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PERSONALIZED RAPID TRANSIT SYSTEMS: A FIRST ANALYSIS

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16. Abstract

In this report a preliminary systems analysis of the Personalized Rapid Transit System concept is given. It includes presentation of the significant advantages and disadvantages of the concept. Questions of System Capacity, Station Capacity, urban grid design and headway requirements are addressed. A review of current manufacturers' systems is given with a functional classification of their major characteristics. Significant and critical component and system needs are described which require further research and analysis. A brief discussion of cost factors is also given.

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1. INTRODUCTION

A personalized rapid transit system (PRT) is a system of small cars operating on a network of guideways on exclusive rights-of-way, taking passengers non-stop from origin to destination, where stations are off-line so that a car picking up or dropping off passengers does not slow down or interfere with traffic on the main line.

The control of a PRT system is automatic, employing a combination of car sensors and on-board controls, generally under the supervision of a central computer. A passenger entering a PRT station either finds a car waiting for him at a boarding dock, or summons one off the mainline or from a parking area by pressing a call button. The car door opens automatically to receive the passenger (or passengers, if travelling in a party). All passengers in a pure PRT are seated. The lead passenger presses a button code for his destination, causing the car doors to close and the acceleration process to begin. The car merges with line traffic and is routed to its destination without stopping at any intermediate stations. On approaching its destination, it is switched off the main line and decelerated to a stop at the station, where the doors open and passengers disembark.

PRT cars now being contemplated seat 4 to 6 passengers, with room for small parcels or luggage. Each passenger can travel alone in a car or, if he prefers, in the company of others. The average occupancy is expected to be similar to that of any automobile, about 1.3 to 1.7 passengers per car. The car is small, 8 to 10 feet long, by 5 to 7 feet wide, weighing about 1500 pounds, i.e., less than a small European automobile. Consequently, the guideway is considerably narrower than that for conventional transit and requires less land. The supporting guideway structures are also less massive. Since costs of land, structures and tunnelling (if any) can account for as much as three-quarters of total transit system investment costs, PRT systems have a potential for reducing investment costs per mile of guideway. Figure 1 illustrates the cost breakdown given by Ford, Roesler and Waddell, for on-call systems.

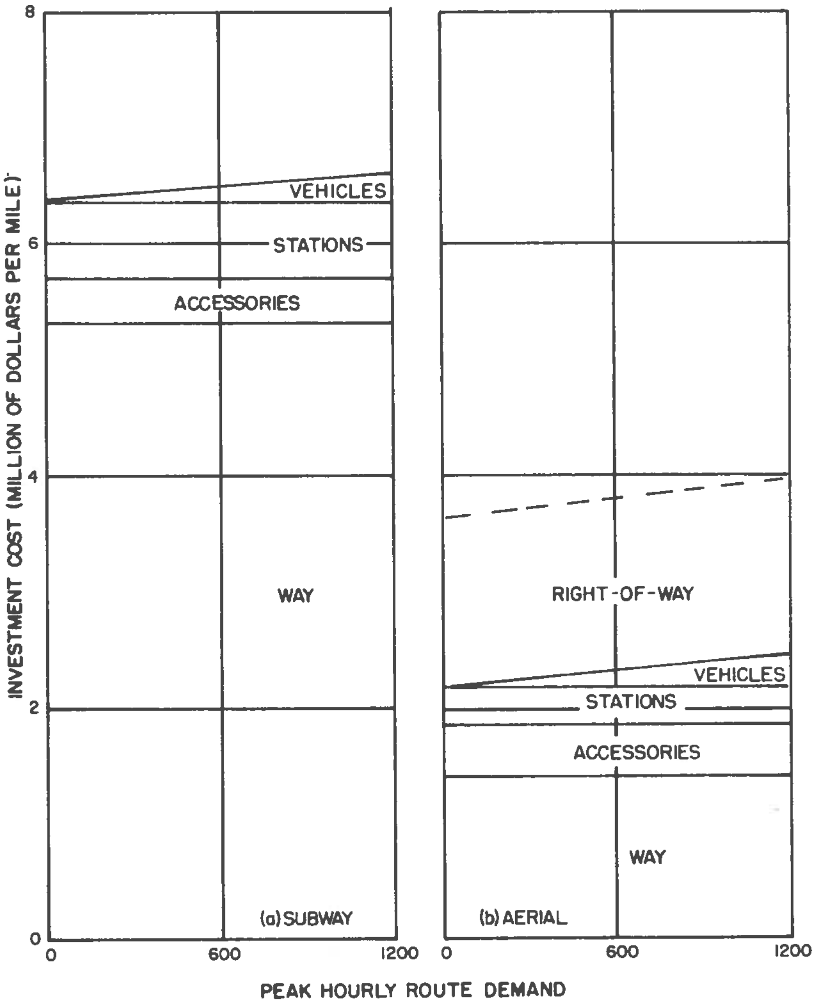


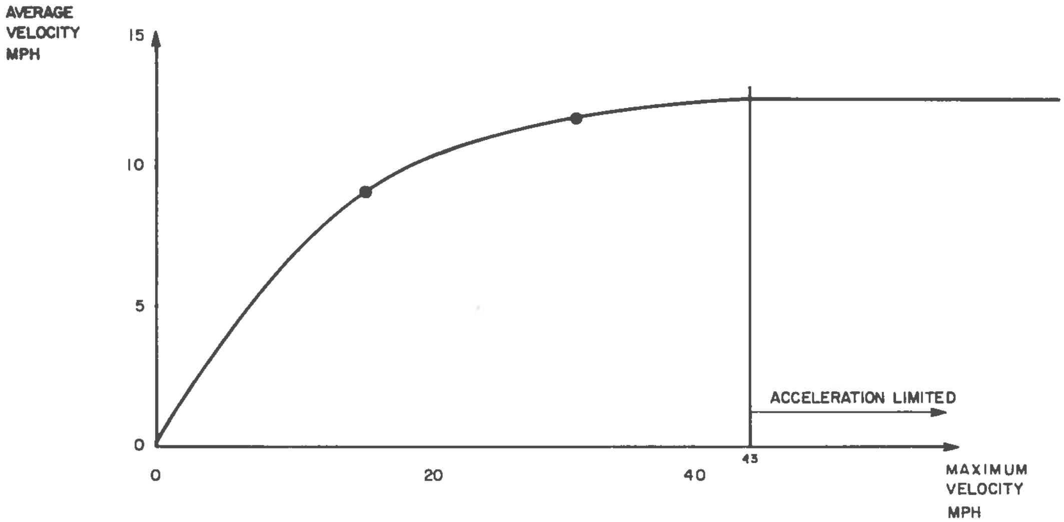
Figure 1. Investment Costs Vs. Peak Hourly Route Demand For a Single Lane On Call System (Source: Ford, Roesler, and Waddell)[1].

1.1 LOGIC OF THE PRT CONCEPT

The PRT concept has evolved as a logical answer to certain requirements which a transit system must satisfy to compete effectively with the automobile in the city. In order to provide a level of service comparable to or better than an automobile, a transit system should be designed so that no one has to walk more than a comfortable distance to reach a station. Two blocks or 1/4 mile is assumed to be the maximum walking distance.

If stations are so closely spaced, any system which requires all vehicles to stop at all stations is too slow. Indeed, assuming 1/4 mile station spacing, an acceleration (deceleration) limit of 3 feet per second per second, and 30-second station dwell times, the average velocity is absolutely limited to 12.6 mph (Figure 2) and actual velocities will never exceed 43 mph. In practice, the average velocity would probably fall considerably below 12.6 mph. On the other hand, to compete with the automobile, it is usually assumed that an average speed of 25 mph or more would be required, so that some sort of off-line station arrangement is necessary.

If passenger transfers are acceptable, then a combination of local and express service could provide the required high average velocity. Transfers, however, are undesirable from the passenger's point of view, inasmuch as they are inconvenient and lengthen trip time. In order to avoid transfers, it is necessary to have service between every pair of stations. Since the number of pairs is large, whereas the number of passengers wishing to travel between any pair is small and unevenly distributed over time, the logical conclusion is that the vehicle fleet should consist of many small vehicles, operating on demand. Finally, it would be prohibitively costly to employ human operators for each vehicle in the fleet, so a totally automated system is required.



ASSUMPTIONS: 1. STATIONS ARE 1/4 MILE APART
2. ACCELERATION LIMIT IS 3'/SEC^2
3. STATION STOPS REQUIRE 30 SECONDS EACH

Figure 2. Average vs. Maximum Velocities of a System with On-Line Stations

The PRTs advantages include smaller land requirements and lower structure costs per mile of guideway. Its narrower, unobtrusive guideways could be fitted more flexibly into the urban environment. It would facilitate the design of true network grids as opposed to conventional radial networks; would be faster than an automobile during rush hours, relieving the commuter of the chore of driving, and making high quality transportation available to those who cannot drive. It would also require far less walking than any conventional public transit system. Service could be maintained during low demand hours. The PRT system would offer many of the conveniences of an automobile, without the attendant congestion and pollution; in fact, offering a level of service higher than any of the other proposed public transit systems, except for the dual-mode PRT (which would operate an ordinary automobile mode off the guideway).

The disadvantages of the PRT are that dense PRT grids could prove expensive (though reliable cost estimates are not yet available) and would present some formidable aesthetic, human factors and technical problems. However, the advantages of the PRT far outweight the disadvantages so that an extensive effort to solve these problems would seem warranted. To obtain an overview of the research that would be required, a description of the major problem areas will be presented, latter returning to some of the more technical problem areas and examine them in greater detail.

1.2 THE PLACEMENT PROBLEM

The biggest problem with the PRT concept is the placement problem, i.e., where to put it. For example, if the PRT network were to consist of a square grid of guideways, spaced 1/4 mile part, as many as 16 stations and an equal number of interchanges might be required in each square mile, and although the guideways and vehicles would be much smaller and more attractive than in conventional transit, a dense above-ground network could not be inserted into a city without massive repercussions. In time, the pressure of accommodating such a network might force an evolution in city architecture. It could, for example, accelerate the trend to multi-level planning and eventually lead to the formation of multi-leveled cities, with pedestrians, automobiles and mass transit at separate levels.

A multi-leveled city would minimize interference between pedestrian and vehicular traffic, allow concealment of unsightly structures, thus becoming desirable in the long run. In the short run, however, where guideways would have to be inserted into an existing architectural environment, the aesthetic cost would be high.

1.3 CLAUSTROPHOBIA IN UNDERGROUND SYSTEMS

An alternative to placing the network above ground would be by using tunnels. This would be expensive, although costs would be brought down by improvements in tunneling technology, likely to occur in the next few decades. Even a breakthrough in tunneling, however, would still leave a major human-factors problem; riding in a small underground vehicle induces feelings of claustrophobia in some people. Even with careful lighting and attention to other human factors in tunnel design, a certain proportion of the public would be unwilling or unable to use the system. For these people, an alternative above-ground system, such as a bus network, would have to be provided, even though the alternative might carry only a small fraction of the total passenger volume. In any case, it is desirable to have more than one mode for passengers to choose from because reliability is increased, a larger range of individual tastes can be satisfied, and variety itself is a virtue.

1.4 THE INTERCHANGE PROBLEM

The most difficult part of the network placement problem, at least for an elevated system, is the location of the interchanges between grid lines.

The turning radius at an intersection is limited by human tolerances for acceleration and depends on vehicle velocity. In order to fit into existing city streets, the turning radius would have to be kept down to 20 to 50 feet (comparable to the turning radius of an automobile). To achieve such a small turning radius, the turning velocity has to be kept between 7 to 13 mph, even if the turn is steeply banked (20 percent). Vehicles would, therefore, have to take turns at low speeds. (This would complicate the control problem, but would not seriously affect trip time, as the number of turns in a single trip need not be large.)

Even with reduced speeds and sharp turns, interchanges would occupy large areas, and reduction of interchange areas is, therefore, important. There are a number of possibilities for reducing interchange areas, including:

1. The use of low cross-section overhead monorail or cable-type guideways (similar to present gondola ski-lift systems). These also have the advantage that banking is accomplished automatically. They do, however, have crosswind and sway problems.

2. The use of vertical switching and overhead (as opposed to alongside) access lanes.

3. The use of one-way routes to simplify interchange topology.

4. The possible use of mechanical transfer devices, such as vehicle elevators, to eliminate the need for cloverleaf interchanges

1.5 LINE CAPACITY PROBLEMS

Because the average occupancy of a PRT vehicle is so much lower than that of a conventional transit vehicle (1.4 to 1.8 mph for PRT versus 100 to 200 mph for conventional transit during

peak hours), attainment of sufficient passenger carrying capacity, though seldom a problem for conventional transit, becomes a major problem for the PRT. The capacity of a PRT line depends on the line velocity and on the headway maintained between vehicles.

The headway generally consists of two components:

1. A component determined by safety conditions.

2. A component reserved for acceleration and merging maneuvers.

The first component is limited by the restriction that headway be greater than the minimum stopping distance. So long as this restriction is accepted, a PRT line can carry no more than 500 to 1500 passengers per hour*. At this rate, the pure PRT concept is limited to low capacity networks. The second component can be reduced by providing off-line acceleration lanes. However, for high speeds (45 mph or greater) these can be long and costly.

The possibility for the future, technologically the most challenging and attractive, is that adequate safety could be ensured at headways smaller than the minimum stopping distance. However, this would entail the use of control systems more sophisticated and expensive than any developed so far.

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*These figures cannot be improved upon by increasing velocity. Because stopping distance increases as velocity is squared, capacity tends to drop off sharply as velocity is increased above 15 mph.

1.6 STATION CAPACITY PROBLEMS

A PRT car requires much more space per passenger than does a conventional railroad car. Consequently, PRT stations would have to be several times larger than present stations per passenger carried. This would mean that stations at major trip centers (tall office buildings, theaters, air terminals, etc.) would be too expensive unless efficient means of loading and unloading of passengers were developed.

Questions of line and station capacity will be explored in latter sections of this report.

1.7 SYSTEM DESIGN PROBLEMS

Short-headway, high-capacity PRT systems would be prone to the development of queing problems and traffic jams. These could be minimized and, perhaps, prevented altogether by proper design of the network and of an appropriate supervisory control system. However, a number of difficult problems in network and supervisory control design would first have to be solved. This area is not too well understood at present, and on which basic research will have to be expanded.

1.8 COMPONENT TECHNOLOGY PROBLEMS

A survey of current manufacturers concepts, (see Section 4. Survey of Manufacturers' Concepts) shows that a lot of effort and ingenuity has already been expanded in the design of guideways, vehicles, suspension systems, propulsion systems and switches for PRT's. A large number of difficult problems remains, particularly in connection with the design of control-communication systems for small headway operations, hazard detection, emergency operation and excessive computer capacity requirements. The prevailing opinion, however, is that the technological problems are within the advancing state of the art and pose no critical, basic difficulties.

1.9 MODIFIED PRT CONCEPTS

Until the problems previously mentioned are solved, the completely personalized or pure PRT concept will remain impractical for any but the least demanding urban applications. However, manufacturers have proposed a variety of modified PRT concepts,

offering less than completely personalized service, which could be implemented in the near future. The manufacturer's modifications usually entail one or more of the following ideas:

1. Passengers are required to share vehicles, at least during peak hours. However, the number of passengers picked up by any vehicle is controlled (in real time), keeping each passenger's travel time below some acceptable maximum.
2. Larger vehicles, accommodating 12 to 40 passengers, some of whom may be standees, are employed during peak hours in a scheduled mode.
3. In order to decrease the number of bulky interchanges, occasional passenger transfers are required.
4. To reduce the need for complex and costly programming, the network layout is simplified, consisting, for example, of a number of closed, intersecting but connected loops.

The quality of service provided by such modified PRT's would be lower than for pure PRT's but considerably better than present systems.

2. PRT CAPACITIES

To put the PRT line-capacity question into prespective, it is noted that a conventional high-capacity, rapid-transit system can carry more than 40,000 passengers per hour per line. Radial corridors in U.S. cities have peak hour passenger flows as high as 60 thousand passengers per hour in New York City, 20 to 30 thousand passengers per hour in cities such as Boston, Washington, and Philadelphia, and as low as two to six thousand passengers in some of the less densely settled cities such as Denver, Seattle and Miami. In Columbia, Maryland, a proposed city of about 100,000, peak hour load would be 1,500 passengers per hour on the most heavily traveled link of guideway, and would average 30 to 40 passengers per hour on a link of the feeder system.[2] To cite another example, an airline terminal designed to handle 450 passenger jumbo-jets at 15-minute intervals requires a capacity of 1,800 passengers per hour, and considerably more if long queues are to be avoided as a result of variations in arrival times, lost baggage, or other delays.

The potential capacities of PRT lines can be viewed against this background of needs. The capacity of a PRT line carrying a bumper-to-bumper flow of cars will be called the ultimate capacity C_u. Assuming the generic PRT vehicle to be 10 feet long,

$$C_u = 528 \times V$$

where V = velocity in mph

At V = 60 mph, C_u = 31,680 vehicles per hour. Assuming an average of 1.5 passengers per vehicle, ultimate passenger capacity is 47,520 passengers per hour. The last figure is comparable to that of a conventional high-capacity line haul link.

Formidable technical problems would have to be overcome to achieve even a fraction of C_u. If, however, a reasonable fraction, such as 30 percent, were attained, then a single PRT line could meet the requirements of some of the medium-sized corridors, and even the largest corridors could be handled by splitting their loads between 3 or 4 PRT lines.

The capacity of a PRT line increases proportionately with velocity and inversely with headway. One way of specifying headway is in terms of the "safety factor*" k, defined by

$$k = \frac{\text{Headway (feet)}}{\text{Emergency stopping distance (feet)}}$$

Emergency stopping distance is usually calculated by assuming an emergency deceleration of about 1/3 g, i.e., about 11 feet per second per second.

The relations between safety factor k, velocity (mph) and capacity (vehicles per hour) are illustrated graphically in Figures 3, 4 and 5. For a fixed safety factor k, capacity first increases with velocity, then reaches a maximum, and finally drops off when the effects of larger headways needed at higher velocities become preponderant (Figure 3).

The more ambitious of the present crop of PRT manufacturers are aiming at k-factors in the 1.6 to 2.5 range and velocities of 30 to 60 mph (Figure 4). These figures imply capacities in the 300 to 1,000 vehicles per hour range. At the upper end of that range where the capacity would be 1,500 passengers per hour (obtained by employing k = 1.6 at 30 mph and assuming an average vehicle occupancy of 1.5), a single PRT line would still not have enough capacity to handle peak passenger flows in the smallest corridors. A single pure PRT line would probably not be able to service even medium sized airport systems, but would have enough capacity for most parts of a model city of the Columbia, Maryland, type, and for many distribution functions. Between two and five parallel guideways would be needed for airports and low-volume corridor applications.

If the pure PRT concept is to have any chance of meeting high-density corridon requirements or providing airport service on a single-lane guideways, then k-factors less than 1 must be considered. (At k = 0.1, line capacity is about 6 to 8 thousand passengers per hour in the 30 to 60 mph range, or about 12 to 17 percent of the ultimate capacity.) Capacity requirements are examined in greater detail in Section 3.

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*Whether the formula defining k provides a true measure of safety, particularly for k less than 1, is a subject of much current debate.

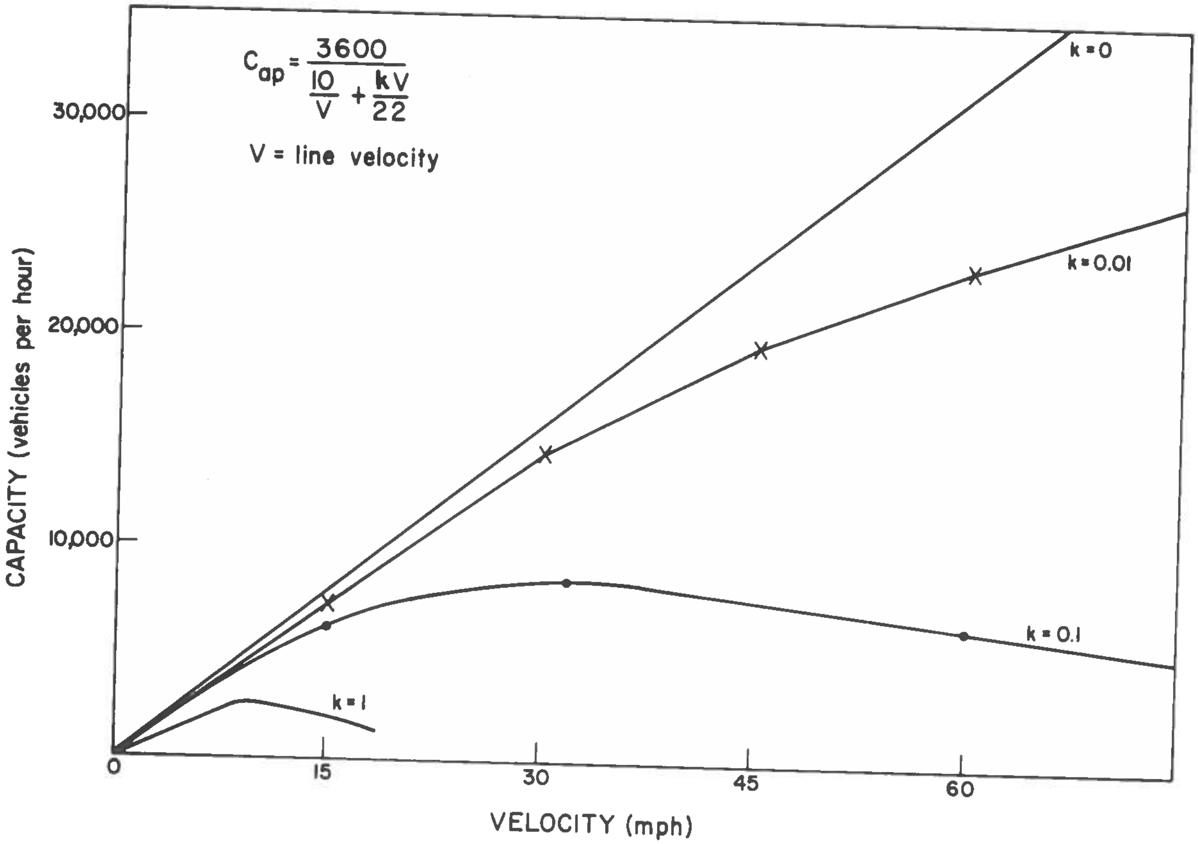


Figure 3. Capacity of a Single Line vs. Velocity For Various k Factors

k-factors of 0.1 at 60 mph with reliability better than that of an automobile would seem to be technically feasible, although an extensive program of development, lasting a decade or more, might be needed to resolve the many problems in the way. The traditional and conservative view, however, is that the public would be reluctant to accept operation at k-factors less than one even if high reliabilities were attained. This reluctance would have to be overcome.

Modified PRT operation, in which several passengers would be required to share one vehicle, could handle small corridor flows. For example, at an average occupancy of six passengers per vehicle, the presently contemplated systems would carry up to 6,000 passengers per line of guideway.

