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16. Abstract

A parametric variation of demand density was used to compare service level and cost of two alternative systems for providing low density feeder service. Supply models for fixed route and flexible route service were developed and applied to determine ranges of relative efficiency. It was found that flexible route bus exhibited a lower sensitivity of cost to level of service provided than did fixed route bus. Flexible route bus can provide better service at the same or higher level of productivity at all demand levels below about 100 passengers per square mile per hour, except when minimal service only is to be provided.

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PREFACE

This report was prepared by the Applications Division of the Transportation Systems Center for the Office of the Assistant Secretary for Systems Development and Technology, U.S. Department of Transportation. It is intended to describe the results of research efforts related to the analysis of urban transportation concepts and does not reflect the official policy of the Department of Transportation.

This study is one of the work items on the project entitled Urban Analysis sponsored by the Office of R&D Policy. Valuable guidance was provided by Mr. Jerry D. Ward, Director of that office. TSC Program Manager for the project was Peter Benjamin. Research and preparation of this report were the responsibility of the author.

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1. SUMMARY

Low density urban areas have traditionally been served primarily by the automobile. As new mass transit facilities that extend into these areas are planned, consideration should be given to providing transit feeder service to line-haul systems, both to reduce the level of auto use and to provide complete origin-to-destination service for those unable to use the automobile.

Two alternative systems for providing access to a transit station are examined: fixed route, fixed schedule bus, and flexible route (door-to-door) subscription bus service. These are each analyzed in a hypothetical service area for a range of assumed transit demand.

The fixed route feeder system can be described in terms of vehicle productivity (passenger trips per vehicle hour) and the service ratio (ratio of average passenger travel time to auto travel time). For an average bus speed, the productivity is proportional to the ratio of the route spacing to the service frequency or, equivalently, to the product of the average passenger walk and wait times. The service ratio is related to the sum of the average walk and wait times. In both cases, a change in the average walk time has the same effect on both productivity and service ratio as a change in the average wait at a fixed level of demand.

Calculation of the system cost per passenger and implied values of passenger time reveal that the fixed route feeder cost is highly sensitive to the service provided when the service is relatively good. The cost sensitivity decreases quickly with worsening level of service.

Flexible route feeder service is analysed on the basis of variation of productivity and service ratio with size of service sectors -- sub-areas within the overall service area in which a vehicle makes its passenger collection tour. The sector size which leads to maximum vehicle productivity is that area which

generates a number of demands during a vehicle round trip just equal to the effective vehicle capacity. These "optimal" sector sizes increase with increasing vehicle size and with decreasing demand density. Vehicle productivity increases with increasing vehicle size and increasing demand density. The service flexibility possible because of the variable sector sizes results in a higher sensitivity of productivity to demand density than to vehicle size. It also results in a lower sensitivity of productivity to level of service than for fixed route bus. Flexible route bus level of service improves with decreasing vehicle loads and increasing demand density. The relationship between service ratio and effective vehicle capacity is found to be approximately linear.

A comparison of fixed route with flexible route feeder bus systems reveals that at the same level of productivity, flexible route bus can provide better service at all demand levels below 100 passengers per square mile per hour. Even when unit operating costs for flexible route bus are assumed 50 percent higher than fixed route bus, flexible route bus can provide as good or better service for the same total cost. Fixed route feeder bus systems become cost-competitive with flexible route bus (except at very low demand densities) only when providing a low level of service, e.g. service ratio greater than about four.

In general, it appears that in low density areas flexible route feeder bus service can provide better service at the same or lower cost than a fixed route bus system. A fixed route system may be less expensive where only minimal service is to be provided.

2. INTRODUCTION

For several decades, the migration of urban population away from city centers has continued unabated. Persons living in low density areas now represent a majority of urban dwellers. Of all the factors contributing to this phenomenon, sometimes known as sub-urbanization, low density development, or urban sprawl, possibly the most important has been the mobility provided by the automobile and its associated facilities. For those who chose to reside some distance from central activity centers, the automobile was a superb transportation form: convenient, comfortable, reliable, speedy. Indeed, it was perhaps too good, for its desirability produced a level of demand for auto transportation that has led to serious problems regarding utilization of existing highway facilities, air quality, energy consumption, and land use. Although some of these problems are being addressed and hopefully reduced by the increasing development of mass transit facilities, which often extend into low density areas, many of these systems exhibit two important deficiencies:

1. They do not serve non-radially-oriented and local trips well and,

2. The most common access mode to these systems will remain the automobile. These facilities should be judged fully successful only if they are not totally dependent on the auto for access.

Although the mobility of non-drivers has always been limited, it is severely restricted in low density areas, where often little or no transit service is available and walk distances are large. The increasing awareness of this situation and the willingness to improve it have stimulated such developments as dial-a-ride bus, perhaps the first mass transportation form that has the potential to provide good service to this segment of the population.

Efforts to reduce the dependency on the auto of those who have no good alternative and to improve the mobility of those having neither auto nor transit alternative will form the main thrust of much of the transportation research and development in the years to come. As part of these overall efforts, examination of the need for alternative transportation modes in low density areas should not be neglected. In this study, two candidate systems for providing feeder service are analyzed and compared. Collection service only is addressed. Although the analysis is presented in a feeder service framework, it can pertain to any type of many-to-one service, i.e., diverse origins to a single destination.

2.1 SCOPE

The service and costs of two alternative transit systems able to provide feeder service in low density areas to a line haul facility will be examined: "conventional" fixed route bus and flexible route (door-to-door) subscription bus. Fixed route systems often can not provide efficient service in very low density areas. Door-to-door bus systems, using vehicles much smaller than conventional buses, have the potential to serve the low density market well at reasonable cost. In particular, during the commuter hours when the majority of trips recur daily, a subscription door-to-door service can be highly efficient, since routing and scheduling can be arranged well in advance.

The two systems are compared using parametric variation of given (assumed) demand densities -- passengers per square mile per hour. It should be noted that while service levels are in part determined from demand densities, it is also true that demand levels are in turn based on service characteristics. Since the effects of service on demand levels are not considered, there is no assurance that, at any given demand, the derived level of service is consistent with the demand assumption. Further, this inconsistency may be aggravated in a comparative analysis, since two systems having different service characteristics are not likely to generate the same demand levels even for the same average travel times. Thus, the theoretical analyses and comparisons presented herein are meant only to indicate which variables affect cost and service levels, their general ranges of interaction, and the relevant trade-offs.

2.2 METHOD OF ANALYSIS

A service area is hypothesized in which transit commuters desiring service to a line haul station are distributed uniformly at a given demand density. Costs and service levels of a fixed route bus serving this area are determined on the basis of route spacing and frequency of service. For an alternative door-to-door system, costs and service levels are based on "service sectors" into which the service area is divided. The sizes of these sectors are determined by the demand densities and vehicle capacity assumed.

The costs of providing feeder service by the fixed route and flexible route systems are examined in terms of the vehicle productivity -- passenger trips per vehicle hour -- an indicator of both operating efficiency and economic feasibility. The vehicle productivity is inversely proportional to the cost per passenger carried (see Figure 1).

The level of service provided is measured by the "service ratio" -- the ratio of bus passenger trip time to auto trip time. To gain proper perspective, this measure should be used in conjunction with the absolute trip time values to avoid the distortion that ratios can cause. For example, the quality of service where the service ratio is 3 for a 15-minute bus trip (5-minute auto trip) may be perceived by some patrons to be better than a ratio of 2 for a 40-minute bus trip (20-minute auto trip). An implied value of time is computed for fixed route and subscription bus feeder systems. That is, since sizing a system specifies both a cost and a level of service (which generally are inversely related), a passenger's value of time can be imputed from the system specifications. This is one indicator of the system's cost sensitivity to the level of service provided. Finally, a comparison of costs and service for the two systems is performed by determining the difference in service levels when equal productivities are achieved. In addition, a rough cost comparison is made for various assumed service levels.

Most of the analysis described below pertains to a feeder service area of four square miles. Since the station is located in one side

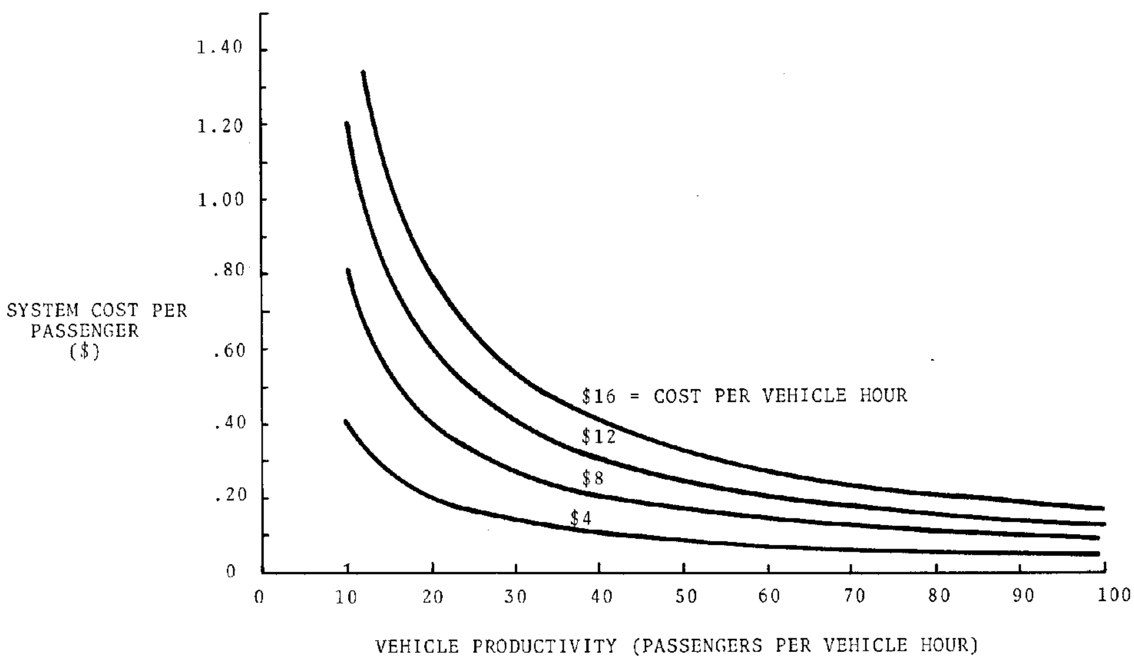


Figure 1. System Cost Vs. Vehicle Productivity

of the service area, a symmetric area assumed on the opposite side of the station makes the discussion directly applicable to a total market area of eight square miles.

In this report, Chapters 3 and 4 describe the analytical supply models used to evaluate fixed route and flexible route bus feeder systems, respectively. Chapter 5 presents service and cost comparisons of the two systems, and Chapter 6 summarizes the conclusions reached in this study. Appendices A and B detail the mathematical formulation of equations used in the analyses of fixed route bus and flexible route bus, respectively. Appendix C contains supplementary analysis charts pertaining to a service area of ten square miles.

3. FIXED ROUTE FEEDER BUS

3.1 INTRODUCTION

A fixed route bus system is relatively simple to manage and operate, and theoretically easy for patrons to understand and utilize. However, buses running on fixed routes and schedules are often inefficient in low density areas because the trip densities are not high enough to allow good service that is also financially feasible. The relationship between a fixed route feeder system's cost and the service provided in terms of passenger walk, wait, and travel time is examined here.

3.2 SYSTEMS DESCRIPTIONS

Fixed route bus service is analyzed for a square service area having the station located in the middle of one side (see Figure 2). Parallel routes extend the length of the service area and are evenly spaced. It is assumed that in this low density area the capacity of the buses is rarely exceeded, and therefore the bus frequency and route spacing are exogenously specified. Except where indicated, an average constant speed of 15 miles per hour is assumed. In order to express the system design specifications from the passenger point of view, the frequency and route spacing can be converted to average passenger wait and walk times, respectively, by assuming one-half the headway for the average wait and one-fourth the route spacing for the average walk distance.

3.3 PRODUCTIVITY

Since fixed route bus productivity (passenger trips per vehicle hour) is directly proportional to route spacing and indirectly to service frequency, it is directly proportional to the product of the walk and wait time (See Appendix A.1 for the derivation of productivity). Figure 3 shows productivity as a function of hourly demand density for a constant bus speed. Walk and wait times are interchangeable, since doubling the frequency has the same effect on productivity as halving the route spacing.

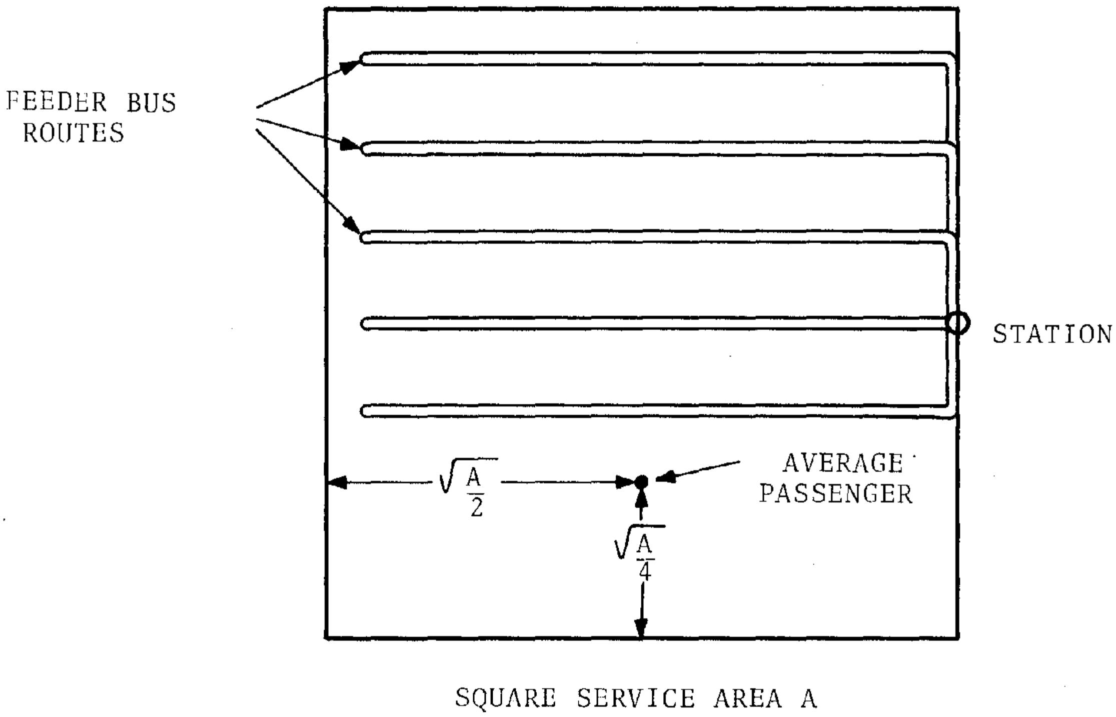


Figure 2. Fixed Route Feeder Bus Service Area

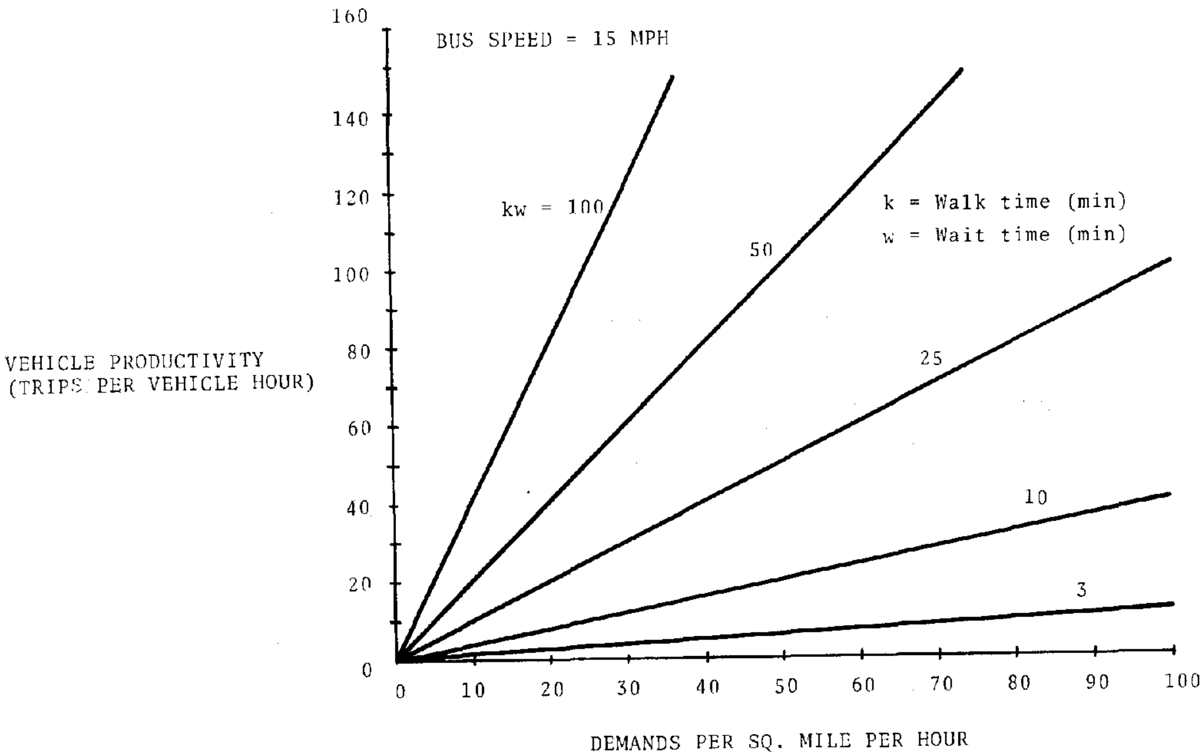


Figure 3. Fixed Route Feeder Bus Vehicle Productivity

To determine the effects of a bus speed which varies with the demand density, a speed function (Figure 4) ranging from a no-stop speed of 20 mph to a low of 12 mph for a maximum of eight stops per mile was postulated (see Appendix A.2 for derivation). In Figure 4, lower walk/wait times result in higher bus speeds, since better service means fewer passengers per bus and therefore fewer stops per bus. The productivity under the variable bus speed assumption is plotted in Figure 5. In comparison to Figure 3, the productivities are relatively higher at low demand densities (where bus speeds are high) and relatively lower at high demand levels (where bus speeds are lower).

