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PROVIDING INCREASED TRANSIT CAPACITY DURING PEAK PERIODS: EXAMINATION OF TWO TECHNIQUES

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16. Abstract

Two techniques for increasing transit capacity without fleet expansion are examined: reducing the extents of bus routes and staggering work hours. Reduction of bus route lengths increases the number of round trips per bus possible in a given time period. For bus routes accessed mainly by auto, it is shown that significant savings in energy due to reduced auto miles travelled are possible by decreasing the lengths of multistop bus routes. Little or no savings are achieved with express bus routes.

Staggering work hours has the effect of greatly increasing the fraction of new transit demand that can be satisfied. It is shown that both the length of the peak period and the percentage travel in the peak hour affect potential transit utilization. Since staggering work hours has detrimental effects on carpooling potential, these effects are also examined. It is found that the benefits to transit of staggering work hours probably exceed the disadvantages to carpooling.

17. Key Words

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PREFACE

This report was prepared by the Systems Applications Division of the Transportation Systems Center for the Office of the Assistant Secretary for Systems Development and Technology, U.S. Department of Transportation. The document 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. The research for this report and its preparation were the responsibility of Donald E. Ward and Donald C. Kendall.

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1. INTRODUCTION

Although for many years the level of transit ridership in this country has been declining, there is evidence that this trend may be beginning to slowly reverse. Reasons for this turnabout are primarily related to restrictions (intentional or otherwise) on automobile usage in urban areas. These restrictions include gasoline shortages and/or high gas prices due to the energy crisis. In addition, increasing environmental concern has caused the growth in urban highway capacity to lag behind the growth in auto usage, resulting in increased peak period roadway congestion. Further controls on automobile use will be imposed by the Environmental Protection Agency to improve air quality in urban areas. Any increase in auto travel will be accompanied by a growth in potential transit ridership. Although the capacity of public transportation systems can be increased through fleet expansion, including larger and faster vehicles, a long time period is required for order and delivery of new vehicles, especially if a large number of orders occurs at the same time. Methods which are more quickly implemented may be necessary to handle short-term increases in transit demand. For example, the imposition of gasoline rationing could quickly overload public transportation during the commuting periods in many major metropolitan areas. This paper examines two techniques for increasing the effective peak period capacity of transit systems without the use of larger vehicle fleets. A basic assumption is made that, due to the greatly increased demand for transit service, any increases in transit capacity achieved are always fully utilized.

The first method involves the reduction of the length of a commuter bus route (having access mostly by automobile) in order to increase the number of round trips per bus possible in a given time period. While the number of seats available for commuters is increased, the number of bus seat-miles operated remains constant. The potential for using the bus line is not lost to those living near the deleted route portions who use auto access. However, since the access distance to the bus route will increase for many who drive to the bus line, the benefits of this method must be evaluated in terms of the energy saved. The relative number of auto-miles traveled by commuters is computed as a proxy for energy consumption.

Most transit systems are designed to accommodate peak hour ridership. Consequently, the potential capacity available in other hours is under-utilized. Staggering work hours, the second method examined, has the effect of greatly increasing the fraction of new transit demand that can be satisfied. However, staggering work hours may have a detrimental effect on the potential for carpooling, another highly efficient means of transportation, since the use of carpools depends on commonality of trip times. The effects of staggering work hours on both transit utilization potential and on potential carpooling are examined here.

1.1 SUMMARY OF FINDINGS

Little, if any, energy savings due to decreased auto-miles are achieved by relocating bus route terminal points for express service. However, for multistop services, the auto-person mile savings may represent a significant fraction of the original miles travelled for route reductions of about 10 percent or more.

Staggering work hours has the effect of greatly increasing the fraction of new transit demand that can be satisfied (with the existing vehicle fleet). Without staggering, the only increases in demand that can be satisfied occur in the non-peak hours of the peak period if it is assumed that maximum capacity is reached in the peak hour. Staggering enables the transit system to serve some or all of a demand increase uniformly across the peak period. The amount of effective additional capacity is sensitive to both the length of the peak period and to the percent of travel occurring in the busiest hour.

The effects of staggering work hours on carpool potential are felt first where the density of work trips is low and travel patterns are diffuse. The potential continues to decrease with increased staggering until only inner, densely populated areas, or areas with trips primarily focused on downtown destinations, remain as candidates for any degree of carpooling. Carpool potential is less sensitive to the length of the peak period than to the fraction of work trips in the peak hour since it is only in the peak hour that significant carpooling potential exists. In general, it appears that the benefits of staggering work hours to potential transit utilization outweigh the detrimental effects on carpooling potential.

2. REDUCTION OF BUS ROUTE LENGTHS

2.1 INTRODUCTION

In many cities the transit commuter is served by bus routes oriented radially toward the central business district (CBD). Since most of these routes are at full capacity during the peak hours, little additional ridership can be handled with the existing fleet and schedules. However, if the terminal point of a bus line were relocated closer to the CBD, more round trips per bus could be achieved and thus the theoretical capacity (measured in person trips) of the bus fleet would be increased without an increase in the number of vehicles. The total number of bus miles travelled would also remain constant. For example, if the length of a bus route were reduced such that the round trip time of a bus decreased from 60 to 50 minutes, then the person trip capacity would be increased by 20 percent.

If access to the bus line is primarily restricted to walking, then little is gained by increasing the bus system capacity in this manner. Substantial ridership is lost where the route has been eliminated. Further, the lost transit riders who can divert to auto are those having the longest trips (since they originate near the end of the original bus line). However, if auto access to the bus route is allowed, and it is assumed that all original bus riders continue to use the service by driving (in some cases further) to the bus line after terminal relocation (probably an optimistic assumption), then substantial benefits in terms of the reduction in number of auto miles travelled may be achieved. As described, the level of benefits gained is dependent on the spatial distribution of transit demand, as well as on the relative reduction in route length. Implicit in this analysis, of course, is that the increased bus system capacity is always fully utilized.

Another way of stating the premise is that reducing the length of a route raises the average passenger load factor since the loads are smallest at the start of a route. It is thus intuitive that the method is inutile where vehicle capacities are reached at or close to the beginning of a route. Indeed, it will be seen that few benefits are achieved by reducing the extent of *express* bus lines.

It should be noted that the foreshortening of an existing bus route is a move which may be operationally infeasible or politically unacceptable. However, partial benefits may be achieved by reducing service (e.g., decreasing frequencies) at the outer portions of a bus route, especially where justified by relatively low load factors, and increasing service in the inner areas.

2.2 ANALYSIS ASSUMPTIONS

The scenario used for the study is shown in Figure 2-1. A bus route with the terminal point (A) located d miles from the CBD requiring t minutes round trip time is shortened to d' miles and t' minutes, respectively. All passenger trips are to the CBD. The new terminal location requires an increase in auto miles travelled for those bus passengers originating outside (to the left) of B. However, a reduction in auto miles travelled may be realized by an increase in overall bus ridership resulting from increased capacity, i.e., former auto users are now able to use the bus.

Four cases are examined in this analysis:

1. Express service from the terminal station; all passengers originate outside of the terminal station (Figure 2-2a).
2. Multistop service; all passengers originate within the original terminal station radius; uniform (flat) trip density distribution (Figure 2-2b).
3. Same as (2) but increasing (toward the CBD) trip density distribution (Figure 2-2c). This form of distribution is perhaps more applicable to a heavily core-oriented city where the population density increases rapidly toward the CBD.
4. Same as (2) but decreasing trip density distribution (Figure 2-2d). Perhaps appropriate for a "spread city"