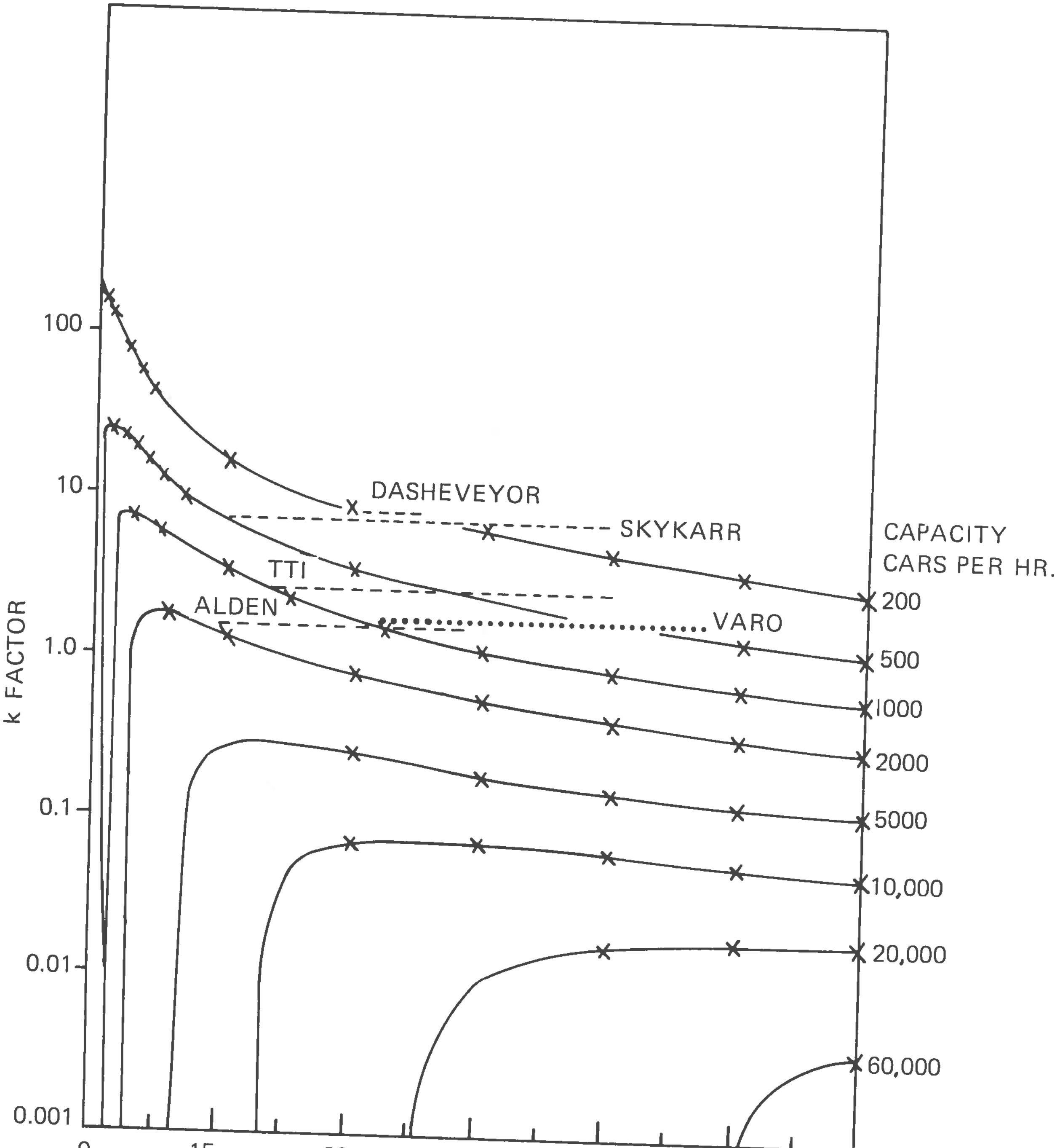


Figure 4. k Factor vs. Velocity For Fixed Capacities

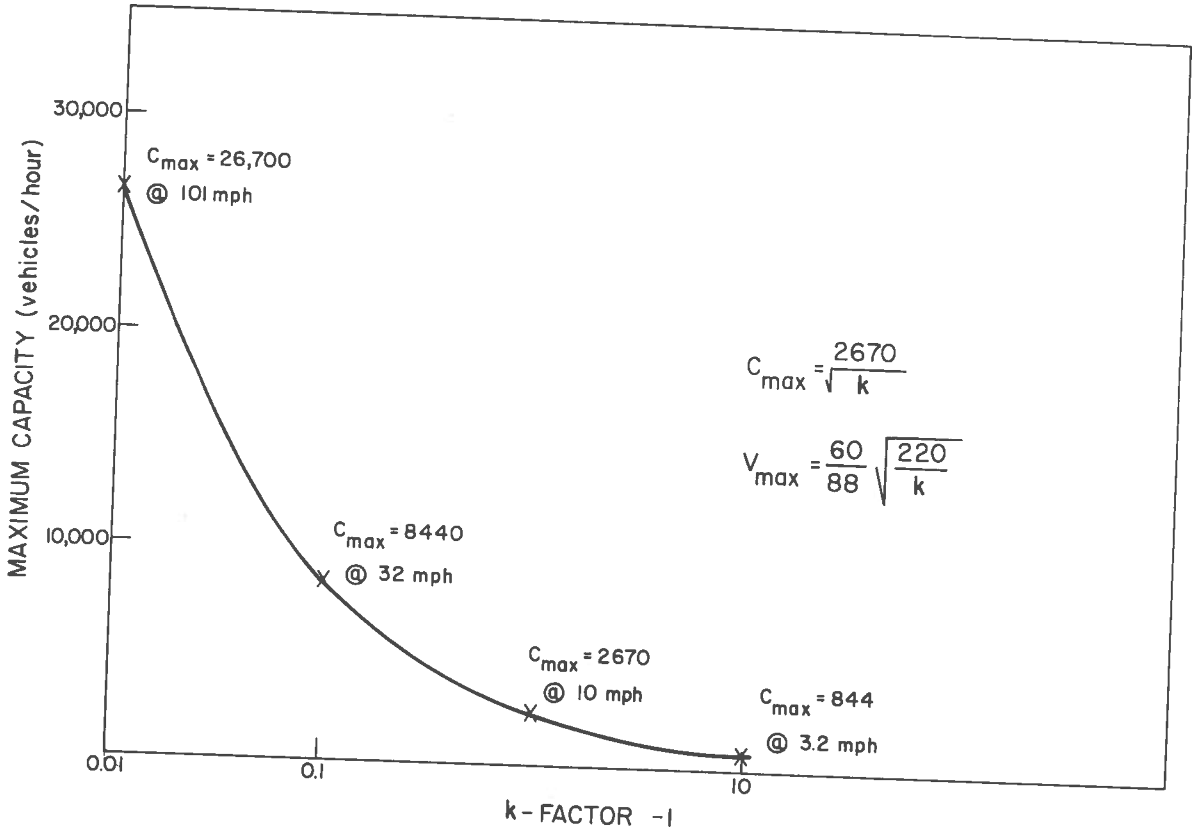


Figure 5. Maximum Capacity vs. k-Factor

2.1 SPEED CHANGE LANES

A key idea underlying the PRT concept is that high-line capacity (passengers per hour) can be obtainable by employing advanced technology to produce small headways at high speeds. One of the chief difficulties with this idea, and one which is not easily susceptible to technological solutions, is that large portions of guideway must be reserved for speed change (acceleration or deceleration) maneuvers near off-line stations. The length of guideway reserved for this purpose increases with the number of stations, and can be long enough to offset any advantage obtained from short headways and high speeds.

The capacity realized in practice depends on the way the speed changes are accomplished. There are three main strategies for accelerating a vehicle from rest at a station to line velocity and, conversely, of decelerating it from line velocity to rest: off-line, on-line, or mixed.

2.1.1 Off-Line Speed Change Strategy. Each station is provided with special lanes reserved for speed change maneuvers. Merging and diverging occurs at line velocity (Figure 6).

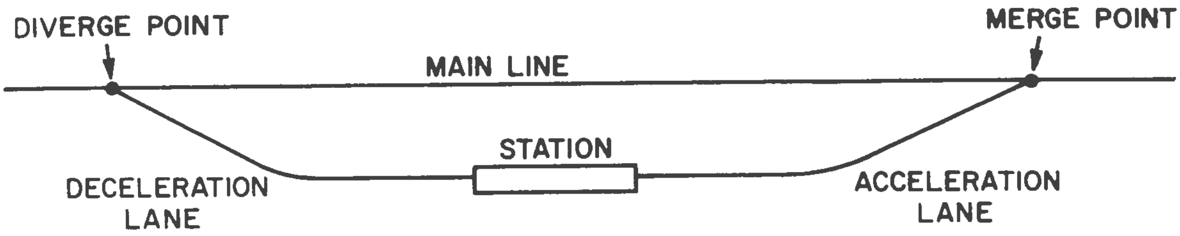


Figure 6. Off-Line Speed Change Strategy

Of the three strategies, the off-line causes the least interference to main-line traffic. However, the length of required speed-change lanes can be long. Indeed, if stations are close together, speed-change lanes can be longer than the main line.

Figure 7 shows the length of acceleration plus deceleration lanes required, (as a function of velocity), assuming acceleration rates of ±3 ft/sec^2 with stations spaced 1/4 mile apart. The length of speed-change lanes expressed as a percentage of main line guideway length follows:

12.2%	at	15 mph
49	at	30
110		45
196		60
306		75

At 60 mph the speed-change lanes of any one station would reach past the next station on the line and almost to the station after that.

The ultimate capacity of a PRT line proportional to line velocity reaches 39,600 vehicles per hour at 75 mph. This capacity, however, is not a realistic measure of guideway utilization because it neglects the length of guideway required for speed-change lanes. A more realistic figure is the capacity per lane of guideway employed, including speed-change lanes. Capacity per lane does not increase without limit as velocity is increased (Figure 11). At a station spacing of 1/4 mile, capacity

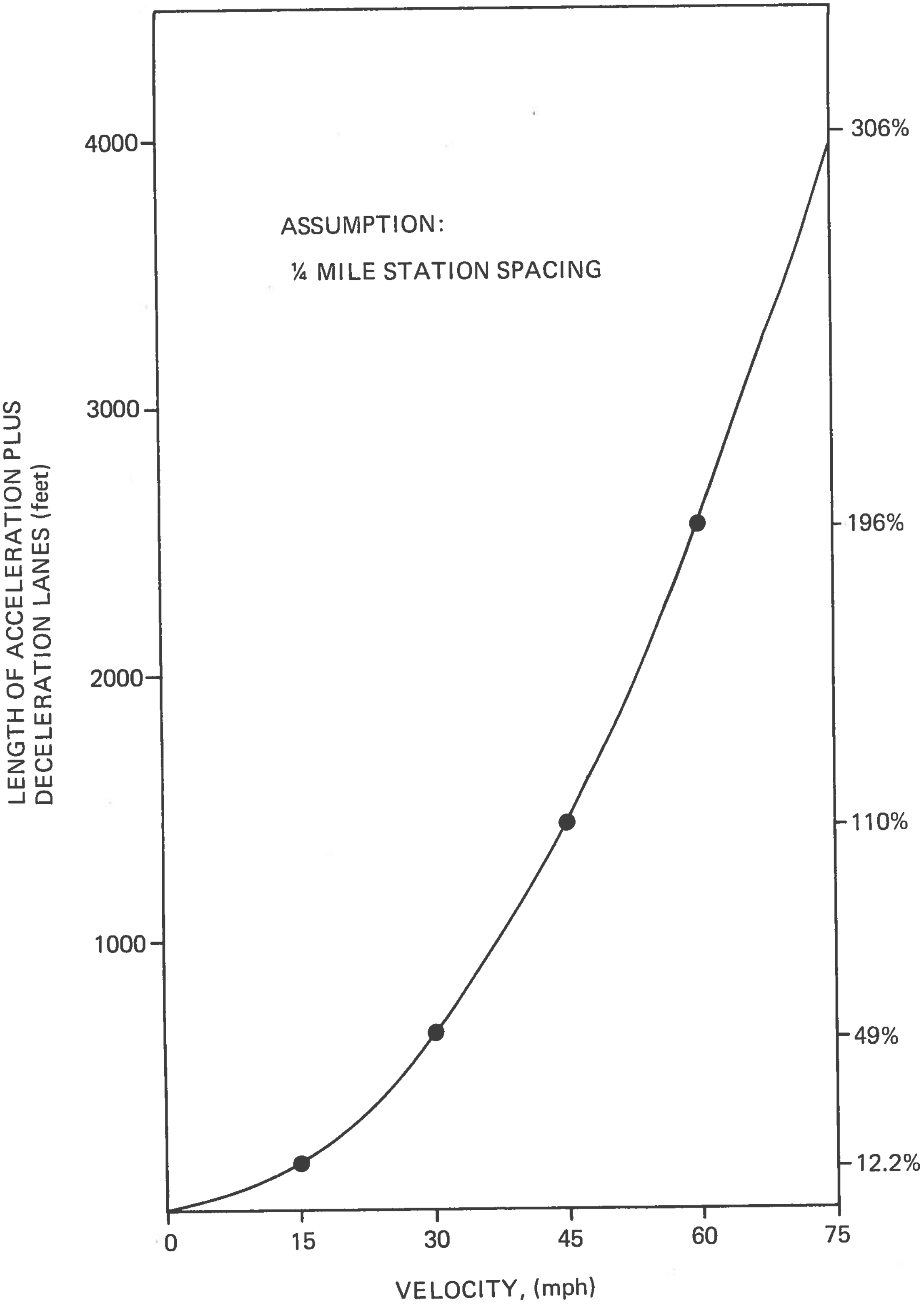


Figure 7. Acceleration and Deceleration Lanes - Length as Function of Line Velocity

per lane reaches a maximum of only 11,327 vehicles per hour (at a speed of 42.9 mph) and gradually drops off at higher velocities. This is for a purely off-line speed-change strategy.

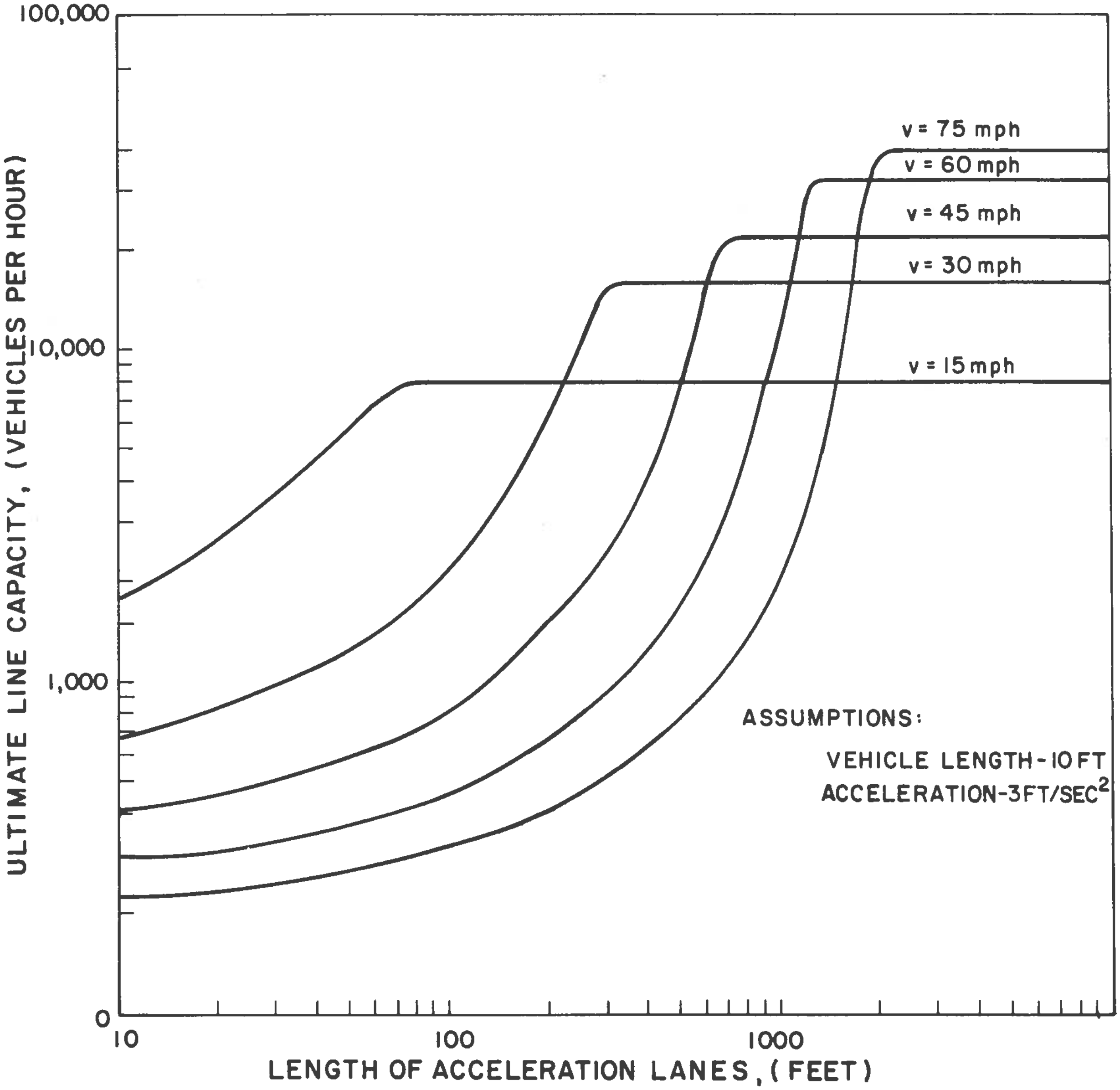


Figure 8. Capacity vs. Acceleration Lane Length For Synchronous-Slot, Partial On-Line Speed-Change Strategy, k = 0

Rather than employ overlapping speed-change lanes, it would probably be more practical to parallel the main line with a continuous local line and connect the two with connecting links (Figure 9).

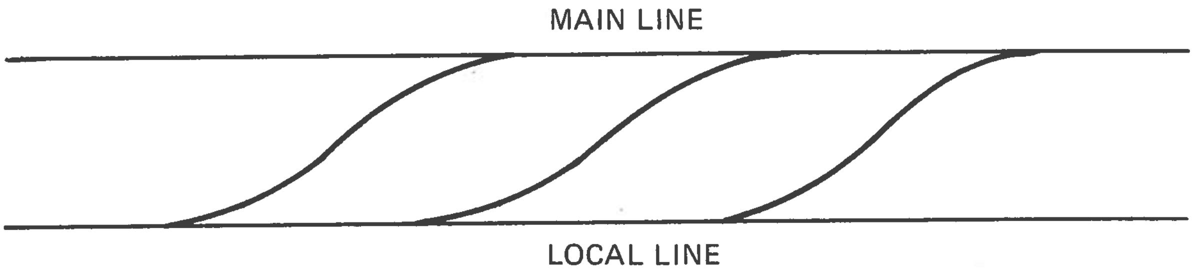


Figure 9. Local and Main Lines

The local line would then be used for short trips and also for speed-change maneuvers.

2.1.2 <u>On-Line and Mixed Speed-Change Strategies</u>. On-line speed-change strategies are those in which merging and diverging are accomplished at creeping speeds, and each speed change is performed on the main line. The mixed strategy is a combination of the on-line and off-line strategies.

An on-line speed-change strategy avoids the use of speed-change lanes altogether. Instead, the spacing between vehicles is increased by the amount required for speed-change maneuvers. The result is a decreased line capacity. Moreover, the need to intermix vehicles traveling at various speeds complicates line operations and the required control system.

2.1.3 <u>Merging Strategies</u>. Several merging strategies could be used in conjunction with an on-line or mixed speed-change strategy:

1. <u>Synchronous Slots</u>: A sequence of imaginary "slots" of equal length travel down the main line at uniform velocity. Each slot is reserved for one vehicle, long enough for all speed-change maneuvers, maintaining the minimum distance required for safety.

2.2 STRATEGY AND CAPACITY

Various speed-change strategies, primarily in terms of the capacities they provide per line of guideway, is evaluated below.

2.2.1 Synchronous Slots. To begin with, the capacities measured in vehicles per hour have been calculated as a function of the length of speed-change lanes (i.e., assuming each station has acceleration and deceleration lanes, all of equal length) for the synchronous-slot, partial on-line, speed-change strategy. The results are plotted in Figures 8 and 10 for k= 0 and k= 1, respectively.

Capacities for the fully off-line and fully on-line strategies (for k= 1) can be read from Figure 10 by taking the length as ∞ or 0.

A reasonable question to ask at this point is whether there is some optimal value for the length of speed-change lanes, where the guideway is employed most efficiently. A natural way of measuring guideway utilization is in terms of the capacity per (total) line C_ℓ, which we define to be

$$C_\ell = \frac{\text{capacity of route (vehicles per hour)}}{\text{total mileage of guideway (including speed change lanes) per mile of route}}$$

A strategy will be termed optimal if it maximizes C_ℓ.

In Figure 11, the results of Figure 10 have been replotted to show C_ℓ as the ordinate. It is clear that for k= 1 the optional strategy is to perform a large part of the acceleration on-line (more than 50 percent at speeds of 60 mph or more). The corresponding curves for k= 0 are not shown, but it should be clear from Figure 8 (where maximum slopes occur near the breakpoints) that the strategy which maximizes C_ℓ for k= 0 is close to being purely off-line.