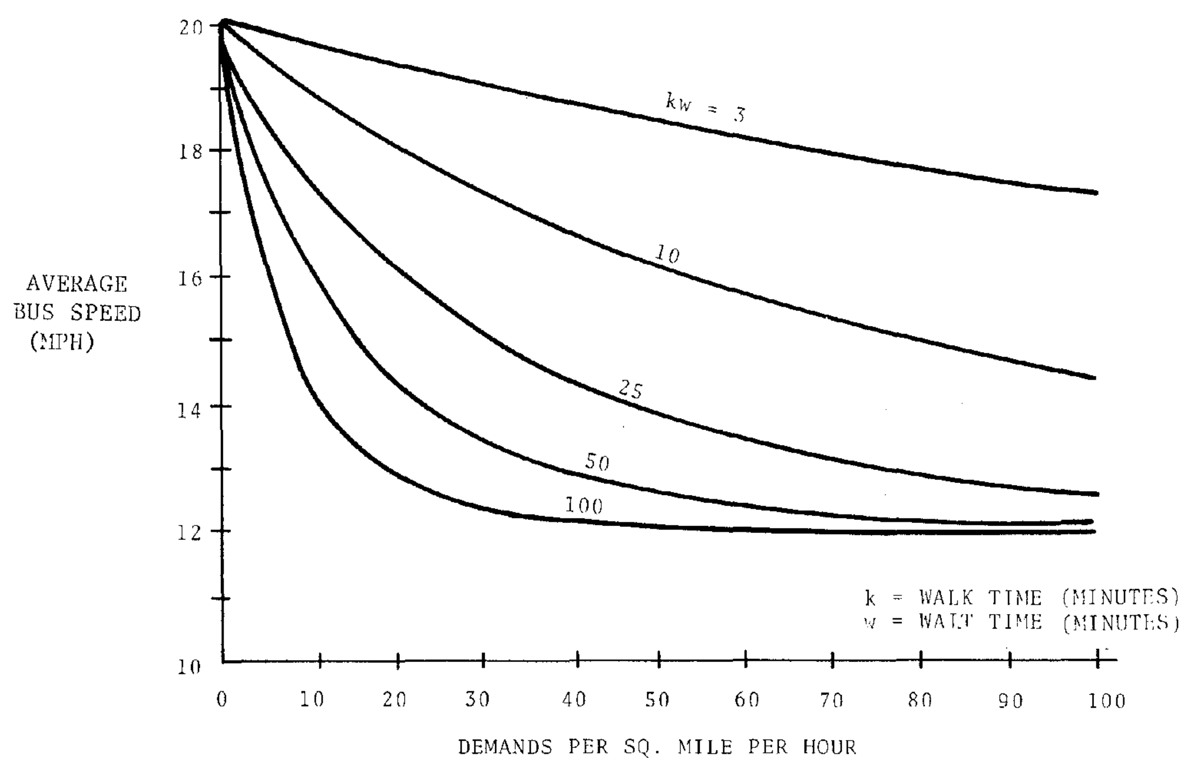


Figure 4. Fixed Route Feeder Bus Speed Function

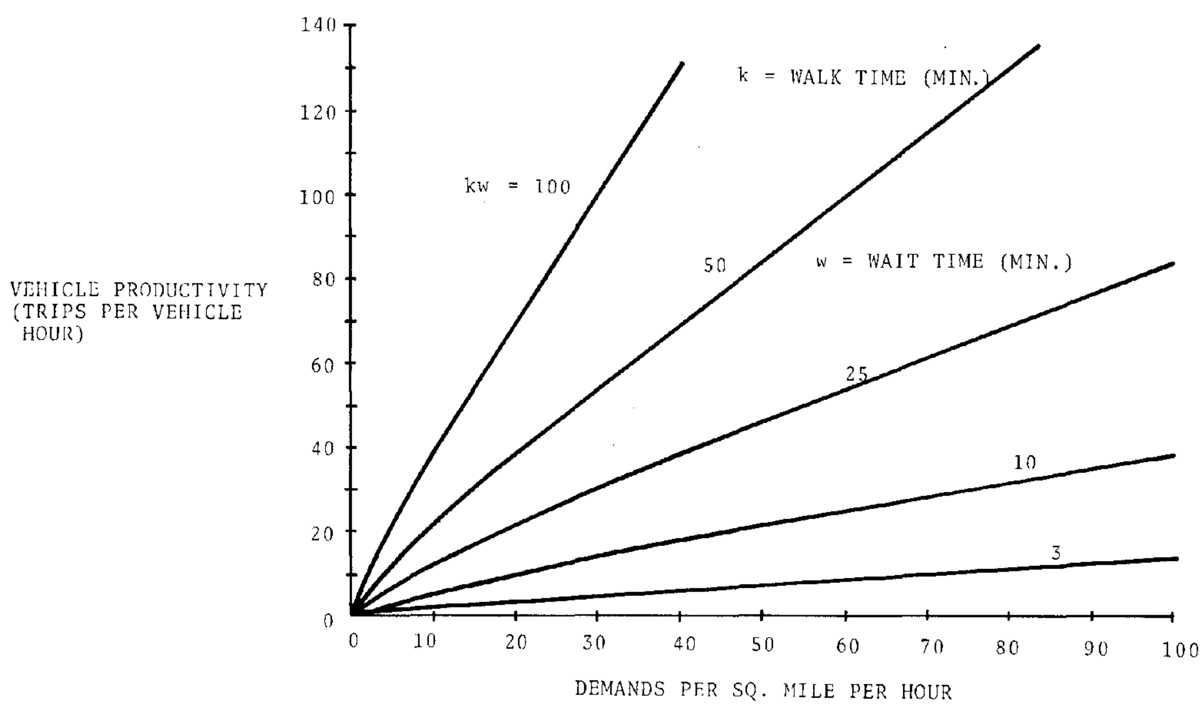


Figure 5. Fixed Route Feeder Bus Vehicle Productivity (Variable Bus Speed)

3.4 LEVEL OF SERVICE

Since the fixed route feeder bus system is not sized according to the demand, the level of service provided (as reflected in the service ratio) is not a function of the demand density for a constant bus speed (see Appendix A.3 for derivation). Figure 6 shows the variation of service ratio with various walk/wait time combinations for a 4 square mile service area (which shall be referred to as "nominal" service -- 5 minute walk and 5 minute wait -- a service ratio of 4.5). Figure 7 shows the same for a bus speed varying with demand sensitivity. As with productivity, a change in the average wait time has the same effect on service ratio as a change in the average walk time.

3.5 COST PER PASSENGER

For a given demand density, the cost per passenger for fixed route feeder service can be computed from the productivity (see Appendix A.4) and is plotted in Figure 8 for an assumed $12 per vehicle-hour of operation. The cost per passenger at a demand level of 50 trips per square mile per hour is shown in Figure 9

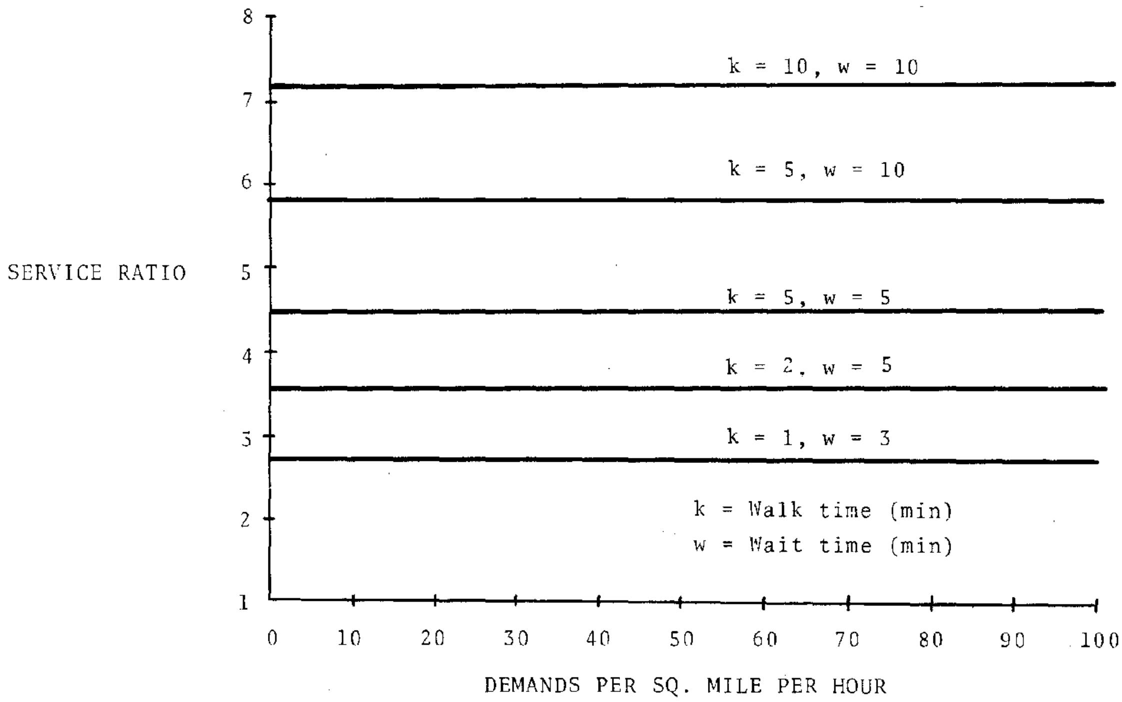


Figure 6. Fixed Route Feeder Bus Service Ratio

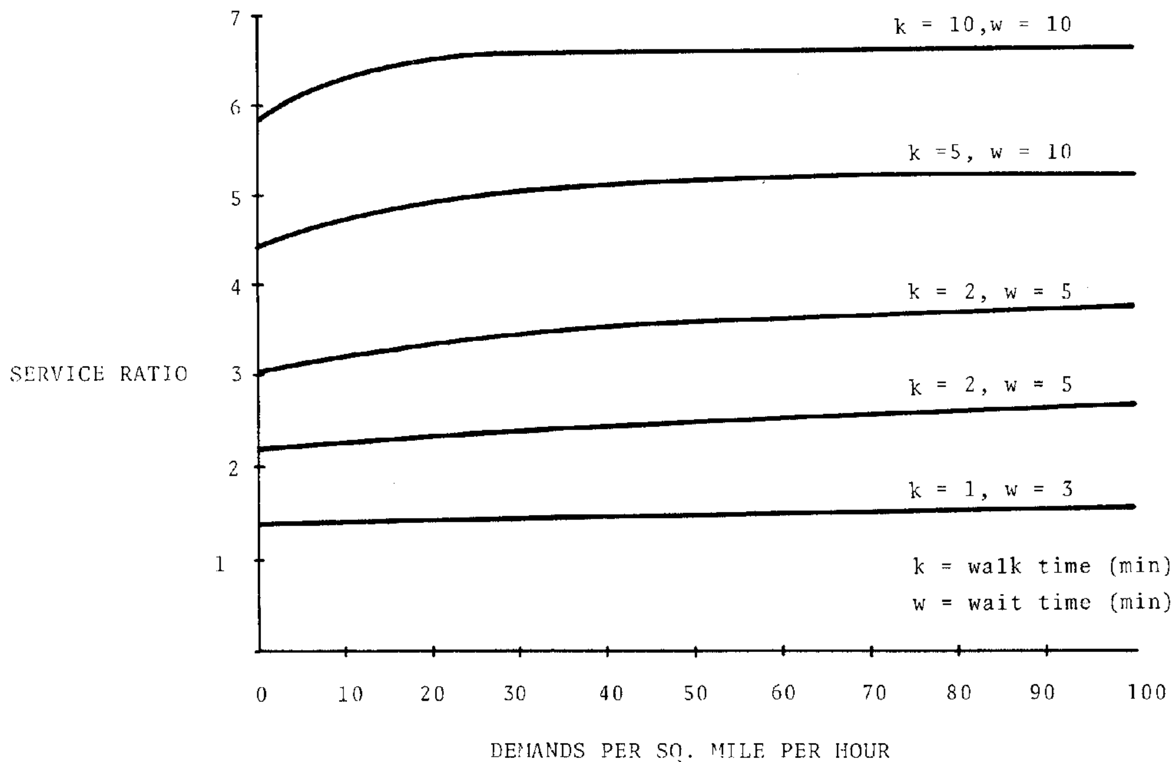


Figure 7. Fixed Route Feeder Bus Service Ratio (Variable Bus Speed)

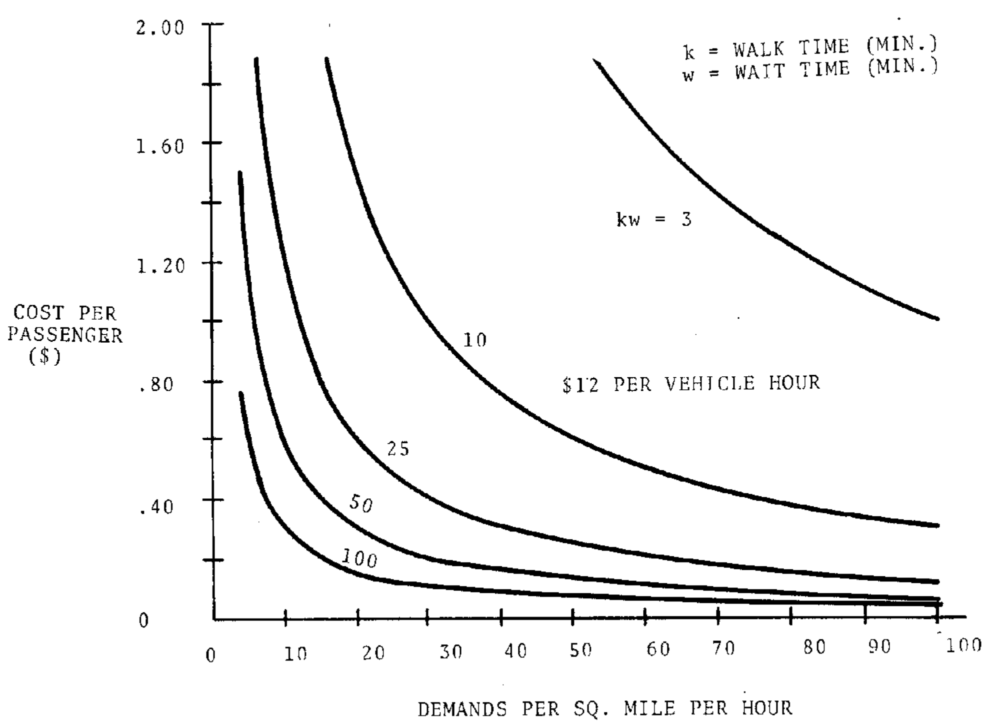


Figure 8. Fixed Route Feeder Bus Cost per Passenger (Demand Variation)

versus the average passenger trip time. (Note that in Figures 9-12 the average passenger line haul time is six minutes.) The crossing of the curves can be explained as follows: Since the total passenger trip time is the sum of the walk, wait, and line haul times (the last of which is constant for a constant average speed), the specifications of total trip time plus a walk or wait time determines the remaining variable (walk and wait are interchangeable). Therefore, any two curves cross where the walk time for one implies that its associated wait time is equal to the walk time for the other.

Since productivity is proportional to the product of the walk and wait times, the cost per passenger for any given total trip time will be minimized where the walk time equals the wait. (In other words, the product of two numbers for a fixed sum is maximized where the two numbers are equal.) The (minimum) cost per passenger is shown in Figure 10 for equal walk and wait times. Nominal service -- 5 minute walk and 5 minute wait -- results in 24 cents per passenger trip at this demand level. Since productivity (but not service) is a function of the demand density, the cost per passenger is indirectly proportional to the demand, e.g., nominal service would cost 12 cents and 48 cents per passenger for demand densities of 100 and 25 passengers per hour per square mile, respectively.

3.6 IMPLIED VALUE OF TIME

The slopes of the cost per passenger curves of Figure 9 can be interpreted as the values of passenger time implied from the operator's (or system designer's) point of view. Figure 11 shows the implied value of time associated with the average passenger trip time. High time values indicate the region where a small change in service level produces a relatively large change in cost. For the assumptions of Figure 11, nominal service results in a value of time of about $3 per hour. As the demand density varies from 100 to 25 passengers per square mile per hour, the value of time varies proportionately from $1.50 to $6.00 per hour, a range which encompasses most values of time reported in the literature in this field.

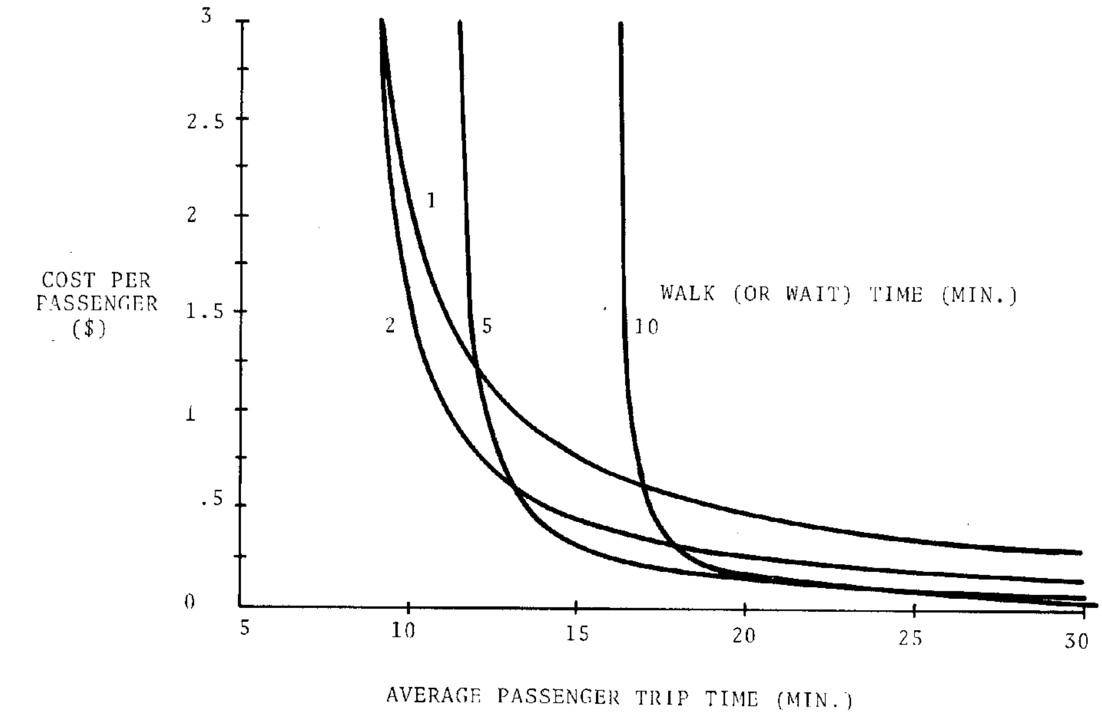


Figure 9. Fixed Route Feeder Bus Cost per Passenger (Trip Time Variation)

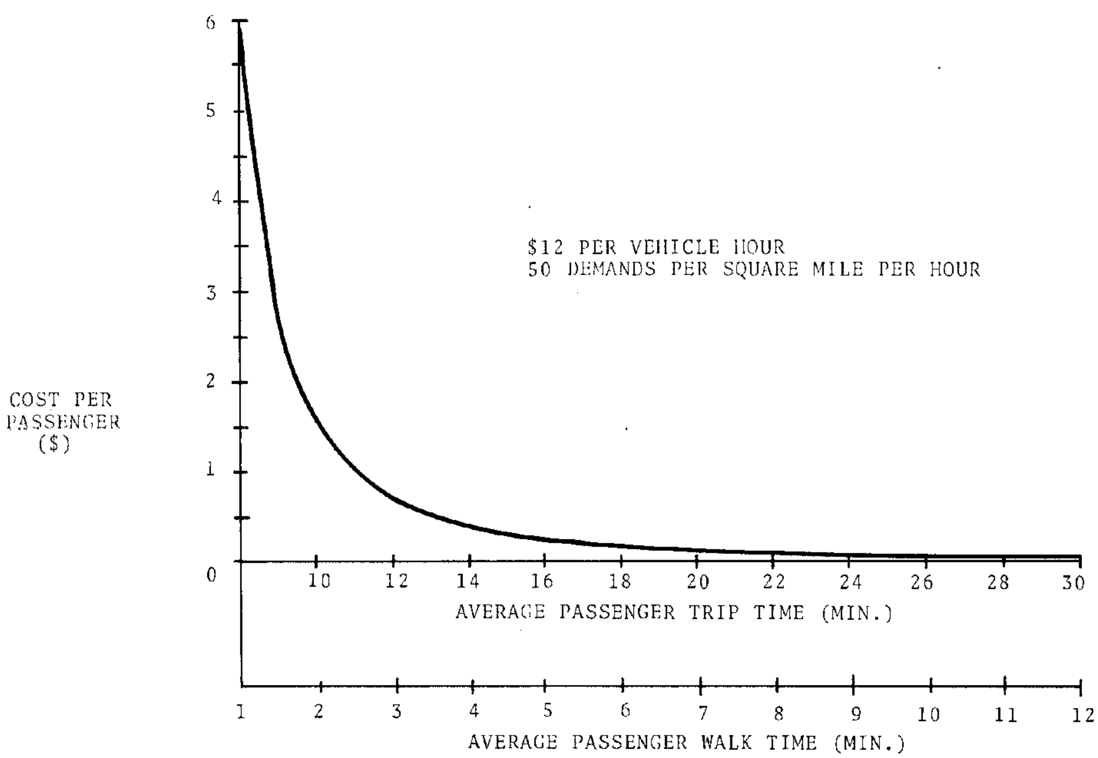


Figure 10. (Minimum) Fixed Route Feeder Bus Cost per Passenger

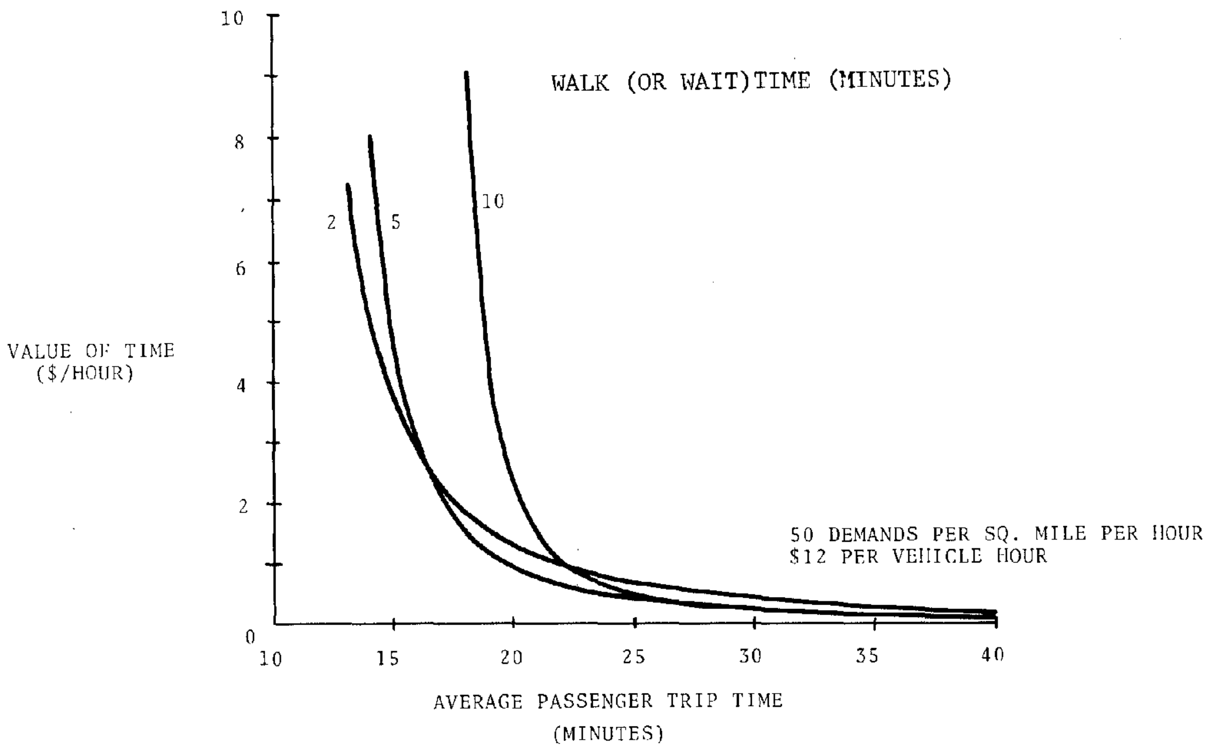


Figure 11. Implied Value of Time for Fixed Route Feeder Bus Service

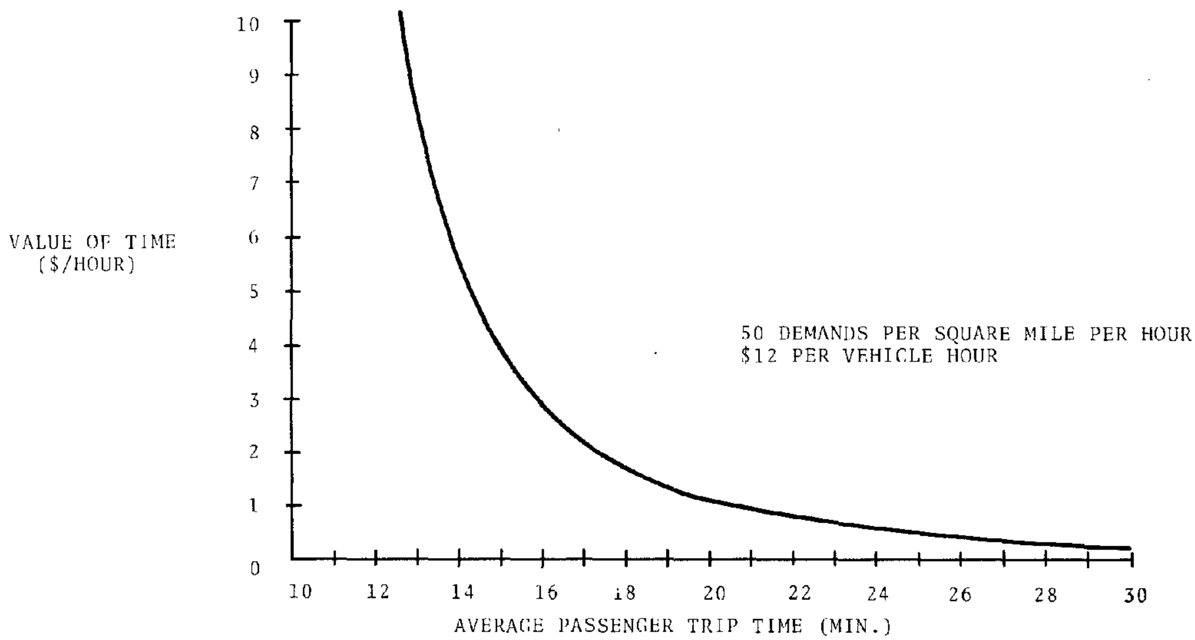


Figure 12. Implied Value of Time for Minimum Cost Fixed Route Feeder Bus Service

Figure 12, the companion curve to Figure 10, shows the implied value of time for minimum cost per passenger, i.e., where walk time equals wait time.

