17 (no Fed)

*Includes auto cost and travel time savings, air pollution and auto accidents.

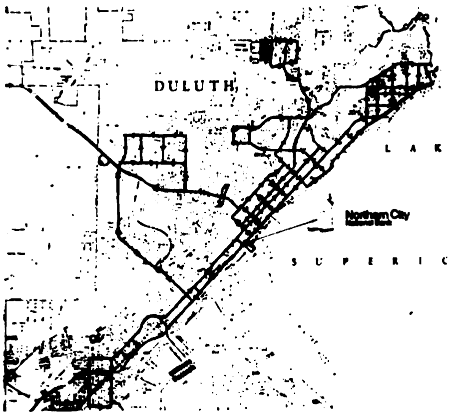

Figure 8 Network evaluated for Duluth

Figure 9

PRELIMINARY PRT NETWORK
CITY OF TRENTON

in the network area. Cost per passenger mile is higher for the limited network in the high trip density area (supported by Equation (11)) and the total cost/passenger mi. for Stage 8 is comparable to total auto cost. Costs per trip are in the same range as dial-a-ride ($.50-$1.25) in other cities and higher than buses ($.40-$.70). A benefit-cost ratio < 1 for the large network is largely due to an excellent highway system in that long trips on PRT take longer than auto trips resulting in a travel time cost instead of benefit.

Duluth is a city with a total population of 100,000 and average population density of about 1,600 p/mi^2. However, since the population and major activity centers appear in clusters, the majority of trip-ends lie in a relatively small land area. As a partial test of the feasibility of PRT, a network of 75 one-way miles with 128 stations was evaluated using Level II computer software. The network, Figure 8, was designed by L. Brady Reed based on a level I analysis and is not further optimized. Summary results for the network are presented in Table 5 based on the cost estimates given in Table 6. Patronage, costs and benefits are comparable to those generated for the Twin Cities network. Benefits are relatively better than Stage 8.

Trenton is an old medium-sized Eastern city. It has a population of 104,000 similar to Duluth's; however, this population is concentrated in a small area (7.8 mi^2) giving it a population density $>$13,000/mi^2. At present, Princeton University's Transportation Program is evaluating transit alternatives for the City of Trenton under a technical studies grant from the US-DOT/UMTA.[25] One of the options is city-wide PRT. As a preliminary exercise, the network, shown in Figure 9 and consisting of 29 route miles and 61 stations, was developed based on a Level I analysis. Cost and benefits of this network were estimated. Because the data base is not yet completed, modal split was assumed to be 50% of the 1972 intra-city vehicular trips. A summary of results are presented in Table 5 based on cost estimates given in Table 6. Results are similar to those obtained in the Twin-Cities and Duluth studies. The cost per passenger mile is high, resulting from the high capital costs. Difficulties in the Trenton network are due in part to an extremely short average trip length of 3.5 miles.

CONCLUSIONS

Quantitative results presented in this paper are not overwhelmingly favorable to area-wide PRT but indicate that well-designed PRT network could be made competitive with the automobile in medium-sized or medium-density cities. The results from the Level I analysis provide easily understood guidelines for detailed network designs. Cost estimates predicted by these "back-of-the-envelope" calculations are upheld in Level II analyses, and the intuition gained on cost and design tradeoffs is most valuable.

Analyses of area-wide networks for the Twin Cities, Duluth, and Trenton are

TABLE 6
COMPARATIVE COST ASSUMPTIONS

	Twin Cities	Duluth	Trenton
guideway/mi.	$1.3M	1.0M	1.5M
stations	$0.4M	0.4M	0.4M
vehicles	$7,000	7,000	7,000
operating	$0.02/mile	0.03/mile	$0.033 (calculated)
maintenance	2% yr. capital	½% yr. capital	1% yr. capital

marginally favorable to PRT. Costs per passenger-mile (assuming no Federal capital assistance) ranges between \$.12 and \$.18 which are slightly higher than present full auto costs and in the range of dial-a-ride costs. Full capital costs of these systems are huge (\$1.2B for the 442 mile Twin Cities network and \$87M for the 29 Trenton network). Because of this capital intensity, "break-even" costs are very sensitive to variations in capital costs. This difficulty is compounded by the fact that we are making cost estimates on nonexisting technology.

On the positive side it is noted that:

(a) the analyzed networks were first guesses from a level I analysis and are not optimized.

(b) a large savings in total transportation energy requirements is gained by PRT, e.g. for Duluth it represented a potential 35% savings in transportation energy.[19]

(c) the potential of combining goods movement with people movement to obtain better daily utilization of the system (lower values of ζ) would yield a distribution of capital costs. The lowest possible value (operating costs) were calculated to be 3.3¢/mile for the Trenton network.

(d) the social benefits of providing auto-like transportation to today's bus captives should be seriously considered.

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FOOTNOTES

1 Numbers in brackets refer to references listed at the end of the paper.

2 Primary contributions came from General Research Co. [5] and Stanford Research Institute [6].

3 This constraint termed the k-factor by Hajdu [11] is k = minimum intervehicular spacing/minimum stopping distance. Enforcement of the constraint $k > 1$ for present hardware would not permit headways < 5 seconds at 30 mph [12, 13].

4 Assuming 35 mph (56 kph) main line speed, 20 mph (32 kph) turning speeds and acceleration and jerk limits of 0.25 g and 0.25 g/sec respectively.

5 $$\mathrm{CRF} = \frac{1}{(1+i)^n + 1} + 1$$

where i = interest rate; n = lifetime (years)

6 Actually $N_g = N_g(V, V^2)$ and (7) could be solved for V^* that minimizes $\$_c$; however, for realistic values of α_v, α_g, t_h and L values of V^* are unrealistically low ($\cong$ 1 mph).

7 This software is more completely documented in [19].

8 It must be emphasized that the statistics presented in this section are tentative in that they were obtained using unproven ridership estimation techniques. Furthermore, the numbers are sensitive to cost estimates of nonexisting technology, which must be regarded as uncertain.