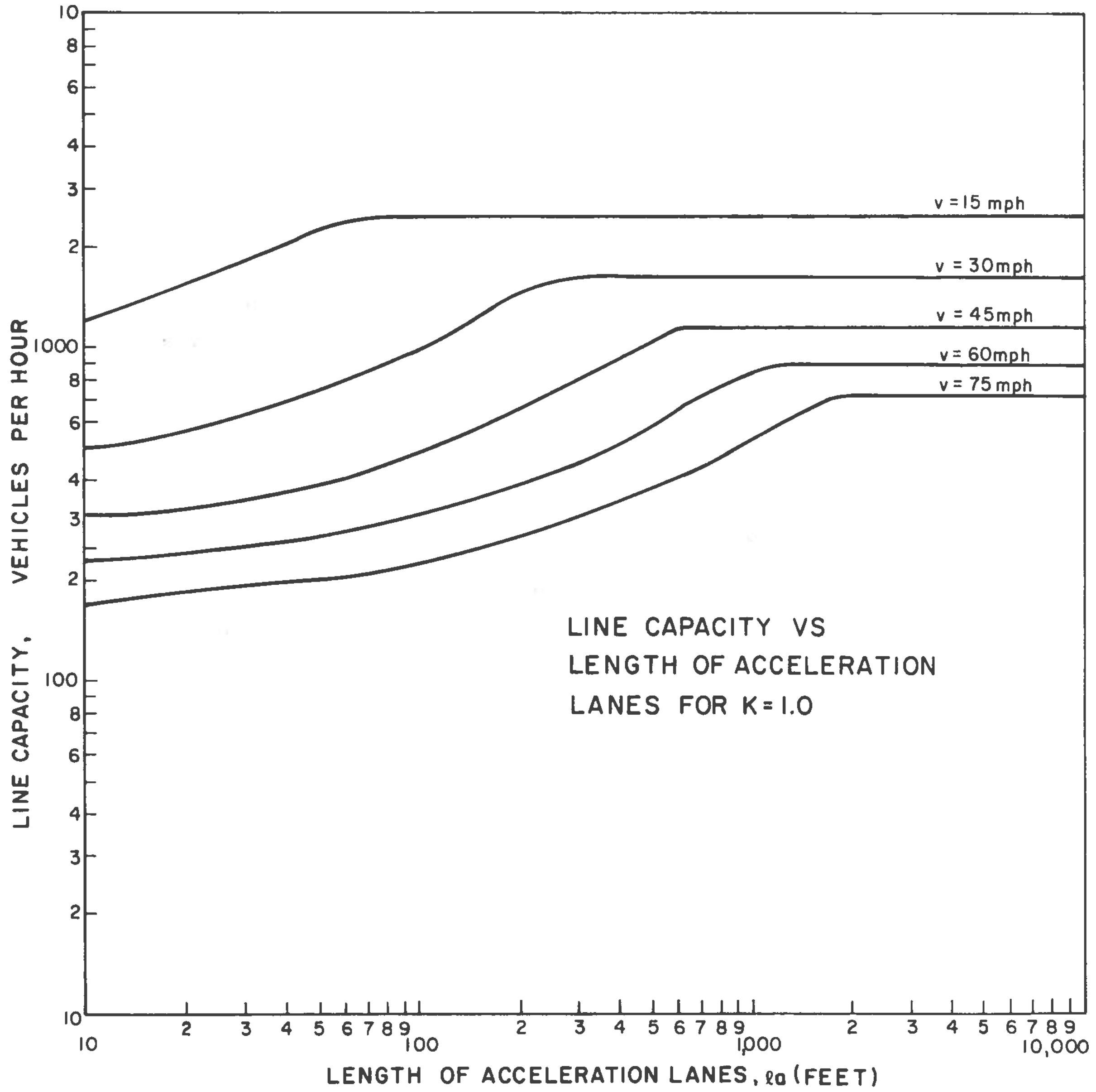


Figure 10. Capacity vs. Acceleration Lane Length for Synchronous-Slot, Partial On-Line, Speed-Change Strategy, k=1

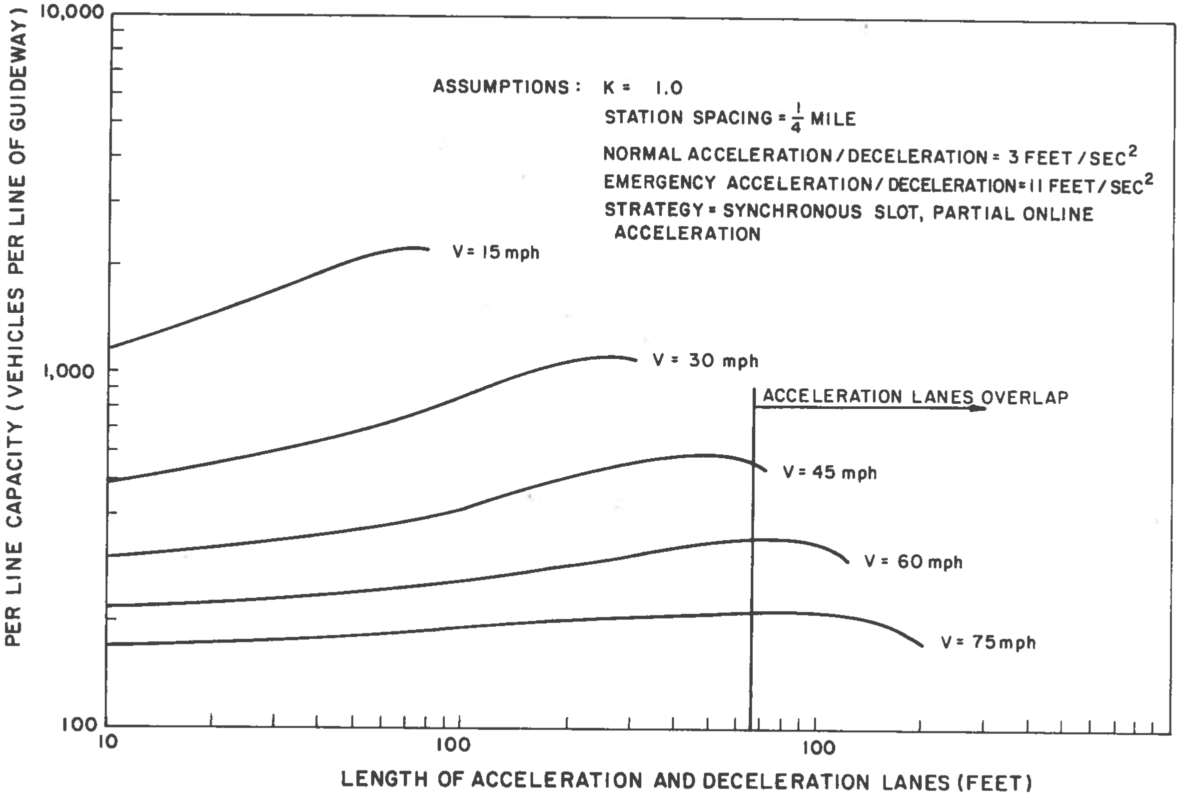


Figure 11. Line Capacity vs. Acceleration Lane Length

Finally, in Figure 12 we show per-line capacity as a function of velocity for various strategies. For the partial on-line strategy, it has been assumed that speed-change lane lengths have been optimized.

The following points are noted in relation to Figure 12 (assuming k= 1.0 and 1/4 mile station spacing):

1. If the required capacity is low, i.e., below the lowest curve in Figure 12, then a purely on-line speed change strategy is best, i.e., minimizes the total length of guideway required.

2. If the required capacity is higher than in 1 but below the dashed line in Figure 12, then the best strategy is to employ a single main line and to add acceleration lanes.

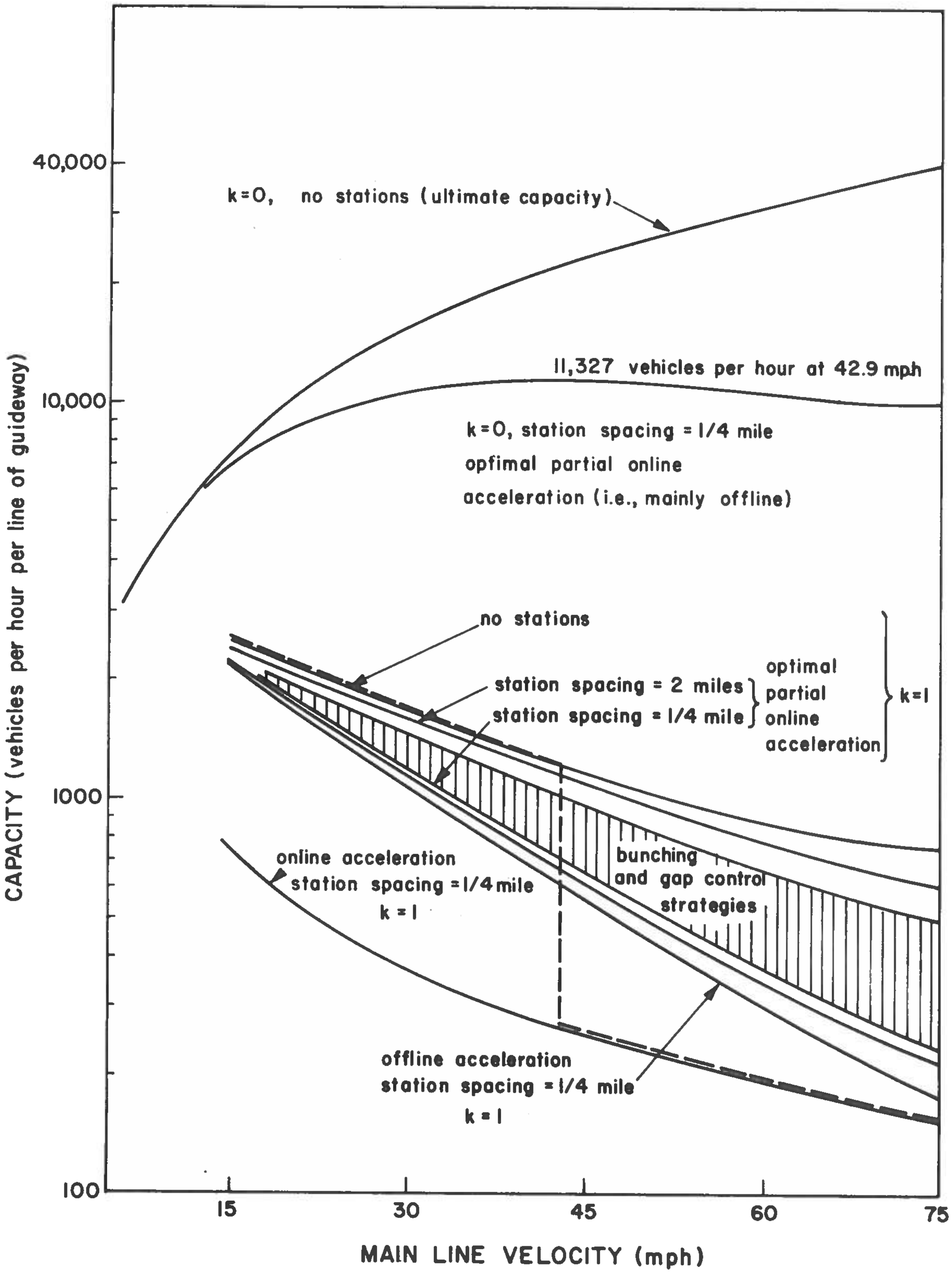


Figure 12. Line Capacity vs. Velocity, Assuming Acceleration/Deceleration Limits are:
Emergency = 11 ft/sec^2
Normal = 3 ft/sec^2

3. If the required capacity is higher, then the best strategy may require the use of several main lines and acceleration lanes.

(The vertical portion of the dashed lines in Figure 12 occurs at 42.9 mph, at which speed acceleration lanes from one station overlap the next station.)

2.2.2 Random Gap Strategy. This strategy has been studied extensively by Ford, Roessler and Waddel,[1] who have shown that under it there is an optimal value for the mean headway. However, this strategy appears to be inferior to the synchronous slot strategy in several respects:

1. Gaps that are too short to be accepted are wasted, with an attendant loss in capacity. This strategy produces a lower capacity and longer waiting time at every speed than the synchronous strategy.
2. The required control system is probably more difficult to implement than for the synchronous strategy.
3. The strategy is not applicable for deceleration. Deceleration must be accomplished on a deceleration lane or with gap control. There appears to be no clear reason, however, for performing acceleration one way and deceleration another.

Since random gap acceptance strategy appears to have little to recommend (except perhaps at long headways), with many of the detailed results in Ref 1 specific to it alone (e.g., results on optimal headways, waiting time, etc.), they will be omitted here.

2.2.3 Bunching and Gap Control. Bunching and gap-control strategies would produce per line capacities higher than the synchronous-slot, partial on-line acceleration strategy, but lower than the no-station capacity (Figure 12). Accurate capacity figures would depend on details of the strategy and have not been calculated.

A strategy is decoupled (totally decoupled) if speed change maneuvers affect the velocity of (at most) a limited number (zero) of following vehicles. The synchronous strategies are totally decoupled, an advantage in that passengers are not subjected to repeated speed changes. The bunching strategy is decoupled (but not totally); The gap-control strategy has the disadvantage of being coupled.

The gap-control strategy would produce higher per-line capacities and lower waiting times (to merge) than the bunching strategy, but these advantages might be overweighed by the loss of decoupling.

2.2.4 Train Operation. A train-operation strategy would offer capacities even higher than those obtainable from a bunching strategy. Although capacity calculations have not been carried out, capacities approaching 1/4 of ultimate capacity might be attainable. Train strategies are decoupled. They require merging vehicles to wait (to form trains in proper sequence). Waiting times would increase with length of trains.

The merits of train vs. bunching strategies from the safety point-of-view are not entirely clear. The vehicles in a train operate at zero headway, but this factor might be offset by the solid coupling between vehicles. It might be easier to achieve public acceptance for a train strategy than for small headway operation.

2.3 EFFECTS OF ACCELERATION LIMITS AND STATION SPACING

The length of required speed-change lanes is inversely proportional to the acceleration limit, which has been taken to be 3 ft/sec^2 throughout this discussion. This is a conservative limit for longitudinal speed changes for the majority of seated passengers. By comparison, a high-powered American automobile which accelerates from 0 to 60 mph in 8 to 10 seconds experiences average accelerations of 8.8 to 11 ft/sec^2, i.e., higher by a factor of about 3. On the other hand, weak or standing passengers (e.g., children) might have trouble with the higher accelerations. As system costs are sensitive to the acceleration figure, further study of the acceleration and jerk problems would be desirable, particularly with reference to the following points:

1. The speed change that can be realized comfortably in a given time interval can be increased by shaping the acceleration-jerk profile to give passengers time to tense their muscles. What is an optimal profile and what is the resulting maximum acceleration?

2. If the proportion of passengers who can not withstand high accelerations is found to be small, it might be worthwhile to have an adaptive acceleration strategy in which passengers could request accelerations lower (or higher) than normal by pressing a button. For example, in conjunction with the synchronous-slot strategy discussed previously, normal acceleration might occur in an interval two "slots" long; weak passengers could request the speed change interval to be increased to three slots; passengers in a hurry might request a single slot acceleration.

The figure of 11 ft/sec^2 for emergency acceleration could probably be increased somewhat for seated passengers, but not by very much.

Station spacing is another parameter to which system costs are very sensitive. The length of speed-change lanes per unit of area and the number of stations per unit area vary inversely with the square of the distance between stations. Thus, an increase in spacing from 0.25 miles to 0.35 miles would approximately halve these costs.

2.4 SAFETY CONSIDERATIONS FOR SMALL HEADWAY OPERATION

The conventional wisdom is that the public will not accept operation at small headways. In the same vein, it is frequently argued that operation of small vehicles at small headways is inherently not as safe as operation of conventional vehicles in trains. This argument is not very well founded and, in fact, strong counter arguments can be made as follows:

1. A fully loaded railroad car exposes 150 to 200 passengers to maximum injury in a crash. As many as 1500 to 2000 passengers might be injured in an accident involving a single 10-car train. On the other hand, a small headway operation would expose less than

   30 passengers at $k = 0.2$

   60 passengers at $k = 0.1$

   120 passengers at $k = 0.05$

   (Assuming fully loaded 6-passenger vehicles; average exposures would be lower.)

2. If a PRT vehicle is involved in a crash, the forces transmitted to succeeding vehicles, assuming they are functioning properly, can be reduced by successive decelerations and by shock-absorbing bumpers. In a train, on the other hand, the force is transmitted the length of the train nearly unattenuated via solid couplers. The only situation in which small headway operation would not be less dangerous than train operation would be one in which brakes of many succeeding vehicles were to fail simultaneously, in which case a multiple crash of the kind encountered on icy highways might occur. (By contrast, the solid coupling in a train is much less likely to fail.) However, overall probabilities might still favor small headway operation.

3. It is easier to design small cars to minimize crash injuries than large ones.

2.5 CONCLUDING COMMENTS ON LINE CAPACITIES

1. The capacity of a PRT line, and hence the feasibility of the entire PRT concept, is highly susceptible to the type of operating strategy employed. For example, at 75 mph the following per line capacities are obtained (Figure 11):

Strategy	k	Station Spacing	Vehicles Per Hour Per Line
Off-line acceleration	0	∞	39,600
Off-line acceleration	0	1/4 mile	9,700
Off-line acceleration	1	∞	710
Off-line acceleration	1	1/4 mile	153

The spread of capacities has a ratio of more than 250:1. A deeper study of potential strategies, especially of training, bunching, and gap-control strategies and attendant waiting times is needed before satisfactory estimates of PRT performance can be obtained.

2. The critical question in PRT design is whether k<1 is acceptable. If it is acceptable, we have a very flexible concept which can yield capacities of many thousands of vehicles per hour per (total) lane of guideway at high velocities (more than 60 mph), and close-station spacings (1/4 mile). If it is not acceptable, then a much more inflexible concept, in which attainment of sufficient line capacity becomes the major problem. Per line capacities available at k=1, at 75 mph, and 1/4-mile station spacing, are in the range of 150 to 300 vehicles per hour depending on strategy. This is inadequate for most urban high-speed applications.

The conventional wisdom is that the public will not accept k<1. In view of the large penalty that must be paid for small headways and the strong arguments that can be mustered in favor of (Section 5) small k-operation, a thorough study of all aspects of the k-factor argument is needed.

3. If simple k<1 operation is rejected, a train strategy might still be acceptable. A train strategy would be much less flexible and might increase waiting times at merge points, but, for simple configurations, could greatly increase capacity. The increased capacity obtained through train operation might be comparable to that of low-medium, capacity line-haul operations. In any case, the merits of train operation versus small k-operation deserve study.

   If the k>1 restriction is insisted upon, then the following conclusions can be drawn:

4. Something must be sacrificed, e.g., speed, station spacing, or per line capacity. Capacity is very sensitive to speed. For example, halving the speed from 60 mph to 30 mph increases capacity by a factor of more than 3, from about 320 to 1020 vehicles per hour per line (under a partial on-line strategy, k=1, station spacing = 1/4 mile).

5. At k>1, it would be advantageous to divide the PRT network into local and long distance grids. The local grid might consist of low-speed (about 20 to 30 mph), closely-spaced (1/4 mile), single lines with capacities of 1000 to 1500 vehicles per hour which would be used for most of the short distance (less than 3 miles) trips and would serve as a collection and distribution system for the long-distance grid. All stations would be on the local grid. The long-distance grid might consist of fast (60 to 75 mph) lines on which all vehicles would travel at constant speeds at minimum safe headways. Each line would have a relatively low capacity (700 vehicles per hour; this figure could be increased somewhat by permitting higher emergency decelerations on long-distance lines). Long-distance lines would be paralleled to provide enough capacity, as in a conventional expressway. The grid spacing for the long-distance system would be large (2 to 4 miles). There would be no stations on the long-distance grid. The two grids would be connected by speed-change ramps entering the high-speed grid at 1 to 2 mile intervals. The advantage of dividing the network into two parts

would be that it would permit high speeds on long trips where they are most needed, while keeping the total length.

The main difficulty with the preceding scheme is that a large number of parallel lines would be required to achieve enough capacity on the high speed grid. Capacity could be increased by train operation which might be limited in the high-speed part only, where there would be no stations and relatively few routes. Alternatively, larger vehicles (8 to 40 passengers) might be employed on the high-speed grid, with passenger transfers required between high and low speed grids during rush hours. The last alternative would represent a departure from completely personalized service. However, passenger transfers could be designed so that passengers would not have to change platforms (vehicles would move instead), and would be much more convenient than at present.

2.6 STATION CAPACITIES

A typical 9 by 6 ft PRT vehicle carrying an average of 1.5 passengers requires 36 ft^2 per passenger carried. By comparison, a conventional 100-ft by 10-ft subway car can pack in 170 passengers at 6 ft^2 per passenger, or 1/6 as much space. The platform facilities of a large PRT station are likely to require 4 to 8 times as much space as in a conventional station. This fact places the PRT concept at a serious disadvantage in comparison to conventional systems, particularly in downtown areas where land is expensive.

This disadvantage is offset somewhat by the fact that PRT stations can be proportioned (to demand) more easily than train stations. Even the smallest train stations must be able to accommodate the longest trains, and, therefore, usually have excess capacity in suburban areas. PRT stations can, furthermore, be subdivided to fit available land parcels, whereas conventional train stations cannot.

Estimated space requirements for stations are shown in Figure 13. These estimates are obtained under the assumptions that each loading dock occupies 60 ft^2 (10'x6') of space, that each dock can unload and load a vehicle carrying 1.5 passengers

on the average in 30 seconds, that docks are operated at 80 percent of capacity, and that the following space factors are valid:

Dock space	1
Platform space	1 to 3 times dock space
Vehicle parking space for 80% dock utilization	0.5 to 2 times dock space
Guideway for in-station movements	1 to 3 times dock space
TOTAL	3.5 to 9 times dock space

(The actual requirements for docks, platforms, parking and maneuvering space for large stations are likely to fall into the range of 5 to 8 times dock space.)

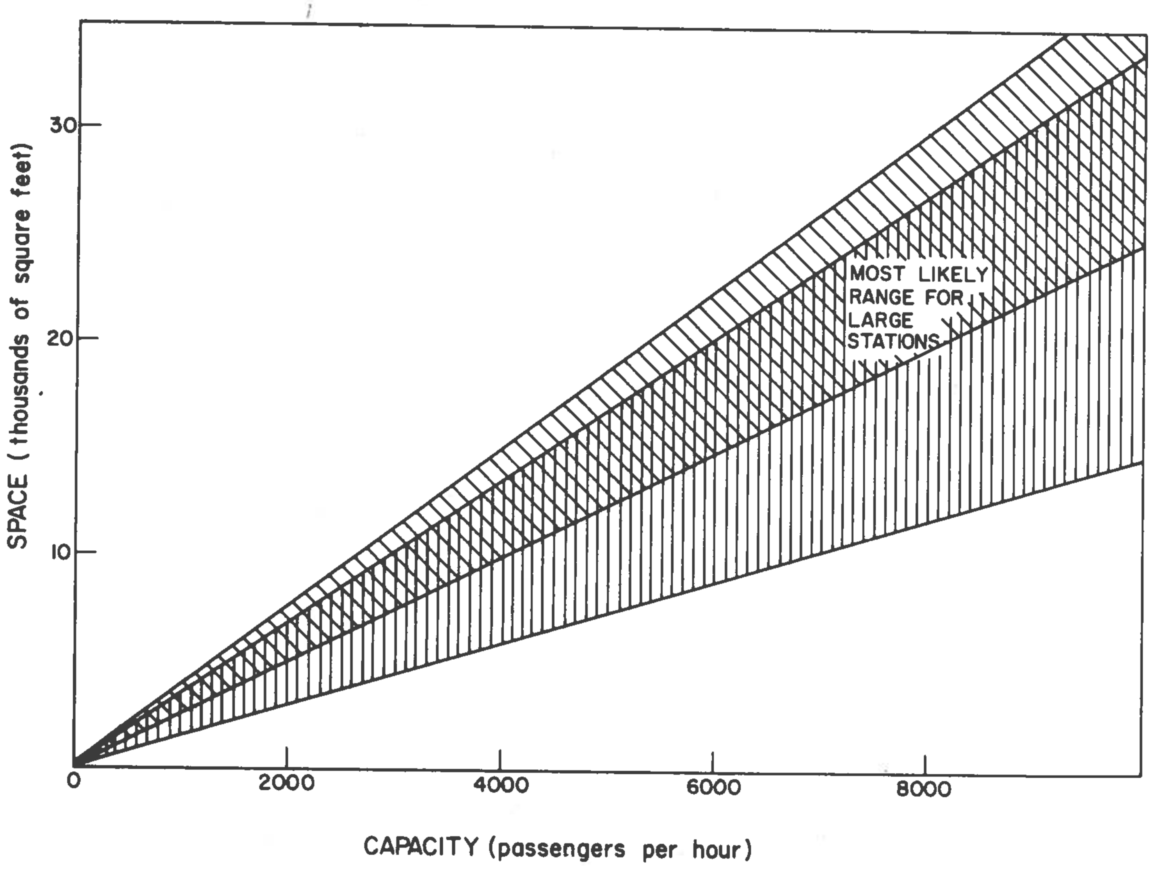


Figure 13. Space Requirements for PRT Stations

A 2,000 passenger per hour PRT station for an airline terminal might require 7,000 ft^2 of space for docks, platforms, guideways and vehicle parking, with added space for waiting rooms, lavatories, staircases, dining and commercial facilities which could equal that amount. In other words, most of one floor of an airline terminal building would have to be given over to PRT operations and this might not be acceptable.

Although PRT stations would undoubtedly consume much more space than conventional stations, it should be remembered that they would consume much less than is being allocated for automobiles. For example, the Eastern Airlines terminal in Boston has five levels of parking space built into it, a large area devoted to parking and roadways around it, and is already suffering from parking space shortages.