4. FLEXIBLE ROUTE SUBSCRIPTION BUS FEEDER SYSTEM

4.1 INTRODUCTION

A fairly recent development in mass transportation for low density areas is the demand-responsive bus system, of which one type is known as dial-a-ride. In this system, the prospective passenger uses the telephone to call a central dispatch center, boards the vehicle when it arrives at his door, rides for a few collection or pickup stops, and arrives at his destination. There is virtually no walk at either end of the trip. The wait for pickup (at the residence end) is inside the home where other business can be taken care of.

Subscription service in commuting periods is often available and usually encouraged; sometimes it is the only type of service offered. The passenger contracts to be picked up at the same time every day. He does not have to phone for daily service. Since this kind of operation is most useful for work trips, its use is likely to be highly dependent on the reliability of promised arrival time by the vehicle.

Doorstep service is usable by all segments of the population. Personalized care by the drivers can facilitate the transportation of the aged, handicapped, and even small children. Not only does this type of system provide good service to those unable to use the auto, but a properly operated system may be able to compete effectively with the auto.

4.2 SYSTEM DESCRIPTION

The subscription feeder bus system described here provides door-to-door service from home to a transit line-haul station. (Although the term "bus" is used throughout, the analysis is applicable to any kind of vehicle, such as van or taxi.) Since requests for service are on a subscription basis and fairly stable, collection routes can be scheduled well in advance and designed to minimize the distance traveled by the fleet. The nature of subscription bus demand and service allows the use of averages in the mathematical development to represent a reasonably realistic operating system.

The analysis of subscription bus feeder service may, in theory, be applicable to a true "dial-a-ride" type operation (except that no passenger wait time is considered for subscription bus). However, the large deviations in demand rate and vehicle routes inherent in the more "dynamic" dial-a-ride system makes the mean values used here much less valid for its operating characteristics.

The concept of "service sectors" (see Figure 13) is used to provide a framework for the mathematical analysis. A service sector is a subarea within the overall service area in which one vehicle makes its collection tour. It can be seen that if demand in a given time period in a service sector is sufficient to require two vehicles, the sector should then be divided into two, thus minimizing the vehicle tour distances by avoiding the overlapping of routes. The sizing of service sectors will be seen to be important in estimating the parametric variations of levels of service and productivity. However, in actual operations the prescheduling of subscription service obviates the need for true service sectors. Routes of schedules can be designed without actual partitioning of the service area into sectors. Presumably, these routes, on the average, reflect approximately the same service and costs as those derived below.

4.3 TRIP COMPONENTS

The components of a subscription bus collection tour and trip, each of which will be described separately, are shown in Figure 13. The service area line haul, during which no stops are made for passengers, is the portion between the station and the service sector. The sector line haul is the distance from the entrance of the service sector to the most remote (from the station) collection stop. The collection tour is the portion of the trip from the first pickup to the sector exit. (Mathematical derivation of the distances and times of the trip components can be found in

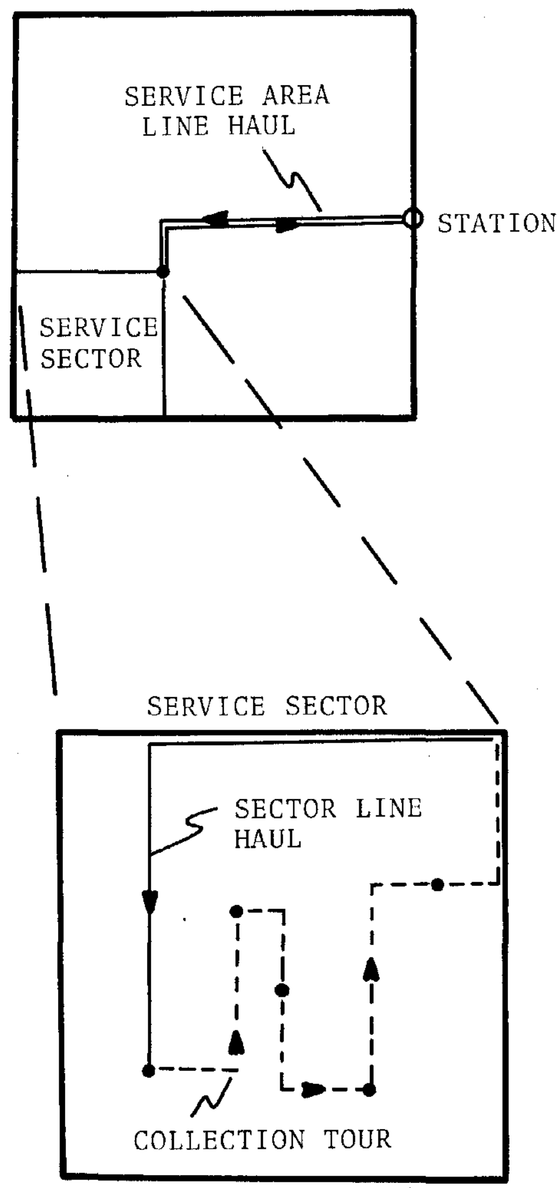


Figure 13. Subscription Bus Service Area

Appendix B.) For simplicity it is assumed that a grid street system exists and that both the service area and sectors are of square shape. Although a square service sector shape produces the minimum sector line haul and tour distance, this is balanced somewhat by the larger service area line haul distance required, especially when sector areas are not very small relative to the service area.

The service area line haul distance varies with the number of sectors in the service area. Figure 14 shows the one-way distance expressed in terms of the length of one side of the service area. As the number of sectors grows very large, the line haul distance approaches three-fourths of the service area side.

The sector line haul distance varies with the number of collection stops. Figure 15 shows the distance expressed in terms of the length of one side of the sector. If there is just one pickup, on the average it is located in the middle of the square, and therefore the line haul distance is the length of one side. As the number of stops grows large, the most remote pickup is located closer to the far side, and the sector line haul distance approaches 1.5 times the length of one side.

The collection tour distance is a linear function of the number of stops and is shown in Figure 16, expressed in terms of a service sector side. The collection tour time is presented in Figure 17 as a function of sector area for four values of n, the average number of stops per collection tour. An n of three would perhaps apply to a taxi-size vehicle. Values of five and ten would be appropriate for vans and minibuses. An n of 20 would be applicable to a medium size bus.

Figure 18 shows the variation with sector area of the total round trip time for several vehicle sizes.

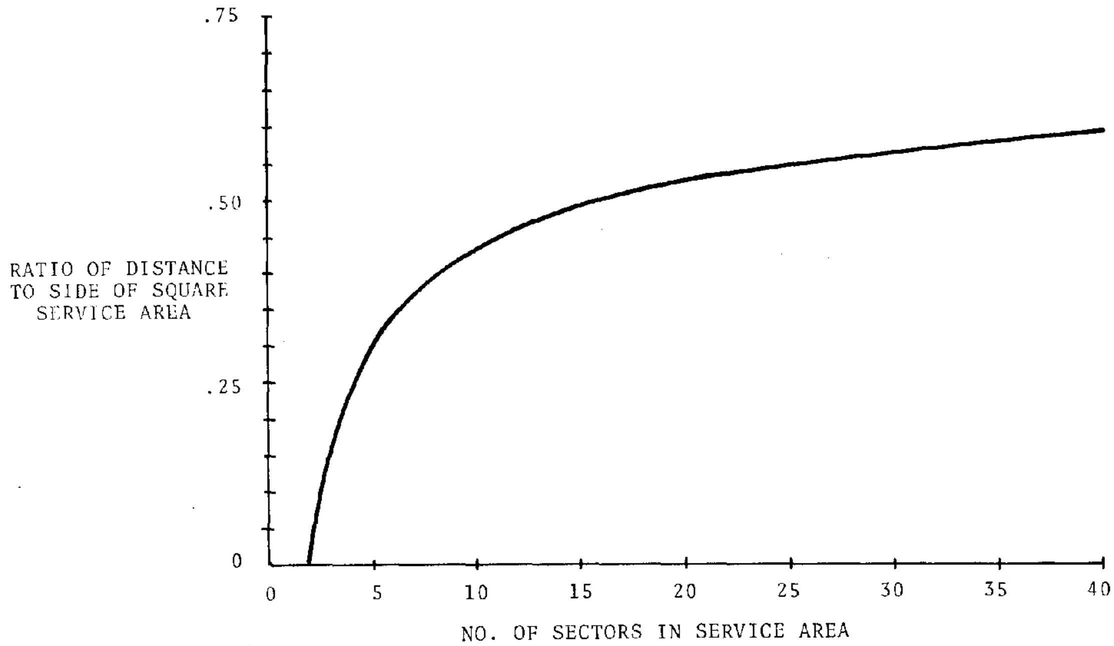


Figure 14. Flexible Route Feeder Bus Service Area Line Haul Distance (Sector to Station)