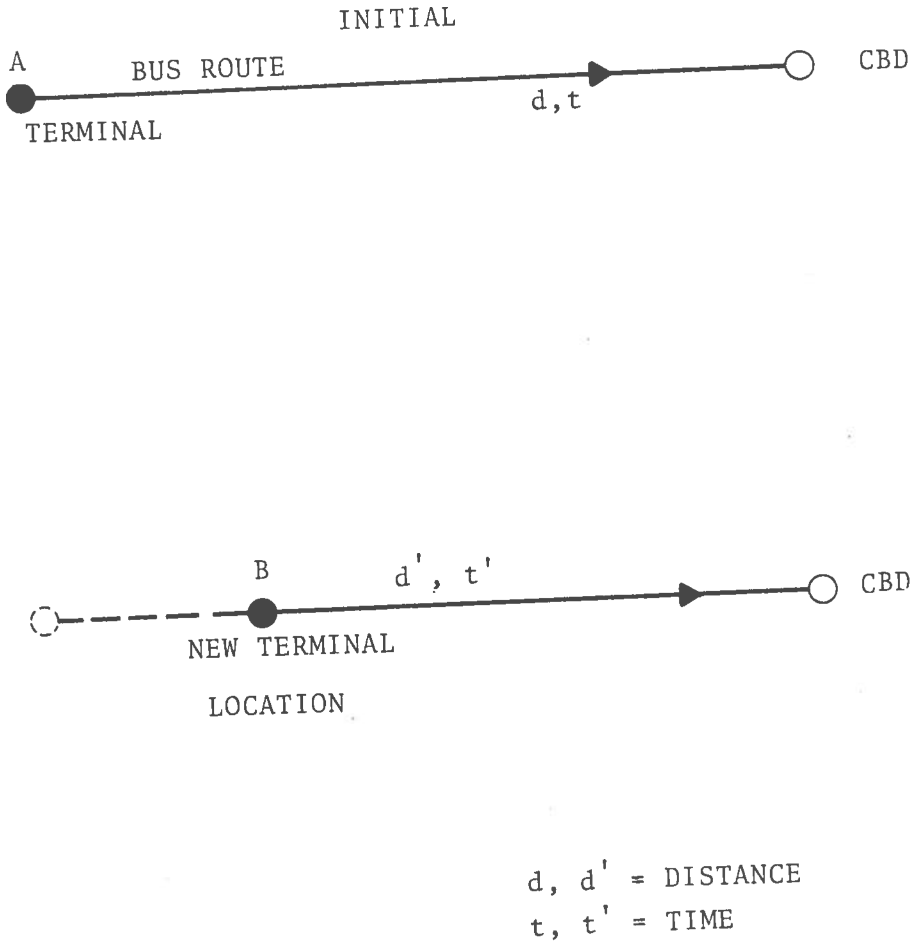

Figure 2-1. Scenario For Bus Route Length Reduction

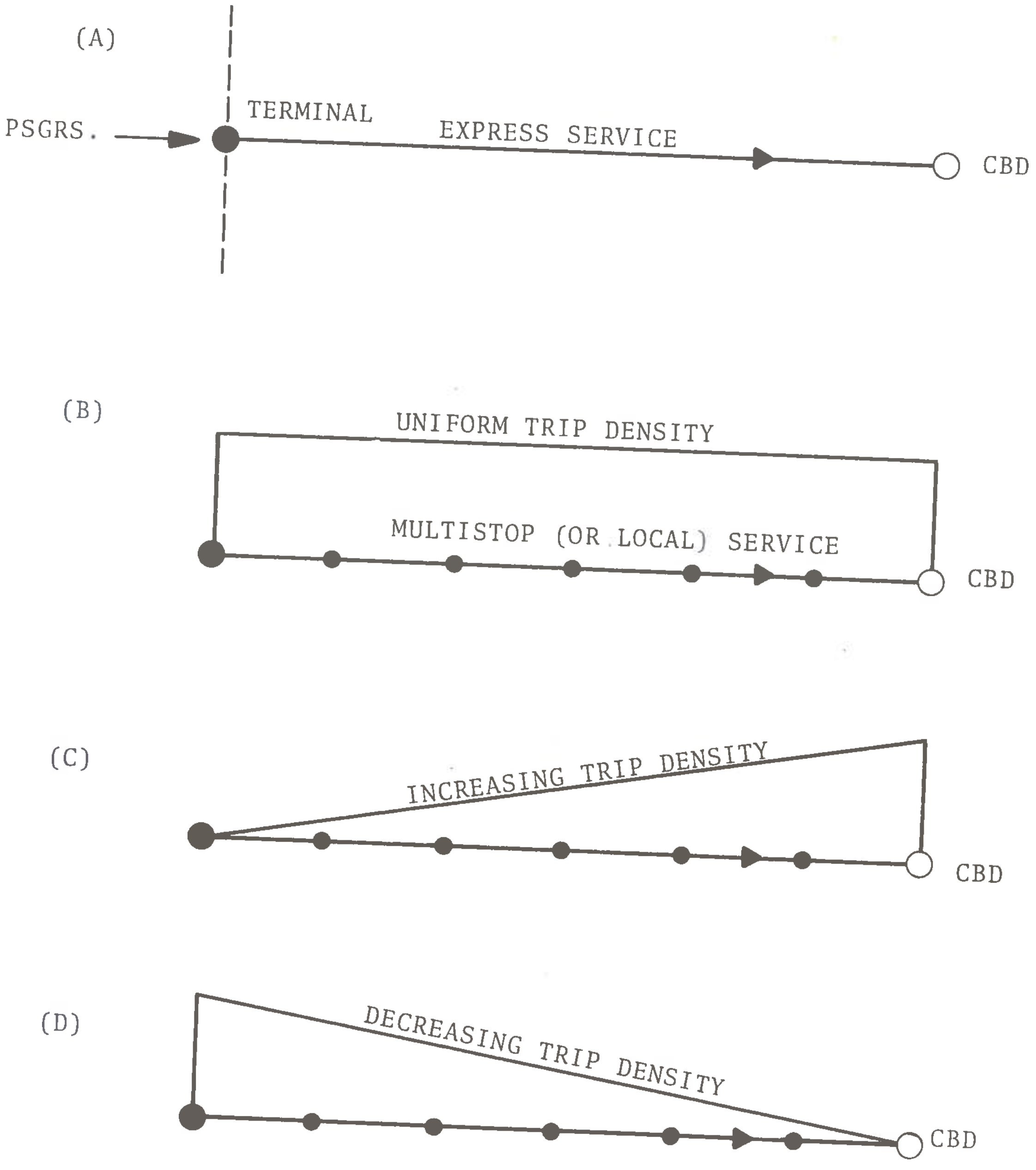

Figure 2-2. Cases For Analysis

type where uniform population density may provide a market that increases with distance to the CBD.

Population distributions of typical urban corridors in this country result in densities (in terms of persons per linear mile of corridor) that decrease (toward the CBD) in the inner areas and increase (toward the CBD) in the outer areas of the city. This suggests that, ceteris paribus, case (3) and case (4) may be more appropriate for suburb-originating and inner area bus routes, respectively.

Several simplifying assumptions are made in the analysis. The bus round trip time is considered to be linearly proportional to the round trip distance. Thus the capacity increases, based on distance reduction, are slightly overestimated since bus speeds normally decrease with distance to the CBD.

In the multistop case, the ridership increase after terminal relocation is assumed to be in proportion to the original trip density distribution. (The peak load point for each bus occurs as vehicles enter the CBD.) The reduction in auto miles travelled by new divertees to the bus are therefore overestimated since it is likely that a larger relative share of new riders would come from the market area within the new terminal location radius.

In calculating changes in miles travelled, only travel in the radial direction is considered. Since travel (for both bus and auto trips) transverse (perpendicular) to the bus route is ignored for the auto commuters who divert to bus, the auto mile savings may be slightly exaggerated since some of those commuters may not have required much transverse travel for their auto trips to the CBD. In addition, for the multistop route cases, radial travel required to the bus stops for bus riders originating within the existing terminal location radius is ignored.

No assumptions regarding auto occupancy are made here. Units are in terms of person-miles of auto travel. Since it is likely that the average occupancy for autos commuting to the CBD is higher than that of autos being used for access to the bus line, any savings in auto miles is likely to be less than proportional to the savings in auto-*person* mile savings presented.

Since most of the assumptions discussed tend to exaggerate the decreases in auto-person miles travelled, the benefits described below should be viewed as the maximum potential.

2.3 EXPRESS BUS CASE

For express bus service, the decrease in auto-person miles travelled due to increased bus ridership is exactly balanced by the additional miles travelled due to terminal point relocation (see Appendix A-1). In other words, the location of the terminal is irrelevant to auto-person miles travelled if the system capacity is fully utilized. (If the increased system capacity due to terminal relocation were not fully utilized, a net *increase* in miles travelled would result.)

However, if one assumes that the energy efficiency of autos increases with distance from the CBD (less stop-and-go-driving), then a net decrease in energy consumption would result from a relocation of the terminal toward the CBD. In addition, from the point of view of traffic congestion, it is more advantageous to locate the terminal as close as possible to the CBD to theoretically accommodate maximum bus ridership, and therefore to remove the maximum number of autos from the highways. Further, in cases where the average bus speed decreases with decreasing distance from the CBD, a larger relative increase in capacity will result from each successive unit move of the terminal toward the CBD. However, the limit of terminal relocation will realistically be reached at the point where commuters no longer perceive the auto-to-bus trip to be "better" than the auto-only trip (i.e., the point at which the assumption of fully utilized capacity is no longer valid.)

2.4 MULTISTOP BUS ROUTE CASES

For the multistop bus routes, the net decrease in auto-person miles for an average demand density of 100 passengers per route mile* (before terminal relocation)is shown in Figures 2-3 to 2-5 for the uniform, increasing, and decreasing trip densities, respectively. Curves are plotted for initial route lengths (d) of 5, 10, and 20 miles against the ratio of the foreshortened route length (d') to the original length. For example, in Figure 2-5, if a bus route of 10 miles is shortened to 8 miles (d'/d = .8), a net decrease of about 1000 auto-person miles would result. For this case, the savings are directly proportional to the route length reduction. Auto-person mile savings are also linearly proportional to the average trip density. (See Appendices B through D for mathematical derivations of the curves.)

For an increasing trip density distribution, auto-person mile savings are small for very small terminal relocations but increases rapidly for large relocations (Figure 2-4). In other words, largest relative savings are achieved by putting the route where most of the passengers are.

For a decreasing trip density distribution, the greatest relative auto-person mile decreases are achieved with small changes in terminal location (Figure 2-3). Large relocations result in successively smaller relative savings since the terminal is being moved farther from the bulk of the trip market. (It can be seen now that the express bus situation is just an extreme case of the decreasing trip density distribution case.)

The benefits described can be put into perspective by presenting the auto-person mile savings as a percentage of person miles (in the radial direction) saved due to original bus passengers (see Figure 2-6). This can be interpreted as follows. Implementation of the (original) bus route has resulted in a reduction in auto-person miles travelled through diversion of auto