3. CAPACITY REQUIREMENTS OF URBAN GRIDS

In the preceding section, the passenger-carrying capacities of PRT lines were estimated. In this section the capacity requirements of various urban passenger systems will be examined to determine whether these requirements can be satisfied by networks or grids of closely spaced PRT lines. Among the specific objectives is to determine whether PRT networks could satisfy the capacity requirements of typical community and Central Business District internal collection-distribution systems.

The context here is one of trying to delineate the maximum that could be accomplished in the long term with the technology now being developed. The concern is primarily with feasibility without regard to costs or benefits. Consequently, emphasis will be placed on the pure PRT concept and on very dense grids (with an average spacing of about 1/4 mile). On the other hand, $k>1$ (i.e., conservative) and a relatively unsophisticated control strategy will be assumed. In order to obtain conservative estimates of feasibility, some of the demand and modal split parameters will be slanted to the high side.

The approach used here is to break up passenger flows into components. Two types of component flows are used in this analysis:

1. Omnidirectional flows, with uniformly distributed origins and destinations, in an unbounded area.

2. Radial flows towards a center, with origins uniformly distributed over a finite circular or square service area.

Each component is characterized by the density of guideways, expressed in miles per square mile, needed to service a given population density with specified demand and modal split characteristics. The overall requirements are obtained by summing the components.

This section is organized as follows: In Section 3.1 a relationship is obtained between uniform grid requirements and demand characteristics. In Section 3.2, recent demand characteristics of U.S. urban areas are documented. In Section 3.3, the results of Sections 3.1 and 3.2 are combined to give guideway density figures for typical demand characteristics. In Section 3.3, a similar analysis is carried out for radial grids with centers. Some typical examples involving community and CBD systems are then worked out in Section 3.4. Finally, conclusions about PRT feasibility are drawn in Section 3.5.

3.1 UNIFORM, CAPACITY-LIMITED GRIDS: CAPACITY EQUATIONS

This section considers the problem of covering an urban area of relatively uniform population density by a comprehensive grid (Figure 14), in which component lines have low capacities and in which the grid design is therefore determined mainly by capacity requirements. Assume that:

1. The grid is comprehensive enough to offer many alternative paths between most pairs of points.

2. Fluctuations in population density are small when population is averaged over an area comparable to the average grid-mesh area.

The preceding two assumptions, together with the low capacity mentioned earlier, make it likely that:

3. The grid layout will be designed to keep the passenger flows approximately equal on all links when averaged over time.

4. The supervisory control system will reroute vehicles to keep passenger flows approximately equal on all links during peak hours; i.e., vehicles will be rerouted from links near saturation to less congested links; the direction of flow will also be adjusted as needed.

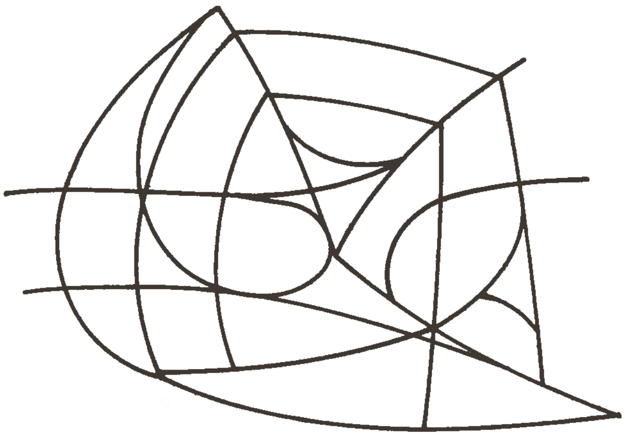


Figure 14. A Comprehensive Grid

The preceding assumptions would hold reasonably well for a collection-distribution grid consisting of PRT lines in a suburb where there were no centers of high population density. They might also hold for a collection-distribution grid within a Central Business District if the grid spacing were kept small. For such a grid we shall calculate the required line capacity.

Let

ρ = population density per square mile

α = average number of total trips generated per person per day (the trip generation rate)

μ_a = fraction of all trips using the grid system (the modal split)

ϕ_p = fraction of public transit trips occurring during the peak hour (the peak hour factor)

γ = ratio of average passenger flow per link-to-link capacity (capacity utilization factor)

L = total guideway mileage per square mile

$\bar{d}$ = average trip length

C = required guideway capacity, passengers per hour per line

ω = peak-hour trips per person on public transit

Then,

$$C = \frac{\phi_p \mu_a \alpha \rho \bar{d}}{\gamma L} = \frac{\omega \rho \bar{d}}{\gamma L} \qquad (1)$$

where,

$$\omega = \phi_p \mu_a \alpha \qquad (1a)$$

Replacing Equation (1) we shall use the equivalent equation

$$C = \frac{\mu_p \phi_a \alpha \rho \bar{d}}{\gamma L} = \frac{\omega \rho \bar{d}}{\gamma L} \qquad (2)$$

where

ϕ_a = fraction of all trips occurring during peak hour

μ_p = fraction of peak-hour trips allotted to public transit

and

$$\omega = \mu_p \phi_a \alpha \tag{2a}$$

In the following section, data for some of the parameters in the capacity equation, based on various studies of U.S. cities, will be presented. In particular, we shall discuss trip generation rates, modal split factors, peak-hour factors and mean travel distances. In later sections we shall employ this data to relate grid spacing to population characteristics.

3.2 URBAN DEMAND CHARACTERISTICS

3.2.1 Trip Generation Rates, α. Peat, Marwick, Livingston and Co. has compiled data on total trips generated daily per person for 60 U.S. cities.[3] The results are shown in Figure 15, and a key to the data points is provided in Tables 1 and 2. Data on trip breakdown by purpose is shown in Figures 16 and 17, based on a (smaller) sample of 14 U.S. cities. In view of the high correlation between automobile ownership and trip generation rates, we have classified cities as "Automobile oriented," "Public transit oriented", or "mixed," and obtained the following approximated ranges for trip generation rates, based on Figure 15.

Trip generation data for subdivisions of cities such as CBD, residential suburbs, etc., is scarce. We shall base our estimates on CBD trip generation and modal split rates on figures provided by Haney for the Dallas CBD for 1980 (projected).[4]

The Dallas CBD occupies a land area of 1.5 square miles, and its population excluding visitors is estimated (using an interpolation of Haney's figures) at 180,000 of whom all but 15,000 are employed within the CBD but live outside it.

3.2.2 Modal Split Factors, μ. The proportion of trips carried by public transportation shows a wide variation across U.S. cities. The automobile oriented cites on the West Coast such as the Seattle-Tacoma SMSA (μ_a = 5.3% of all trips), the Los Angeles-Long Beach SMSA (μ_a = 7.6% of work trips), and the San Diego SMSA (μ_a = 5.5% of work trips), are at the lower end of the scale. On the other end of the scale are figures for central cities of public transit oriented centers such as Boston (40% of

TABLE 1. LISTING OF 1960-BASED ANALYSIS AREAS 2

Area #	Description
001	Abilene, Texas
002	Akron, Ohio
003	Albany, Georgia
004	Albany-Schenectady-Troy, New York
005	Albuquerque, New Mexico
006	Allentown-Bethlehem-Easton, Pennsylvania-New Jersey
007	Altoona, Pennsylvania
008	Amarillo, Texas
009	Ann Arbor, Michigan
010	Asheville, North Carolina
011	Atlanta, Georgia
012	Atlantic City, New Jersey
013	Augusta, Georgia-South Carolina
014	Austin, Texas
015	Bakersfield, California
016	Baltimore, Maryland
017	Baton Rouge, Louisiana
018	Bay City, Michigan
019	Beaumont-Port Arthur, Texas
020	Billings, Montana
021	Binghamton, New York
022	Birmingham, Alabama
023	Boston, Massachusetts
024	Bridgeport, Connecticut
025	Brockton, Massachusetts
026	Brownsville-Harlingen-San Benito, Texas
027	Buffalo, New York
028	Canton, Ohio
029	Cedar Rapids, Iowa
030	Champaign-Urbana, Illinois
031	Charleston, South Carolina
032	Charleston, West Virginia
033	Charlotte, North Carolina
034	Chattanooga, Tennessee-Georgia
035	Chicago, Illinois
036	Cincinnati, Ohio-Kentucky
037	Cleveland, Ohio
038	Colorado Springs, Colorado
039	Columbia, South Carolina
040	Columbus, Georgia-Alabama
041	Columbus, Ohio
042	Corpus Christi, Texas
043	Dallas, Texas
044	Davenport-Rock Island-Moline, Iowa-Illinois
045	Dayton, Ohio
046	Decatur, Illinois
047	Denver, Colorado
048	Des Moines, Iowa
049	Detroit, Michigan
050	Dubuque, Iowa
051	Duluth-Superior, Minnesota-Wisconsin
052	Durham, North Carolina
053	El Paso, Texas
054	Erie, Pennsylvania
055	Eugene, Oregon
056	Evansville, Indiana-Kentucky
057	Fall River, Massachusetts-Rhode Island
058	Fargo-Moorhead, North Dakota-Minnesota
059	Fitchburgh-Leominster, Massachusetts
060	Flint, Michigan
061	Fort Lauderdale-Hollywood, Florida
062	Fort Smith, Arkansas
063	Fort Wayne, Indiana
064	Fort Worth, Texas
065	Fresno, California
066	Gadsden, Alabama
067	Galveston-Texas City, Texas
068	Gary-Hammond-East Chicago, Indiana
069	Grand Rapids, Michigan
070	Great Falls, Montana
071	Green Bay, Wisconsin
072	Greensboro-High Point, North Carolina
073	Greenville, South Carolina
074	Hamilton-Middletown, Ohio
075	Harrisburg, Pennsylvania
076	Hartford, Connecticut
078	Houston, Texas
079	Huntington-Ashland, West Virginia-Kentucky-Ohio
080	Huntsville, Alabama
081	Indianapolis, Indiana
082	Jackson, Michigan
083	Jackson, Mississippi
084	Jacksonville, Florida
085	Jersey City, New Jersey
086	Johnstown, Pennsylvania
087	Kalamazoo, Michigan
088	Kansas City, Missouri-Kansas
089	Kenosha, Wisconsin
090	Knoxville, Tennessee
091	Lake Charles, Louisiana
092	Lancaster, Pennsylvania
093	Lansing, Michigan
094	Laredo, Texas
095	Las Vegas, Nevada
096	Lawrence-Haverhill, Massachusetts-New Hampshire
097	Lawton, Oklahoma
098	Lewiston-Auburn, Maine
099	Lexington, Kentucky
100	Lima, Ohio
101	Lincoln, Nebraska
102	Little Rock-North Little Rock, Arkansas
103	Lorain-Elyria, Ohio
104	Los Angeles-Long Beach, California
105	Louisville, Kentucky-Indiana
106	Lowell, Massachusetts
107	Lubbock, Texas
108	Lynchburg, Virginia
109	Macon, Georgia
110	Madison, Wisconsin

TABLE 1. LISTING OF 1960-BASED ANALYSIS AREAS 2 (Continued)

Area #	Description
111	Manchester, New Hampshire
112	Memphis, Tennessee
113	Meriden, Connecticut
114	Miami, Florida
115	Midland, Texas
116	Milwaukee, Wisconsin
117	Minneapolis-St. Paul Minnesota
118	Mobile, Alabama
119	Monroe, Louisiana
120	Montgomery, Alabama
121	Muncie, Indiana
122	Muskegon-Muskegon Heights, Michigan
123	Nashville, Tennessee
124	New Bedford, Massachusetts
125	New Britain, Connecticut
126	New Haven, Connecticut
127	New London-Groton-Norwich, Connecticut
128	New Orleans, Louisiana
129	New York, New York
130	Newark, New Jersey
131	Newport News-Hampton, Virginia
132	Norfolk-Portsmouth, Virginia
133	Norwalk, Connecticut
134	Odessa, Texas
135	Ogden, Utah
136	Oklahoma City, Oklahoma
137	Omaha, Nebraska-Iowa
138	Orlando, Florida
139	Paterson-Clifton-Passaic, New Jersey
140	Pensacola, Florida
141	Peoria, Illinois
142	Philadelphia, Pennsylvania - New Jersey
143	Phoenix, Arizona
144	Pittsburg, Pennsylvania
145	Pittsfield, Massachusetts
146	Portland, Maine
147	Portland, Oregon-Washington
148	Providence-Pawtucket-Warwick, Rhode Island-Massachusetts
149	Provo-Orem, Utah
150	Pueblo, Colorado
151	Racine, Wisconsin
152	Raleigh, North Carolina
153	Reading, Pennsylvania
154	Reno, Nevada
155	Richmond, Virginia
156	Roanoke, Virginia
157	Rochester, New York
158	Rockford, Illinois
159	Sacramento, California
160	Saginaw, Michigan
161	St. Joseph, Missouri
162	St. Louis, Missouri-Illinois
163	Salt Lake City, Utah
164	San Angelo, Texas
165	San Antonio, Texas
166	San Bernardino-Riverside-Ontario, California
167	San Diego, California
168	San Francisco-Oakland, California
169	San Jose, California
170	Santa Barbara, California
171	Savannah, Georgia
172	Scranton, Pennsylvania
173	Seattle, Washington
174	Shreveport, Louisiana
175	Sioux City, Iowa
176	Sioux Falls, South Dakota
177	South Bend, Indiana
178	Spokane, Washington
179	Springfield, Illinois
180	Springfield, Missouri
181	Springfield, Ohio
182	Springfield-Chicopee-Holyoke, Massachusetts
183	Stamford, Connecticut
184	Steubenville-Weirton, Ohio-West Virginia
185	Stockton, California
186	Syracuse, New York
187	Tacoma, Washington
188	Tampa-St. Petersburg, Florida
189	Terre Haute, Indiana
190	Texarkana, Texas-Arkansas
191	Toledo, Ohio-Michigan
192	Topeka, Kansas
193	Trenton, New Jersey
194	Tucson, Arizona
195	Tulsa, Oklahoma
196	Tuscaloosa, Alabama
197	Tyler, Texas
198	Utica-Rome, New York
199	Waco, Texas
200	Washington, D. C. -Maryland-Virginia
201	Waterbury, Connecticut
202	Waterloo, Iowa
203	West Palm Beach, Florida
204	Wheeling, West Virginia-Ohio
205	Wichita, Kansas
206	Wichita Falls, Texas
207	Wilkes-Barre-Hazleton, Pennsylvania
208	Wilmington, Delaware-New Jersey
209	Winston-Salen, North Carolina
210	Worcester, Massachusetts
211	York, Pennsylvania
212	Youngstown-Warren, Ohio
213	Salem, Oregon
214	Bloomington-Normal, Illinois
215	Fayetteville, North Carolina

TABLE 2. CONTIGUOUS AREA GROUPINGS

Analysis Areas		Contiguous Areas Included	
#	Area	#	Area
23	Boston, Massachusetts	23	Boston, Massachusetts
		96	Lawrence, Haverhill, Massachusetts
		106	Lowell, Massachusetts
24	Bridgeport, Connecticut	24	Bridgeport, Connecticut
		133	Norwalk, Connecticut
		183	Stamford, Connecticut
35	Chicago, Illinois	35	Chicago, Illinois
		68	Gary, Hammond, East Chicago, Indiana
57	Fall River, Massachusetts	57	Fall River, Massachusetts
		124	New Bedford, Massachusetts
59	Fitchburg, Leominster, Massachusetts	59	Fitchburg, Leominster, Massachusetts
		210	Worcester, Massachusetts
76	Hartford, Connecticut	76	Hartford, Connecticut
		125	New Britain, Connecticut
126	New Haven, Connecticut	113	Meridan, Connecticut
		126	New Haven, Connecticut
		201	Waterbury, Connecticut
129	New York, New York	85	Jersey City, New Jersey
		129	New York, New York
		130	Newark, New Jersey

TABLE 3. DAILY TRIPS PER PERSON GENERATED IN SMSAs

Automobile Oriented SMSAs	Mixed SMSAs	Public Transit Oriented SMSAs
2.2 - 3.3	1.9 - 2.8	1.6 - 2.3

TABLE 4. TRIPS IN THE DALLAS CBD (1980)

Trip Type	Total Daily Trips	Daily Trips Per Person
External trips (1 end outside CBD):	650,000	3.5
Internal trips (both ends in CBD) excluding walking:	230,000	1.3
Internal walking trips:	450,000	2.5
Internal walking trips longer than 1/5 mile:	125,000	0.7
Internal trips excluding walking trips of 1/5 mile or less:	355,000	2

work trips), Philadelphia (41% of work trips) and, to take an extreme case, New York (61% of work trips).

In general, use of public transit tends to increase with population density, congestion, availability of public transit, and inversely with automobile ownership. For the purposes of this study it will be enough to establish some representative ranges for the modal split percentage, without attempting to stratify it in any detail. To this end we have assembled some representative figures from various sources in Tables 5 through 9.[3,4,5] It should be noted that Table 5 refers to total trips over urbanized area, Tables 6 and 7 to work trips over SMSAs and central cities respectively, and Table 8 to total trips across CBD boundaries. Moreover, some of the data is old, and current figures would likely be lower, particularly in the case of CBDs.

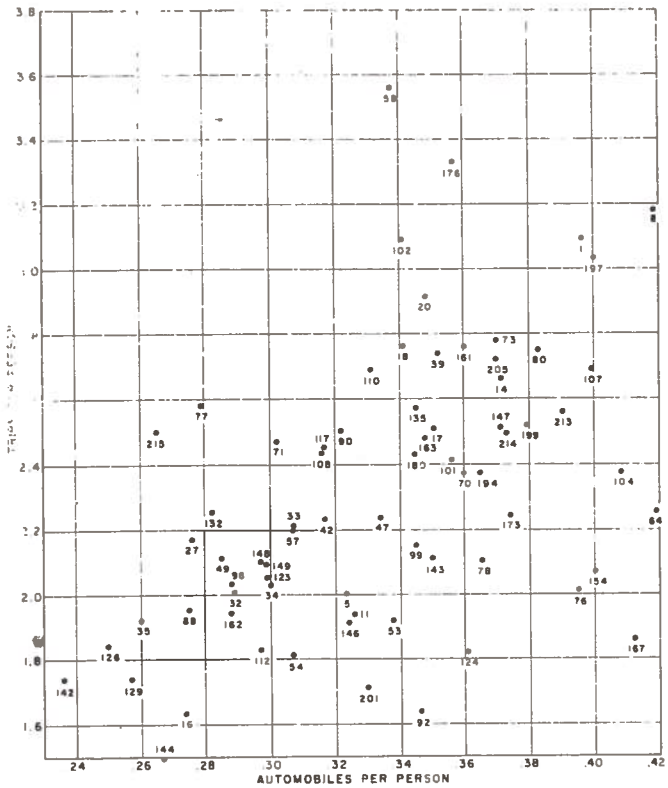


Figure 15. Stratification of Trips Per Person By Population

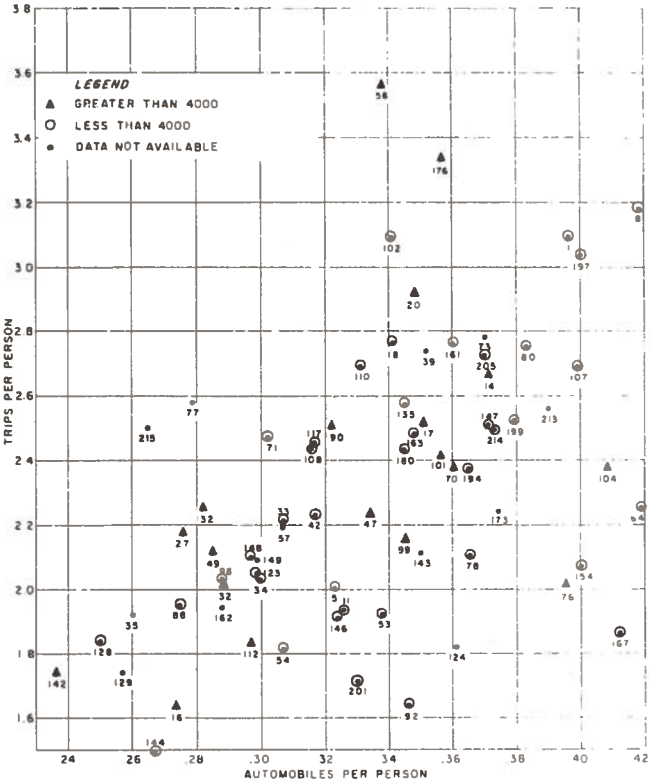


Figure 16. Projection of Urban Personal Transportation Demand (Source: Peat, Marwick, Livingston and Co.)[3]

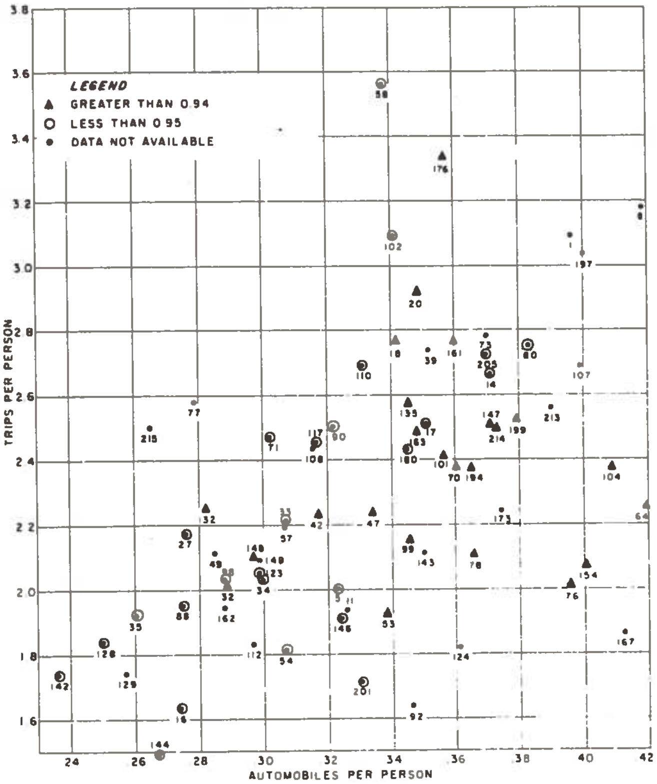


Figure 17. Trips Per Person Vs. Automobiles Per Person As A Function of Population

Table 5. Overall Modal Split Data for Nine Urban Areas

City	Study Starting Date	Population	Modal Split % of All Trips on Public Transit
Chicago	55	6.8m	25
Pittsburgh	58	1.4m	20
Washington	60	2m	33*
San Juan, P.R.	64	697th	23
Milwaukee-Racine-Kenosha	63	1.7m	9.2
Minneapolis	60	1.4m	12
Buffalo, N.Y.	62	1.25m	8
Seattle-Tacoma	60	1.4m	5.3
Erie, Pa.	62	178th	4

*For the a.m. peak hour

Source: (M.J. Fertal, E. Weiner, A.J. Balek, A.F. Sevin, "Modal Split," Report of U.S. Dept. of Commerce, Bureau of Public Roads, Office of Planning, Dec., 66).[6]