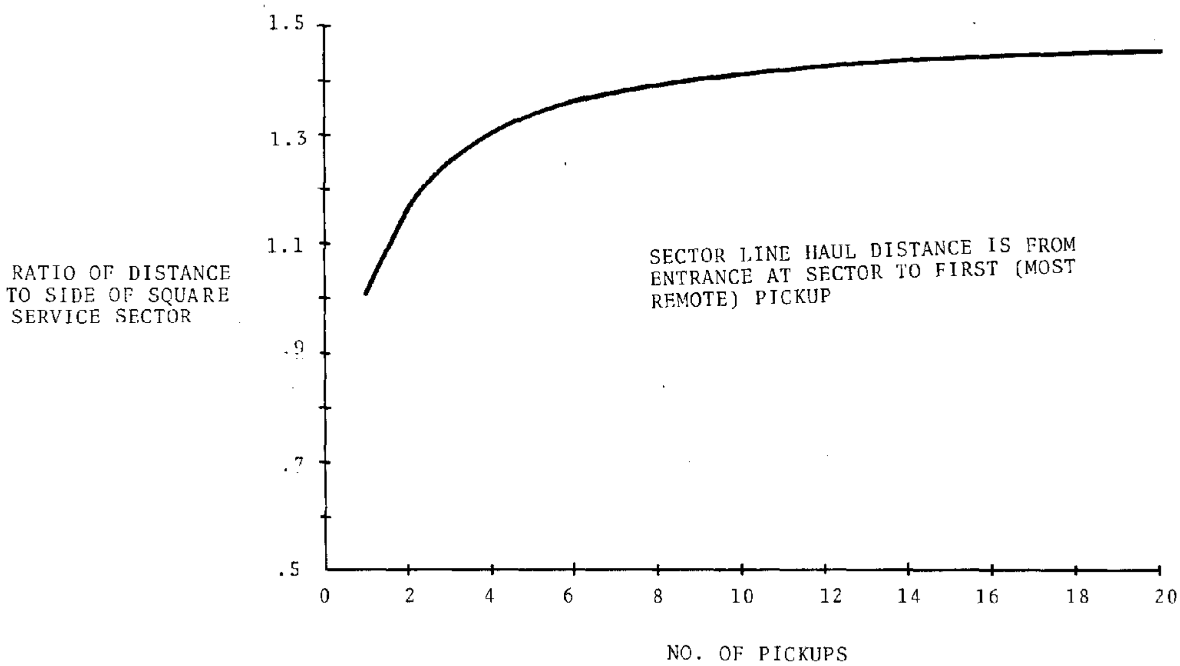


Figure 15. Flexible Route Feeder Bus Sector Line Haul Distance

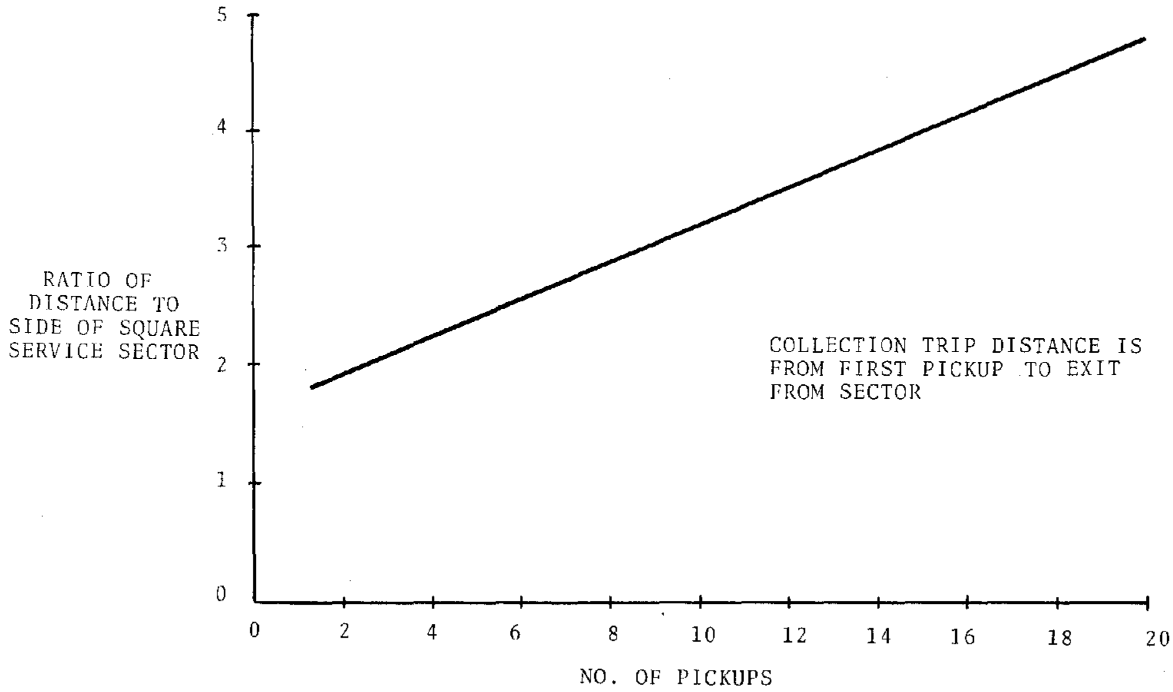


Figure 16. Flexible Route Feeder Bus Collection Tour Distance

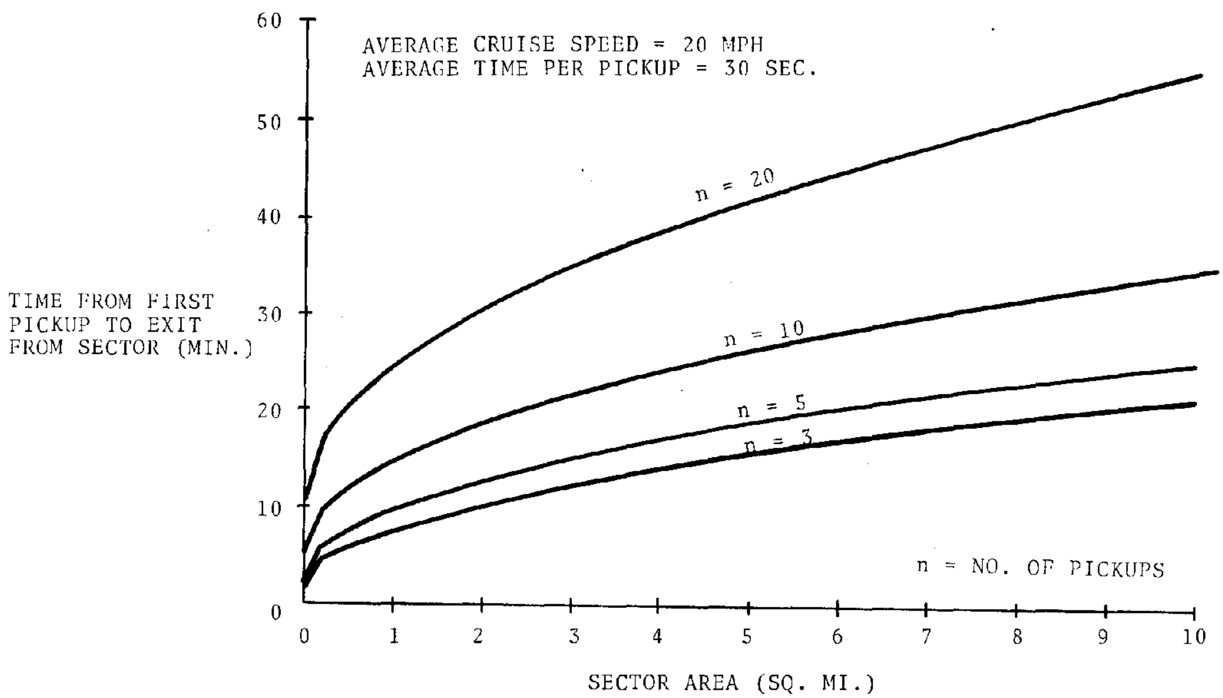


Figure 17. Flexible Route Feeder Bus Collection Tour Time

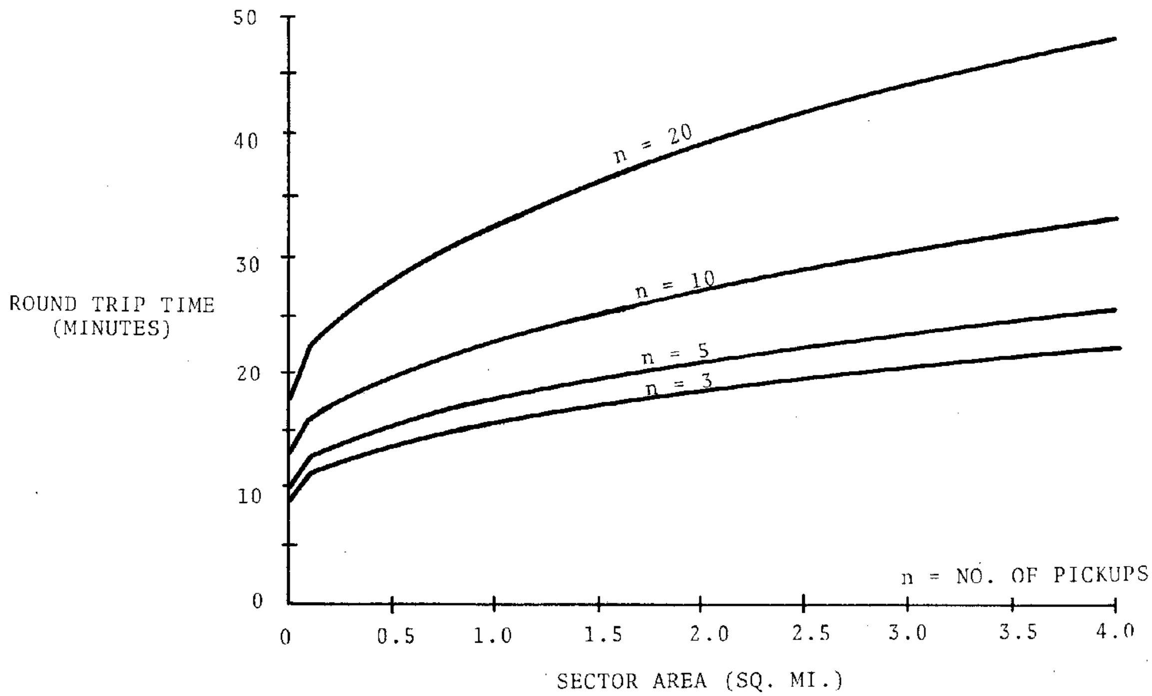


Figure 18. Flexible Route Feeder Bus Round Trip Time

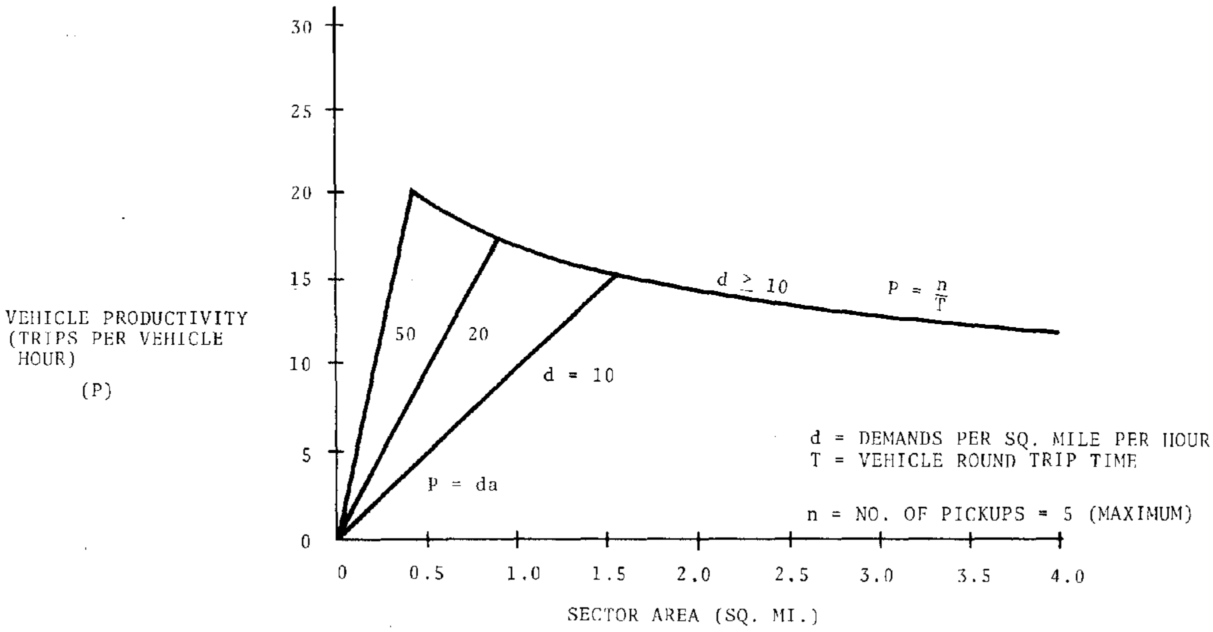
4.4 PRODUCTIVITY

The variation of productivity with sector size is shown in Figure 19 for a maximum of five average pickups per tour and for three levels of demand. If the sector size is so small that fewer than five demands are generated during the round trip time of a vehicle, the productivity (trips per vehicle hour) will be equal to the number of demands per hour generated in the sector (since all can be handled by one vehicle):

$$P = da$$

where P = vehicle productivity
d = demand density
a = sector area

This function is represented by the straight line portions of the chart.



(a)

Figure 19. Flexible Route Feeder Bus Vehicle Productivity (n = 5)

For larger sector areas, the sector demand must be handled by more than one vehicle, and productivity is therefore determined by the round trip time of the vehicle:

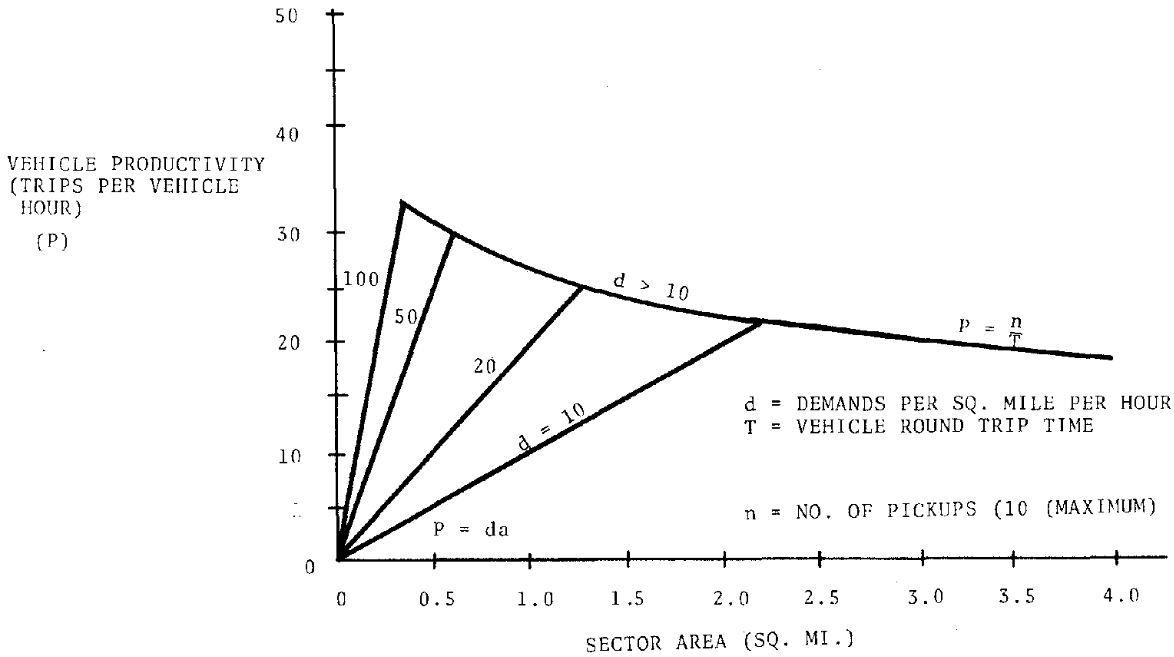
$$P = \frac{n}{T}$$

where n = average number of pickups
T = vehicle round trip time

This equation is the curved portion of Figure 19.

The intersection of these curves for any demand density is the point at which the theoretical maximum productivity is obtained for the assumed effective vehicle capacity. Below this point, the sector area is not large enough to generate sufficient demand to fill a vehicle; above this point, the larger round trip times reduce the number of passengers that can be carried by a vehicle in an hour.

Figure 20 shows the productivity for an average load of ten pickups per vehicle. The maximum productivity for a given demand density is achieved at a larger sector area than in Figure 19, due to greater vehicle capacity.



(a)

Figure 20. Flexible Route Feeder Bus Vehicle Productivity (n=10)

4.5 LEVEL OF SERVICE

The variation of subscription bus level of service with sector size, as expressed through the service ratio, is shown in Figure 21. (The service ratio is the ratio of average bus passenger trip time to average auto travel time.) The average bus passenger trip time is comprised of one-half the time required at pickup stops, plus one-half the collection tour time, plus the time required for a one-way line haul. The passenger time does not include any wait time at point of origin, since it is assumed that the bus maintains a reliable schedule. The service ratio may therefore be slightly understated because a patron would likely request service a few minutes earlier than actually desired to account for possible delays. The slight change in slope of the curves noticeable at a two square mile sector area occurs where the service area line haul distance becomes zero.

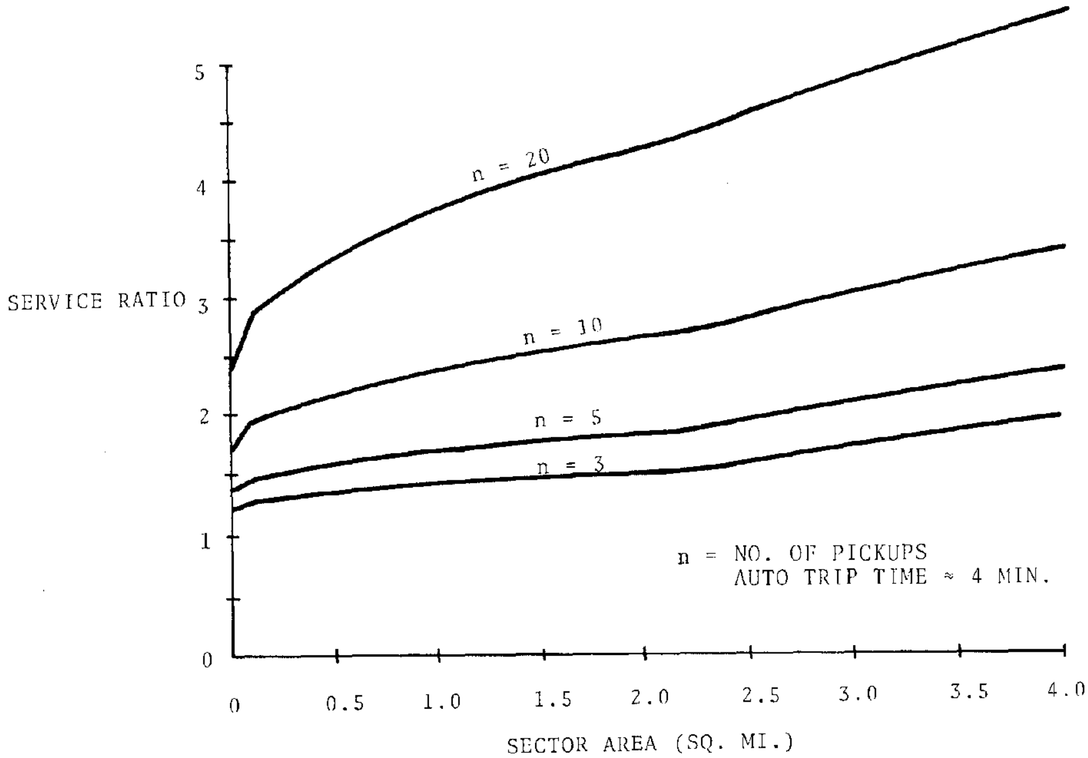


Figure 21. Flexible Route Feeder Bus Service Ratio

4.6 SECTOR SIZE FOR MAXIMUM PRODUCTIVITY

It has been shown that, for any level of demand, there exists a sector size which produces maximum vehicle productivity. These "optimal" sector sizes can be determined by locating the points where the assumed demand (passenger trips generated in each sector) is in equalibrium with the available supply (vehicle trips serving each sector). The demand generating function must produce exactly the number of pickups per vehicle round trip in the time required to make the round trip:

$$n = (T)(a)(d)$$

where n = average no. of pickups per tour
T = vehicle round trip time
a = sector size
d = demand per sq. mile per hour

The supply function is the vehicle round trip time, shown above to be function of n, a, d and the service area.

The two simultaneous equations with two unknowns T and a can be solved to give the optimal sector size. The solution is graphically illustrated in Figure 22. The hyperbolic curves are the function $T = \frac{n}{d} \frac{1}{a}$ plotted for several values of $\frac{n}{d}$. The parabolic curves are the same vehicle round trip time curves of Figure 18. The intersections of the two sets of curves represent the solutions of the two equations and indicate the sector area for maximum productivity. Values of this optimal sector area for a given demand density are plotted in Figure 23. In general, these areas are somewhat smaller than sector sizes found in studies of "spontaneous" demand-responsive systems in which service is desired a short time after the request. In those systems, there must be a fairly large market area from which to select the pickup stops that will enable "real time" design of reasonably efficient routes. The prescheduling of subscription service allows the hypothetical sectors to be of smaller size.

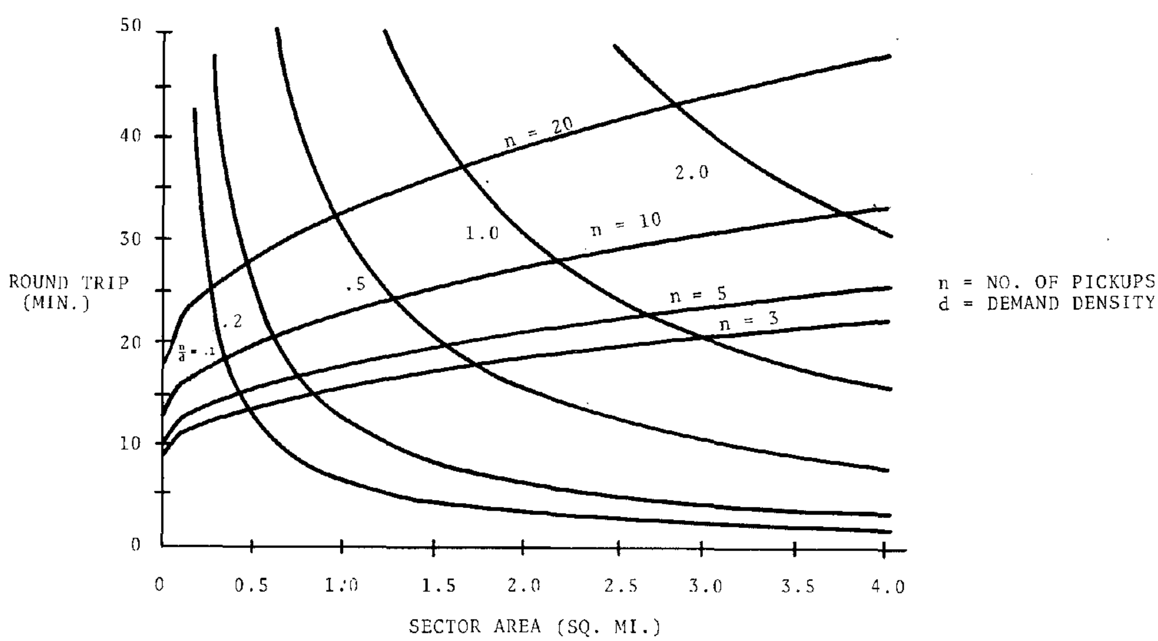


Figure 22. Feeder Bus Equilibrium Between Demand Rate and Service Rate

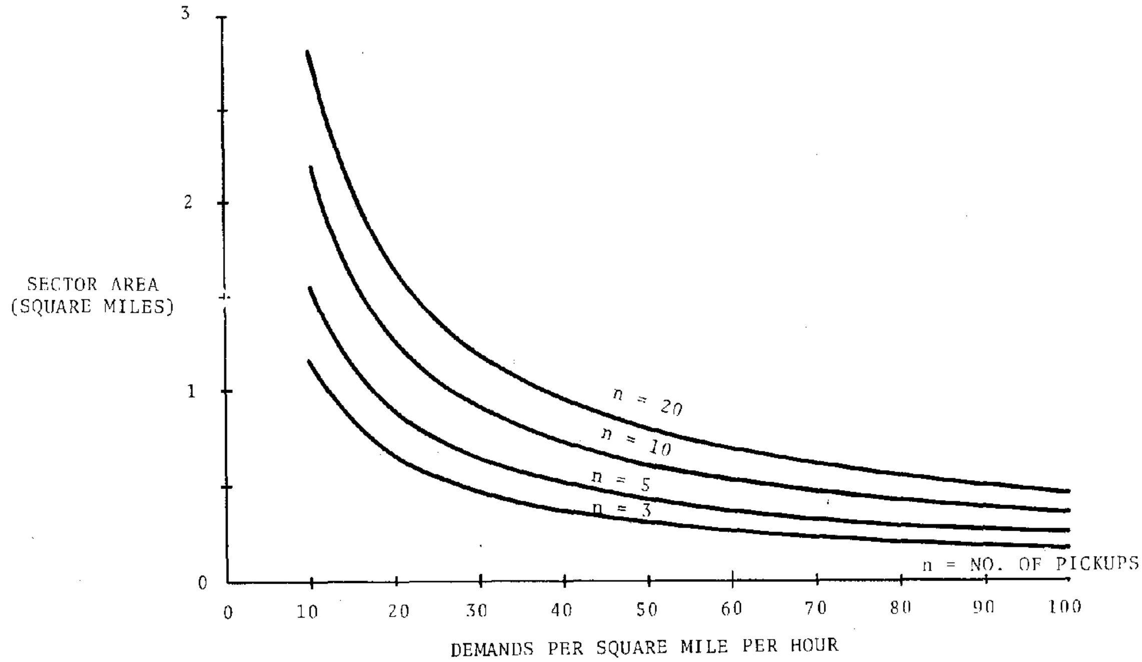


Figure 23. Flexible Route Feeder Bus "Optimal" Sector Area

Figure 24 shows the variation of vehicle round trip time with demand density when sectors are sized for maximum productivity. The slopes of the curves tend to be rather small because where the sectors are small and therefore collection tour times are short, the service area line haul times are greater and partially compensate. In other words, the average vehicle travels roughly the same distance regardless of sector size to reach the sector center (whether most of the trip is part of the collection tour or the line haul portions); the sector size only determines the degree of deviation for pickup stops from a direct route.

Figures 25 and 26 show the service ratio and vehicle productivity, respectively, for optimal sector size. Since productivity is indirectly proportional to round trip time, the sensitivity of productivity to demand density is much less than to the number of passengers served per hour. For a given effective vehicle capacity, the productivity shown is theoretically achievable only under favorable conditions, i.e., demand density uniform over time and service area. Thus the values are somewhat higher than those found in most existing demand responsive operations.