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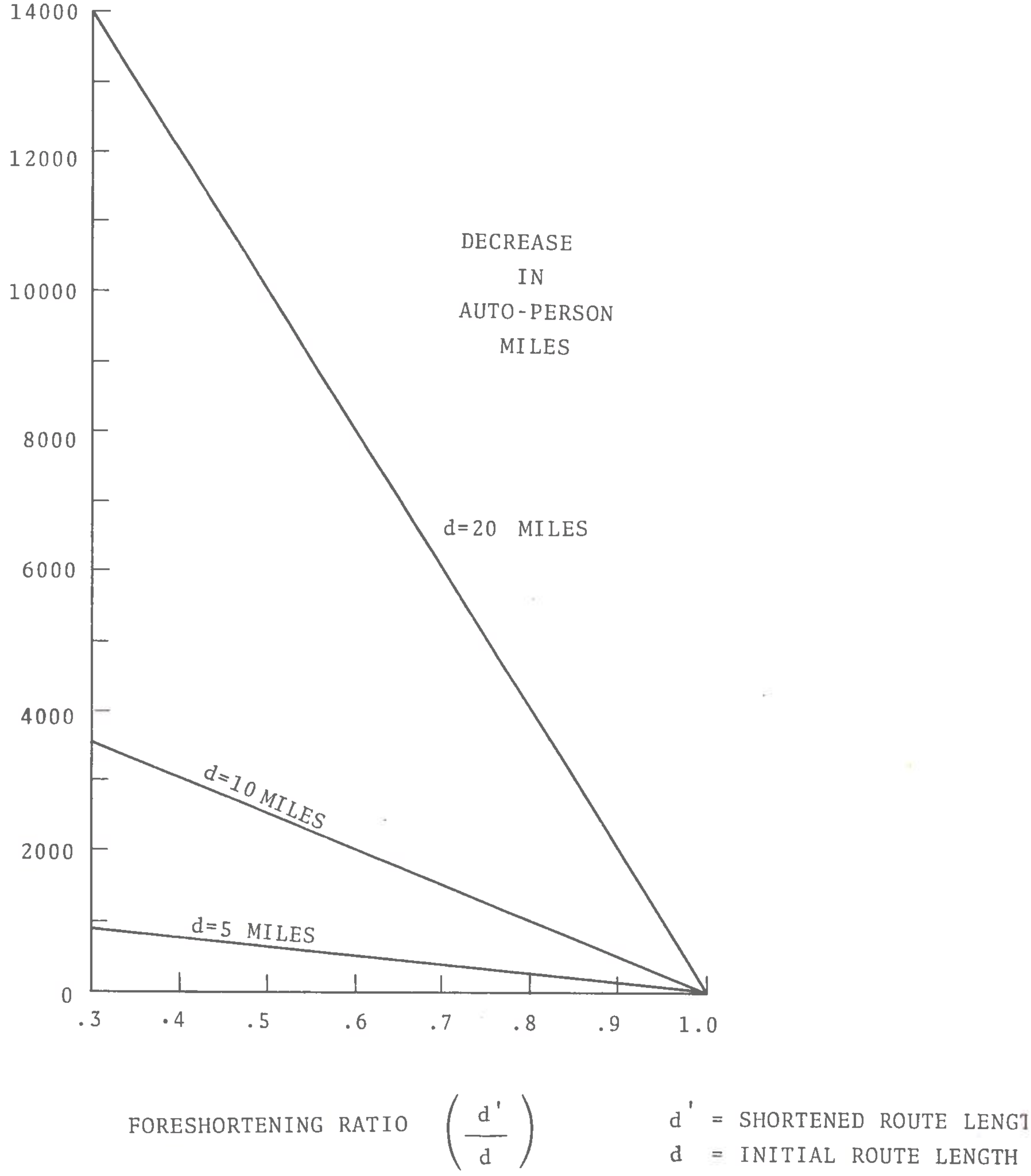
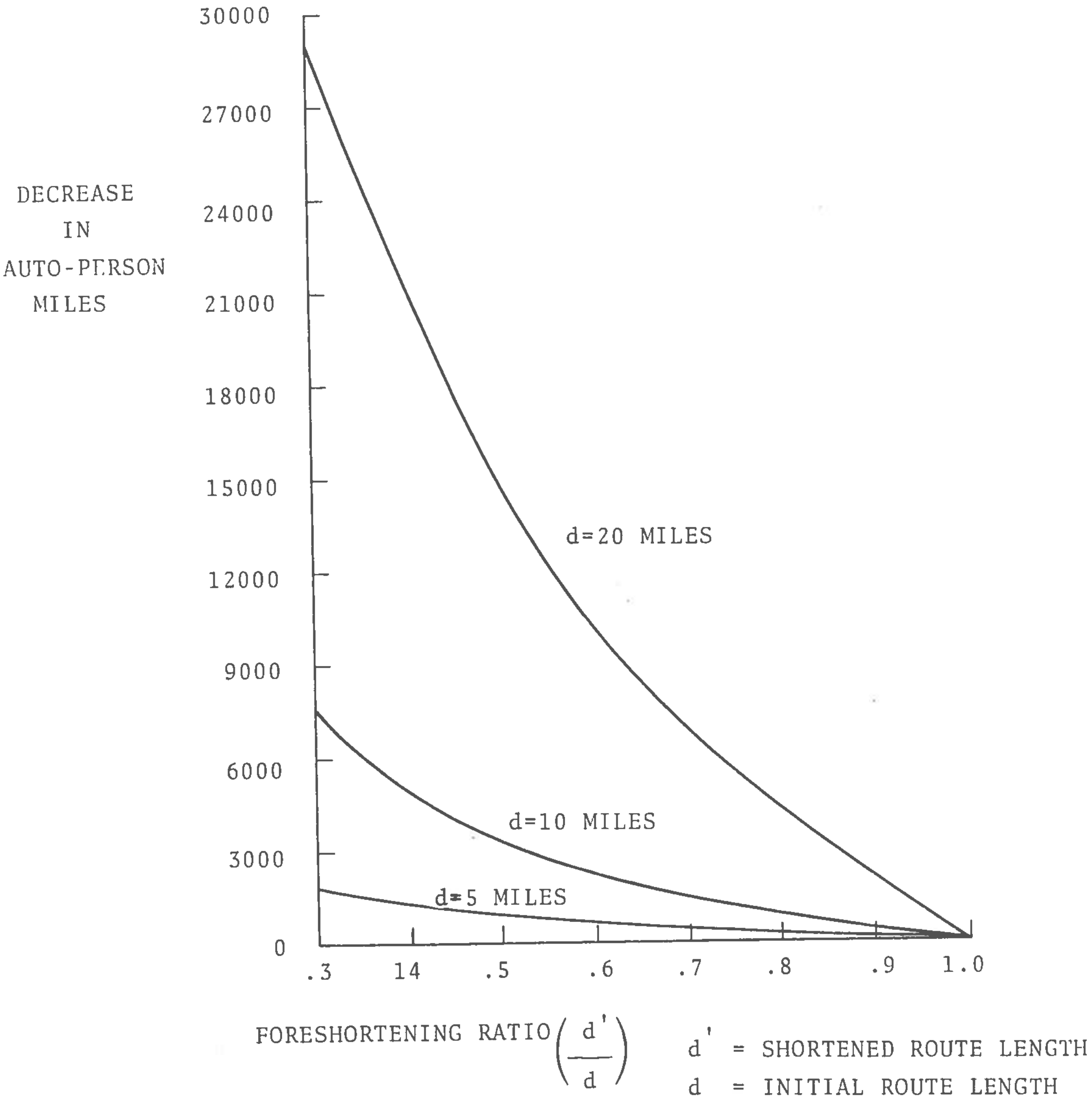
*If these 100 trips occurred in one hour, the associated bus headways (for a 50-passenger bus) would be 1.5, 3, and 6 minutes corresponding to route lengths of 20, 10, and 5 miles, respectively. Thus this assumed level of demand reflects a reasonable range of peak hour service.



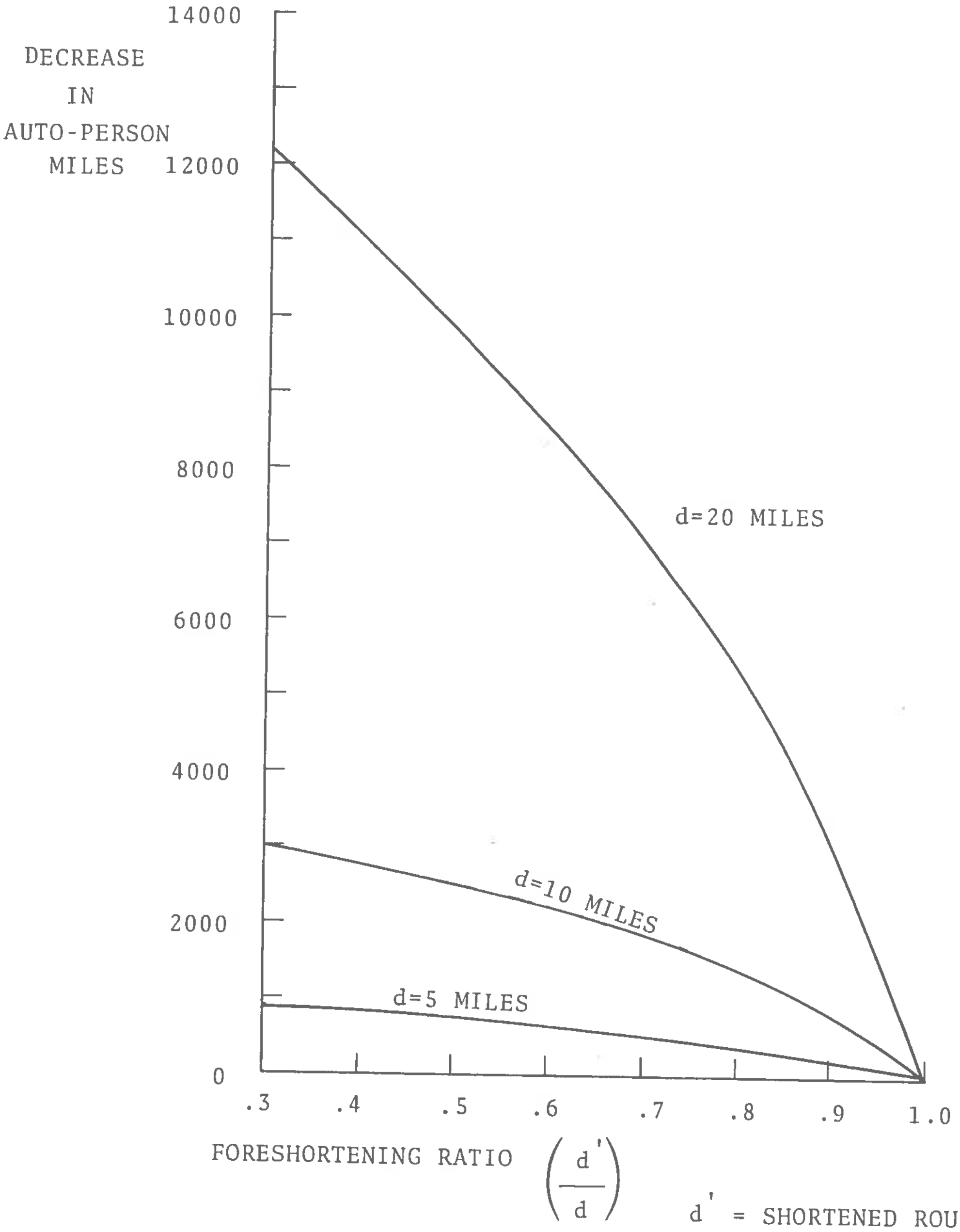
ORIGINAL AVERAGE DEMAND DENSITY = 100 TRIPS PER ROUTE MILE

Figure 2-3. Auto-Person Mile Savings (Uniform Trip Density)



ORIGINAL AVERAGE DEMAND DENSITY = 100 TRIPS PER ROUTE MILE

Figure 2-4. Auto-Person Mile Savings (Increasing Trip Density)



d' = SHORTENED ROUTE LENGTH
d = INITIAL ROUTE LENGTH

ORIGINAL AVERAGE DEMAND DENSITY = 100 TRIPS PER ROUTE MILE

Figure 2-5. Auto-Person Mile Savings (Decreasing Trip Density)