TABLE 6. PERCENT OF WORK TRIPS CARRIED BY PUBLIC TRANSPORTATION, FOR SMSAs

SMSA	%
Atlanta, Georgia	16.7
Baltimore, Maryland	18.5
Boston, Massachusetts	23.6
Buffalo, New York	16.1
Chicago, Illinois	29.7
Cincinnati, Ohio	16.6
Cleveland, Ohio	21.7
Dallas, Texas	10.9
Detroit, Michigan	12.6
Houston, Texas	10.4
Kansas City, Missouri, Kansas	11.6
Los Angeles-Long Beach, Ca.	7.6
Milwaukee, Wisconsin	21.5
Minneapolis-St. Paul, Minnesota	13.9
New York, New York	51.4
Newark, New Jersey	12.3
Philadelphia, Pennsylvania	26.2
Pittsburgh, Pennsylvania	18.8
St. Louis, Missouri	15.9
San Diego, California	5.5
San Fancisco, California	17.3
Seattle, Washington	11.1
Washington, D.C.	22.2
Patterson-Clifton-Passaic, N.J.	20.2

Source: (G.K. Zenk, M. Frost, "Cities and Transportation: A Factor Analysis of Public Areas," Urban Engineering and Transportation, ASME Winter Annual Meeting, Dec, 1968).[7]

TABLE 7. PERCENT OF WORK TRIPS CARRIED BY PUBLIC TRANSPORTATION, FOR CENTRAL CITIES

Central Cities	%
Atlanta, Georgia	27.9
Baltimore, Maryland	28.0
Boston, Massachusetts	40.0
Buffalo, New York	26.7
Chicago, Illinois	39.5
Cincinnati, Ohio	22.3
Cleveland, Ohio	30.0
Dallas, Texas	15.6
Detroit, Michigan	21.6
Houston, Texas	12.5
Kansas, City, Missouri, Kansas	17.6
Los Angeles-Long Beach Ca.	12.4
Milwaukee, Wisconsin	28.4
Minneapolis-St. Paul, Minnesota	20.1
New York, New York	61.0
Newark, New Jersey	38.0
Philadelphia, Pennsylvania	41.2
Pittsburgh, Pennsylvania	32.1
St. Louis, Missouri	29.3
San Diego, California	7.8
San Francisco, California	36.8
Seattle, Washington	17.9
Washington, D.C.	37.8
Patterson-Clifton-Passaic, N.J.	19.6

Source: (G.K. Zenk, M. Frost, "Cities and Transportation: A Factor Analysis of Public Areas," <u>Urban Engineering and Transportation</u>, ASME Winter Annual Meeting, Dec, 1968).[7]

TABLE 8. NUMBER OF PEOPLE ENTERING CENTRAL BUSINESS DISTRICTS ON A TYPICAL WEEKDAY

1960 SMSA Rank	City	Date of Count	1950 Urbanized Area Population	People Entering Downtown			
				Percent	Number	Percent by Auto	Percent by Transit
1	New York, N.Y.	1956	12,296,117	27	3,316,000	22.2	77.8
2	Chicago, Ill.	1960	4,920,816	17	864,733	40.6	59.4
3	Los Angeles, Calif.	1960	3,996,946	17	678,977	75.2	24.8
4	Philadelphia, Pa.	1955	2,922,470	35	1,018,000	46.3	52.7
6	San Francisco, Calif.	1954	2,022,078	20	400,000	51.0	49.0
7	Boston, Mass.	1954	2,233,448	58	1,263,350	40.8	58.2
9	St. Louis, Mo.	1957	1,400,058	23	323,500	61.6	28.1
11	Cleveland, Ohio	1954	1,383,599	27	370,000	46.0	54.0
--	Toronto, Ont.	1955	1,253,000	30	380,026	42.1	57.6
12	Baltimore, Md.	1955	1,161,852	33	385,431	69.0	31.0
18	Milwaukee, Wis.	1958	829,495	32	262,000	67.6	32.4
21	Kansas City, Mo.	1957	698,350	29	203,689	72.0	28.0
28	New Orleans, La.	1956	659,768	63	413,443	59.9	40.1
20	Seattle, Wash.	1954	621,509	30	185,050	65.3	34.7
30	Providence, R.I.	1957	583,346	53	308,778	79.6	20.4

Source: (Wilbur Smith and Associates, Future Highways and Urban Growth, New Haven, 1961, p. 100).[8]

TABLE 9. EXTERNAL TRIPS--CORDON CROSSINGS IN AND OUT OF THE DALLAS CBD

Combined Inbound and Outbound Crossings* of the Cordon	1950 Core	1958 CBD	1964† CBD	1980A CBD	1980B CBD	2000 CBD
Vehicles						
Trucks and buses	19,000	25,000	75,000	75,000	80,000	85,000
Taxis	7,000	140,000	300,000	30,000	30,000	35,000
Cars	104,000			395,000	345,000	430,000
Total	130,000	165,000	375,000	500,000	455,000	550,000
Persons						
In buses	100,000	92,000	94,000	100,000	160,000	200,000
In autos and taxis	155,000	200,000	534,000	550,000	490,000	600,000
Total	255,000	292,000	628,000	650,000	650,000	800,000
Persons per auto	1.4	1.4		1.3	1.3	1.3
Percentage of persons via transit	39%	32%		15%	25%	25%

---

* Data for normal weekday from 6:00 a.m. to 6:00 p.m. except in 1964.
† Count in 1964: 7:00 a.m. to 6:00 p.m. includes through trips.

Source: (DeLeuw, Cather and Company, Long-Range Transportation Plan for The Central Business District, Dallas, Texas, Chicago, Illinois, 1965, p. 43).9

Zenk and Frost[7] have classified cities into "automobile oriented" (Seattle, Los Angeles, Dallas) and transit oriented (New York, Boston, Philadelphia). We shall employ their classification in conjunction with the data in Table 5-11 to obtain the following approximate ranges for modal split factors:

TABLE 10. MODAL SPLIT RANGES*

	Automobile Oriented	Mixed	Transit Oriented
SMSA (% of peak hour trips, μ_p) (excluding all walking trips)	5-15	16-25	25-50
Central City (% of peak hour trips, μ_p) (excluding all walking trips)	7-18	19-35	36-60
CBD (% of daily cordon crossings, μ_a) (excluding all walking trips)	15-30	30-40	40-70
CBD (% of daily internal trips (excluding walking trips shorter than 0.2 miles)	20-33	33-50	20-75

*The derivation of Table 10 involved a number of rough approximations. In estimating SMSA and central city modal splits, it was assumed that the percentage of daily working trips allotted to public transportation approximates the percentage of peak hour total trips on public transportation. The percentages obtained in this way are likely to be high, i.e., conservative for the purposes of calculating network capacity requirements. Percentages for the CBD are based mainly on the results for Dallas and Chicago given in Haney.[4]

3.2.3 Peak Hour Factors, ϕ. The percentage ϕ of trips occurring during the peak hour is usually estimated at (See Haney)[4]

For all trips (ϕ_a):	7-14%
For conventional public transit systems (ϕ_p):	12-25%

3.2.4 Public Transit Peak Hour Trip Generation Rates. (See Table 11). By combining the results of Sections 1-5, and adjusting them for such factors as the tendency for the peak hour factor ϕ_p to be high when the modal split μ_a is low and vice versa, we obtain the following approximate estimates for the number ω of peak hour trips contributed to the public transit system per person:

TABLE 11. PEAK HOUR DAILY TRIPS ON PUBLIC TRANSIT PER PERSON (ω)

Orientation Area Type	Automobile Oriented	Mixed	Transit Oriented
SMSA	0.008-0.05	0.03-0.07	0.04-0.12
Central City	0.015-0.06	0.04-0.1	0.06-0.14
CBD internal trips*	0.03-0.08	0.06-0.12	0.09-0.16
CBD cordon crossings*	0.05-0.2	0.15-0.4	0.3-0.7

*per employee.

3.2.5 Average Peak Hour Trip Distance, $\bar{d}$. Comprehensive data on travel distances for U.S. cities is scarce. Available results for six cities (with populations between 120,000 and 4 million) show average trip distances between 3 and 5.1 miles (see Figure 18).[2]

Available data on work trips (see Figures 19 and 20) strongly suggests that average trip distances for work trips are longer than for other kinds. Since a large proportion of work trips occur during peak hours, we can expect the average distance for all peak hour trips to be greater than the average distance for all trips. A high quality transportation system moreover, might have the effect of increasing average travel distances.

Our data for average trip distances for travel entirely within the CBD is limited to the figure given for the Dallas CBD by Haney, which is 2500 feet.[4] As most CBDs occupy areas of 0.3-2.2 square miles (Exceptions: New York, 9.1 square miles; Washington, 6.1 square miles), average distances for internal CBD travel are likely to be in the range 1/3 - 1-1/2 miles.

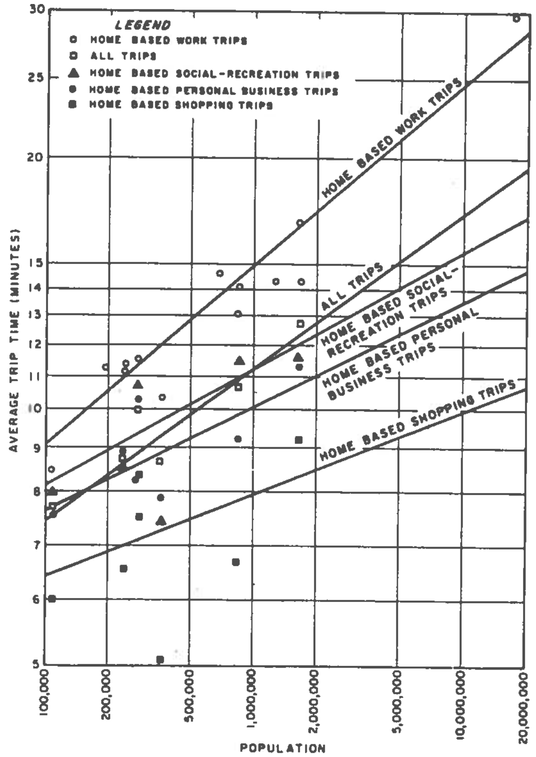


Figure 18. Average Trip Distance vs Population

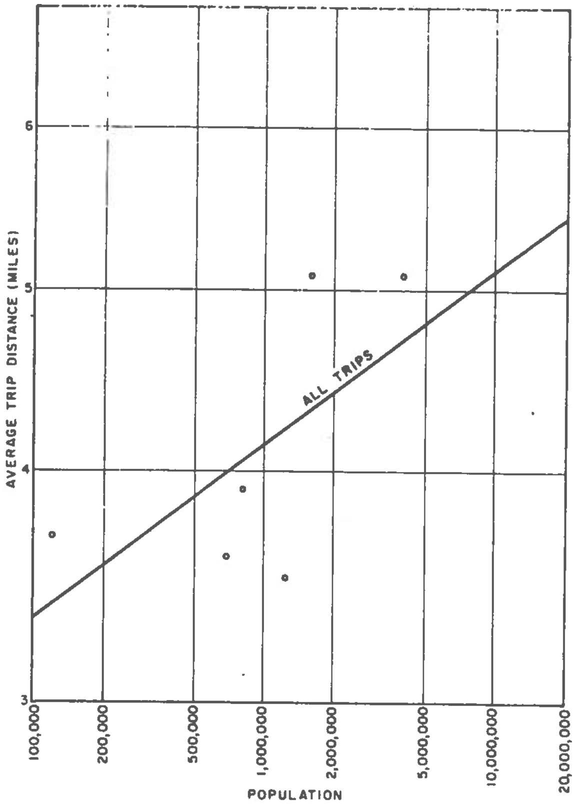
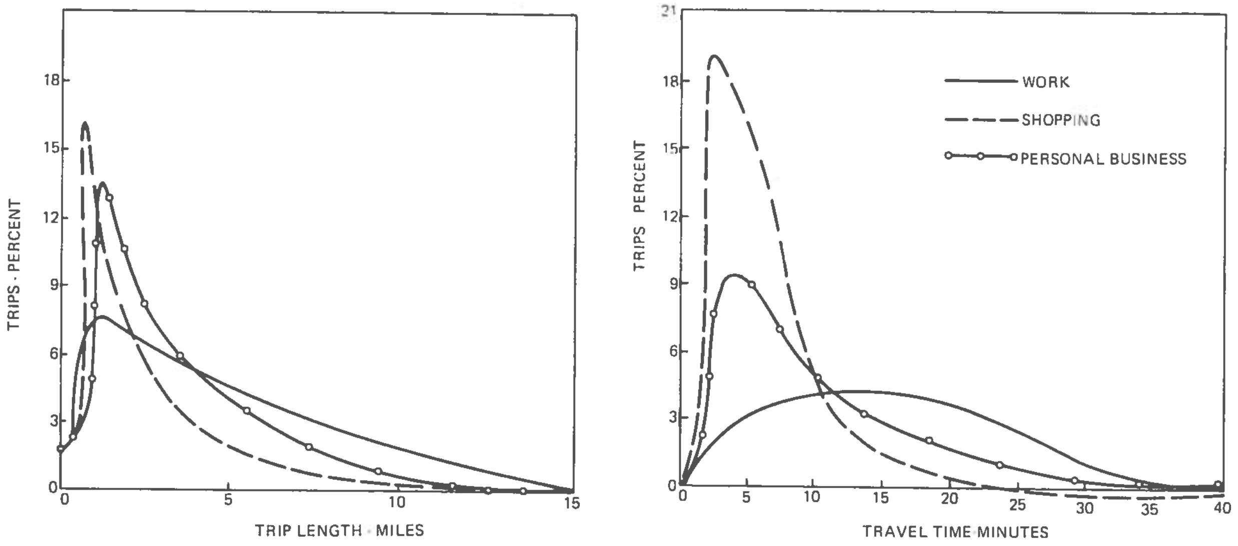


Figure 19. Average Trip Time vs Population by Trip Purpose



A. TRIP LENGTH DISTRIBUTION-TOTAL PERSON TRIPS (MILWAUKEE)

B. TRIP DURATION DISTRIBUTION-TOTAL PERSON TRIPS (BALTIMORE)

Figure 20. Distribution of Person-Trips, by Trip Length and Duration, for Selected Purposes

TABLE 12. TRIP DISTANCES AND DURATIONS BY PURPOSE
(Milwaukee)

Purpose	Distance Average	(miles) Median	Duration Average	(minutes) Median
Work	5.1	2.5	17.6	15.4
Shopping	2.8	1.5	9.	7.6
School	3.0	1.9	11.7	8.9
Personal Business	3.5	2.0	--	--
Social, recreation	4.6	2.6	--	--

Source: ("Land Use-Transportation Study," Vol. 1, "Inventory Findings 1963," Southeastern Wisconsin Regional Planning Commission, p. 148).[10]

3.2.6 <u>The Capacity Utilization Factor, γ .</u> In general it will be impossible to operate each link of a complex network at capacity. This fact is reflected by introducing a utilization factor γ , which will always be less than 1. The utilization factor depends on the nature of demand fluctuations and, most importantly, on the manner in which the network is operated. We shall assume that the network will be operated to maintain γ as high as possible by:

1. Providing many alternative paths between origin-destination pairs, and rerouting vehicles to reduce the load on heavily travelled paths

2. Designing the grid layout to equalize high loadings as nearly as possible

Even so, it would take a remarkable spatial uniformity of peak hour demand to achieve γ greater than 0.5 and much lower values might have to be tolerated where variations in demand are high. For the purposes of this analysis we shall arbitrarily assume the (rather high) value $\gamma = 0.5$.

3.3 PRT GRIDS IN UNIFORM URBAN AREAS

In Sections 3.1 and 3.2 we related line capacity requirements to urban area passenger demand characteristics, and estimated some typical ranges for demand parameters. In Section 2,

we had estimated line capacities that would be available under various operating conditions. We shall now combine these results to obtain feasibility ranges for PRT grids. Figure 21 shows feasible average trip distance $\bar{d}$ vs. population density, with the trip generation rate ω, guideway length per square mile L, and line velocity as parameters. The following assumptions are made.

1. That there is a uniform spatial distribution of demand, free of major "centers";

2. that a "synchronous slot", k=1, strategy is used without resort to such capacity increasing devices as training or gap control. Vehicle capacities available are:

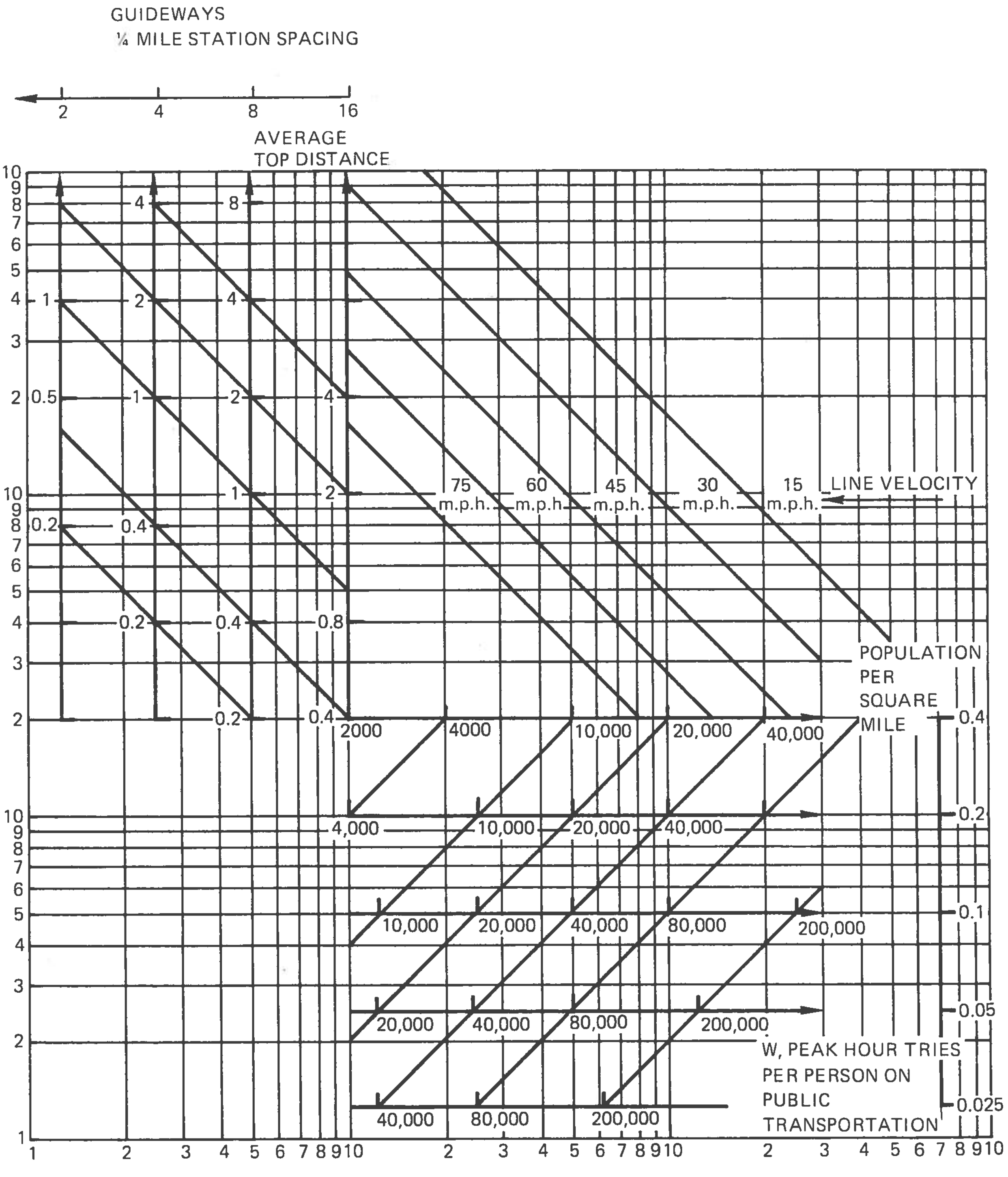
Velocity	Cars per hour
15 mph	2150
30 mph	1120
45 mph	600
60 mph	340

3. that average car occupancy is 1.6;

4. that the capacity utilization factor γ is 0.5;

5. for purposes of calculating grid spacing only, (not for calculating the guideway length per square mile L), the grid is assumed square, (see Section 4.1 below for a discussion of station spacing).

3.3.1 Station Spacing and Grid Layout. Suppose that station spacing is determined by the requirement that maximum walking distance should be less than 2 blocks of 1/8 mile each. This can be accomplished with minimum station density by placing stations at the corners of a square grid, in which the distance Δ between adjacent stations is 2 blocks, i.e., 1/4 mile.



*ASSUMING SQUARE GRID.

Figure 21. PRT Uniform Grid Feasibility

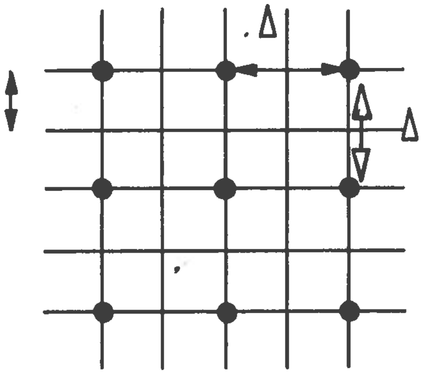


Figure 22. Square Grid

The length of guideway needed to interconnect stations will be calculated.

If traffic is unidirectional then we can interconnect all stations with a minimum of $L = \frac{1}{\Delta}$ miles of guideway per mile, i.e.

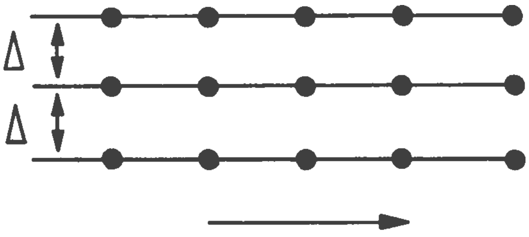


Figure 23. Unidirectional Network

At the other extreme, if traffic is omnidirectional then $L \leq \frac{2}{\Delta}$

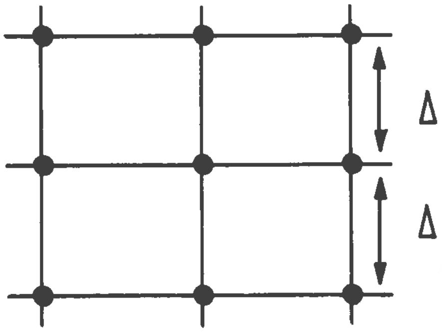


Figure 24. Omnidirectional Network

In practice there would usually be some demand perpendicular to the major direction of travel and at least 25% of the guideway would be laid in the minor direction to accommodate this demand and to provide flexibility in rerouting. In that case $\Delta = \frac{4}{3L}$ and $L = \frac{4}{3\Delta}$. Consequently, in practice station spacing Δ would be in the range $\frac{4}{3L}$ to $\frac{2}{L}$. In order to provide Δ = 1/4 mile, L would be in the range 5.3 to 8 miles of single lane guideway per square mile.

If a guideway density of 5.3-8 miles/square mile were enough to satisfy capacity requirements (see Figure 21) then a layout of single lane guideways would provide the required small walking distance. (The direction of flow on individual links could be adapted to demand so as to maximize the capacity utilization factor γ .) If, however, the capacity provided by 8 lanes per mile were found to be inadequate, then it would be cheaper to use multi-lane guideways, and to keep grid spacing fixed at 1/4 mile perpendicular to the direction of major travel, than to use single-lane guideways and reduce grid spacing.

3.4 CAPACITY REQUIREMENTS FOR GRIDS WITH CENTERS

In this section we shall examine the capacity requirements of a grid connecting a community to a center such as a rail terminal, movie theater, etc., at which a large number of trip destinations (origins) are concentrated. For simplicity we shall assume that trip origins (destinations) are uniformly distributed over a "service area" which lies within a fixed "service radius" R of the center, and that no trips originate beyond the service radius.