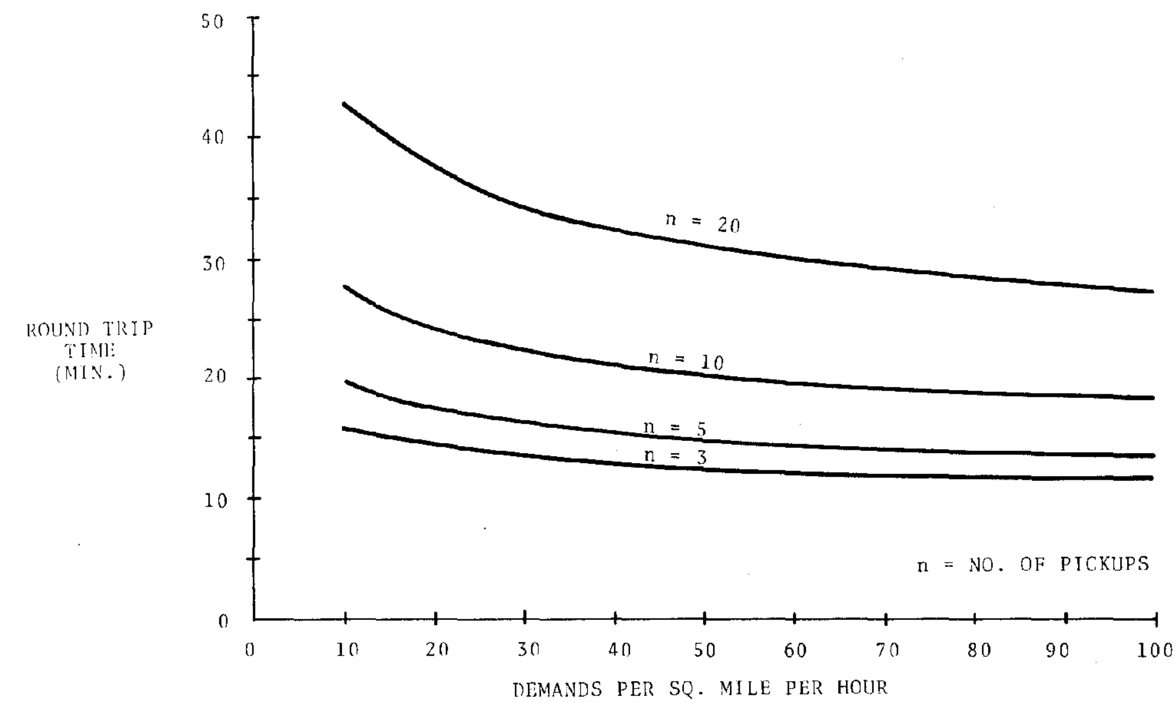


Figure 24. Flexible Route Feeder Bus Round Trip Time

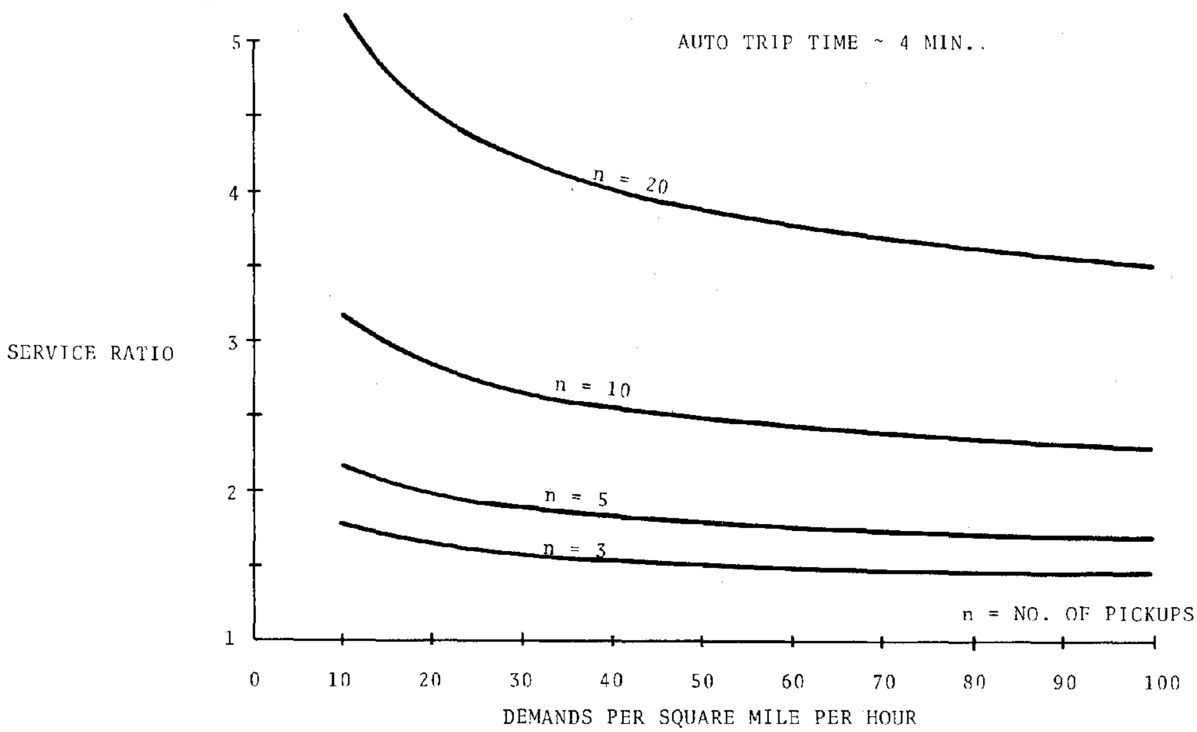


Figure 25. Flexible Route Feeder Bus Service Ratio

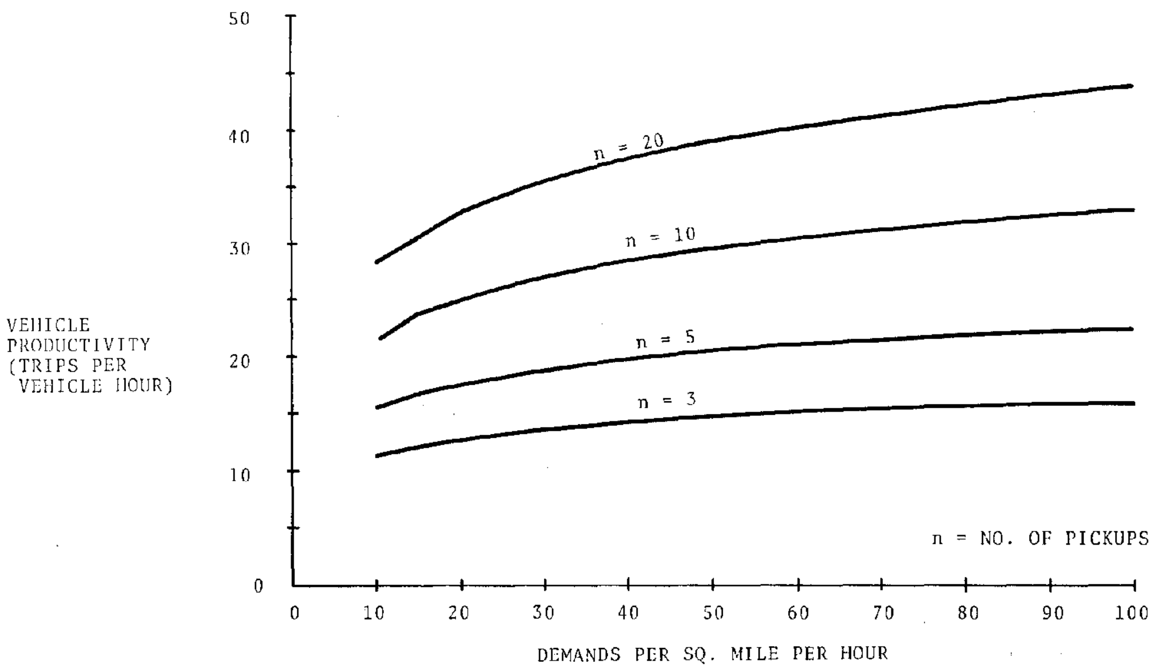


Figure 26. Flexible Route Feeder Bus Vehicle Productivity

A rough relationship between service ratio and the average number of pickups per tour can be determined for any demand density. Figure 27(a) shows the variation of service ratio with n for three demand density values. Linear relationships are indicated. For example, a demand density of 50 trips per square mile per hour results in:

$$L \approx 1.1 + 1.4n$$

where L = service ratio

n = average number of pickups

The variation of vehicle productivity versus n is shown in Figure 27(b). These relationships appear to be roughly parabolic.

Thus, for a demand density at 50:

$$P \approx 9 \sqrt{n}$$

where P = vehicle productivity

These functional forms seem to be applicable for the demand density range 10-100 passengers per square mile per hour.

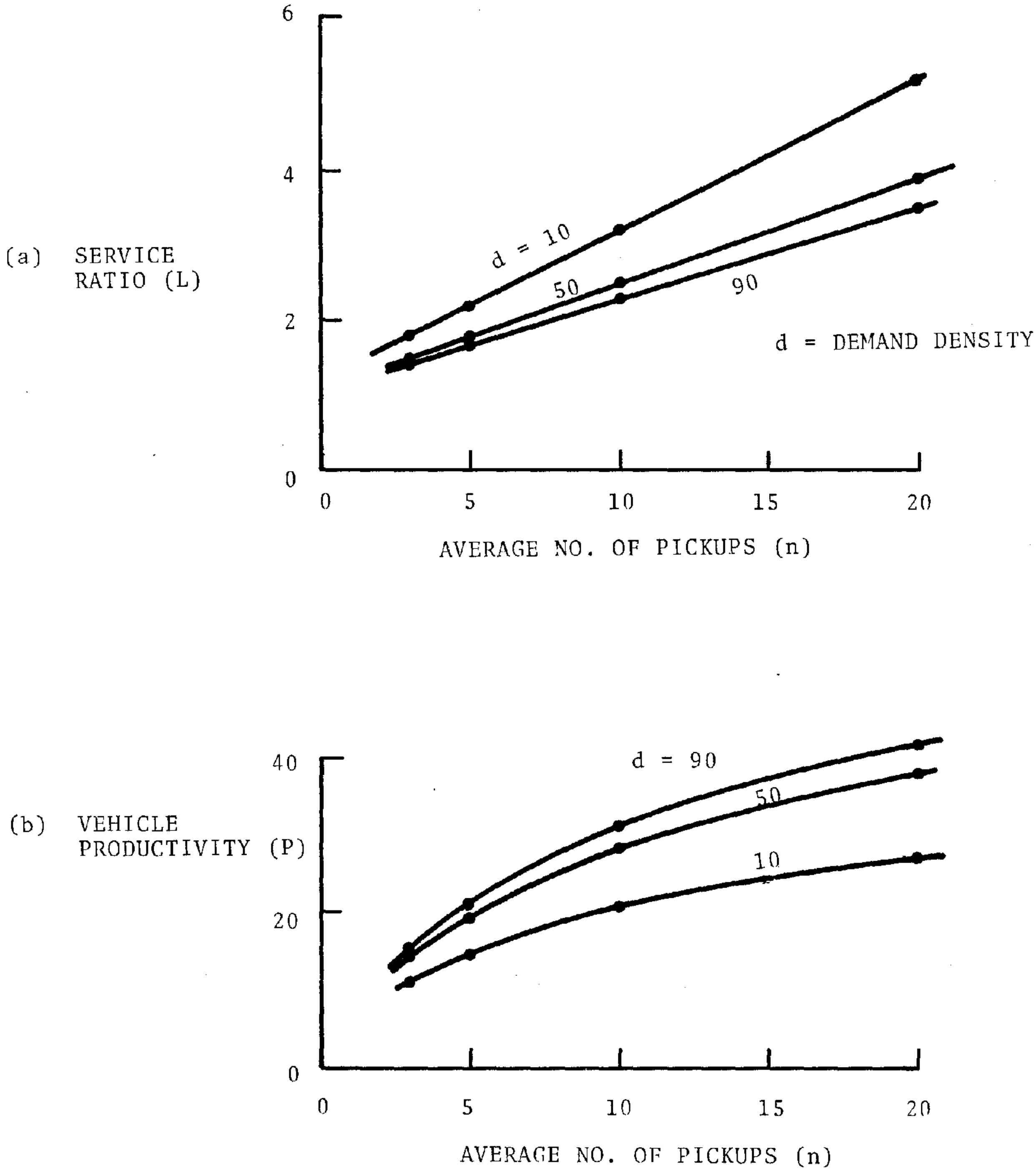


Figure 27. Flexible Route Feeder Bus Service Ratio, Variation with n

4.7 COST PER PASSENGER AND IMPLIED VALUE OF TIME

The cost per passenger carried is inversely related to average vehicle productivity. The cost per passenger is shown in Figure 28, using a unit cost of $12 per vehicle hour. (Although this figure is probably low, it is used to provide direct comparison with the fixed route service. If other unit costs are preferred, per passenger costs can be scaled appropriately.) The relatively flat slopes of the curves should be compared to those of fixed route bus (Figure 8). The fixed route bus cost per passenger shows a higher sensitivity to demand at lower demand levels.

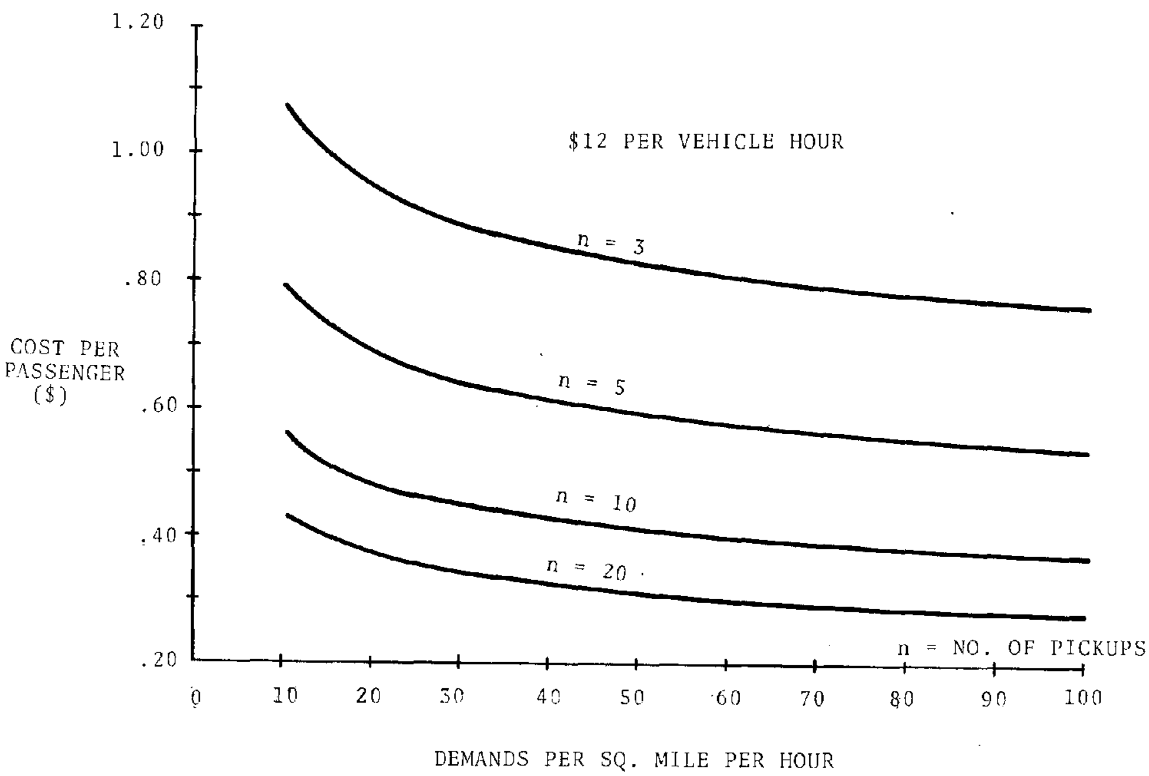


Figure 28. Flexible Route Feeder Bus Cost per Passenger

The variation of flexible route bus cost per passenger with the service provided (in terms of the average passenger trip time) can be developed (see Appendix B.4). Figure 29 depicts this relationship for a demand density of 50. At this demand level the slope of the curve becomes steep below a travel time of about ten minutes; this portion of the curve corresponds to a range of vehicle sizes where the average number of pickups per tour is less than about ten.

Figure 29 also shows for the same demand density the fixed route bus cost per passenger. The graph indicates that, if unit costs are the same, fixed route bus is more cost-efficient at service levels resulting in average trip times of higher than about fifteen minutes (including about nine minutes walk plus wait time). Below fifteen minutes, flexible route bus provides less expensive service. (Note that fifteen minutes represents a service ratio of slightly higher than 4. Figure 25 shows that even the large flexible route bus vehicles can provide better service at the given demand density.) The point at which the curves cross would shift to the left for higher demand levels and to the right for lower demand levels. The

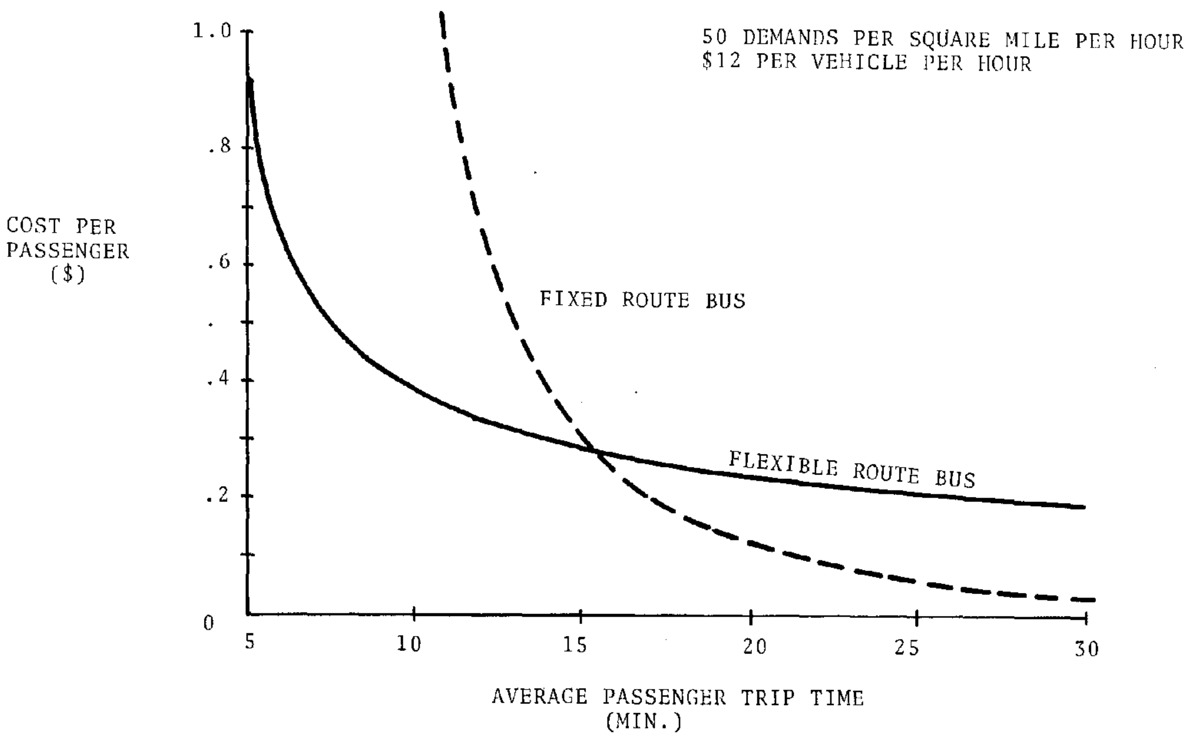


Figure 29. Comparison of Cost per Passenger (Variation with Travel Time)

reason is that while the fixed feeder bus route productivity is linearly related to the demand, flexible route bus productivity rises less rapidly with increased demand (Figure 26).

The implied value of time for an average passenger trip time is shown in Figure 30. For the range of travel times, the values of time for flexible route bus are lower than those of fixed route bus (Figure 12), indicating the lower cost sensitivity to the service provided for flexible route bus. In other words, small changes in flexible route bus service result in smaller changes in cost than changes in fixed route bus service.

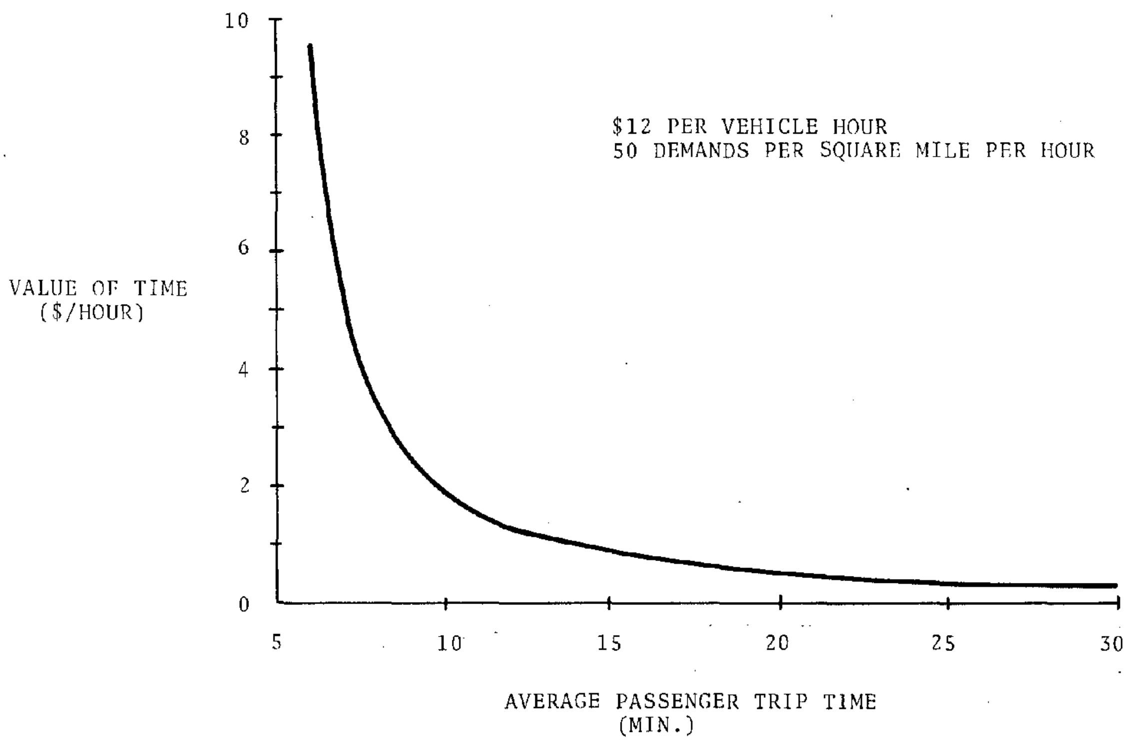


Figure 30. Implied Value of Time for Flexible Route Bus Feeder Service

5. SERVICE/COST COMPARISON

The relative costs of providing fixed route and flexible route bus feeder service can be examined in terms of the associated levels of service. Figure 31 shows the fixed route feeder bus service ratio (bus time: auto time) where its productivitity is equal to that of flexible route bus. The area above and to the right of any curve is the region where the fixed route bus productivity exceeds flexible route bus; below and to the left of any curve, flexible bus productivity is higher. As one example, the fixed route bus service ratio for "nominal" service (5 minute walk and 5 minute wait) is about 4.5 (see Figure 6). From the dashed line in Figure 31, it can be seen that fixed route bus productivities are higher than flexibile route bus for demand densities above 10-35 demands per square mile per hour (depending on the subscription bus size compared). (If unit vehicle-hour costs are equal for both systems, then costs per passenger carried in this demand range are equal.) It will be shown below, however, that this higher productivity is achieved only by sacrificing service to the passenger.