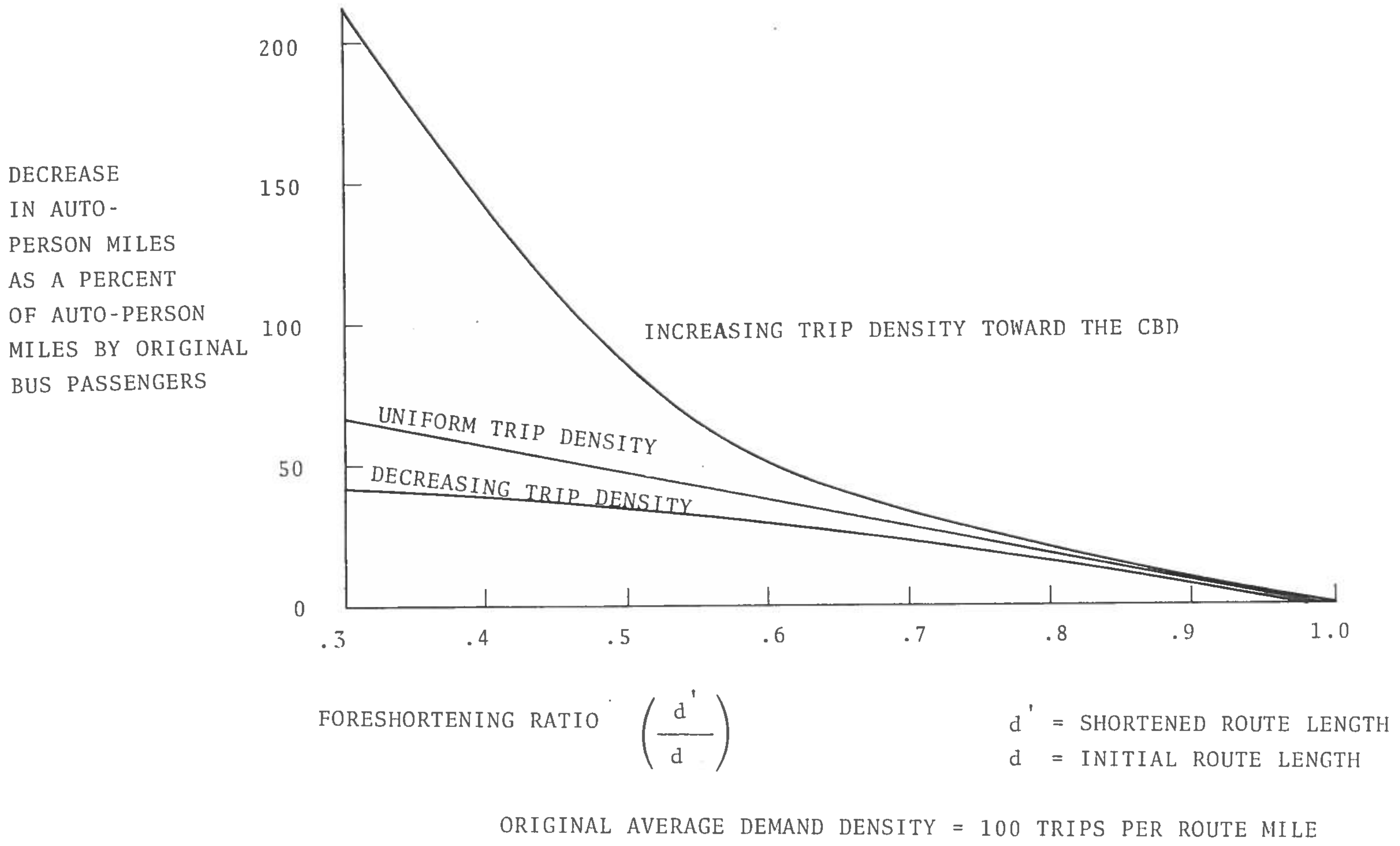


Figure 2-6. Relative Auto-Person Mile Savings

travellers to transit. A further reduction (the percentage indicated in Figure 2-6) can be achieved by shortening the bus route length. (Note that savings do not vary with the initial route length when expressed in percentage form.) Therefore, the percentage represents a potential savings relative to the original benefits of the bus route. Some of the original auto-person mile benefits, however, were cancelled by the energy required for the original bus miles. Shortening of the bus route length reduces auto-person miles without increasing bus miles.

Figure 2-7 shows the savings very roughly as a percentage of the initial (before route shortening) radial auto-person miles originating in the bus route market area. (This number would be smaller if calculated on the basis of total corridor auto-person miles unless the bus route extended the full length of the corridor.) For a 50 percent modal split the relative savings are the same as shown in Figure 2-6 for the uniform trip density since auto and bus ridership are equal.

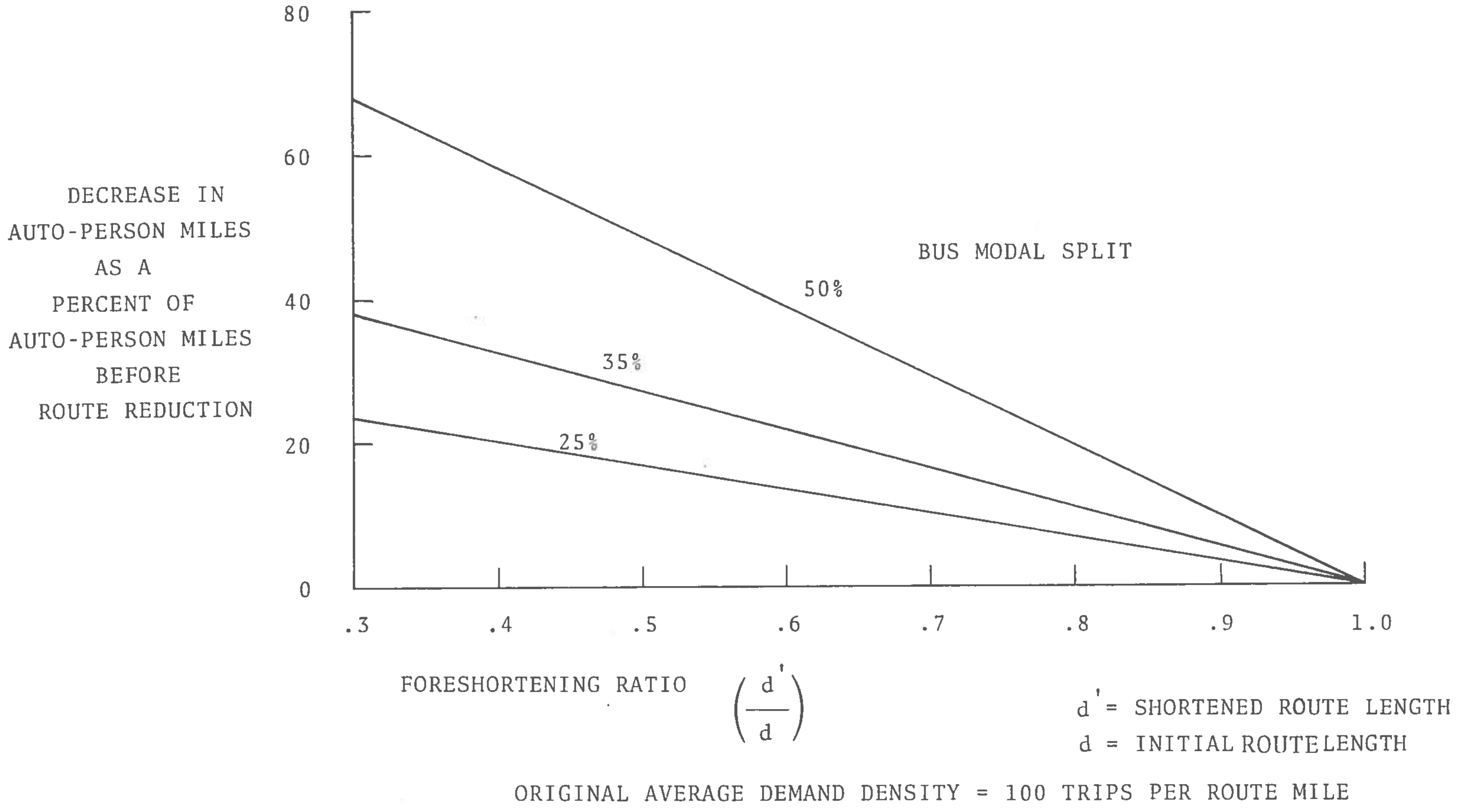


Figure 2-7. Relative Auto-Person Mile Savings (Uniform Trip Density)

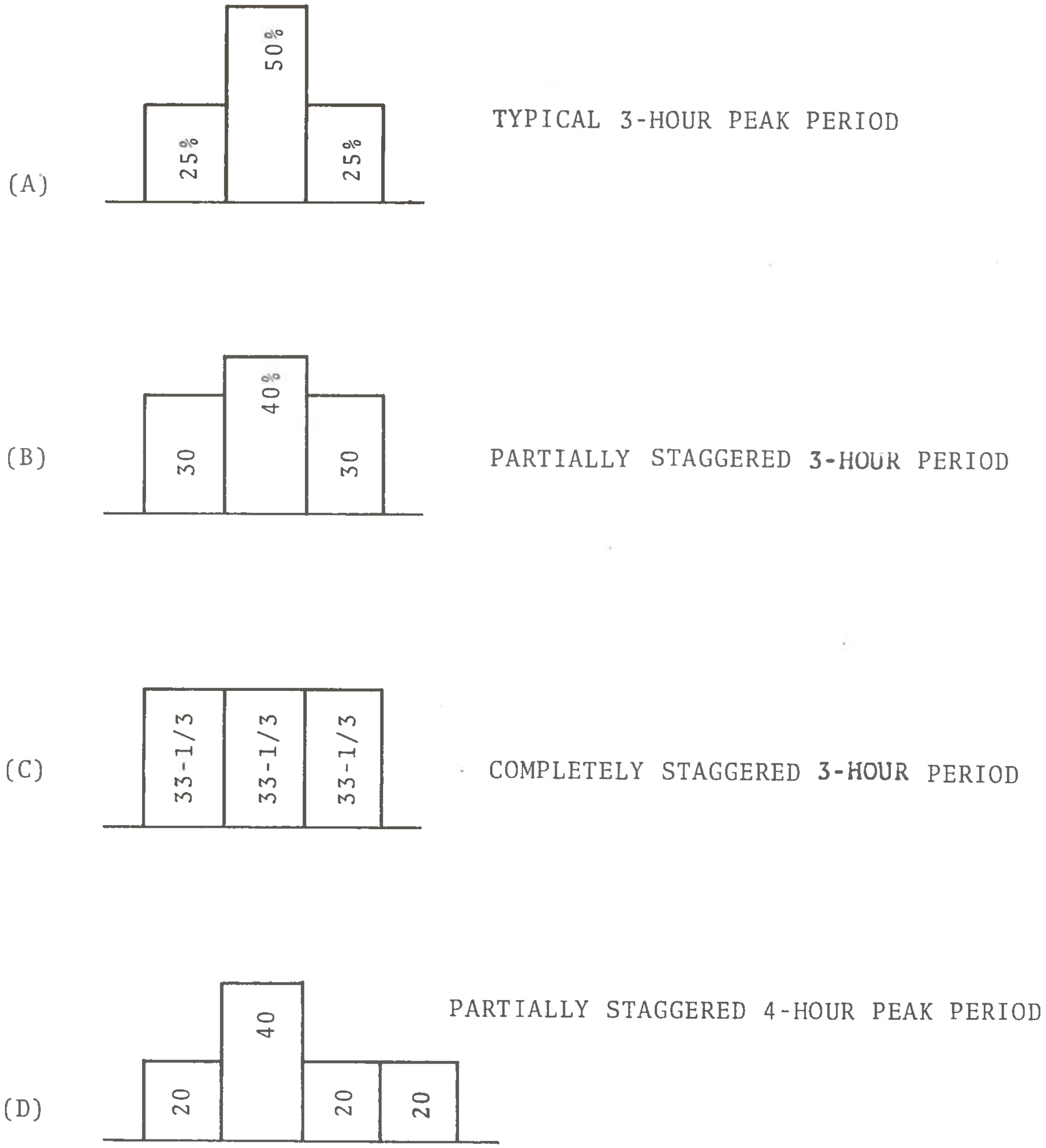
3. THE EFFECTS OF STAGGERING WORK HOURS ON CARPOOL POTENTIAL AND ON TRANSIT UTILIZATION POTENTIAL

3.1 INTRODUCTION

Staggering work hours has been used in a number of urban areas, e.g., New York and Washington, to reduce crowding on public transportation and to reduce automobile congestion during peak commuting hours. Although an enormous amount of cooperation among employers and employees is required for successful use of this method, significant benefits in terms of reduced travel time and increased comfort for commuters may be achieved. Staggering work hours, if implemented on a large scale, can also be used to increase the effective capacity of transit systems, whether "congested" or not, if an increase in demand warrants the additional capacity. It is a method that not only may be useful in the short term, but the continued use of staggered hours can produce substantial long term cost savings due to a reduction in the number of new vehicles required. This study examines the benefits in terms of the relative transit capacity increases possible for both partial and complete staggering.

While staggering work hours creates circumstances by which an existing transit fleet can accommodate an increase in demand for transit service, it may have detrimental effects on the potential number of people who can carpool. These effects are examined in an "abstract city" scenario in which representative numbers and types of trips are made in the commuting period.