The simplest grid layout for servicing a center might entail having radial lines in a circular service area:

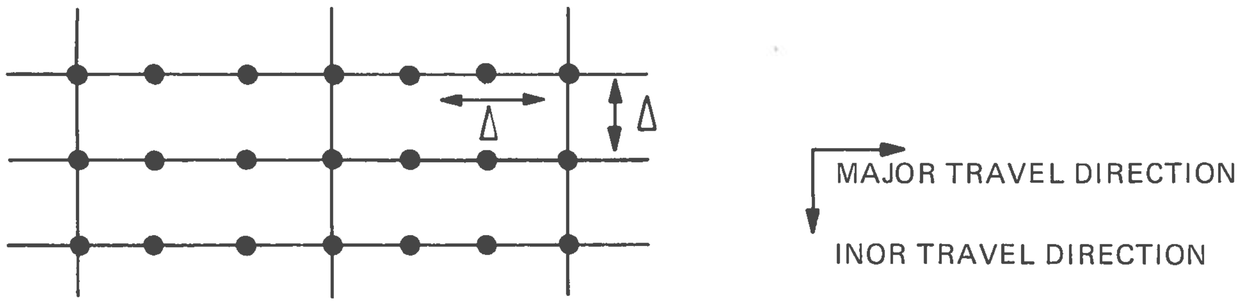


Figure 25. A Network with Major and Minor Directions

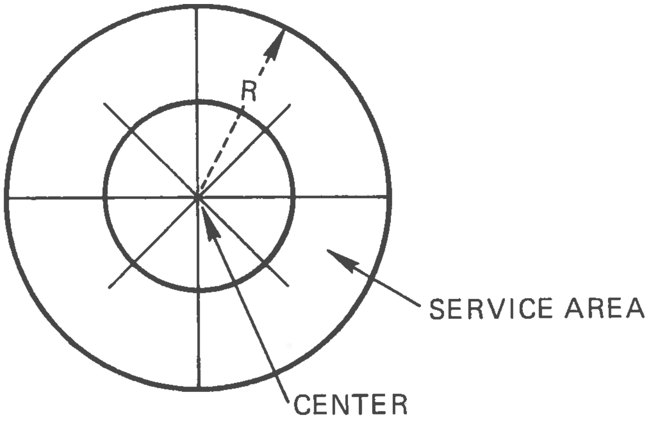


Figure 26. Radial Grid

In general, however, the center servicing grid might have to fit into or reinforce an existing grid, and there might not be the freedom to choose a radial grid layout. For the purposes of this study we shall assume, unless noted otherwise, that the center in question lies at one of the nodes of a square grid. By "service area of radius R" we shall mean an area whose distance from the center measured along the grid is R miles or less. In a square grid the area will be diamond (i.e., square) shaped. The results we shall obtain will be useful for circular grids as well.

We shall derive equations for the number of lines and for line density required to handle center trips as a function of distance from the center.

3.4.1 Guideway Density Equations

Let T = number of trips with one end at center during peak hour;

R = service radius of center in miles;

r = distance from center in miles;

$C(v)$ = Capacity* of one line expressed as a function of line velocity v.

$n(r)$ = number of lines of guideway extending to a distance r from the center.

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*Assuming 1/4 mile station spacing and synchronous slot mixed (on/off line) acceleration strategy.

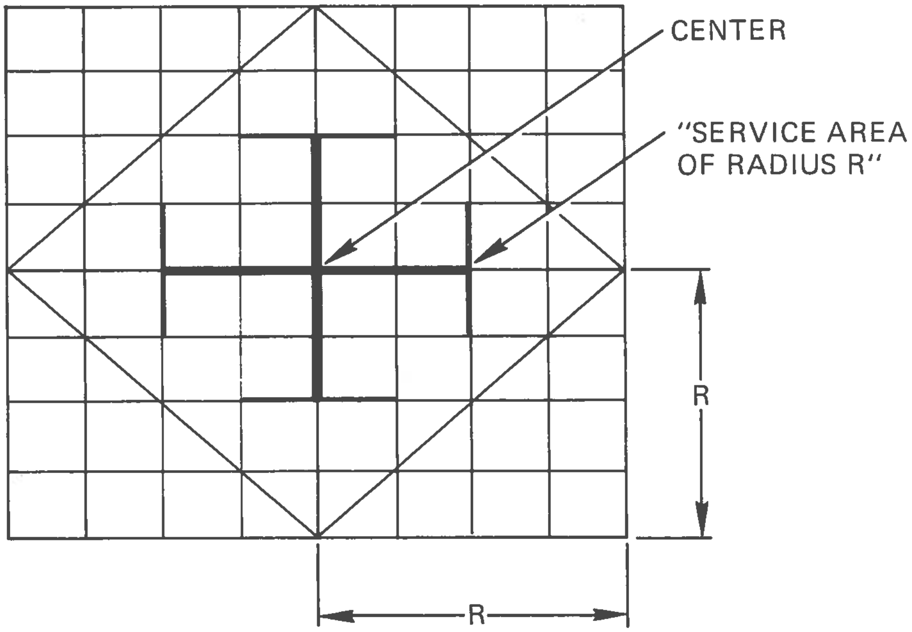

Figure 27. A Square Grid

L(r) = guideway density in miles per square mile at a distance r from the center.

Then,

for square grids,

$$n(r) = \frac{T}{C(v)} \left(1 - \left(\frac{r}{R}\right)^2\right) \quad (3)$$

$$L(r) = \frac{T}{4R} \; \frac{(1 - (\frac{r}{R})^2)}{(\frac{r}{R})} \quad (4)*$$

for circular grids,

n(r) same as for square

$$L(r) = \frac{T}{2\pi R} \; \frac{(1 - (\frac{r}{R})^2)}{(\frac{r}{R}))} \quad (4a)$$

Equations (3) and (4) are depicted graphically in Figures 28 and 29.

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*If radial line can be employed for center directed trips within the square grid pattern, then L(r) is reduced by $\frac{1}{\sqrt{2}}$; Equation 4 and Figure 28 were obtained using this assumption.

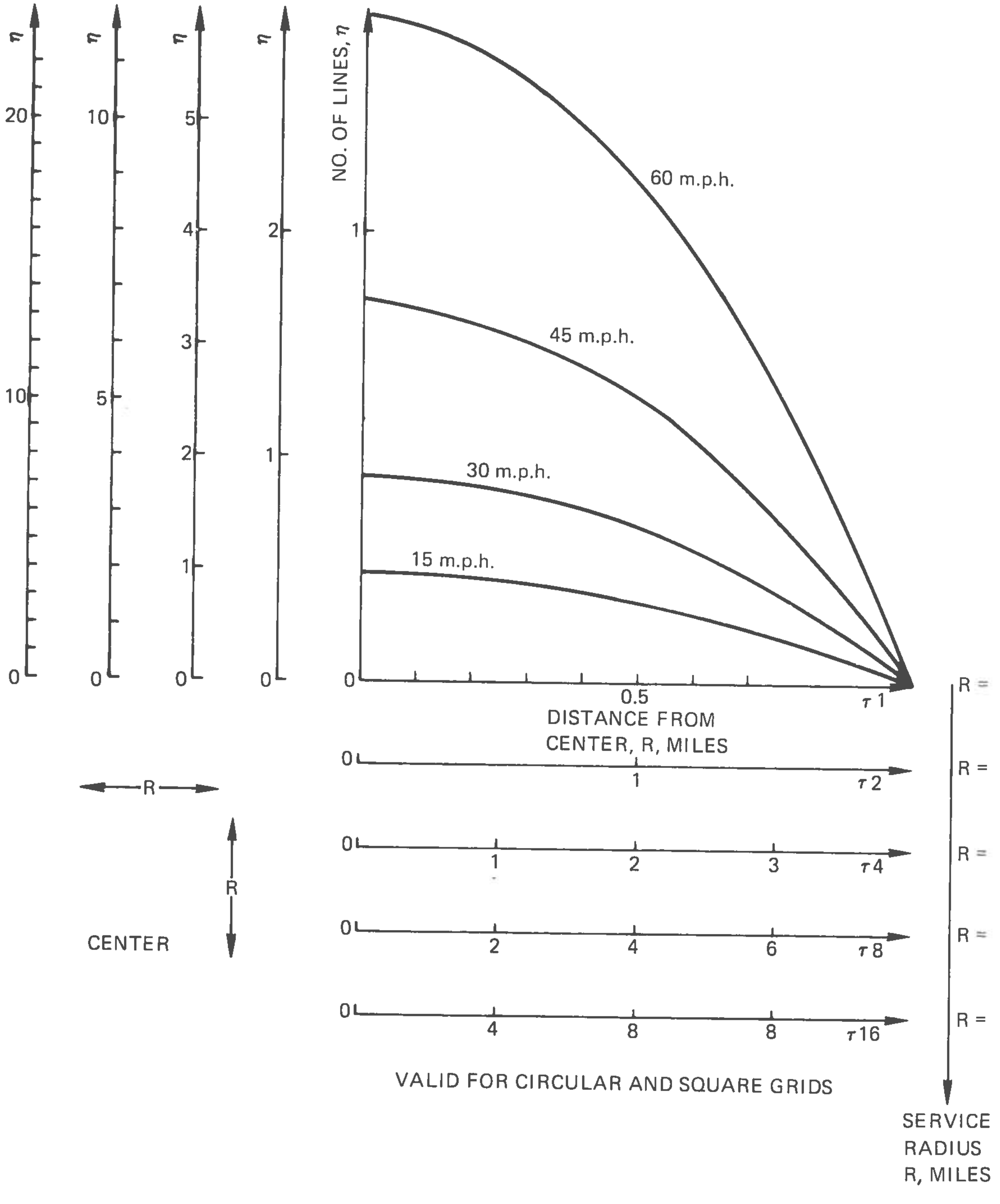

Figure 28. Number of Lines Required vs. Distance from Center*

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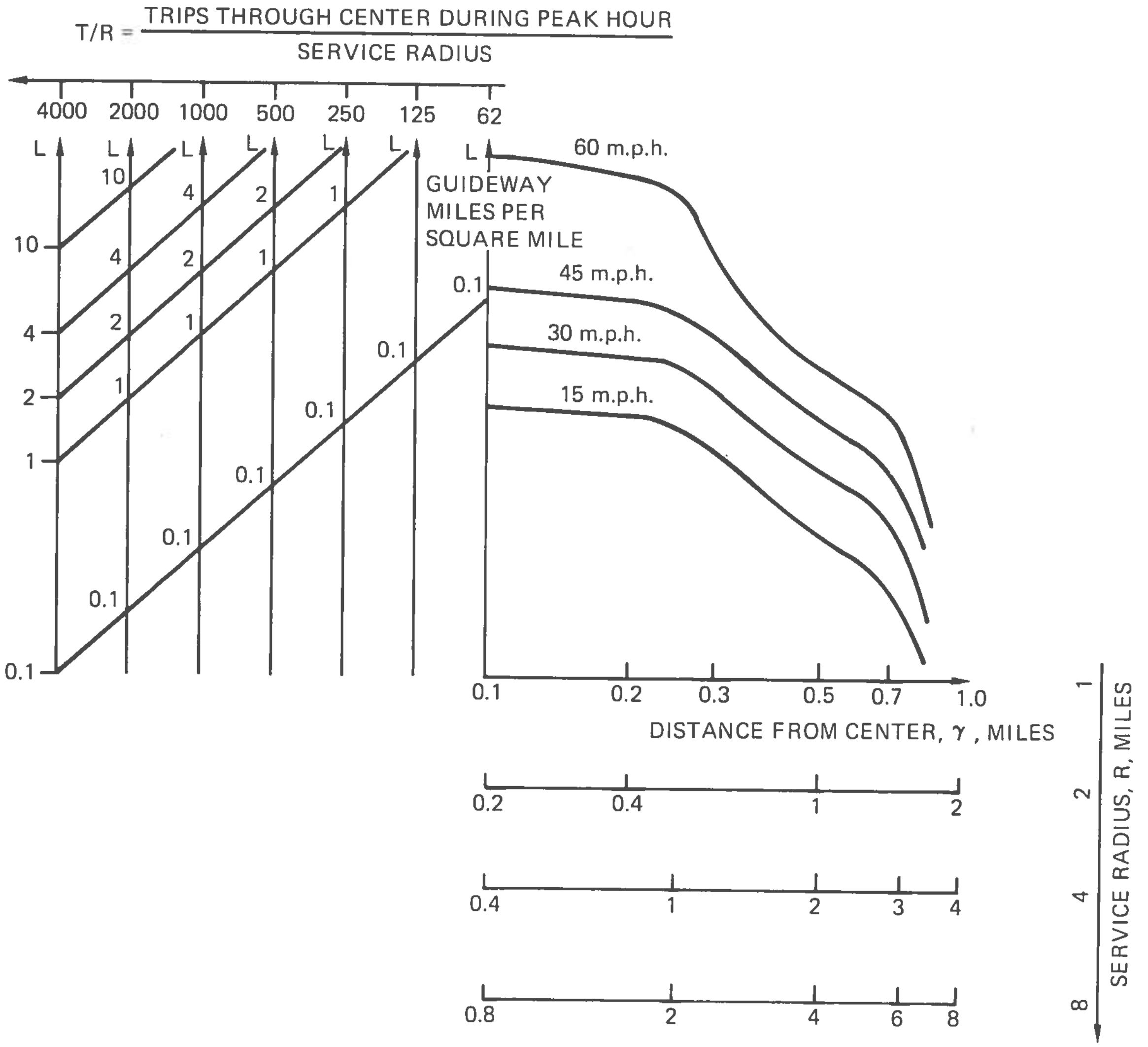
*Valid for circular and square grids.



* L VALVES SHOWN ARE FOR RADIAL GRIDS IN SQUARE SERVICE AREA
MULTIPLY BY 2 = 1.414 SQUARE GRIDS IN SQUARE SERVICE AREA
MULTIPLY BY 2 2 = 0.897 CIRCULAR GRIDS IN SQUARE SERVICE AREA

Figure 29. Line Density vs. Distance From Center*

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*L values shown are for radial grids in square service area, multiply by $\sqrt{2} = 1.414$ in square grids in square service area, multibly by $\frac{2\sqrt{2}}{\pi} = 0.897$ for circular grids in circular service area

3.4.2 Total Guideway Length Required

Let G = Total guideway mileage required.

ω_c = Average number of peak hour trips with one end at center generated per person.

Then, for a square grid in a diamond service area,

$$G = \frac{\omega_c}{C(v)} \cdot \frac{4}{3} R^3 \qquad (5)$$

$$= \frac{T.}{C(v)} \quad \frac{2}{3} R \qquad (6)$$

and, for a radial grid in a circular service area,

$$G = \frac{2\pi \omega_c}{C(v)} \cdot \frac{R^3}{3} \qquad (5a)$$

$$= \frac{T}{C(v)} \quad \frac{2R}{3} \qquad (6a)$$

3.4.3 Average Trip and Line Length

In both radial and square cases,

Average trip length

= Average line length

$$= \frac{2}{3} R \qquad (7)$$

Consequently we shall employ the notation

$$\bar{d}_c \triangleq \frac{2}{3} R.$$

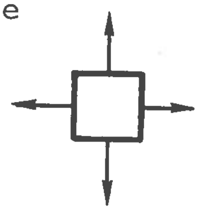
3.4.4 Average Guideway Density

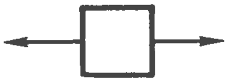
The average guideway density $\bar{L}$ is

$$\bar{L} = \frac{G}{\text{Service Area}} = \frac{\omega_c \rho}{C(v)} \quad \bar{d} \qquad (8)$$

Remark: The expression (8), for guideway density in the case of a grid serving a center, is similar to the expression which would be obtained from Equation (1) for a uniform grid, provided average trip distance $\bar{d}$ is taken to be $\frac{2}{3}$ R.

3.4.5 Short Time Overload Capability. In case of unexpected, short overloads, all traffic not terminating at a given station could be diverted around it. In that case the station could handle a load equal to 4 times line capacity if located at a node and 2 times line capacity otherwise.





Accordingly, we define the short term overload capacity C_o to be

C_o = 4 x line capacity for stations at node intersections

= 2 x line capacity for stations between node intersections

The resulting values of C_o (in passengers per hour) are:

Line velocity mph	C_o at node stations	C_o between node stations
60	1360	680
45	2400	1200
30	4500	2250
15	8400	4200

3.5 EXAMPLES OF PRT CAPACITY CALCULATIONS

3.5.1 A Community System. Envision a self contained, compact, industrial-residential community within the central city. A very high level of service PRT network is to be installed to provide internal transportation and collection/distribution facilities for a line-haul system. The network is to have the following characteristics:

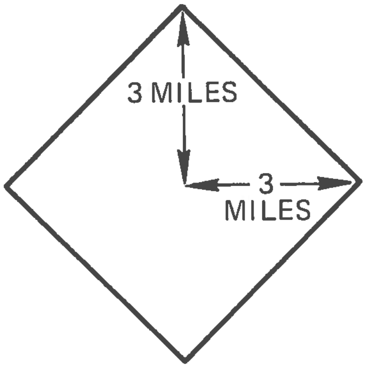


Figure 30. Proposed Service Area

Service radius (assuming square grid) $R = 3$ miles

Service area $= 2R^2 = 18$ square miles

Average internal trip length $\bar{d}_{int} = 2$ miles

Maximum walking distance = station spacing = 1/4 miles

Fraction of all trips with an end in service area that are internal, i.e., have both ends in service area = 2/3

We shall determine the population density that such a system could service with a $k = 1$, synchronous slot, mixed on/off line acceleration-merging strategy.

It will be assumed that automobile ownership in the area is low so that the number α of trips generated per person per day is also low at:

$$\alpha = 1.7 \text{ trips per person per day.}$$

The modal split μ_a will be assumed near the middle of the central city range for transit-oriented cities (Table 10)

$$\mu_a = 0.44 \text{ of all trips,}$$

The peak hour factor will be taken at the middle of the range in

$$\theta_p = 0.1$$

Hence

$$\omega = 1.7 \times 0.44 \times 0.1 = 0.075 \text{ peak hour public transit trips per person daily.}$$

The purely internal component of ω is

$$\omega_{int} = \frac{2}{3}\omega = 0.05 \text{ peak hour public transit trips per person per day.}$$

We shall calculate guideway requirements for various components of passenger flow, such as internal trips, external trips, trips to centers, etc.

Internal Trips. Under the preceding assumptions, a PRT network could service the uniformly distributed component of internal trips as follows:

TABLE 13. INTERNAL TRIPS

Miles of guideway per square mile	Line velocity, mph	People per square mile
4	60	10,900
	45	19,200
8	60	21,800
	45	38,400
10	45	48,000
	30	88,000

External Trips. Under our hypotheses the PRT network acts as a collection and distribution system for one or more line haul stations, and the external peak hour trip generation rate ω_{ext} is

$$\omega_{ext} = \frac{1}{3}\omega = \frac{1}{2}\omega_{int} = 0.025 \text{ trips per person on transit during the peak hour.}$$

The guideway density required to service external trips is proportional to the average trip distance, $\bar{d}_{ext}$. For a single station at the center, $\bar{d}_{ext}$ is given by Equation (7) and is

$$\bar{d}_{ext} = \frac{2}{3} R = 2 \text{ miles} = \bar{d}_{int}$$

If there is more than one station, $\overline{d}_{ext}$ is reduced. We shall assume that if there are S stations then the service radius of each is $\frac{R}{S}$ miles. The additional guideway mileage needed to service external trips can now be obtained from Equations 6, 7, and 8. Guideway mileage for external trips, expressed as a percentage of the guideway mileage for internal trips, depends on the number of line haul stations employed, and as:

TABLE 14. EXTERNAL TRIPS

No. of Line Haul Stations	Guideway Mileage Needed for External Trips as % of Mileage for Internal Trips
1	50%
2	25%
3	17%
4	13%

Under the preceeding conditions each line-haul station would have characteristics which are depicted in the following two tables:

TABLE 15. STATION CHARACTERISTICS

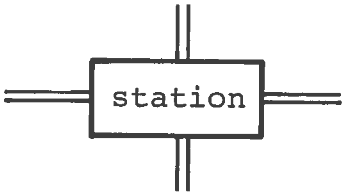
Population Density per Square Mile	Peak Hour Trips per Line Haul Station			
	1 Station	2 Stations	3 Stations	4 Stations
20,000	9,000	4,500	3,000	2,300
45,000	20,300	10,150	6,800	5,100

TABLE 16. STATION CHARACTERISTICS

		Population Density			
		20,000		45,000	
		Speed, m.p.h.		Speed, m.p.h.	
		60	45	45	30
No. of Stations	Area Served per Station, Square Miles	Maximum No. of PRT Lanes through* Station	Maximum No. of PRT Lanes through* Station	Maximum No. of PRT Lanes through* Station	Maximum No. of PRT Lanes through* Station
1	18	9	5	11	7
2	9	5	3	6	4
3	6	3	2	4	3
4	4.5	3	2	3	2

*Each lane passing through a station provides two lanes of access to the station

It would be convenient to keep the total number of lanes passing through a station at 4 or less, since the station could then be served by two double-lane lines at one of the grid nodes (assuming that the station would not be used for trips passing through).



This could be accomplished at the lower of the speeds shown in each population category using two stations, and at the higher speeds using 3 stations. The corresponding increases in guideway mileage for handling external trips would be 25% and 17%.

Trips to Preplanned Community Centers. A portion of the trips in any community are focused on centers such as theaters, shopping centers, etc. To a first approximation, the inclusion of a center in a community does not alter the total guideway mileage

needed, provided average trip distance for center trips is the same as for community trips. However, it may affect the guideway layout, requiring higher than average guideway density near the center. This may not present too much of a difficulty provided that,

1. The location of the center is known beforehand so that its requirements can be included in the guideway plan
2. The number of lines converging on the center is not inordinately high

A good example of a center with high (short duration) trip demands is a theater in which all patrons leave at the same time. Suppose that the theater seats 3000 persons and that 50% are to be accommodated on the PRT within a 15-minute period. The short term load on the theater station is 6000 passengers per hour.

This requires:

TABLE 17. STATION REQUIREMENTS

No. of Lines Terminating* at Station	Line Velocity
11	60
7	45
4	30

If the theater station were placed at a grid node, i.e., having lines entering from 4 directions, then high load requirements could be satisfied by reinforcing the network in the vicinity of the station with multiple lines, as follows.

TABLE 18. REINFORCEMENT

Speed mph	Maximum No. of Reinforcing Lines per Direction	Configuration
60	2	
45	1	
30	No reinforcement required	

---

*Each line passing through the station provides two lines terminating at station.

By reducing speed to 45 mph in the vicinity of the station, station requirements could be met by doubling 3 of the four lines entering the station. This might not be inordinately expensive, especially if the station handled a large load throughout most of the day, e.g. if the theater is part of a planned shopping complex.

Trips to Unforeseen Centers. A more difficult situation would occur if a theater-type station were to be added to an existing grid, requiring reinforcement of the surrounding lines. The worst such situation would occur in a grid operating near saturation. The total additional guideway mileage required, given by Equation 5, would be

Speed, m.p.h.	Additional Guideway Miles
60	22
45	12.5
30	6.8

These requirements represent the extreme case of a saturated system during the peak hour. They would be reduced greatly, (see Figure 28) if theater hours were picked not to coincide with rush hours.