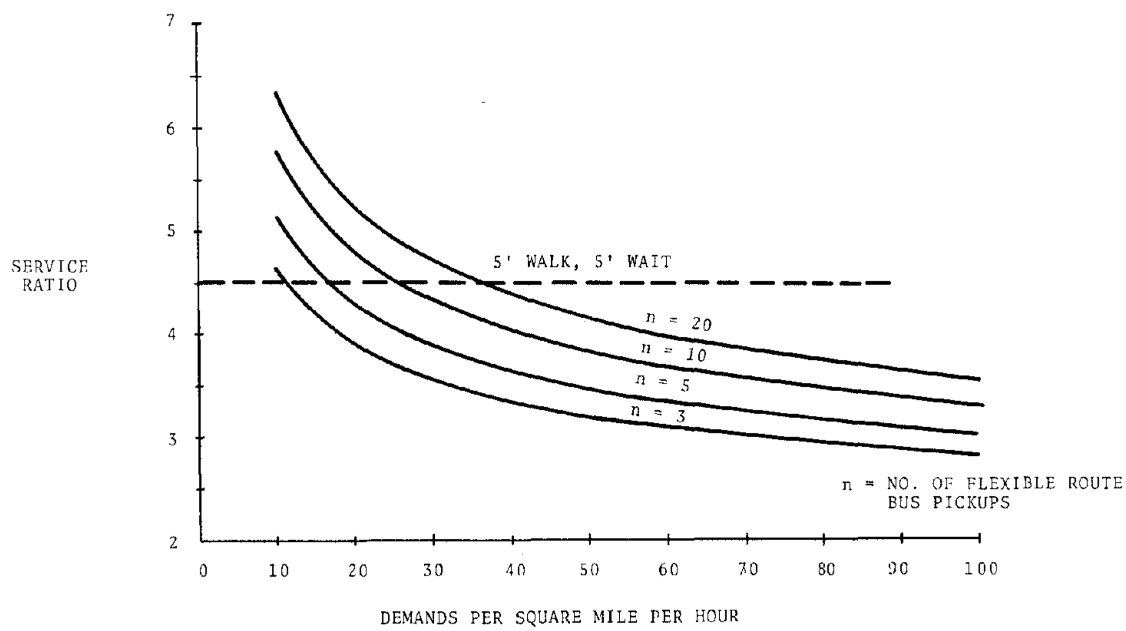


Figure 31. Fixed Route Feeder Bus Service Ratio for Equal Vehicle Productivity

For fixed route bus service designed for an average of three minute walk and three minutes wait (a service ratio of 3.3), the demand range above which fixed route productivities are higher than flexible route bus increases to 40 to 60 demands per square mile per hour for small flexible bus vehicles (n = 3 to 5) and to over 100 for larger size buses.

Figure 32 compares the average fixed route bus passenger trip time to that of flexible route bus for equal productivities. The region above any curve indicates where fixed route productivities exceed flexible route bus. This chart indicates that, for all levels of demand below 100 trips per square mile per hour, flexible route feeder bus provides better service for the same level of efficiency expressed in terms of passengers carried per vehicle hour (and for the same total cost if equal unit costs are assumed). The difference in service is greater for smaller sizes of flexible route bus vehicles which allow greatly reduced trip times. The comparisons made here re-emphasize the greater cost sensitivity to service of fixed route feeder service compared to flexible route service.

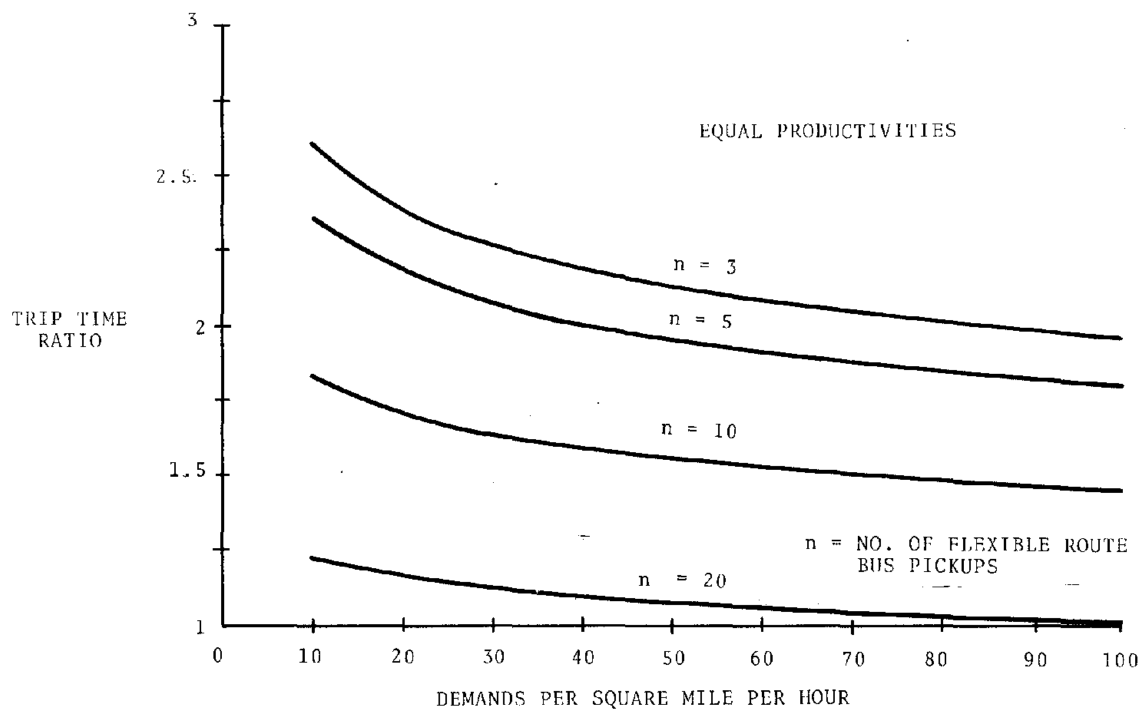


Figure 32. Trip Time Ratio, Fixed Route: Flexible Route

Figures 33 and 34 are charts similar to those described above, but here it is assumed that unit vehicle hour costs for flexible route bus are 50% higher than fixed route service. Under this assumption, nominal fixed route bus service can be provided at lower cost than flexible route bus service at demand densities higher than about 20. For three minute walk, three minute wait service, the ranges of equal cost are 25-35 trips per square mile per hour if considering small flexible route bus vehicles, and 55-75 for larger vehicles. Figure 34 indicates that a fixed route bus system can provide slightly better service for the same cost per passenger as flexible route bus vehicles serving 20 passengers at demand densities above 30 passengers per square mile per hour. For all other (smaller) vehicle sizes, flexible route bus still provides better service for the same cost.

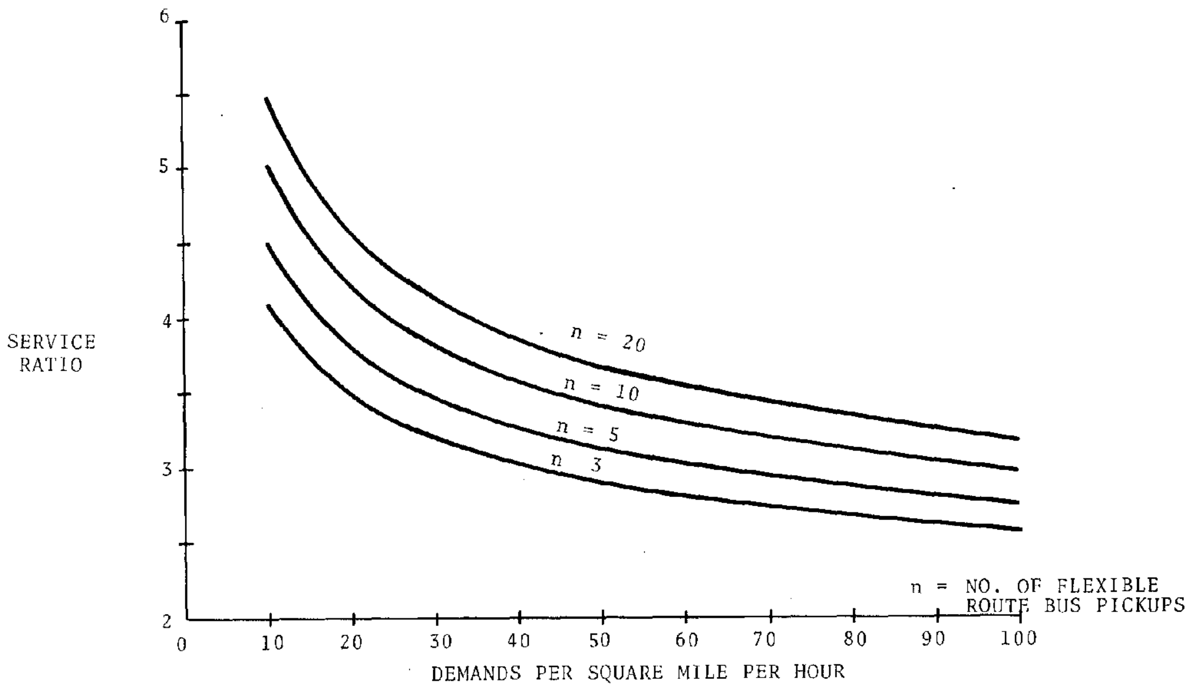


Figure 33. Fixed Route Feeder Bus Service Ratio for Equal Cost per Passenger (Assuming Unit Vehicle Cost 50% Higher for Flexible Bus)

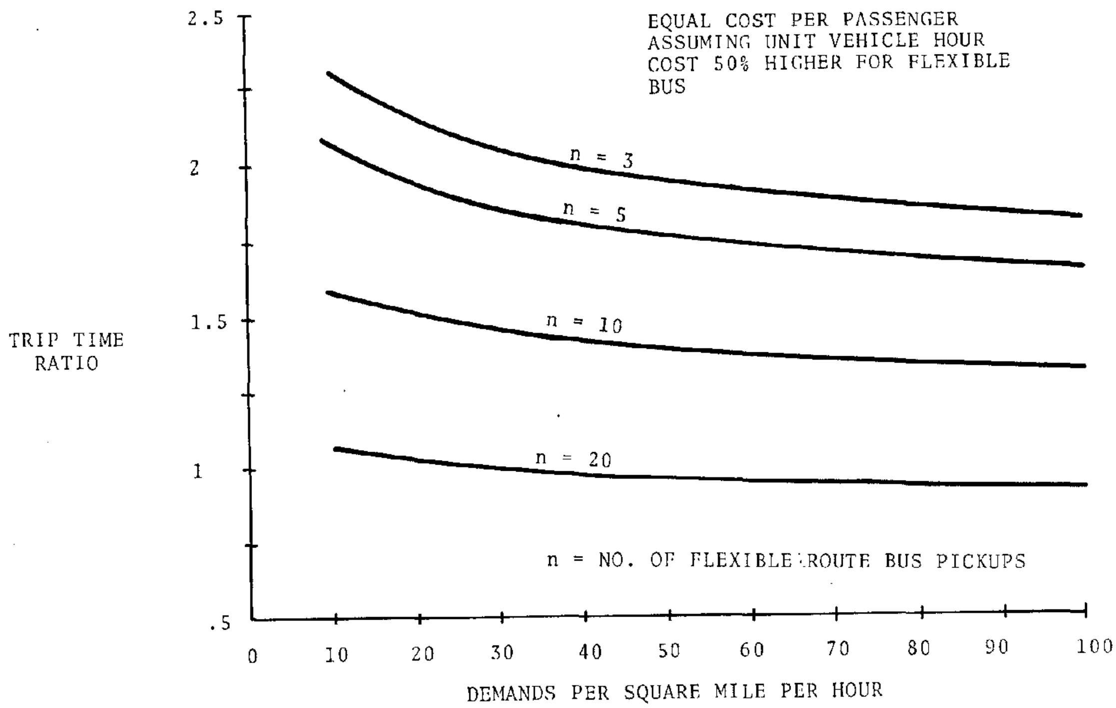


Figure 34. Average Passenger Trip Time Ratio, Fixed Route Bus: Flexible Route Bus

Figures 35 and 36 show cost/service comparisons assuming a fixed route bus speed varying inversely with demand (Figure 4). In comparison with Figures 31 and 32 (for constant bus speed), the fixed route bus service improves relative to the small (n = 3, 5) flexible route bus vehicles for equal productivities, but worsens relative to the large flexible route bus vehicles (n = 20). Since the larger vehicles have higher productivity, this productivity level can only be achieved by the fixed route bus with larger route spacing and/or lower frequency, leading to relatively low bus speeds. The opposite is true for the small flexible route bus vehicles.

The converse comparison can be made by examining the vehicle productivities of the two systems when operating at same levels of service. Figure 26 shows that a reasonable range of service ratios for flexible route feeder bus extends up to about 4.0. The ratio of fixed route feeder bus vehicle productivity to that of flexible route bus for three levels of demand density is plotted in

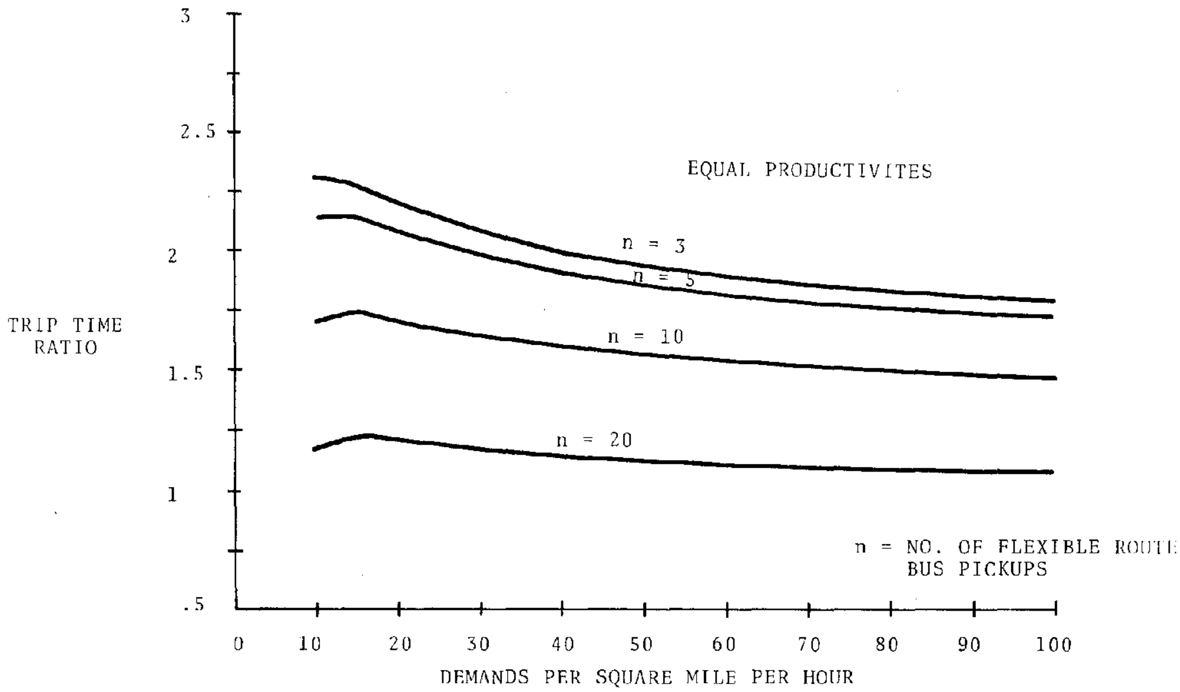


Figure 35. Trip Time Ratio, Fixed Route: Flexible Route (Variable Bus Speed)

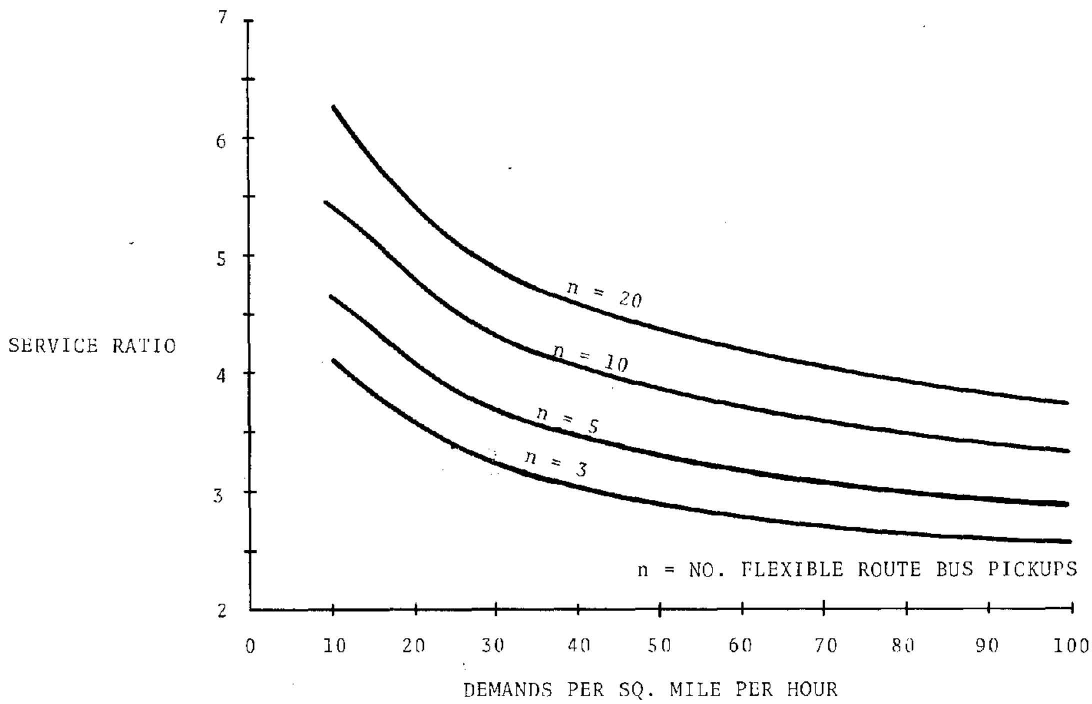


Figure 36. Fixed Route Bus Service Ratio for Equal Productivities (Variable Bus Speed)

Figure 37 for this range of equal service ratios. It can be seen that, except for a combination of high service ratio and high demand (where a very large flexible route bus vehicle is implied), the flexible route bus vehicle productivity exceeds fixed route bus productivity throughout. Note once again that the relative fixed route bus productivity drops off steeply with improved level of service.

Figure 38 shows comparative costs per passenger, based on twelve dollars per vehicle hour for three service levels (including a service ratio of six, well outside the service range of an efficiently operating flexible route system). This figure re-emphasizes that for the range of demand densities studied, the fixed route bus system becomes cost-competitive only as the service ratio worsens to about four. The service/cost relationships can be summarized as follows:

- An improvement in service at the same demand density results in higher cost per passenger for both systems.
- To maintain the same cost per passenger while improving service, increases in patronage must be achieved.
- The higher the demand density, the better the service level at which fixed route bus is competitive with flexible route bus.