Staggering work hours is defined here as either extending the length of the period during which commuter travel takes place, reducing the percentage of commuter travel occurring in the busiest (peak) hour, or both. The peak period is determined totally by the length (number of hours) and percentage of travel occurring in the peak hour (the "peaking factor"). Travel in the remaining hours is assumed to be distributed equally. Figure 3-1 presents examples of cases studied. Figure 3-1a is a three-hour peak period with a 50 percent peaking factor, typical of many



TYPICAL 3-HOUR PEAK PERIOD

PARTIALLY STAGGERED 3-HOUR PERIOD

COMPLETELY STAGGERED 3-HOUR PERIOD

PARTIALLY STAGGERED 4-HOUR PEAK PERIOD

Figure 3-1. Peak Period Examples

large urban areas. In Figure 3-1b, a partial staggering scheme has reduced this percentage to 40 while maintaining the same length peak period. In Figure 3-1c, complete staggering (equal travel in each hour) has taken place. In Figure 3-1d, staggering has involved both a reduction in the peaking factor and a spreading of the peak period.

3.2 EFFECTS OF STAGGERING WORK HOURS ON PEAK PERIOD TRANSIT UTILIZATION

The effects on transit utilization are determined under the basic assumption that existing fleets are sized according to peak hour demands. The results in terms of capacity increases, therefore, reflect the level of service inherent in the initial peak hour state of the system (before staggering). For example, if there is an average of 20 percent standees before staggering work hours, then the same standee level is implied in the capacity increases presented here after staggering. Alternatively, if peak hour frequencies are sufficiently high to allow only an average 80 percent load factor, then results represent this same level of service and comfort.

In the nonpeak hours of the peak period, more passengers *could* be accommodated (up to the same level as that of the peak hour) if the demand existed. It will first be determined how many more passengers could be carried by existing fleets if an overall increase in transit demand occurred (e.g., due to gasoline rationing) *without* any staggering of trip times.

If it is assumed that the trip population from which the new transit trips are taken (i.e., former auto users) are temporally distributed in the same manner as the original transit trips, then some of the new demand which occurs can be satisfied, but a fraction of the new demand equal to the peaking factor will not. An example using a 3-hour peak period and 60 percent peaking factor is shown in Figure 3-2a. In Figure 3-2b, a 100% increase in total demand in illustrated. Four-tenths of that 100% (that occurring in the nonpeak hours) can be handled by the existing transit system since the available capacity (shown in dashed lines

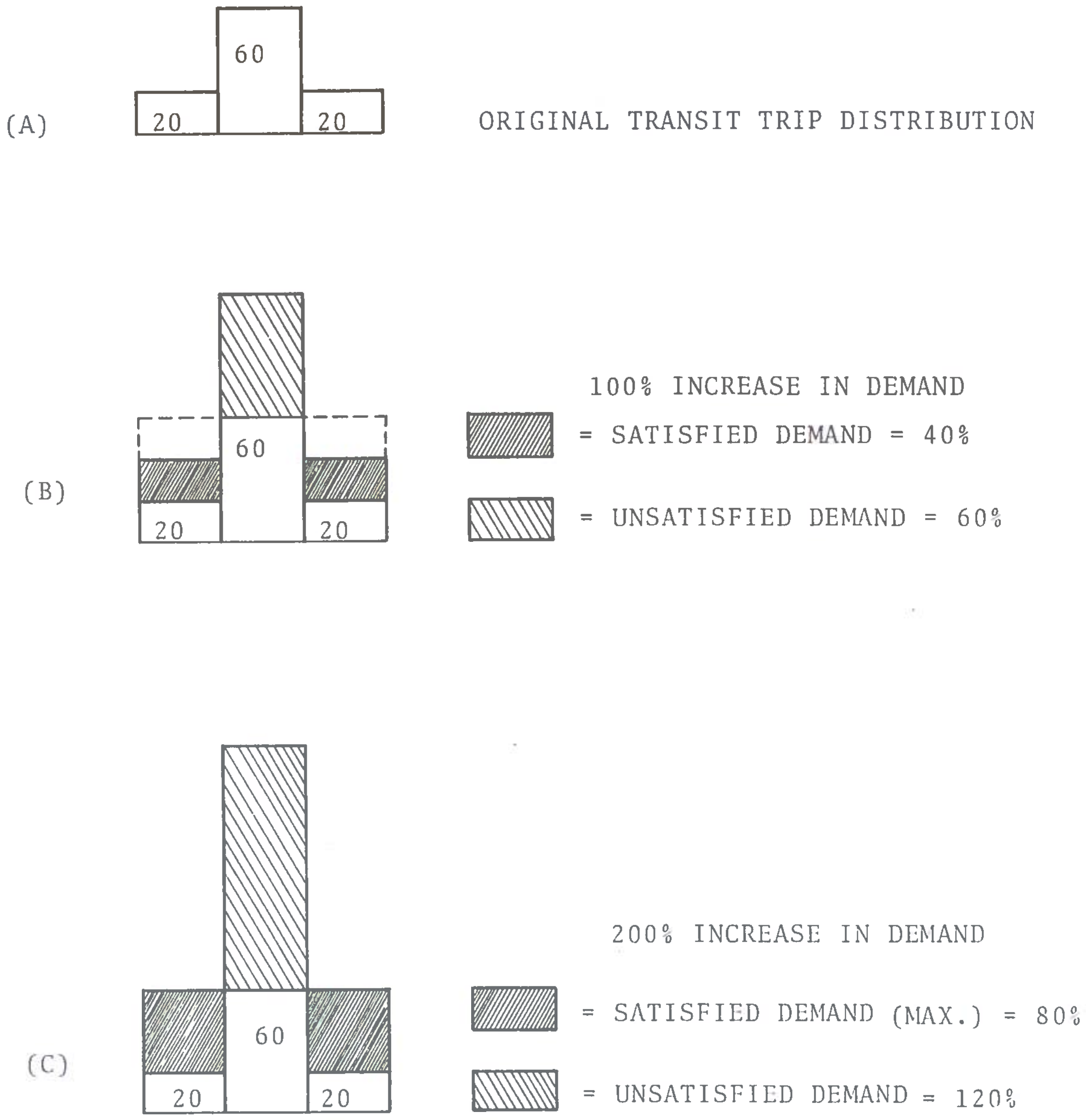


Figure 3-2. Example of Available Transit Capacity (Without Staggering)

as determined by the original peak hour ridership) is not exceeded. (None of the new demand occurring in the peak hour can be satisfied.) In fact, four-tenths of any demand increase up to a total increase in demand of 200 percent can be accommodated (Figure 3-2c). At this point, no further ridership can be carried in the nonpeak hours since full capacity has been reached.

The example can be generalized for a peak period having a length of m hours and peaking factor of p. The maximum percentage *increase* in ridership that can be handled is then:

$$R_{max} = mp - 100$$

The minimum percentage increase in total demand required to achieve the maximum satisfied ridership is:

$$I_{min} = 100 \left[\frac{\frac{p}{100 - p}}{m-1} - 1 \right] = \left(\frac{mp - 100}{100 - p} \right) 100$$

For any increase in demand, the fraction F of the total demand which can be satisfied (until full capacity is reached) is:

$$F = \frac{R_{max}}{I_{min}} = \frac{(mp - 100)\ (100 - p)}{100\ (mp - 100)} = \frac{100 - p}{100}$$

This is just the fraction of demand occurring in the nonpeak hours. (Note that F becomes discontinuous at $p = 100/m$, or in other words, when the demand distribution is perfectly flat.) R_{max} and I_{min} for three peak period lengths (2, 3, 4 hours) are plotted in Figures 3-3 to 3-5, respectively. It can be seen that while the maximum increase able to be handled (R_{max}) increases linearly with the original peaking factor, the minimum increase in *total* demand ($I_{min} - R_{max}$) increases nonlinearly. The effects of the length of the peak period can be more clearly seen in Figure 3-6, where the maximum satisfied is plotted for the three peak periods.