3.5.2 Other Community Systems. To take another example of a community system, consider a larger, richer, automobile-oriented community, further from the city center. We might expect to find a larger number of daily trips per person α, a smaller modal split μ_a and a larger average trip distance $\bar{d}$. The following numbers might be taken as representation.

$\alpha = 3.5$ trips per person per day

$\mu_a = 0.2$

$\bar{d} = 3$ miles

$R = 5$ miles

The resulting net peak hour trip generation rate per person would be

$$\omega = 3.5 \times 0.2 \times 0.1 = 0.07$$

or about the same as in the previous example. The average trip distance is 1.5 times greater, so the population figures in Table 13 would have to be multiplied by $\frac{1}{1.5} = 0.67$. The number of line

haul stations might have to be doubled to serve the much larger area.

3.5.3 Overall Community Requirements. On the basis of the calculations we can begin to draw conclusions about the possibility of meeting community requirements in U.S. cities. First however, some facts concerning city structure should be recalled.

Some Notes on U.S. Cities (See Figures 31 and 32). We note that: 1) all U.S. cities except New York have average central city populations of less than 20,000 per square mile (Table 19); 2) local densities generally drop below that figure 5-8 miles from the CBD center; and, 3) densities generally drop below about 45,000 per square mile beyond 2-3 miles from the city center. Consequently we can think of the city as being composed of a core and two rings.

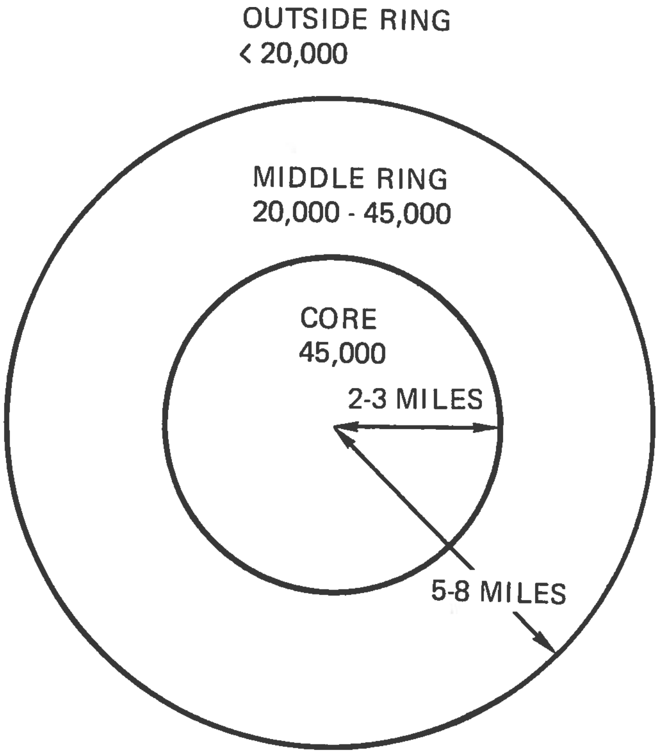


Figure 31. Annular City Structure

TABLE 19. POPULATION DENSITIES OF CENTRAL CITIES

Central Cities	Population Density
Atlanta, Georgia	3802
Baltimore, Maryland	11886
Boston, Massachusetts	14586
Buffalo, New York	13522
Chicago, Illinois	15836
Cincinnati, Ohio	6501
Cleveland, Ohio	10789
Dallas, Texas	2428
Detroit, Michigan	11964
Houston, Texas	2560
Kansas City, Missouri Kansas	3506
Los Angeles-Long Beach, California	5638
Milwaukee, Wisconsin	8137
Minneapolis-St. Paul, Minnesota	7326
New York, New York	24697
Newark, New Jersey	17170
Philadelphia, Pennsylvania	15743
Pittsburgh, Pennsylvania	11171
St. Louis, Missouri	12296
San Diego, California	2979
San Francisco, California	15553
Seattle, Washington	6295
Washington, D. C.	12442
Patterson-Clifton-Passaic, New Jersey	12056

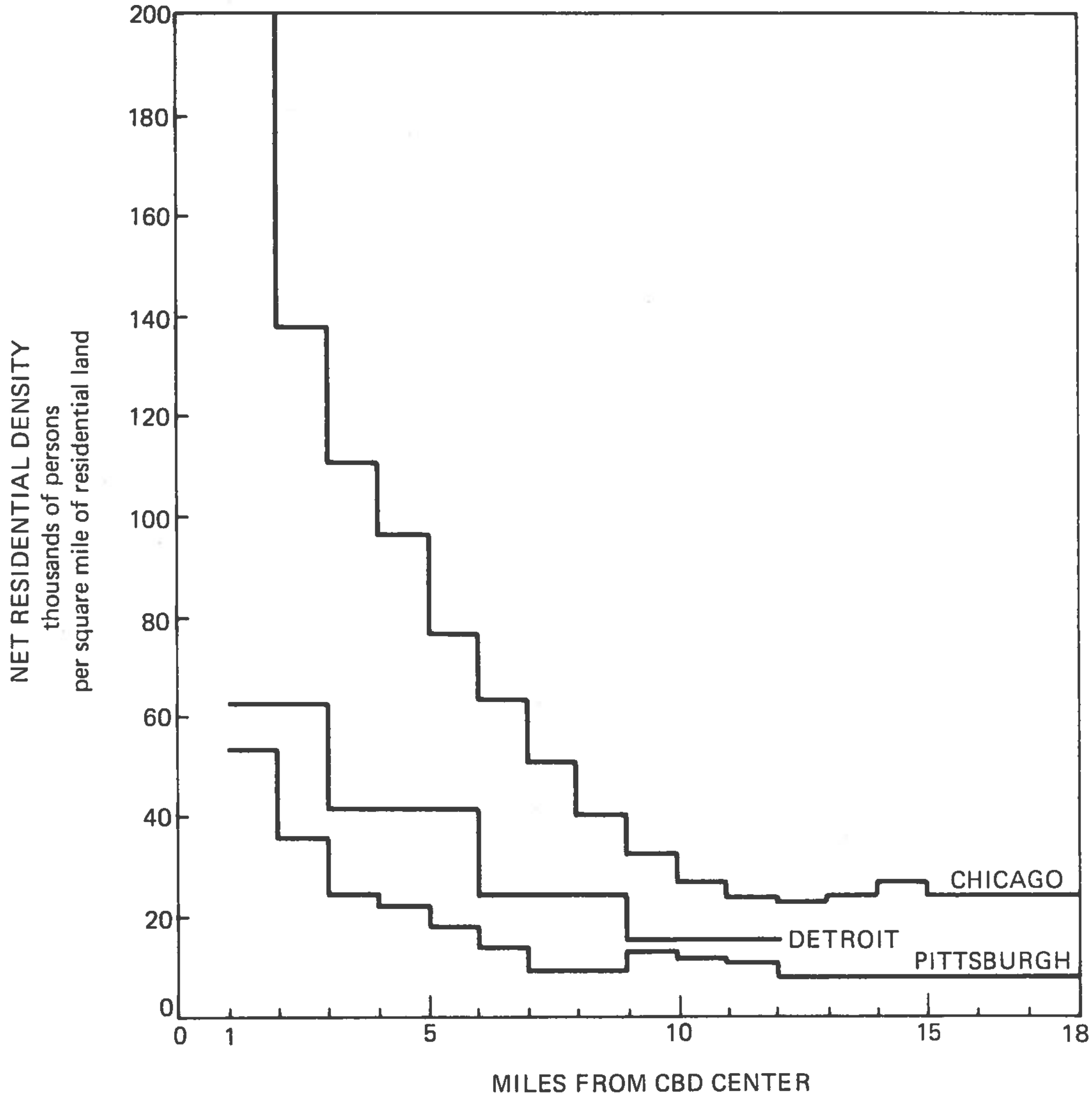


Figure 32. Net Residential Density, By Distance from the CBD Center

Source: Meyer, Kain and Wohl,[11] "The Urban Transportation Problem", (Harvard University Press, Cambridge, Massachusetts, 1965) p. 207
Derived from: CHICAGO-Chicago Area Transportation Study, Final Report, Vol. 2, Data Projections, July 1960, Table 29, p. 112;
DETROIT-computed from Detroit Metropolitan Area Traffic Study, "Report on the Detroit Area Traffic Study", part 1, "Data Summary and Interpretation", Lansing, Michigan, Table 8, p. 30, and Table 38, p. 123;
PITTSBURGH-"Pittsburgh Area Transportation Study, Final Report", Vol. 2, "Forecasts and Plans, Pittsburgh, February 1963.

Capacity Requirements for Community Systems. It follows that service could be supplied in almost any U.S. city, to a community which does not penetrate the core; under the conditions shown in the following table:

TABLE 20. CAPACITY REQUIREMENTS FOR COMMUNITY SYSTEMS

Ring	Line Velocity mph	Miles of Guideway per Square Mile (Including Acceleration Lanes)	Type of Guideway for 1/4 Mile Station Spacing
Outer <15,000 persons per square mile	60	9	Mostly single lane
Outer 15-20 thousand persons per square mile	60	12	Mixed single and double lane
	45	7	Single lane
Middle	45	15	Double lane
	30	8	Single lane

Table 20 was obtained by taking the results of Table 13 and a) increasing guideway requirements by 25% for trips to line haul stations (assuming 2 line haul stations in the community) and, b) another 25% to provide a reserve for unforeseen trip centers.

Comments. If short term overloads (discussed in the next section) are disregarded for the moment, then pure PRT community service could be supplied for the majority of U.S. cities. This would entail using 1/4 mile station spacing and single lane guideways in the less populated portions of the outer ring.

In the more populated outer ring portions, occasional double lane guideways or a reduction in speed to 45 mph would be required. In the middle ring the reduction in speed to 45 mph and the use of double lane guideways would be undertaken simultaneously or, if double lane guideways were excluded, a speed reduction to 30 mph would be needed.

These remarks are predicated on the assumption that the PRT systems of adjacent communities would not be linked to allow inter-community travel. If they were, the average travel distance $\bar{d}$ might be sharply increased, and the combined network overloaded.

Short Time Overloads. The short time overload capability is a measure of the ability of the network to adapt to unexpected overloads without extensive guideway redesign. Assuming that the largest overloads in a community system would be comparable to those resulting from the introduction of a new theater, a value of 6000 passengers per hour would be desirable at the nodes of a community system, more or less independently of population density. Under the present assumptions this would require dropping the line velocity to an undesirably slow 18 mph near the overflow point. In order to provide satisfactory overload characteristics it would be desirable to be able to increase line capacity, for short durations of 15-30 minutes, by at least 250% at 45 mph. Such an increase could be obtained by reducing k factors below 1, by training vehicles, or by using larger vehicles for overflow situations.

3.5.4 Linked Community Systems in the Outer Ring.

In the outer ring, at population densities of 15 thousand or less, it would be feasible to link community PRT systems to provide intercommunity service at 60 mph, provided the network remained separated from inner ring communities. Although linking of communities would introduce some long trips, the proportion of such trips would not be large. If, for example, the respective average trip distances for intra and inter community trips were

$\bar{d}_1$ = 2 miles for 75% of trips

d_2 = 10 miles for 25% of trips

then the overall average trip distance would be $\bar{d} = 4$ or double the figure in the first example. The modal split, moreover, would probably be much lower, perhaps half the previous figure of 44%. Consequently linked outer-ring service would be feasible.

3.5.5 CBD Internal Service.

A CBD internal system is a community system with 1) a low average trip length, 2) low line velocity requirement, 3) high population density, and 4) a very large proportion of peak hour external trips. Consider, for example, the following representative figures:

$R = 0.75$ miles

$\bar{d} = 0.5$ miles

ω internal = 0.12 trips per person during peak hour

ω external = 0.5 trips per person during peak hour

Employing Figure 21 we obtain the following operating conditions

guideway miles per square mile = 8

maximum population density at 30 mph = 119,000.

maximum population density at 15 mph = 230,000.

The internal needs of the CBD can easily be met for most CBDs (disregarding unexpected overloads for the moment).

External trips during the peak hour would present more of a problem. If 16 miles of guideway per square mile were reserved for external trips, the maximum populations served would be

at 30 mph,	56,000 per square mile
15 mph,	115,000 per square mile

The combined internal and external requirements for a density of 100,000 persons per square mile would be

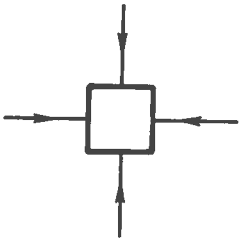
34.9 miles/square mile at 30 mph
17.5 miles/square mile at 15 mph

One of the major areas of difficulty would occur at the transfer points between the internal PRT and external line-haul systems. Let the population density be 100,000 per square mile. The total number of lanes joining the PRT system to line haul stations would be,

at 30 mph: 40

15 mph: 21

If each line-haul station were limited to having 4 lanes entering,



the toal number of stations required would be

at 30 mph 10

15 mph 6

These figures appear high but not impossible. A line speed between 15 and 20 mph within the CBD would appear to be feasible for all but the densest CBDs.

The short time overload capability for the CBD would be

4400 passengers per hour at 30 mph

8500 passengers per hour at 15 mph

an improvement by a factor of 2-3 would appear desirable.

3.6 CONCLUSIONS

Capacity requirements of a variety of urban applications have been estimated in order to determine whether they could be satisfied by a pure PRT network with 1/4 mile station spacing and a "simple" operating strategy. By a simple operating strategy we mean a k-greater-than-or-equal-to-one, synchronous slot, mixed on/off line acceleration strategy, without recourse to train operation or gap control. The peak hour requirements can be viewed as consisting of two parts: 1) The normal requirements, representing the repetitive and expected parts of passenger demand; and 2) the overload requirements, representing the unusual and unexpected fluctuations from normal.

3.6.1 Community and CBD Systems. - A pure PRT system of simple type could satisfy the normal requirements for most community applications within U.S. cities. By community applications we mean applications in which a network spans an isolated subarea of a city, with a (low) average trip distance of 2-3 miles, and with connections to a line haul network which provides inter-community service. For community systems in the outer ring, single lane lines at speeds of 45-60 mph could provide enough capacity for population densities up to 20,000 persons per square mile. In the middle ring, population densities as high as 45,000 could be serviced by using double lane guideways, or reducing speed to 30-45 mph, or both. Inside the CBD the use of double lane guideways and a low speed of about 15-20 mph would extend short distance (less than 1 mile) service to population densities up to 100,000.

At population densities near the limits mentioned in each category above, adequate capacity could only be achieved through very intensive guideway utilization, which would place a heavy burden on the central computer to optimally route and reroute all vehicles. There would be little tolerance for errors in scheduling.

Line haul stations in each community would have to be subdivided into 2-3 units in each outlying community, and 4-8 units within the CBD, to keep the number of PRT lines entering each line haul station tolerably small.

The preceding discussion applies solely to the normal component of passenger flow. A pure PRT network of simple type would not have adequate short time overload characteristics for most community applications, being particularly deficient in this respect at the higher speeds, i.e., 45-60 mph. In order to meet the overload requirements, line capacity would have to be increased for short durations (15-30 minutes at a time), over localized portions of the network, by a factor of 2-4 at the lower speeds (15-30 mph), and as much as 4-10 at the higher ones. These temporary increases could be achieved in several ways:

1. By reducing k factors into the range 0.5 - 0.1
2. by operating trains of 2-15 cars in overload situations
3. by maintaining a fleet of larger vehicles of 12 passenger capacity for overload relief

In order to achieve the "normal" capacities mentioned previously, a grid of roadways spaced approximately 1/4 mile apart would be required, with interchanges at most crossings. Interchanges would clearly present a formidable problem. Various strategems could be employed to reduce their number and complexity, e.g., the use of one-way lines with turns permitted at selected crossings only, as in present day street systems. However, such strategems would increase average trip distances, a factor we have not considered here.

3.6.2 Line Haul Systems. - It would be impractical to operate line-haul type roadways similar to present commuter systems but using PRT vehicles in a pure PRT mode. For example, a CBD of 1.5 square mile area and having a population density of 100,000 per square mile consisting mainly of employees, could have as many as 75,000 passengers leaving on public transit during the rush hour. At present these might be carried on 4-6 transit lines carrying 15,000-25,000 passengers each. If each transit line were replaced by 60 mph PRT lines of simple type, then each line would have to carry 40-75 lanes. Capacity increases by a factor of 10-20 would be required to make line-haul type operation worth considering (this would entail operations at k factors less than 0.1, or train operation, or the use of larger vehicles, or a combination of the three).

3.6.3 City-Wide Networks. - Rather than emulate the present-day division of transit into line-haul and community collection-distribution parts using PRT lines, it would be more efficient to cover the city with a grid of uniform spacing. Such a grid would have maximum speeds of 60 mph in the outer ring, dropping of to 30 mph in the middle ring, and 15 mph at the CBD center. In the outer ring, moreover, high speed, station free lines reserved for nonstop long distance trips might be interspersed with slower speed lines (which require shorter acceleration lanes) for local travel.

The guideway requirements for city-wide service would depend very much on the population profile. On the basis of our estimates for community systems, it seems likely that they might be feasible for cities as large as Pittsburgh, in which CBD population density reaches a peak of about 50,000 per square mile and drops off below 10,000 in the outer ring.

4. SURVEY OF MANUFACTURERS' CONCEPTS

There are more than 100 vehicle-guideway concepts for PRTs in existence, of which at least 10 have reached some sort of prototype stage. Some of the more interesting* concepts, whose major operating characteristics are shown in Table 21, are grouped in Table 22 according to Suspension (Pneumatic tire, Air Cushion, Steel-wheels-on-rail) and Support (overhead, underfoot). These major groupings have been adopted because they indicate the principal advantages, disadvantages, and critical technologies of the resulting systems.

4.1 UNDERFOOT/PNEUMATIC TIRE SYSTEMS

The system in which vehicles ride on pneumatic tires supported underfoot is the only category in Table 22 that is directly extendable to dual mode operation. (The other categories could palletized, but that would require the addition of costly pallet transfer facilities). A dual mode capability is considered important by those planners who believe that only dual mode systems have enough flexibility to provide the sort of high-level widespread service that will be used in the future (i.e., door to door service for those with cars at their disposal and high quality public transit for those without cars or unable to drive).

The Alden Starrcar[12] is a good example of an underfoot pneumatic system. The guideway uses flat cement surfaces with curbs. Vehicles are steered by automatic controls turning the front wheels. Steering is controlled by a pair of guidewheels which rotate in the horizontal plane, tracking the curb. One wheel presses against each curb. A switch is simply a fork in the guideway. Switching is accomplished by a decision of the control system to track one curb or the other at an intersection.

The Alden switch is an example of an onboard switch, i.e., one in which the only moving parts are onboard the vehicle. Onboard switches have the advantage of being positioned before the vehicle reaches the switching junction. Consequently, a stream of vehicles operating at fractional headways can be switched quickly to their intended directions. (Guideway switches, on the other hand, require movement of some portion of the guideway or track. The guideway mass that has to be moved is generally large

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*The systems shown in Table 21 include the vehicle concepts evaluated by APL, to which have been added the Uniflow and URBA because of their unique suspension ideas.

TABLE 21. SYSTEM CHARACTERISTICS

						Vehicle Characteristics			Operating Characteristics			
Vehicle System	Guideway	Vehicle Support	Propulsion Power Supply Volts	Switching	Type of Control	Passenger Capacity	Dimensions, Length, Width, Height, in Feet	Weight Empty Lbs	Operating Speed mph	Maximum Speed mph	Minimum Headway Seconds mph	X Factor
Alden Starrcar	Cement Roadway Underneath	Rubber tires	10 h. p. electric synchronous motor, hydraulic 575 a. c. drive	On board via steering control	Central computer	6 or 15	10, 6, 6.	600 or 900	15-40	60	1. 6 at 15	1. 6
Dasheveyor Transit	Cement beams underneath	Rubber tires	d. c. electric motors; 20-100 h. p. depending on 13. 8 kv a. c. applications	via On board switch	Central hardware logic	6, 12, 24, or 48. (only 24 pass. vehicle has reached prototype stage)	21. 7, 6. 5, 7. 5.	14, 800 not including drive units (for the 24 pass. vehicle)	30	38	35 at 30	17. 5
Sky-Kar Transivator	Overhead steel 1-beam monorail	Rubber tired bogeys	pair of 10 h. p. d. c. electric motors 480 V a. c.		Wayside	12 (6 seated, 6 standing)	12. 6, 5, 8. 25.	2600	15 (7. 4 mph on switch curves)	60	7 at 15	7
Transportation Technology Inc.	Cement roadway underneath	Air Cushion pads	l. i. m. 25-34 h. p. average N. A.	by Guideway displacement	Central computer	6 or 12 (12 passenger vehicles used during peak hours only)	10 or 13. 5 7. 4 6. 5	1300 or 1800	20 on curved portions and near switches 60 on straight parts	60	10 at 60	2. 5
Varo Monocab	Overhead box section steel monorail, covered	Rubber tired bogeys	d. c. permanent magnet motor N. A.	via On board mechanical switch	divided between central computer, stations, and on board	6	8, 5. 1 4. 9	1200	34, on straight sections 68	68	3. 7 at 34	1. 6
Uniflo	Metal roadway	Airjets in guideway	Airjets in guideway	by Airjets in guideway	N. A.	8	15, 3. 7, 2.	1000				
Urba	Overhead special section steel monorail	Air cushion enclosed in guideway	l. i. m.	N. A.	N. A.	N. A.						

*Assuming maximum deceleration of 11 feet per second^2.

TABLE 22. SUSPENSION AND SUPPORT CLASSIFICATION FOR SOME PROTOTYPE PRT SYSTEMS

Suspension Type / Guideway Location	Pneumatic Tires	Air Cushion Suspension	Steel Wheel On Rail Suspension**
Underfoot Guideway	Alden Dasheveyer* Westinghouse*	Transportation Technology Inc. UniFlo	Pullman Inc.*
Overhead Guideway (Monorail)	Varo Moncab Sky Kar Transivator	Urba	

*Prototype seats 20 passengers or more, and would have to be scaled down for PRT use.

**The Pullman concept is listed here in order to include a representative of steel-wheel-on-rail technology. However, data on operating characteristics was not available at the time of writing.

4.2 OVERHEAD/PNEUMATIC TIRE SYSTEMS

Environmental hazards can be eliminated by placing the entire guideway and vehicles in an enclosure. This is expensive and makes the guideway more obtrusive. A cheaper solution is to enclose the guideway only, and to leave the vehicles exposed (although some might find the frequent passage of exposed vehicles more objectionable than the presence of a large enclosure). Enclosing of the guideway is easiest if it is overhead, so that necessary openings in the enclosure can be included in its bottom surface, and if the guideway is in the shape of a compact monorail.

Varo Monocab[15] has produced one of the more advanced overhead pneumatic-tire designs. The Varo guideway is a hollow structure of rectangular cross section, with a slot along the bottom running the length of the guideway. A four-wheel rubber-tire bogie propelled by D.C. permanent magnet motors rides along the lower flanges inside the guideway. The cab is suspended from the bogie by a column passing through the slot. The bogie is steered by passive horizontal-plane guidewheels.

One of the difficulties with overhead guideways is that it is difficult to design an onboard switch. (At a switch junction, the column supporting the cab must be able to cross the guideway spur which is not in the direction of travel). Varo has designed an onboard switch, with gaps in the flanges at the switch junction, which allow the vertical column to pass through. Only one of the four wheels of a bogie can be over a gap at one time. At that time a righting moment is supplied by one of a pair of horizontal-plane neoprene-tired wheels pressing against a plate in the guideway located over the gap. The Varo switch represents an ingenious solution to the overhead switch problem, although it is cumbersome, with a large number of wheels and interlocks. It might be expected to be noisy and to give a jerky ride, though these problems could probably be reduced through careful refinement of the design.