For larger service areas, the same general relationships hold between flexible route bus and fixed route feeder systems. Appendix C contains sample charts for a 10-square mile service area similar to those described in detail above for a 4-square mile service area. Theoretically, larger service areas imply the following:

	Fixed Route	Flexible Route
Sector Area	--	smaller
Round Trip Time	higher	higher
Service Ratio	lower	lower
Vehicle Productivity	same	lower

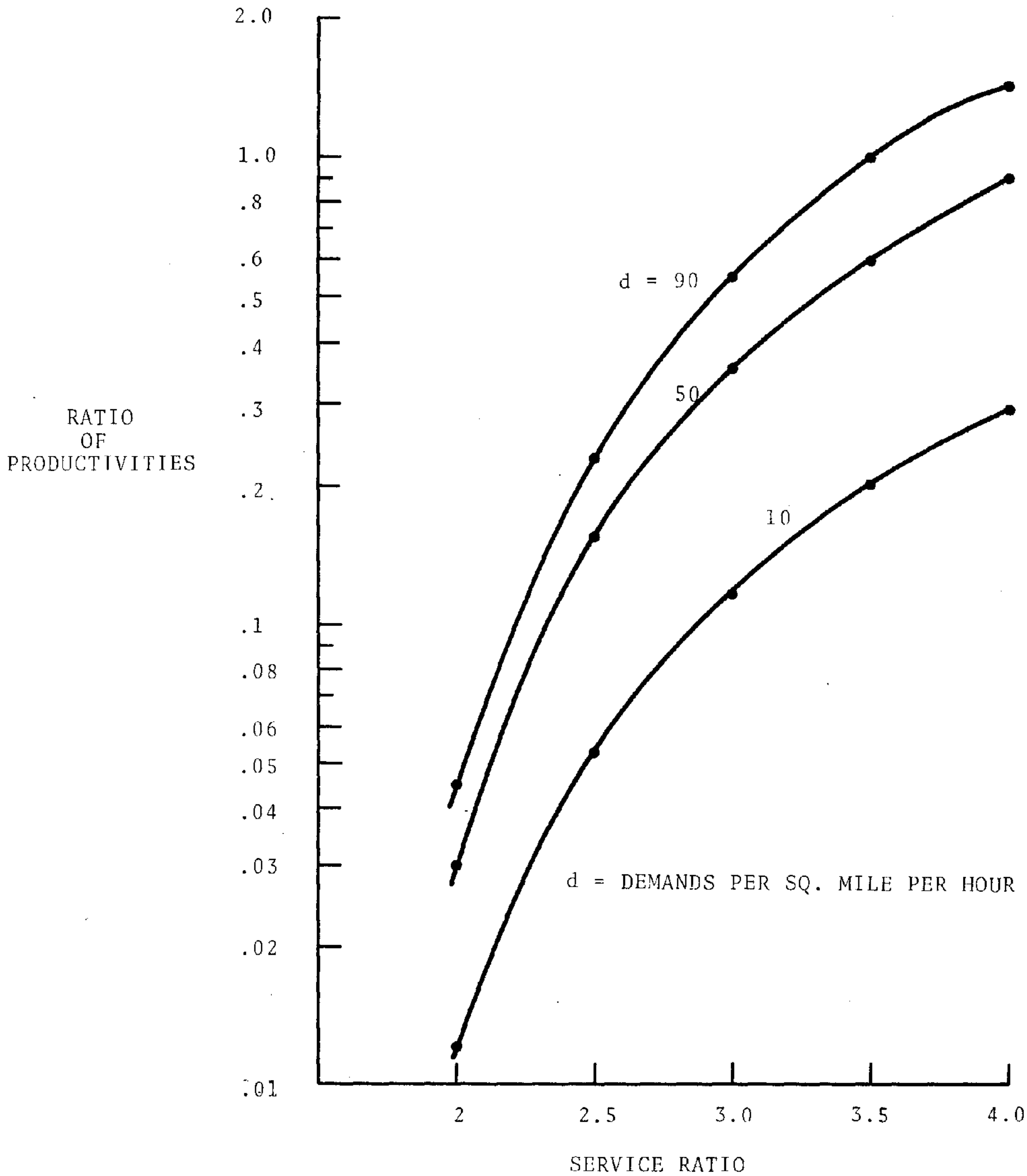


Figure 37. Vehicle Productivity Ratio (Fixed Route: Flexible Route)

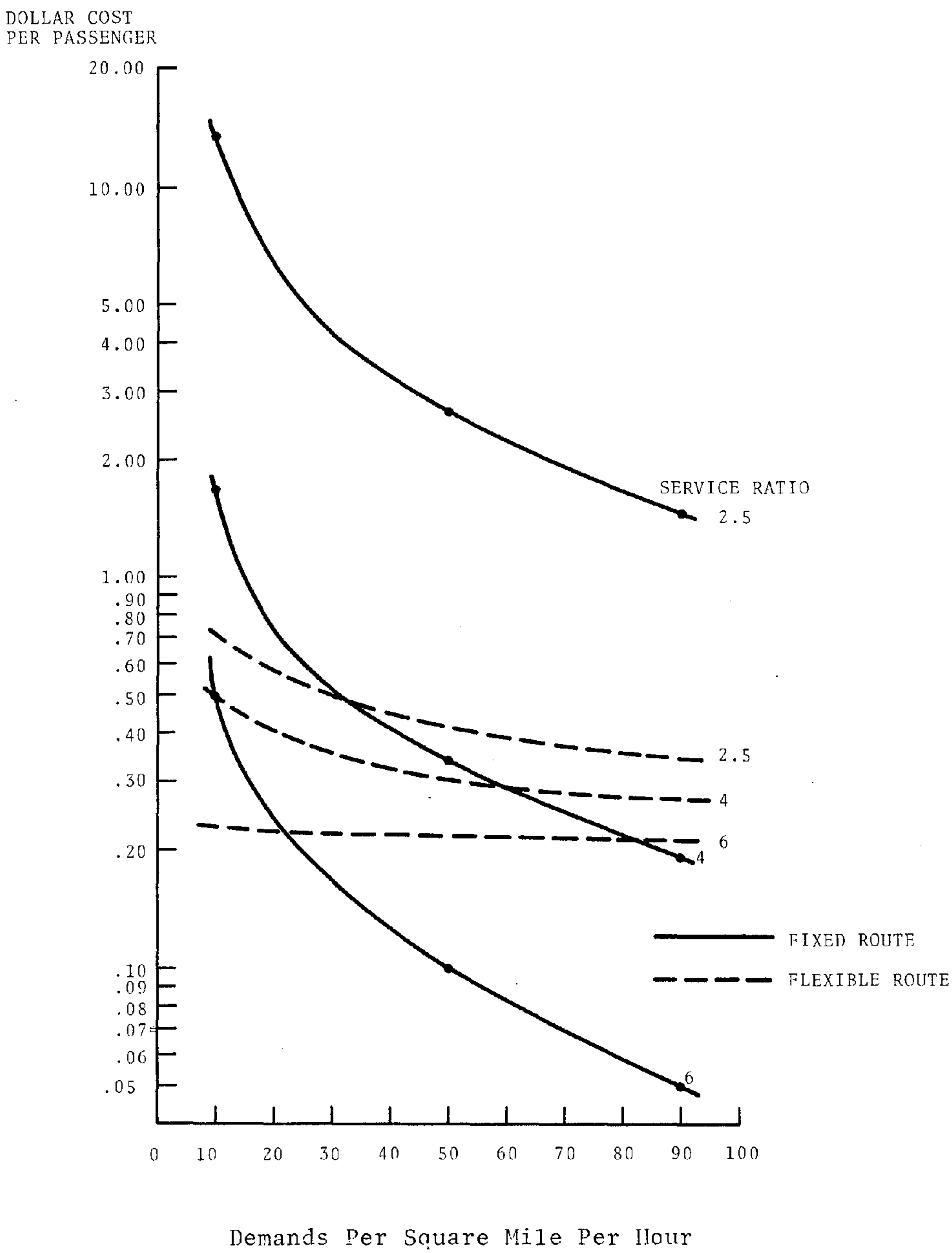


Figure 38. Cost per Passenger

The productivity of the small flexible route bus vehicles falls off much faster with increasing service area than the large capacity vehicles, since the longer line haul time is a much larger percentage of the tour. Figure 39 compares the average trip times by flexible route and fixed route feeder bus for equal productivities in a ten-square mile service area. Comparison with the equivalent chart for a four-square mile area (Figure 32) shows that flexible route bus service improves relative to fixed route service for the large flexible route vehicles (n = 20), but worsens for the small vehicles (n = 3, 5).

Figure 40 shows that for nominal fixed route bus service (5-minute walk, 5-minute wait) in a 10-square mile area, the demand range where the vehicle productivity exceeds that of flexible route bus is about the same as for a four-square mile service area -- above 10-35 demands per square mile per hour.

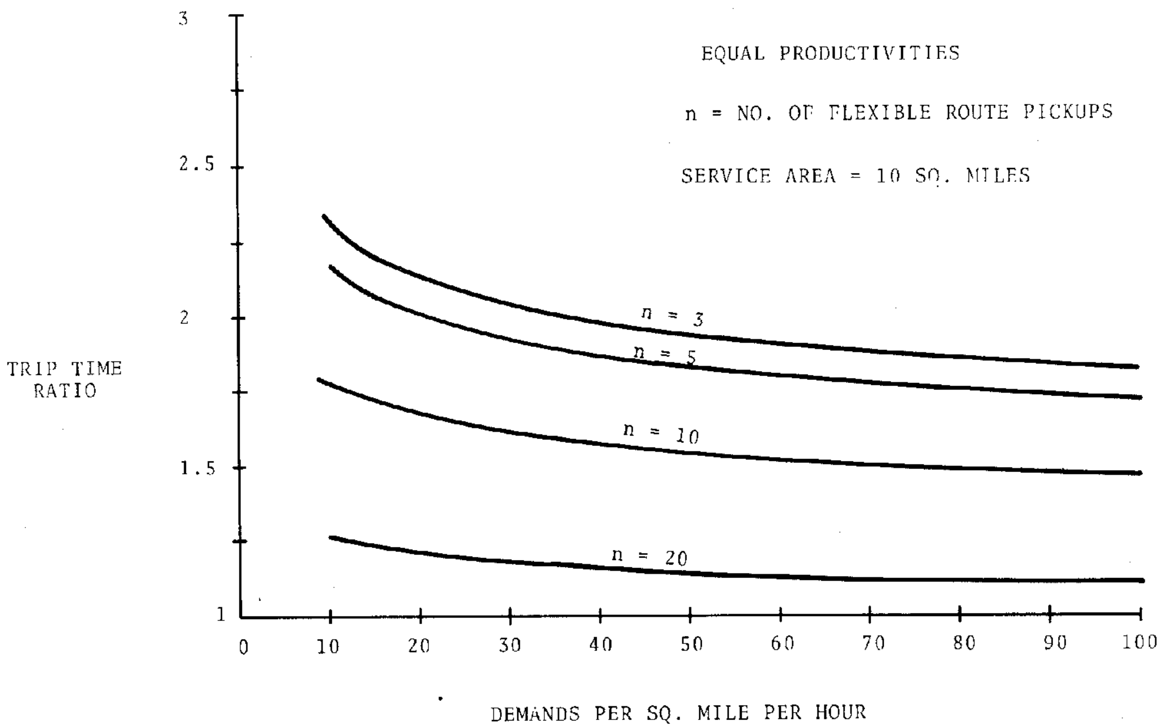


Figure 39. Trip Time Ratio, Fixed Route: Flexible Route

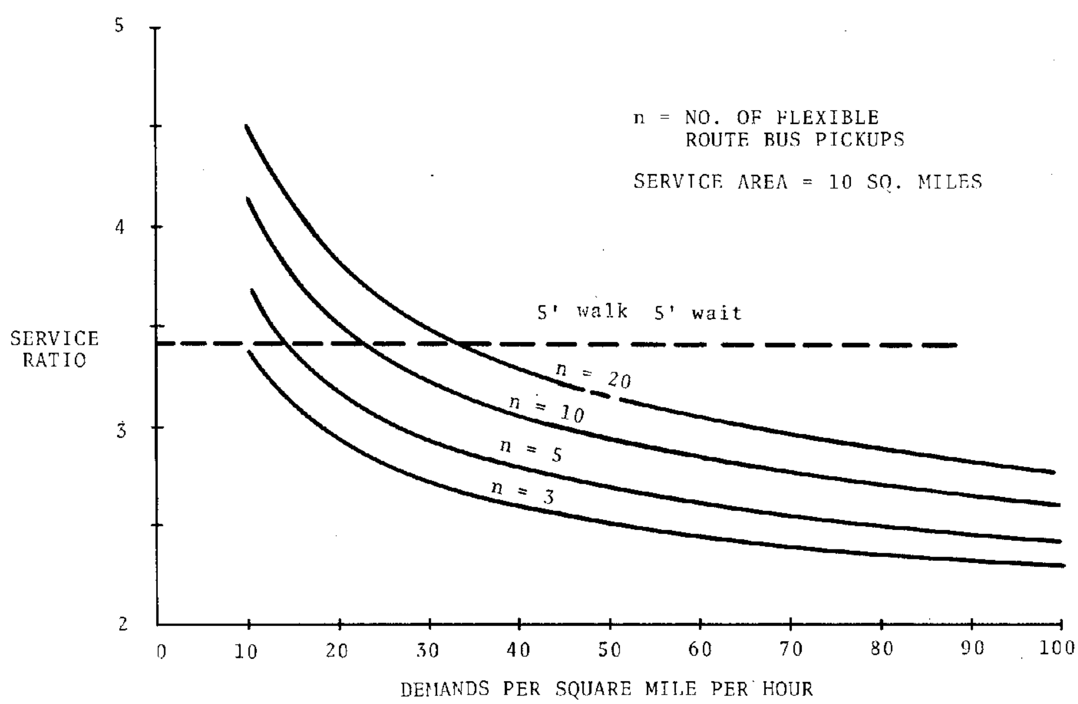


Figure 40. Fixed Route Feeder Bus Service Ratio for Equal Productivity

6. CONCLUSIONS

The comparison of fixed route feeder bus and flexible route subscription feeder bus systems can be made from both equal cost and equal service points of view. For the range of demand densities studied, flexible route bus provided as good or better service for the same cost per passenger than fixed route bus, even when the unit vehicle hour cost for flexible route bus was assumed 50 percent higher.

For the same level of service that flexible route bus could provide, the fixed route bus vehicle productivity exceeded that of flexible route bus only at the high end of the demand density scale and only when compared with a large flexible route bus vehicle. If flexible route bus vehicle-hour unit costs are 50% higher than fixed route bus, then fixed route bus may be able to provide the same level of service at a slightly lower cost per passenger when the service ratio exceeds about 3.0.

If comparing subscription bus service (operating in the range of service ratios about 1.5 to 4) with "nominal" fixed route bus feeder service (5 minutes walk and 5 minutes wait time -- a service ratio of about 4.5), then fixed route bus achieves higher vehicle productivities where demand densities are above 10-35 passengers per square mile per hour. When 50 percent higher flexible route bus unit vehicle-hour costs are assumed, less expensive fixed route bus service can be provided for all demand densities above about 20.

The flexibility allowed in designing routes for subscription feeder bus service results in a lower cost sensitivity to the service provided than that of fixed route feeder service. Flexible route bus also demonstrates a lower sensitivity of cost to the level of demand than fixed route bus, except at relatively high demand densities. Service area size has relatively little effect on the overall comparison of fixed route and flexible route bus feeder systems. However, as size increases, large flexible route bus vehicles gain in efficiency relative to both small capacity vehicles and to fixed route service.

In general, it appears that for providing good feeder service in low density areas, a door-to-door flexible route subscription bus service may be more efficient than a fixed route bus. If it is desired merely to provide no better than fair feeder service, then a fixed route system may be less costly, except at very low demand densities.

BIBLIOGRAPHY

DEMAND ACTUATED TRANSPORTATION SYSTEMS. Highway Research Board Special Report No. 124 1971. Proceedings of the Third Annual Conference on Demand Responsive Transportation Systems, June 1972.

Mason, F. J. and J. R. Mumford (Ford Motor Co., Dearborn, MI). COMPUTER MODELS FOR DESIGNING DIAL-A-RIDE SYSTEMS. Paper presented at the Society of Automotive Engineering Congress, Detroit, MI, January 1972, SAE Paper 720 216.

Massachusetts Institute of Technology, Cambridge, MA. Urban Systems Lab. THE DIAL-A-RIDE TRANSPORTATION SYSTEMS, SUMMARY REPORT. Daniel Roos et. al., March 1971, Sponsored by UMTA, Report USL-TR-70-10, PB 201-129.

Massachusetts Institute of Technology, Cambridge, MA. Urban Systems Lab. ECONOMIC CONSIDERATIONS FOR DIAL-A-RIDE. Joseph Stafford et. al., March 1971, Sponsored by UMTA, Report USL-TR-70-11, PB204-OS4.

Massachusetts Institute of Technology, Cambridge, MA. Urban Systems Lab. SCHEDULING ALGORITHMS FOR A DIAL-A-RIDE SYSTEM. Nigel H. M. Wilson et. al., March 1971, Sponsored by UMTA, Report USL-TR-70-13, PB 201-808.

MITRE Corp., Washington, D.C., A CONCEPTUAL OVERVIEW OF DEMAND-RESPONSIVE TRANSPORTATION SYSTEMS. Douglas Medville, February 1973, Sponsored by UMTA, PB 220-863/5.

MITRE Corp., Washington, D.C. A DEMAND, SUPPLY, AND COST MODELING FRAMEWORK FOR DEMAND RESPONSIVE TRANSPORTATION SYSTEMS. Bert Arrillaga and Douglas M. Medville, December 1973, Paper M73-232.

APPENDIX A
FIXED ROUTE SUPPLY MODEL EQUATIONS

A.1 FIXED ROUTE FEEDER BUS PRODUCTIVITY

Productivity (P), defined as the number of passenger trips per vehicle hour, can be computed by dividing the hourly passenger demand by the fleet size:

$$P = \frac{dA}{N}$$

where d = demands per square mile per hour
A = size of service area (square miles)
N = number of buses required

N = (bus round trip time) (number routes) (number buses per route per hour)

For a square service area with the station in the middle of one side, the average round trip distance is 2.5 times the length of a side ($2.5\sqrt{A}$) and the round trip time is therefore:

$$\frac{2.5\sqrt{A}}{V_B}$$

where V_B is the average bus speed

The number of routes is the length of the service area side divided by the route spacing. The route spacing can be defined in terms of an average walk time to the bus route. If k is the average walk time and 3 miles per hour is used as an average walking speed, then the average walk distance is 3k. Therefore, the route spacing is four times the average walk distance, or:

12k miles per route

The number of routes is then $\frac{\sqrt{A}}{12k}$.

If the average wait for the bus w is defined as one-half the headway, then the bus frequency is:

$$\frac{1}{2w}$$

Then

$$P = \frac{dA}{\left(\frac{2.5\sqrt{A}}{V_B}\right)\left(\frac{\sqrt{A}}{12k}\right)\left(\frac{1}{2w}\right)}$$

$$= 9.6 \; w \; k \; d. V_B$$

P is plotted in Figure 3 as a function of d for an average speed of 15 miles per hour and for various combinations of walk and wait time.

A.2 FIXED ROUTE FEEDER BUS VARIABLE SPEED

In order to derive a fixed route feeder bus speed which varies with the demand density, a maximum possible eight stops per mile is assumed. If there are Q passengers per route mile per bus, and these Q passengers distribute themselves randomly over the eight stops, the expected number of stops having exactly g passengers waiting for each bus is:

$$E(g) = \binom{Q}{g} \frac{7^{Q-g}}{Q-1}$$

Therefore, the expected number of stops per mile x each bus will have to make is

$$x = E(>0) = 8 - E(0) = 8 \left[1 - \left(\frac{7}{8}\right)^{Q}\right]$$

Using roughly 15 seconds for a stop (including acceleration and deceleration) independent of the number of passengers boarding, and a non-stop speed of 20 miles per hour, the bus speed V_B can be expressed as:

$$V_B = \frac{1}{\frac{1}{20} + \frac{x}{240}} = \frac{4800}{240 + 20x}$$

where x is described above

$Q = 24\ kdw$

d = demands per square mile per hour

k = average walk time (hours)

w = average wait time (hours)

V_B is plotted in Figure 4 as a function of d for various combinations of walk and wait time.

A.3 FIXED ROUTE FEEDER BUS SERVICE RATIO

The average person in a square service area is located a distance of 3/4 of a side from the station situated in the middle of a side. Therefore, the average passenger trip time to the station is:

$$k + w + \frac{.75\ A}{V_B}$$

where k = average walk time (hours)

w = average wait time (hours)

A = service area (square miles)

V_B = average bus speed

If V_A is the average auto trip time to the station, then the ratio of bus time to auto time is:

$$\frac{k + w + \frac{.75\sqrt{A}}{V_B}}{\frac{.75\sqrt{A}}{V_A}} = \frac{(k + w)\ V_A}{.75\sqrt{A}} + \frac{V_A}{V_B}$$

The service ratio is plotted in Figures 6 and 7 as a function of demand density for various combinations of walk and wait time and for a fixed speed and variable speed function (Figure 4), respectively.

A.4 FIXED ROUTE FEEDER BUS COST PER PASSENGER AND IMPLIED VALUE OF TIME

The cost per passenger C can be computed by dividing a vehicle-hour cost U by the productivity P (Figures 7 and 8).

$$C = \frac{U}{P}$$

$$= \frac{U}{9.6 \text{ wkd } V_B}$$

where w = wait time (hours)

k = walk time (hours)

d = demands per square mile per hour

V_B = average bus speed (15 mph)

The variation of C with passenger trip time for a demand density of 50 is shown in Figure 9. Minimum cost per passenger with respect to the walk and wait time is shown in Figure 10.

The implied value of time can be defined as the (absolute value of the) change in cost per passenger for a unit change in travel time. Since a unit change in walk time produces an equivalent change in travel time, the slope of the cost curve with respect to the walk time will yield the desired function:

$$\text{Value of time} = \left|\frac{dC}{dw}\right| = \frac{U}{(9.6)\ (k)\ (d)\ V_B)\ w^2}$$

This relationship is plotted in Figure 11 for various walk times as a function of average passenger trip time. Figure 12 is a plot of this equation for minimum cost (k = w).

APPENDIX B
TIME AND DISTANCE COMPONENTS OF SUBSCRIPTION BUS FEEDER SERVICE

B.1 SERVICE AREA LINE HAUL

The average service area line haul distance D_L (station to nearest corner of a sector) expressed in terms of a side of the service area can be approximated as a function of the number of sectors within the service area. D_L will approach three-fourths of the length of a side when the number of sectors grows large (i.e., the sector size becomes very small):

$$D_L = \sqrt{A}\left(.75 - \frac{1}{\sqrt{N}}\right) \qquad (N > 1)$$

$$= \sqrt{A}\left(.75 - \frac{1}{\frac{\sqrt{A}}{\sqrt{a}}}\right)$$

$$= .75\sqrt{A} - \sqrt{a} \qquad (D_L \geq 0)$$

where A = size of service area
N = number of sectors in service area
a = size of sector

For N = 1, D_L is taken to be zero.

The one-way service area line haul time t_L is therefore:

$$t_L = \frac{D_L}{V_A}$$

where V_A = average auto speed (25 mph)

$\frac{D_L}{\sqrt{A}}$ is plotted in Figure 14 as a function of N.

B.2 SECTOR LINE HAUL

The sector line haul distance D_S is the distance from the entrance (corner) of the sector to the first pickup (most distant from the station). The average location of the farthest pickup will be dependent on the number of pickups. For a square sector:

$$D_S = \sqrt{a} \left[.5 + \frac{n}{n + 1} \right]$$

where a = area of sector

n = average number of pickup stops

$\frac{D_S}{\sqrt{a}}$ is plotted in Figure 15 as a function of the number of pickups.