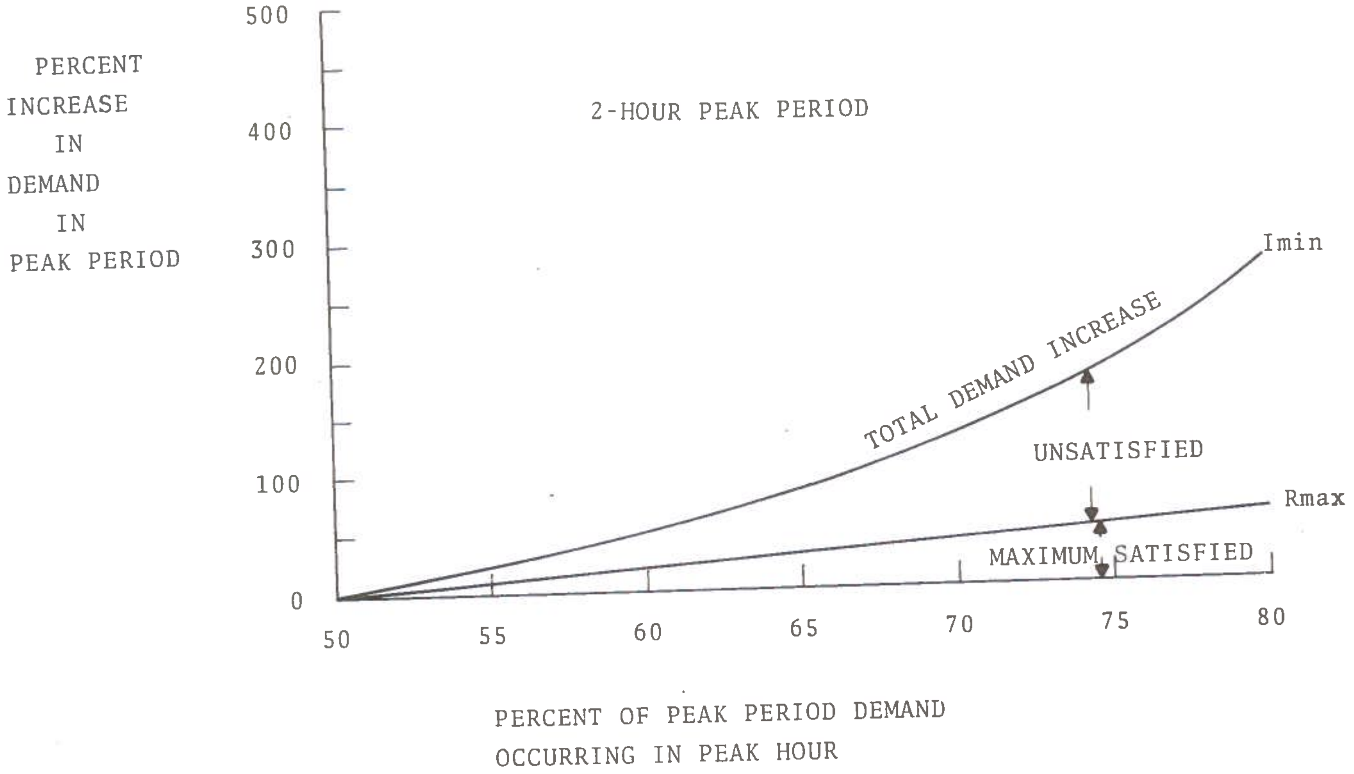


Figure 3-3. Potential Ridership Increase (No Staggering), 2-Hour Peak Period

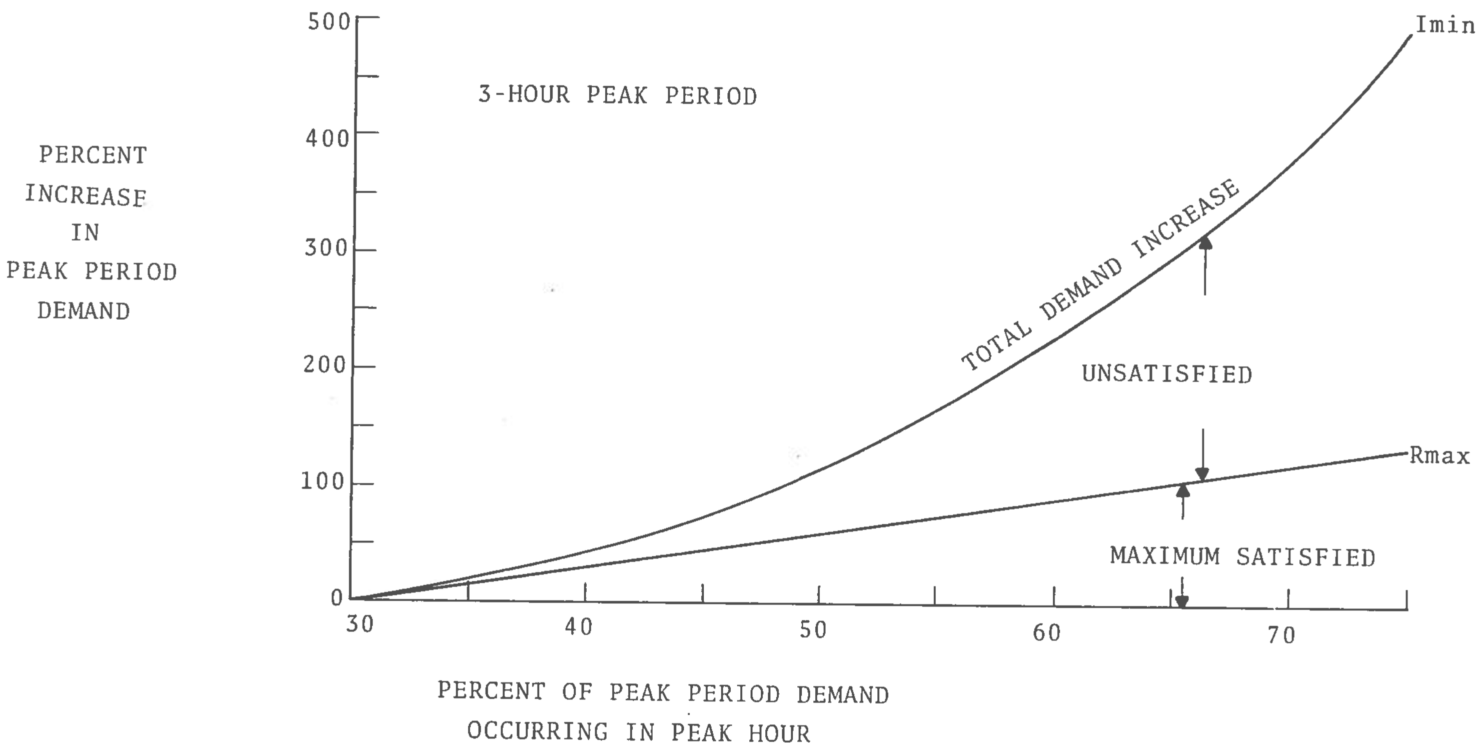


Figure 3-4. Potential Ridership Increase (No Staggering), 3-Hour Peak Period

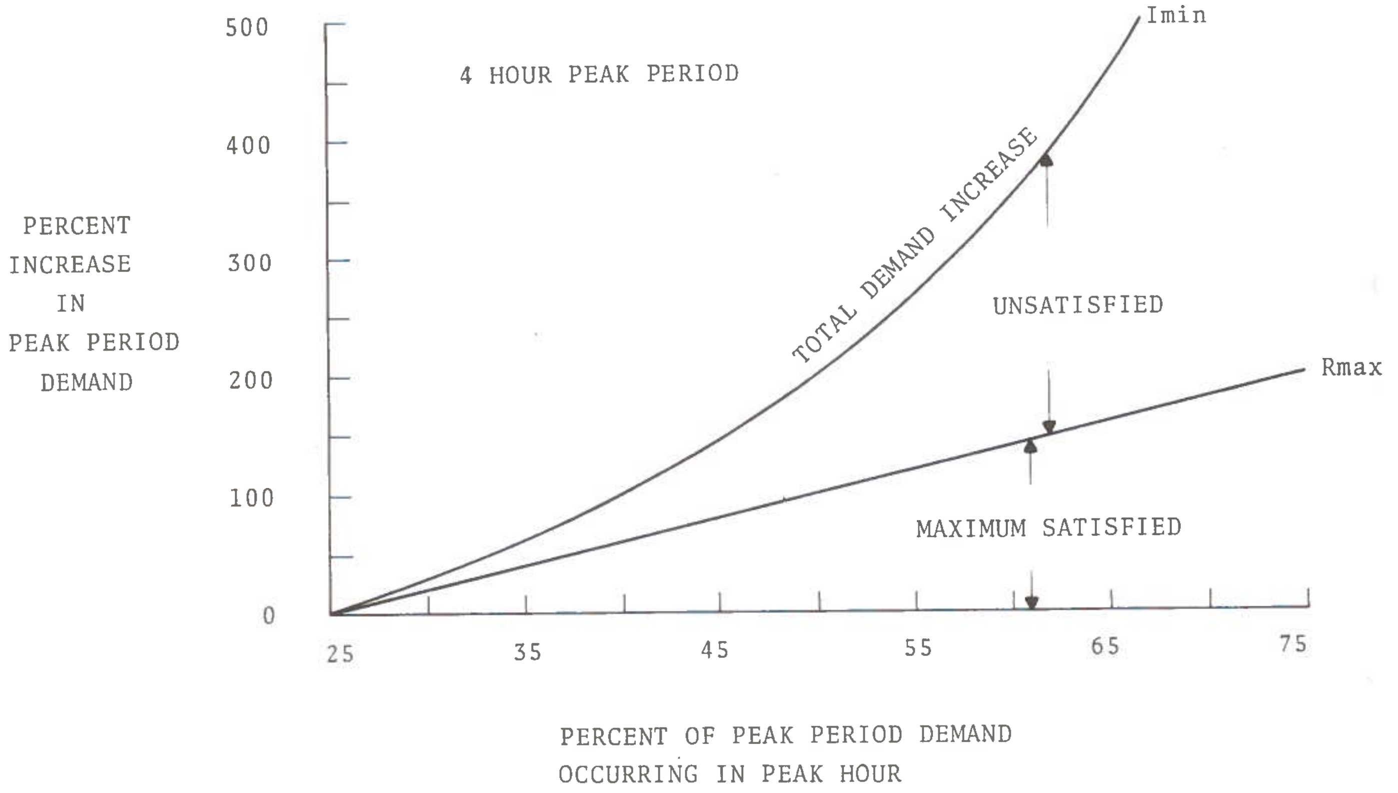


Figure 3-5. Potential Ridership Increase (No Staggering), 4-Hour Peak Period

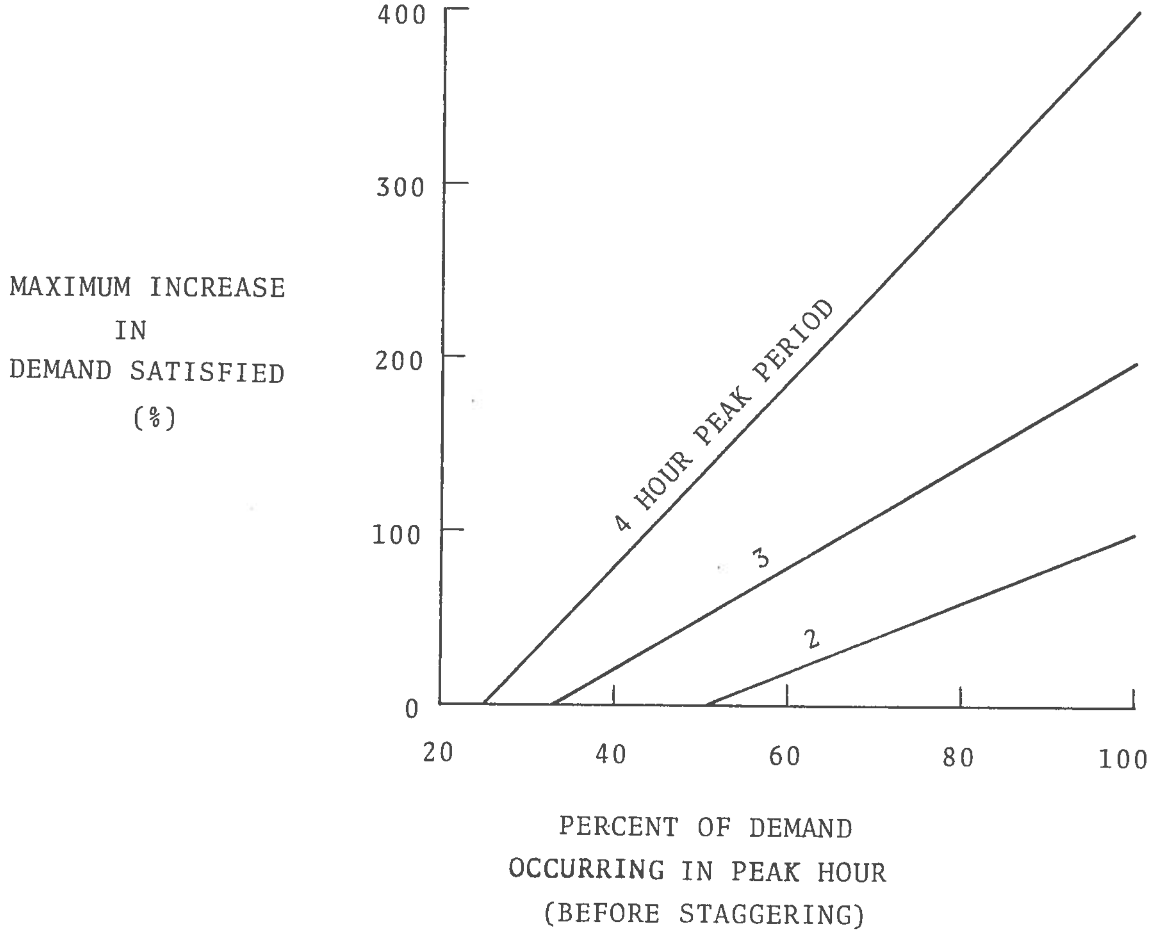


Figure 3-6. Potential Ridership Increase

Further insight can be gained by examining the effects at the extremes. If the distribution of trips is *almost* flat, a large fraction of an increase in demand can be satisfied but only up to a small absolute amount. (For an absolutely flat distribution, no increase in demand can be accommodated.) As the peaking factor *approaches* 100 percent, only a small fraction of the demand increase can be satisfied but the absolute amount approaches a maximum if the increase in total demand is large enough. (When 100 percent of the demand occurs in the peak hour, although theoretically the largest magnitude of demand could be satisfied in the nonpeak hours *no* increase in demand can occur in the nonpeak hours under the no-staggering assumption. Mathematically, an infinite demand increase must occur for any to be satisfied. This is an illogical case by definition as well as by reason since, if all of the demand occurs in the peak hour, there exists a one-hour peak period.)