The Sky-Kar[16] Transivator Concept is similar to Varo's but appears to be less advanced in many aspects of its development. The guideway beam has an I cross section which was left uncovered on early prototypes, but could easily be covered.

Overhead monorail vehicles adjust themselves naturally so that the force of gravity is perpendicular to the vehicle floor. They do, however, tend to have sway problems in high crosswinds.

Pneumatic tire systems in general are susceptible to puncture failures. The possibility of tire failure can be made negligible with plastic foam and by mounting them in redundant pairs.

4.3 UNDERFOOT/AIR CUSHION SYSTEMS

Air cushions have an advantage over rubber tires at very high speeds, in excess of 100 mph, where heat generated by flexing causes tires to fail quickly. Air cushions also reduce the need for accurate track alignment. However, since very high speed operation is not being contemplated, the advantage of air cushions for PRT use is not so clear.

Air cushions eliminate friction wear but introduce additional power and maintenance requirements for airblowers. The power consumed by airblowers is usually 10 - 15% of propulsion power, which would not be large enough to weigh heavily against air cushions if there were other good reasons for using them.

Manufacturers who have adopted air cushions claim that they can provide a smoother, quieter rides than tires. However, tires used in conjunction with a well designed suspension could probably match the air cushion ride. Moreover, although air cushions do not squeak as tires do, they produce a hiss that could be objectionable. It does seem probable, however, that the use of low-pressure, large area cushions, coupled with proper design of air valves and exhausts, could produce low-noise cushions.

TTI (Transportation Technology Inc.)[17] has produced one of the most thoroughly engineered vehicle-guideway prototypes in the underfoot/air-cushioned category. TTI uses very low profile 6-passenger vehicles supported on 4 air cushion pads each. The air cushion pad (Hovair) consists of a circular plate about 30 inches in diameter attached at the edges to a flexible circular diaphragm. Air is supplied by a pair of 1 to 2 hp blowers per vehicle, the blowers being mounted in small sound-insulated housings. Air is fed to the air cushion pads by flexible hoses. (Power consumption of air-cushion pads depends on the roughness of the running surface. TTI employs a steel-trowel smoothed surface.)

Guidance in the TTI system is accomplished by horizontal-plane rubber-tired wheels pressing against the guideway curbs. Air cushion pad guidance is also being contemplated. Switching is accomplished by electromagnets in the guideway curbs which act on ferrous material in the vehicle skirts and pull the vehicle to the left or right as required. (Electromagnets can be placed on board the vehicle instead if there are more switches than vehicles). Mechanical wheel latches back up the electromagnets.

Since air cushion systems provide no traction, propulsion forces must act directly on the vehicle. Linear induction or air reaction motors appear to be the prime candidates for tractionless propulsion systems.

TTI employs a LIM (linear induction motor) with primary on the vehicle. The LIM, in addition to being independent of traction, has the advantage of having no moving parts. These advantages are offset by several disadvantages however:

1. Because the LIM must develop full force without intermediate gears or levers it is much heavier for a given power rating than a rotary motor. LIMS can easily account for 30% - 40% of vehicle weight. (The TTI vehicle employs four LIM primaries weighing 500 lbs).

2. It is difficult to maintain a small uniform air gap in motion. LIM motors therefore experience large losses in force and energy. Furthermore, forces can not be controlled as accurately as in a rotary machine.

TTI takes 3-phase power by brushes off a power rail. If a large enough number of vehicles were employed, it would be practical to place the primaries in the guideway and have a completely passive vehicle (at least as far as propulsion is concerned).

TTI vehicles are normally braked by applying reverse motor thrust. In emergencies the air blowers are shut off and the vehicles skid to a halt. Emergency deceleration rates depend on the condition of the running surface, and variations in this condition could produce difficulties in short headway operation.

One of the most interesting suspension-propulsion concepts has been developed by Uniflo Corp.[18] Uniflo vehicles are totally passive, forces for levitation and propulsion being supplied entirely by air jets mounted in the guideway. Air jets are controlled automatically, either by a central controller or by the pressure of vehicles passing over the guideway. Valves open only when a vehicle passes over, and close when it has passed.

Uniflo favors the rather expensive option of covering the guideway in order to provide protection from the environment and to avoid the need of carrying air-conditioning equipment onboard vehicles. Although Uniflo has not produced a full scale prototype, it has tested its suspension-propulsion concept in baggage handling applications.

Underfoot air-cushioned systems are susceptible to the same environmental hazards as underfoot pneumatic-tired systems, though there are some minor differences in effect: The air exhaust helps to brush away snow and small particles; the air pads are generally more susceptible to rupture by sharp large objects than are tires. In either case, environmental hazards pose a serious problem.

4.4 OVERHEAD/AIR CUSHION SYSTEMS

The environmental hazard problem can be solved as in the pneumatic-tire case by suspending the vehicle from a bogie riding inside a hollow beam structure. A system of this kind called the URBA has been prototyped and tested in France. Air pressure, regulated by protruding plates and baffles in the bogie and in the guideway, keeps the bogie lifted away from the guideway surface and also provides lateral guidance. On-board switching would be difficult to accomplish in such an overhead system, but a switch similar in principle to Varo's could presumably be developed.

Although information on the URBA is meager, what little is available indicates that it is one of the most interesting of the available suspension-guideway concepts.

4.5 UNDERFOOT/STEEL WHEEL ON RAIL SYSTEMS

Steel wheel on rail systems lack the versatility and dual-mode capability of pneumatic tires, or the low noise friction-free potential of air cushions. They tend to produce uncomfortable oscillations. However, they have the great advantage that there are so many railroad lines in existence. In England, Bush has advocated a rail-based PRT concept which has been called the Bush Automatic Rail Taxi. No prototypes appear to have been constructed, however.

Pullman has built 30-passenger automatic rail cars, which, however, have not been designed for pure PRT operation. There does not, in fact, appear to be any strong inclination at present to develop a rail-based PRT system.

5. COSTS

The cost figures included in this report are based on the APL study "Parametric Analysis of Generic Urban Transit Systems",[1] some of whose main results are illustrated graphically in Figures 33 through 37.

In Figure 33, aerial system guideway construction costs (in millions of dollars per mile) are shown for single land guideways as a function of live load per span. For loads greater than 10,000 lbs. per span construction costs rise rapidly, suggesting potentially large savings from the use of small vehicles on light structures.

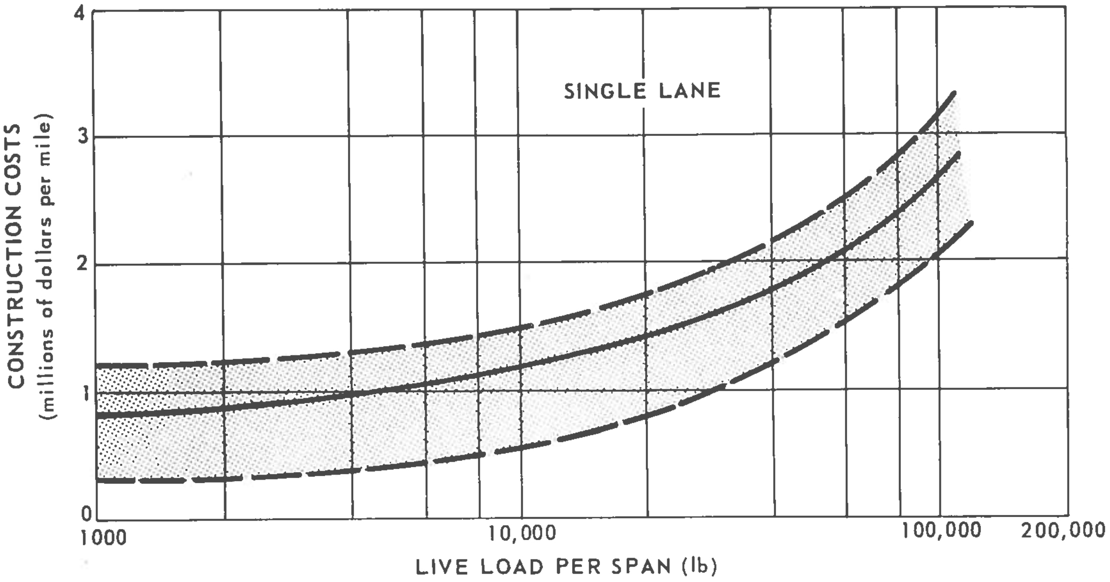

Figure 33. Aerial System Guideway Construction Costs Versus Live Load Per Span (Source: Ford, Roesler, and Waddell)[1]

In Figure 34, average right-of-way costs are shown to increase linearly with width. Urban right-of-way costs are shown as being double those for suburban areas, but these estimates are subject to wide variations.

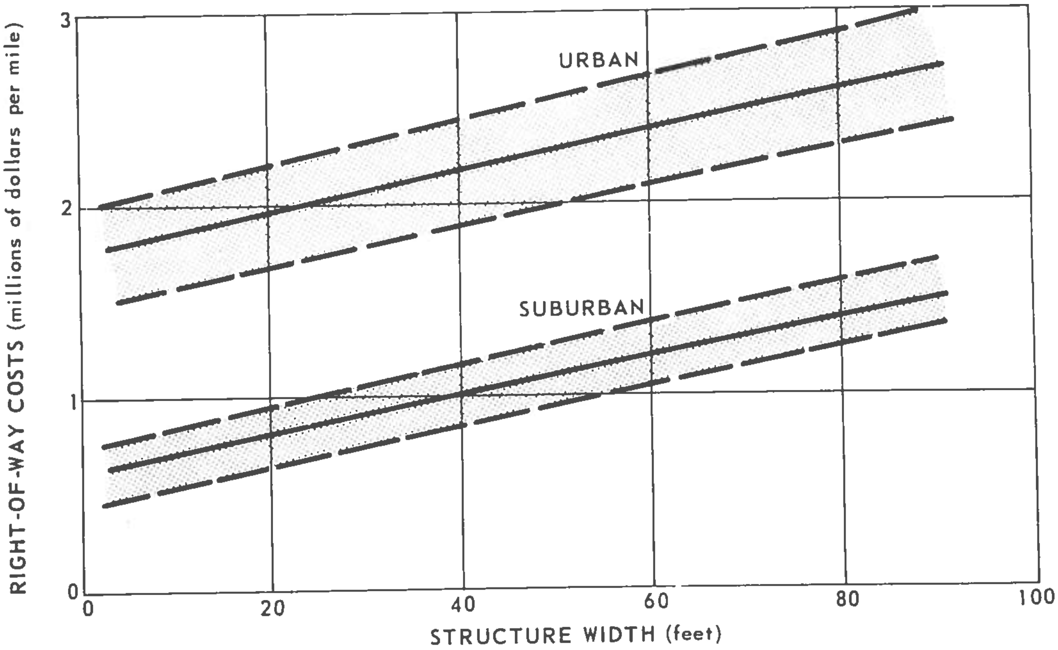

Figure 34. Right-Of-Way Costs Versus Structure Width (Source: Ford, Roesler, and Waddell)[1]

In Figure 35, tunneling costs are shown as a function of excavation diameter and geological conditions. In urban areas the possibility of tunneling is receiving increased consideration. It is noteworthy that the cost of cut and cover construction is high compared to the cost of tunneling through all but unconsolidated wet rock.

APL's estimates of investment and operating costs per mile were obtained mainly for low capacity, single lane systems. For such systems investment costs are relatively insensitive to operating strategy (see Figure 36); location (above, below, or at grade) is likely to be a more important factor. However, our investigation suggests that these conclusions would not be valid for high capacity, high speed operation, where investment costs would be quite sensitive to operating strategy. Operating costs (Figure 37) are, of course, sensitive to operating strategy in all cases.

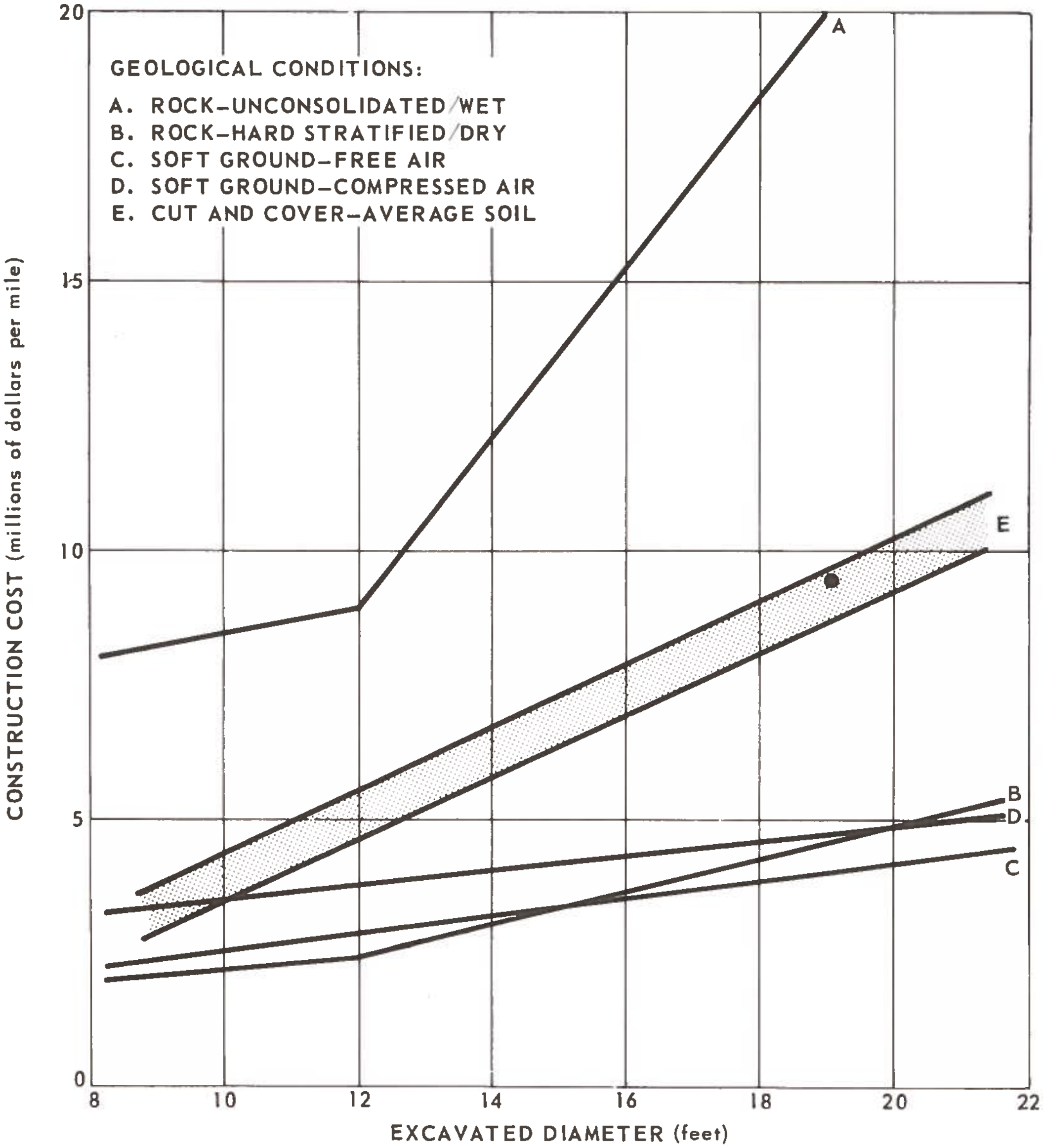

Figure 35. Tunneling Construction Costs Versus Excavated Diameter. (Source: Ford, Roesler, and Waddell)[1]

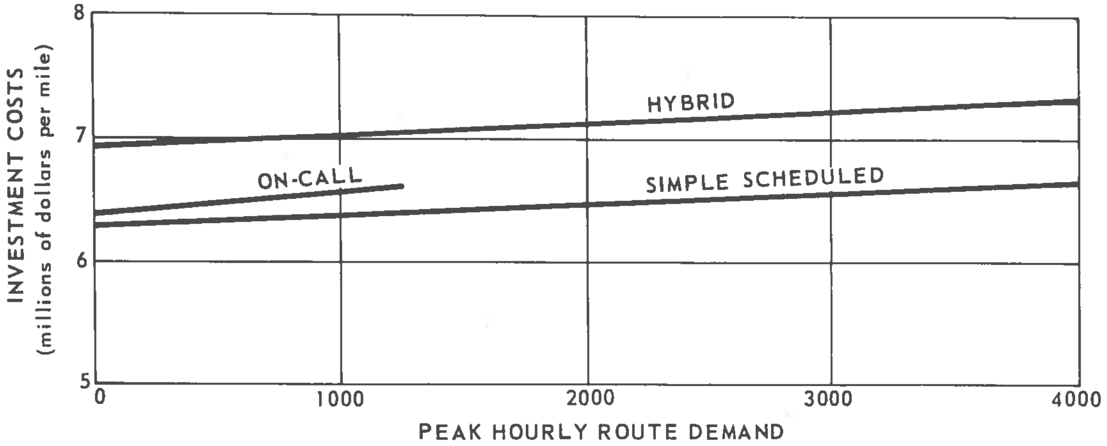

Figure 36. Investment Costs Versus Peak Hourly Route Demand, Hybrid/On-Call/Simple-Scheduled Single-Lane Subway Systems

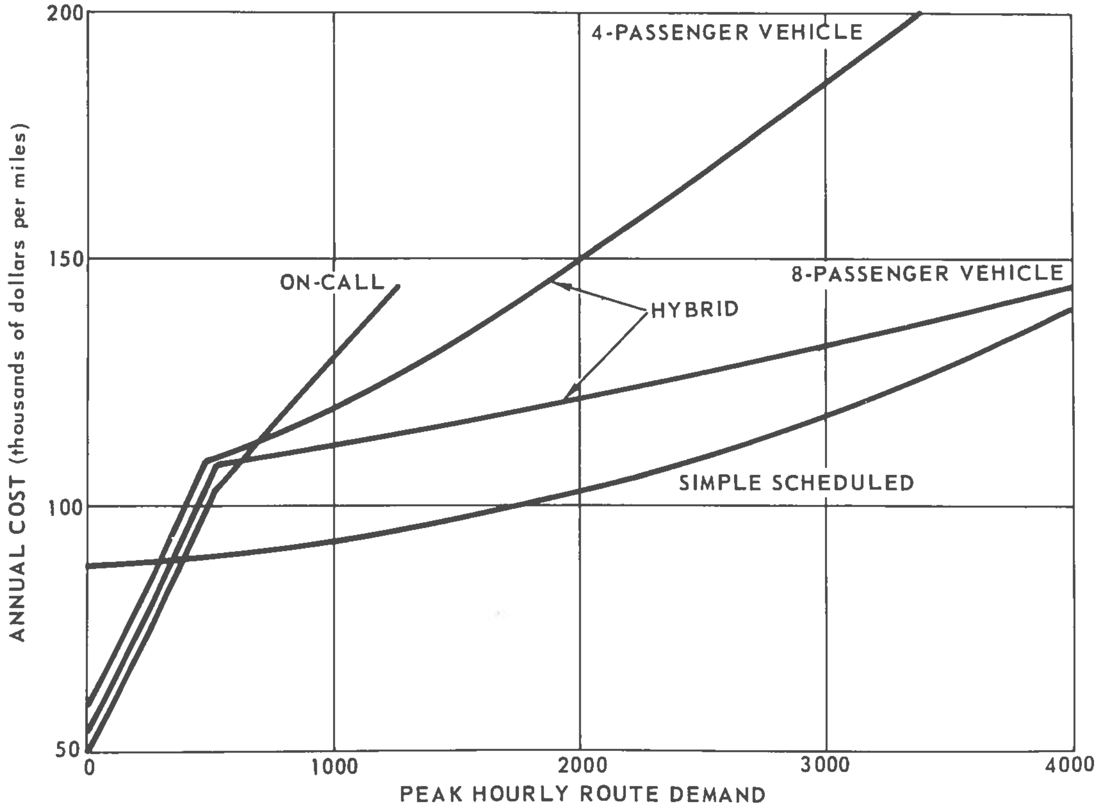

Figure 37. Annual Operating Costs Versus Peak Hourly Route Demand, Hybrid/On-Call/Simple-Scheduled Single-Lane Subway Systems (Source: Ford, Roesler and Waddell)[1]

6. REFERENCES

1. Parametric Analysis of Generic Urban Transit Systems, B.M. Ford, W.J. Roesler, and M.C. Waddell, APL/JHU TPR 001, December 1969, PB-188984.

2. Columbia Transit Program, Phase 1 Final Report, Concept Formulation, prepared by Bendix Corp., Ann Arbor, Michigan for Columbia Park and Recreation Association, April 1970.

3. Projection of Urban Personal Transportation Demand, Peat, Marwich, Livingston and Company, March 1968, PB-178276.

4. Future Urban Transportation Systems: Desired Characteristics-MR-1, D.G. Haney, Stanford Research Institute, May 1967.

5. Guidelines for New Systems of Urban Transportation: Urban Needs and Potentials, Barton-Aschman Associates, Inc., May 1968.

6. Modal Split, M.J. Fertal, E. Weiner, A.J. Balek, and A.F. Sevin, U.S. Department of Commerce, Bureau of Public Roads, Office of Planning, December 1966.

7. "Cities and Transportation: A Factor Analysis of Public Areas," G.K. Zenk and M. Frost, Urban Engineering and Transportation, ASME Winter Annual Meeting, December 1968.

8. Future Highways and Urban Growth, Wilbur Smith and Associates, New Haven, Connecticut, 1961.

9. Long Range Transportation Plan for the Central Business District, Dallas, Texas, DeLeuw, Cather and Company, Chicago, Illinois, 1965.

10. Land Use Transportation Study: Vol. 1, Inventory Findings 1963, Southeastern Wisconsin Regional Planning Commission, 1963.

11. The Urban Transportation Problem, J.R. Meyer, J.F. Kain, and M. Wohl, Harvard University Press, Cambridge, Massachusetts, 1965.

12. Alden Capsule Transit System: Control Subsystems and Baseline Definition, Alden Self Transit Systems Corporation, Bedford, Massachusetts, APL/JHU Contractor Report No. TCR 011, May 1970, PB-192737.

13. *Dasheveyor Transit and Cargo Systems: A Baseline Definition*, Dasheveyor Company, Los Angeles, California, APL/JHU Contractor Report No. TCR-006, May 1970, PB-192734.

14. *A Westinghouse Vehicle System for Major Activity Centers: A Baseline System Definition*, Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania, APL/JHU Contractor Report No. TCR-010, May 1970, PB-192738.

15. *The Varo Monocab System: A Baseline Definition*, Varo, Inc., Garland, Texas, APL/JHU Contractor Report No. TCR-009, May 1970, PB-192728.

16. *SKY-KAR Transivator System: A Baseline Definition*, SKY-KAR Corporation, Ft. Worth, Texas, APL/JHU Contractor Report No. TCR-007, May 1970, PB-192727.

17. *Transportation Technology Distribution System for a High Density Urban Area: A Baseline Definition*, Transportation Technology, Inc., Warren, Michigan, APL/JHU Contractor Report No. TCR-008, May 1970, PB-192739.

18. "The Uniflo Personal Rapid Transit System," L.E. Berggen, Paper No. 71011, *Automotive Engineering Congress*, Society of Automotive Engineers, January 11-15, 1971.