The sector line haul time t_s is therefore:

$$t_s = \frac{D_s}{V_A}$$

where V_A = average auto speed (25 mph) .

B.3 COLLECTION TOUR

The equation for the sector tour distance D_c (distance from first pickup to exit from sector) was approximated from a Ford dial-a-ride simulation study* which utilized the "traveling salesman" minimum path algorithm.

$$D_c = 2 \sqrt{a} \quad (.8 + .08n)$$

where a = sector area
n = number of stops

Therefore, the collection tour time is:

$$t_c = \frac{D_c}{V_c} + ns$$

where V_c = average collection speed (20 mph) (not including stops)

s = average time per stop (30 secs.)

$\frac{D_c}{\sqrt{a}}$ is plotted in Figure 16 as a function of the number of stops; t_c is shown in Figure 17 as a function of the size of sector area.

Figure 18 shows the total round trip time for sector area and number of stops.

*Mason and Mumford, "Computer Models for Designing Dial-A-Ride Systems," Automotive Engineering Congress, January 1972.

B.4 SUBSCRIPTION BUS FEEDER SERVICE COST PER PASSENGER AND IMPLIED VALUE OF TIME

For a demand density of 50 passengers per square mile per hour, the productivity P and service ratio L can be expressed in terms of the average number of pickups per tour n (see Figure 27):

$$n = 1.1 + .14n \qquad (1)$$

$$P = 9 \sqrt{n} \qquad (2)$$

If t is the average passenger trip time by subscription bus, then:

$$L = \frac{t}{b} = \frac{t}{\frac{.75 \sqrt{A}}{V_A}} \qquad (3)$$

where b = average auto time

A = service area size (4 square miles)

V_A = average auto speed (25 mph)

Substituting L into equation (1):

$$n = \frac{9.5 V_A t}{\sqrt{A}} - 7.9$$

Substituting n into (2):

$$P = 9\left[\frac{9.5 V_A t}{\sqrt{A}} - 7.9\right]^{1/2}$$

The cost per passenger C as a function of t can be calculated by dividing a unit cost per vehicle hour of operation U by P:

$$C = \frac{U}{P} = \frac{U}{9} \left[\frac{9.5\ V_A t}{\sqrt{A}} - 7.9 \right]^{-1/2}$$

This fraction is plotted in Figure 29 for the following values:

U = \$12 per vehicle-hour

V_A = 25 miles per hour

A = 4 square miles

The implied value of time is the first derivative of the cost per passenger:

$$\text{Value of time} = \left| \frac{dC}{dt} \right|$$

$$= \frac{0.53}{\sqrt{A}} UV_A \left[\frac{9.5V_A t}{A} - 7.9 \right]^{-3/2}$$

This function is presented in Figure 30 for the above parameter values.

APPENDIX C
SUPPLEMENTARY CHARTS FOR
TEN SQUARE MILE SERVICE AREA

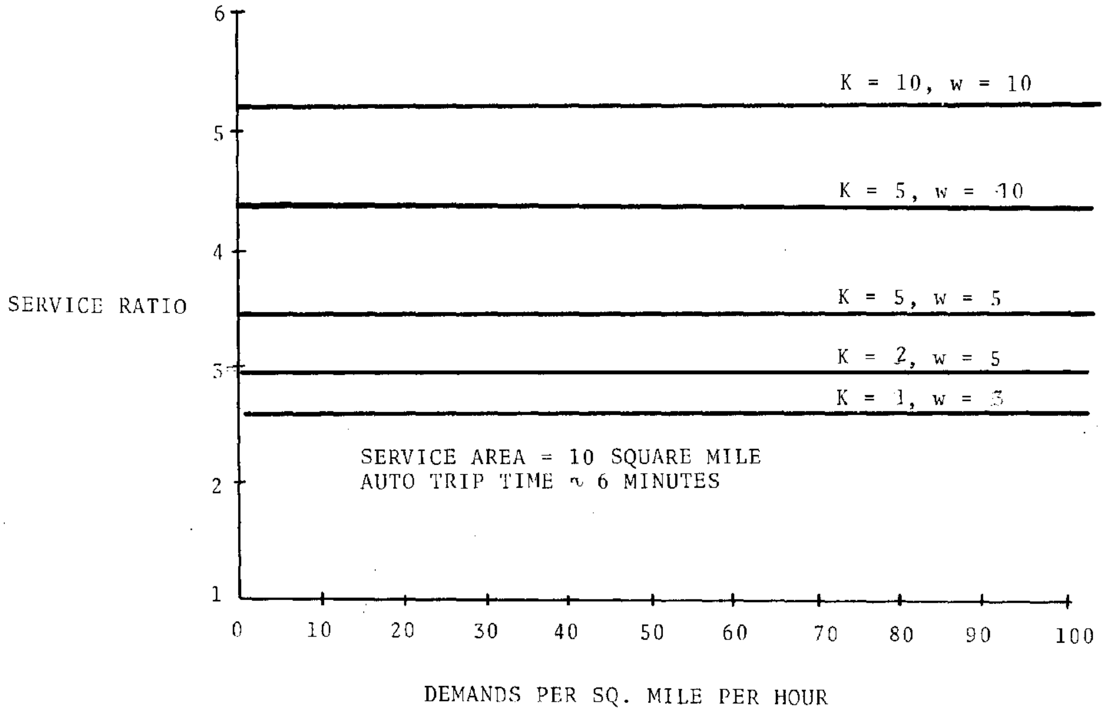


Figure C-1. Fixed Route Feeder Bus Service Ratio

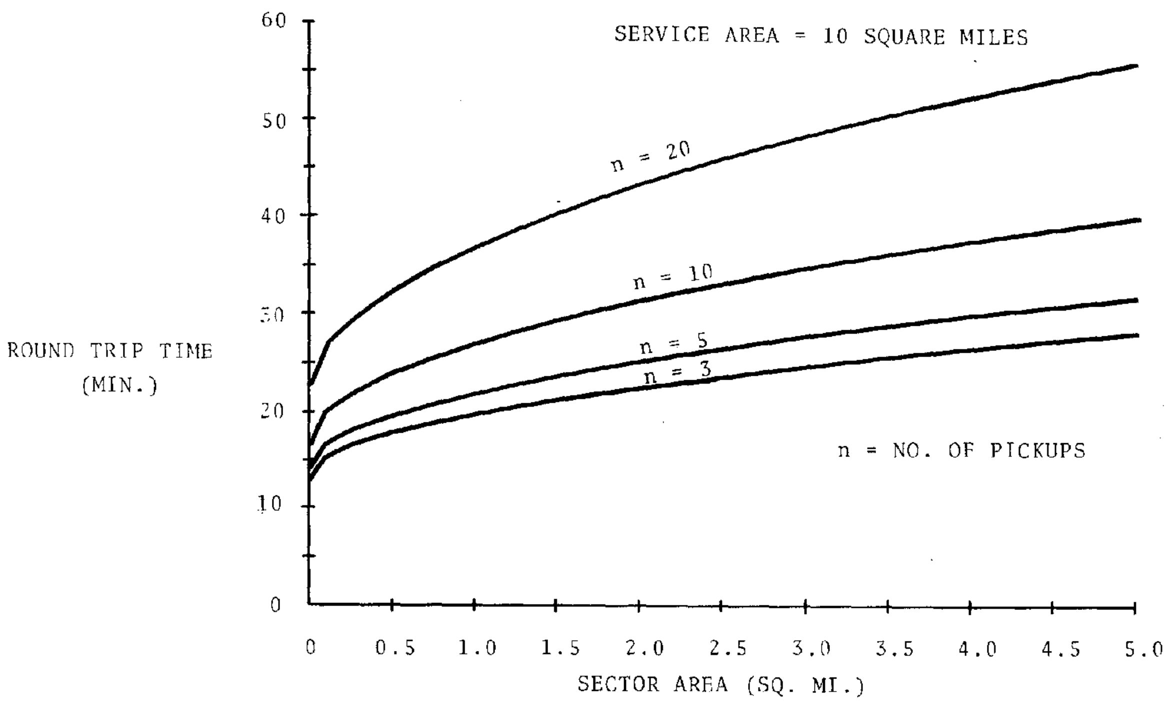


Figure C-2. Flexible Route Feeder Bus Round Trip Time

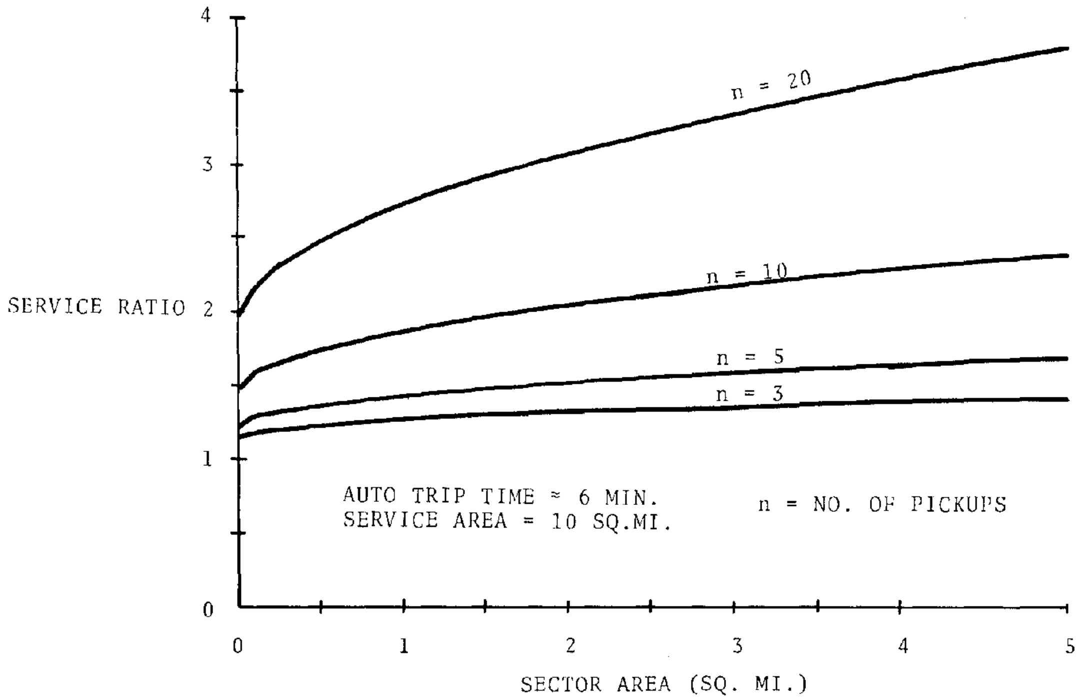


Figure C-3. Flexible Route Feeder Bus Service Ratio

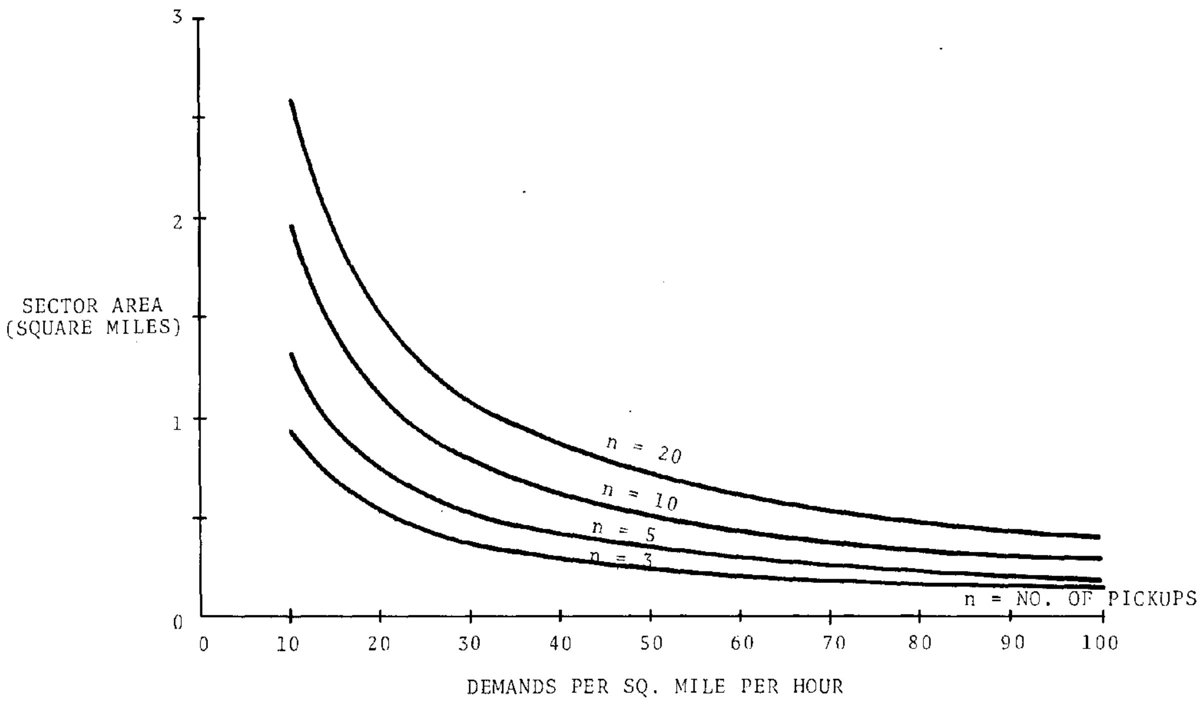


Figure C-4. Flexible Route Bus "Optimal" Sector Area

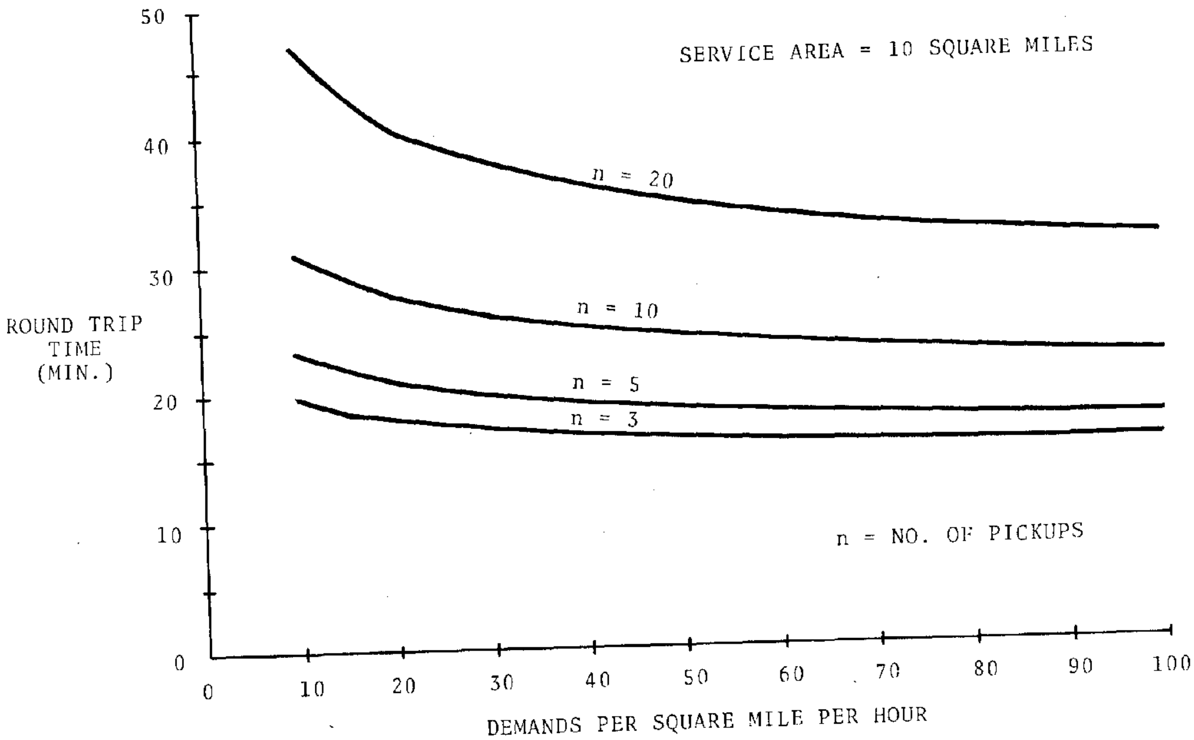


Figure C-5. Flexible Route Bus Round Trip Time

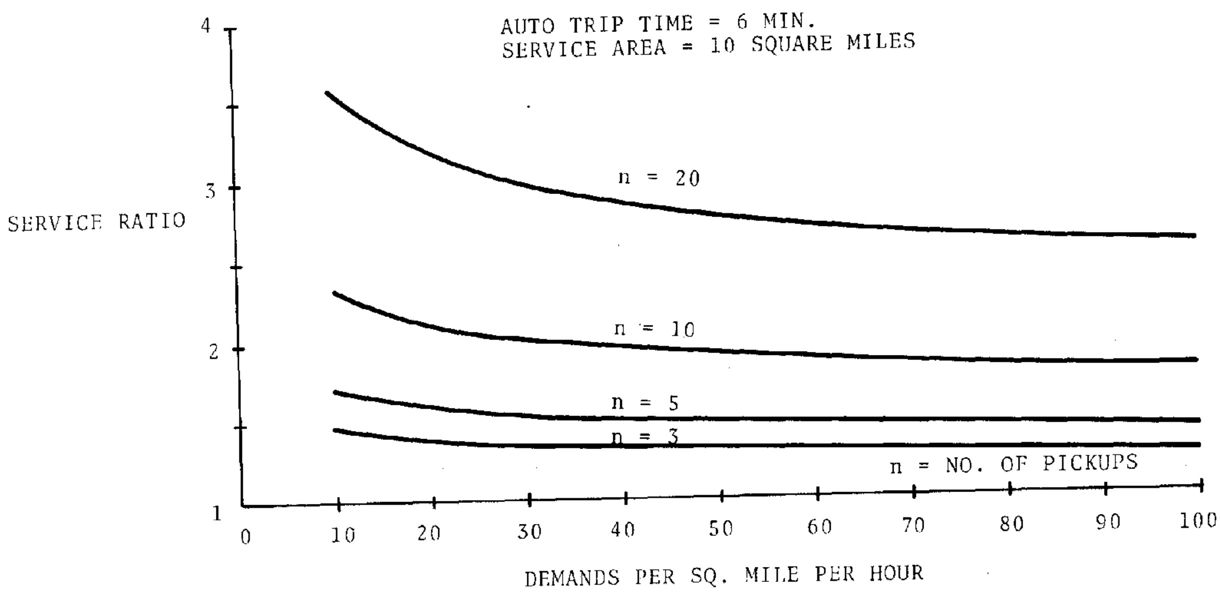


Figure C-6. Flexible Route Feeder Bus Service Ratio

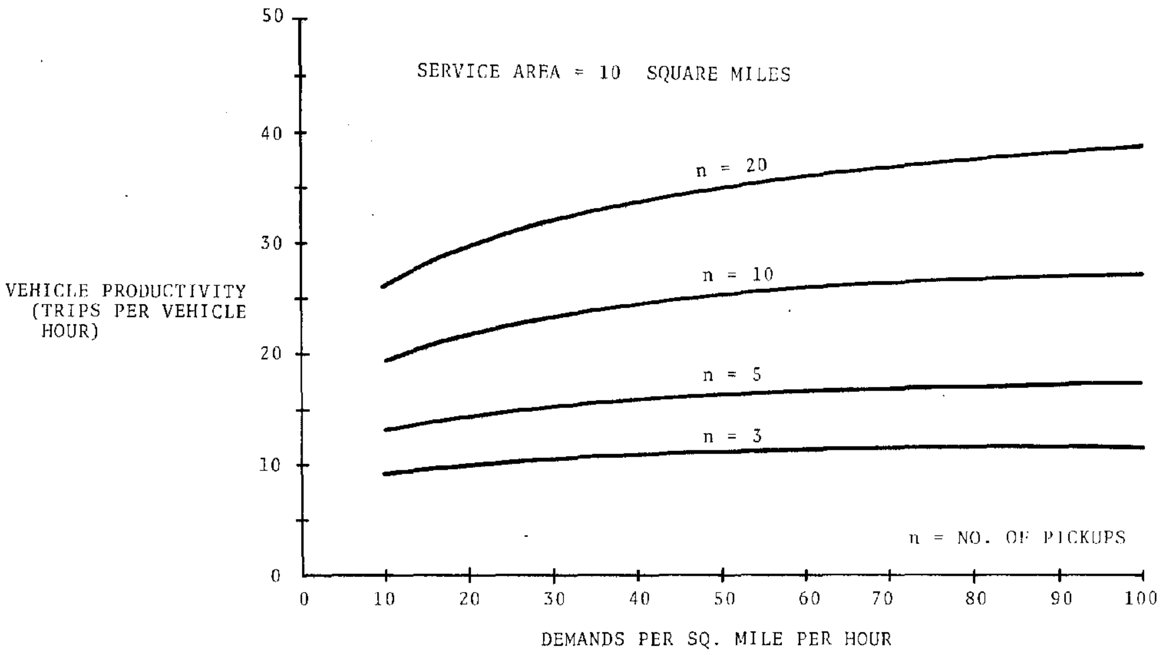


Figure C-7. Flexible Route Feeder Bus Vehicle Productivity