Now the effects of staggering trip times can be examined. If some of the peak hour demand is shifted to the nonpeak hours, then some of any demand increase which occurs in the peak hour can be accommodated in that hour. Therefore, a larger percentage of the total demand increase can be satisfied (although the maximum satisfied remains the same since it is dependent only on the length of the peak period). Figure 3-7 carries the example of Figure 3-2 a bit further by assuming a staggering of trip demand which reduces the percentage in the peak hour to 40 percent (Figure 3-7b). If an increase in total demand of 50 percent is generated (Figure 3-7c), all of this increase can be accommodated since the original transit fleet capacity designed for a 60 percent peaking factor is not exceeded. At this point any further increase occurring in the peak hour cannot be handled, but there is still capacity remaining in the nonpeak hours. The maximum satisfied demand is achieved for a total demand increase of 100 percent (Figure 3-7d), eight tenths of which can be accommodated.

Figure 3-8 shows for a two-hour peak period the maximum increase in demand satisfied, the minimum total demand increase required to achieve the maximum satisfied, and the resulting

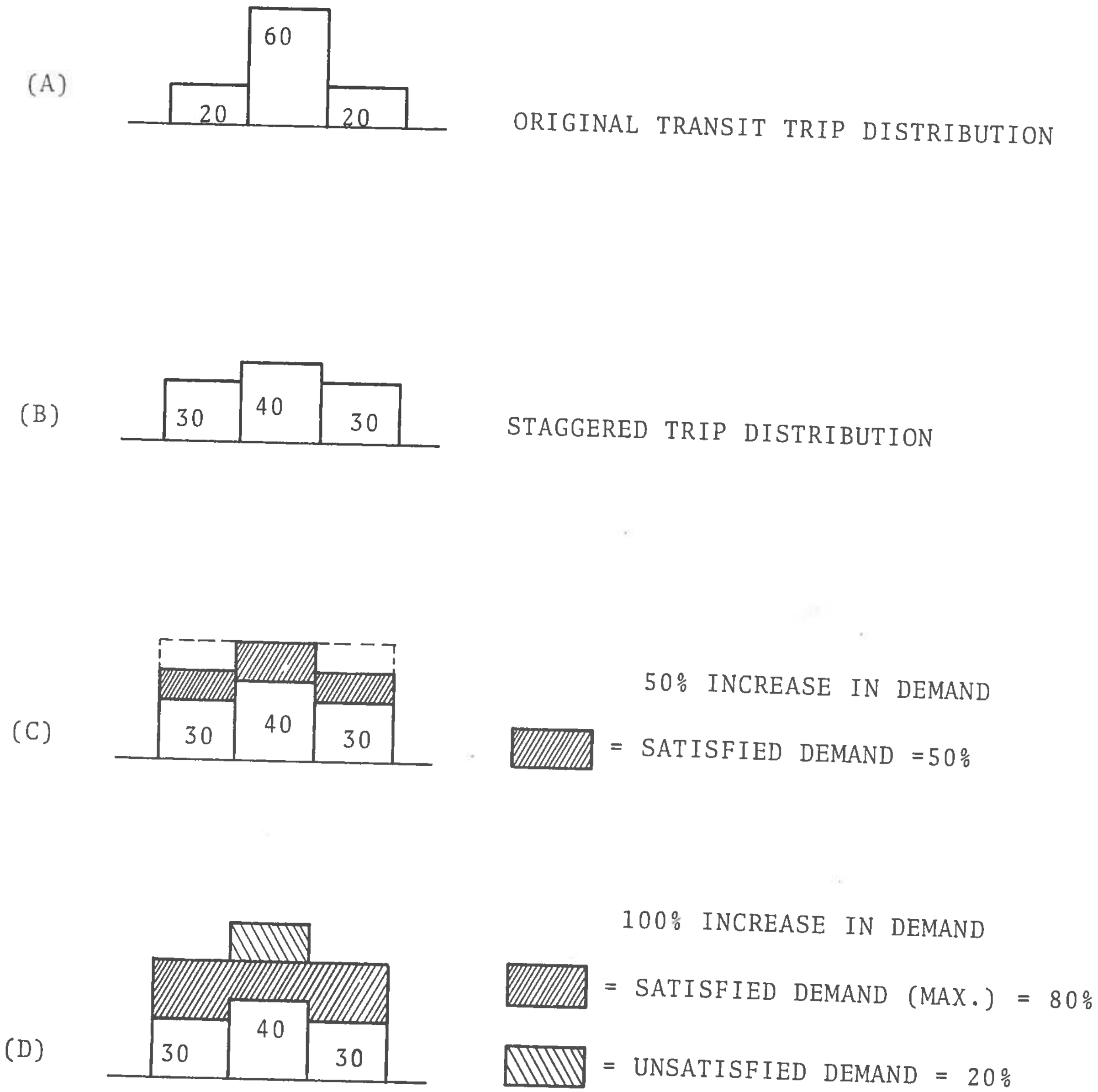


Figure 3-7. Examples of Available Transit Capacity (with Staggering)

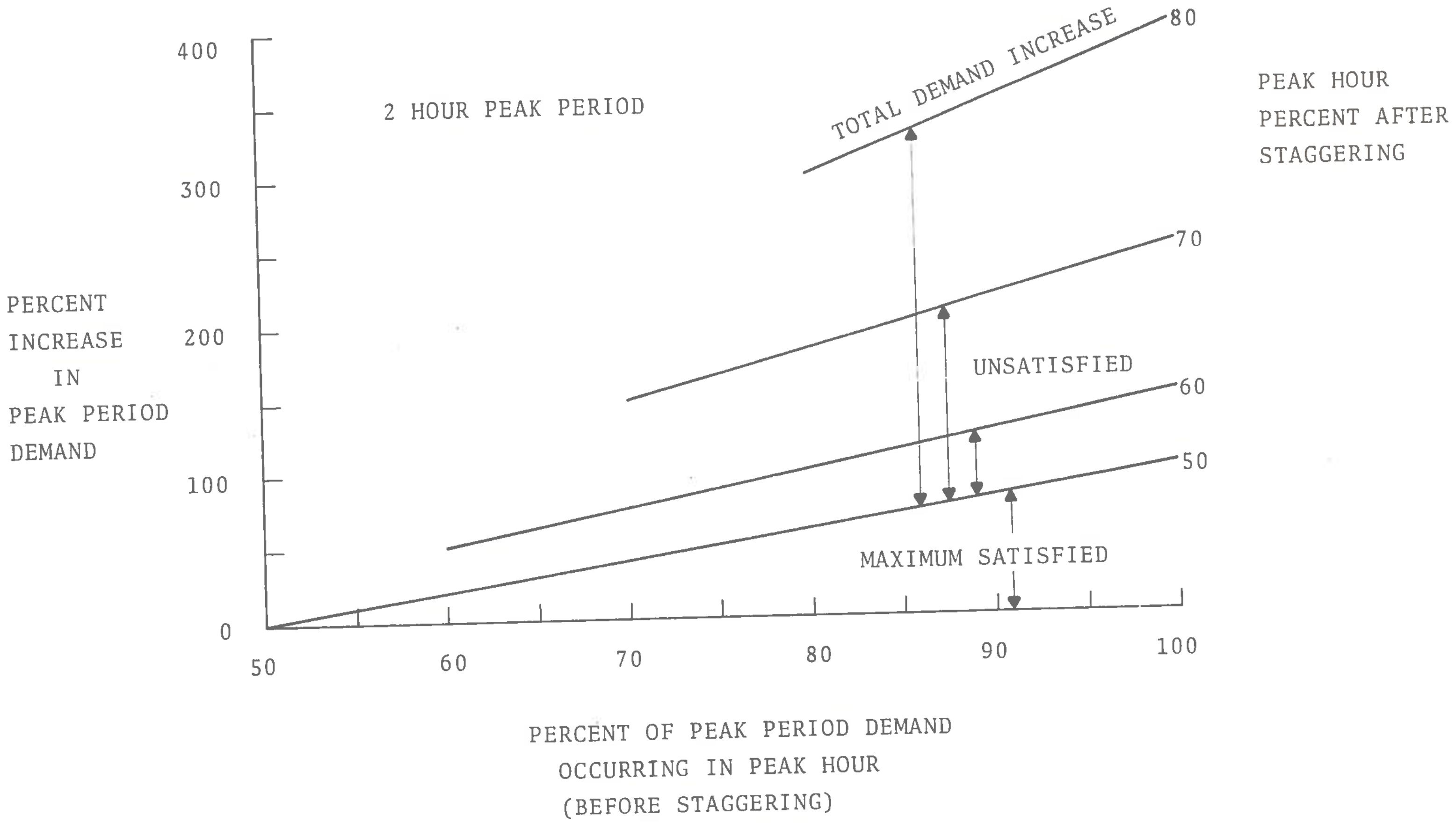


Figure 3-8. Potential Ridership Increase With Staggering, 2-Hour Peak Period

magnitude of unsatisfied demand for various peaking factor assumptions for before and after staggering. Note that while the maximum is not affected by staggering, the fraction of total demand satisfied increases as the percentage of demand occurring in the peak hour after staggering decreases. For full staggering (50 percent in each hour), *all* of the demand increase which occurs can be accommodated up to the maximum indicated. The greatest potential is achieved, of course, when 100 percent of the demand before staggering occurs in the peak hour. Mathematical derivation of the most general case is presented in Appendix B-1.

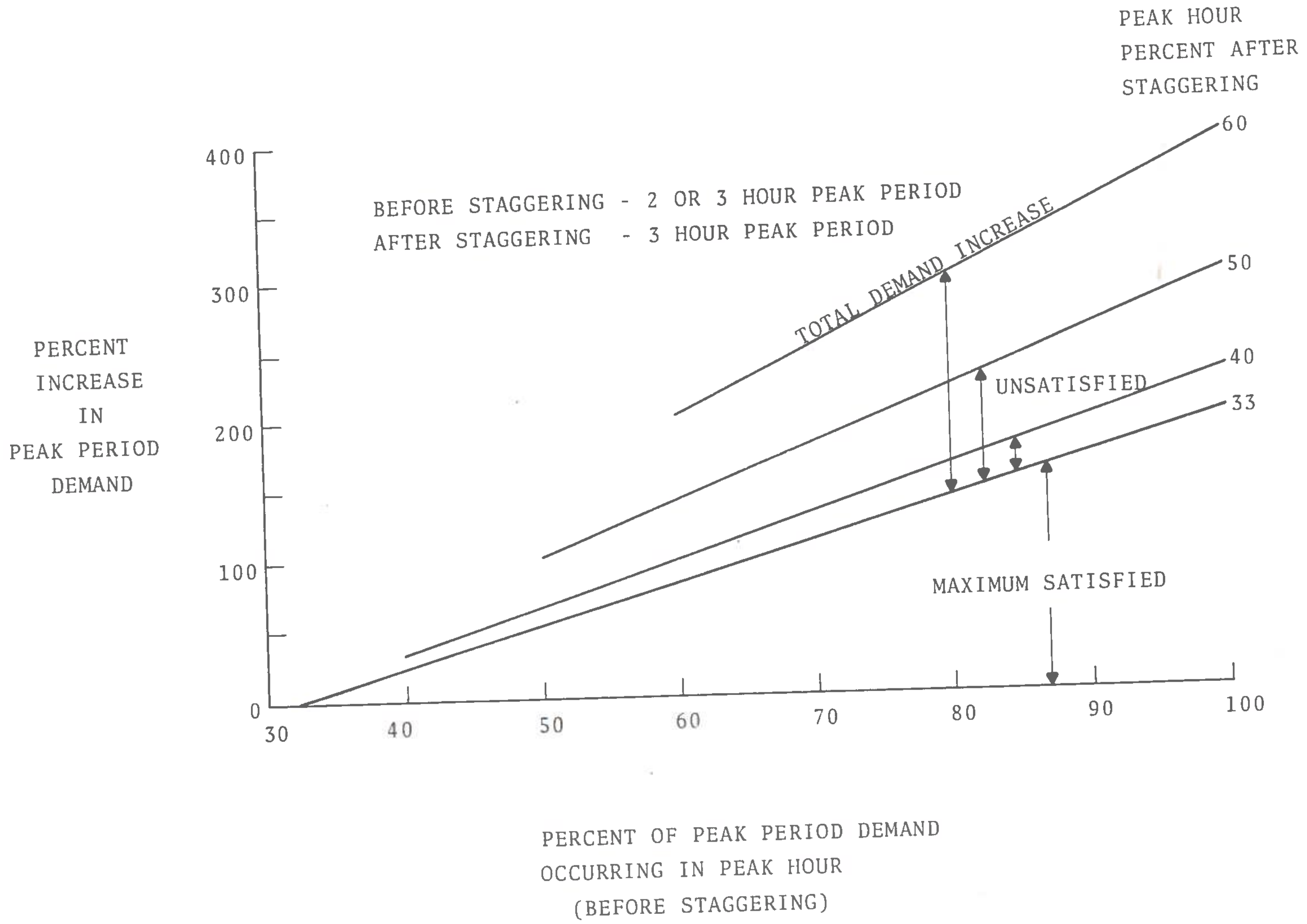
Figures 3-9 and 3-10 are similar charts for peak periods after staggering of 3 and 4 hours, respectively. For a given peak period after staggering, the length of the peak period before staggering is irrelevant since the available fleet capacity is determined only by the "before" peaking factor.

The continuous effects of staggering as overall demand increases can be seen in Figure 3-11 where for a 3-hour peak period and an initial peaking factor of 50 percent, the increase in demand satisfied is shown for an increase in total demand. The greater the staggering, the greater the range in which all of the demand increase is satisfied, and the sooner the maximum achievable satisfied demand is reached. Figure 3-12 is a similar plot for an initial peaking factor of 70 percent.

3.3 EFFECTS OF STAGGERING ON CARPOOL POTENTIAL

The number of potential carpoolers was determined by a model based on "Plastictown," a profile of a hypothetical urban area. Plastictown is divided into three areas (see Figure 3-13):

1. The central business district - a circular area of 1 mile radius.
2. An inner area surrounding the central business district with a radius of 8 miles.
3. Six "corridors" projecting from the inner area into the surrounding suburbs.



Potential Ridership Increase With Staggering, 3-Hour Peak Period After Staggering

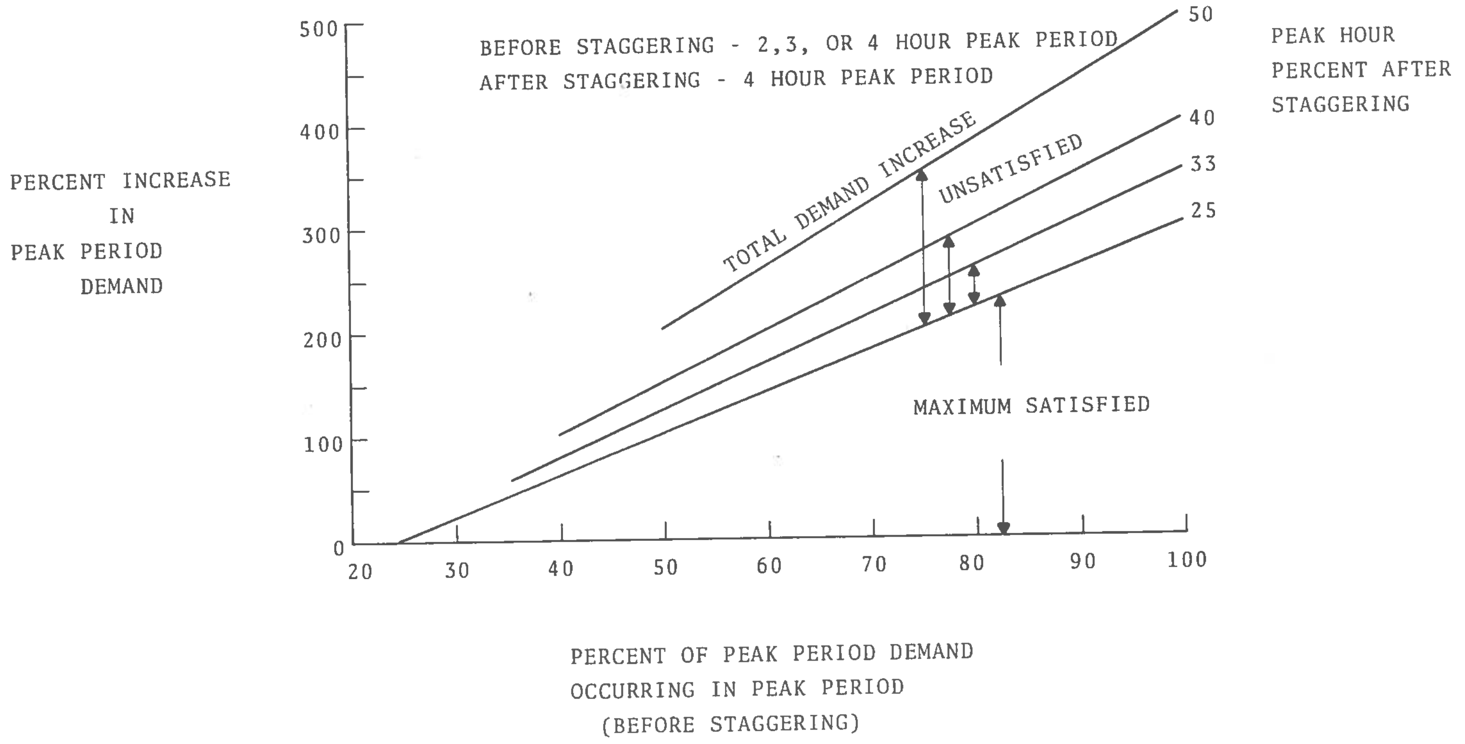


Figure 3-10. Potential Ridership Increase With Staggering, 4-Hour Peak Period After Staggering

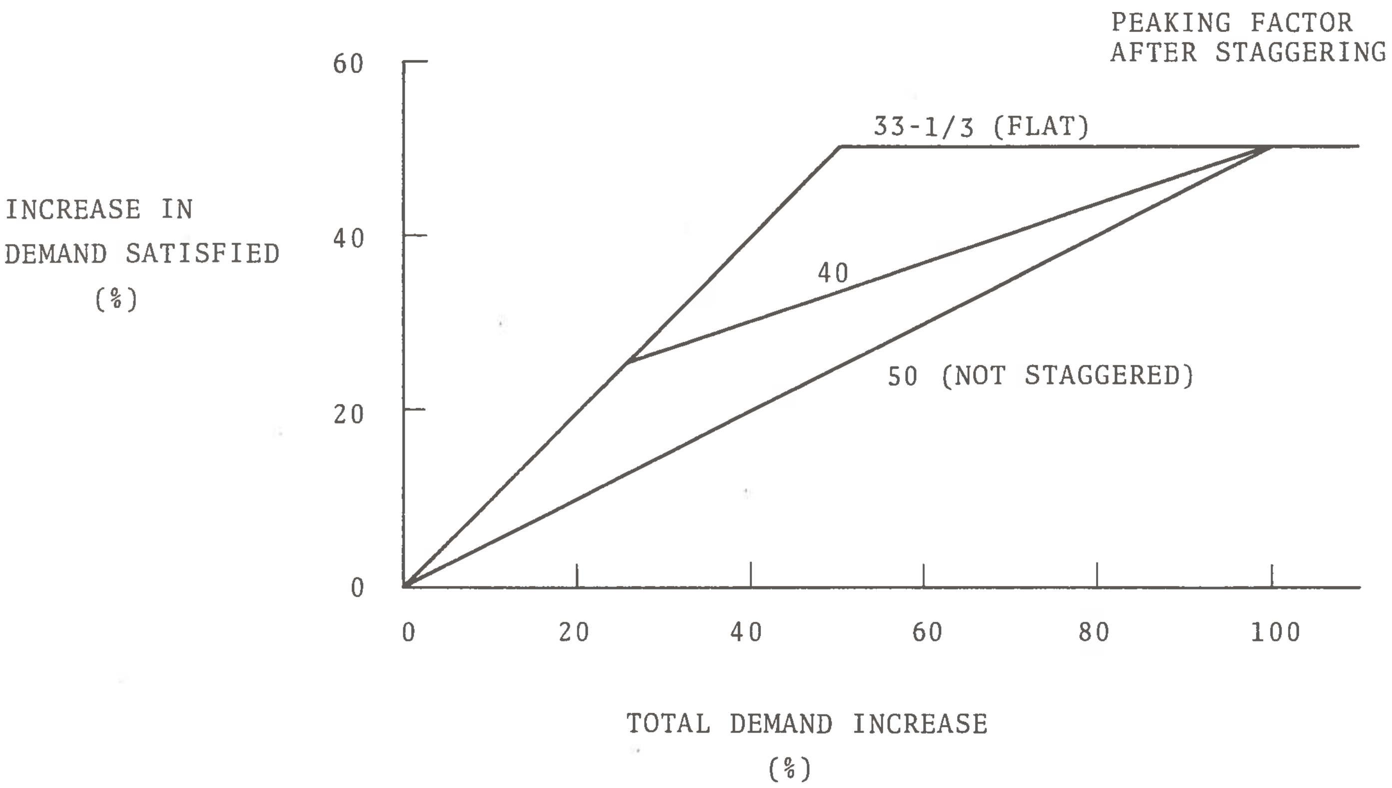


Figure 3-11. Demand Increase Satisfied (3-Hour Peak Period, Initial 50% Peaking Factor)

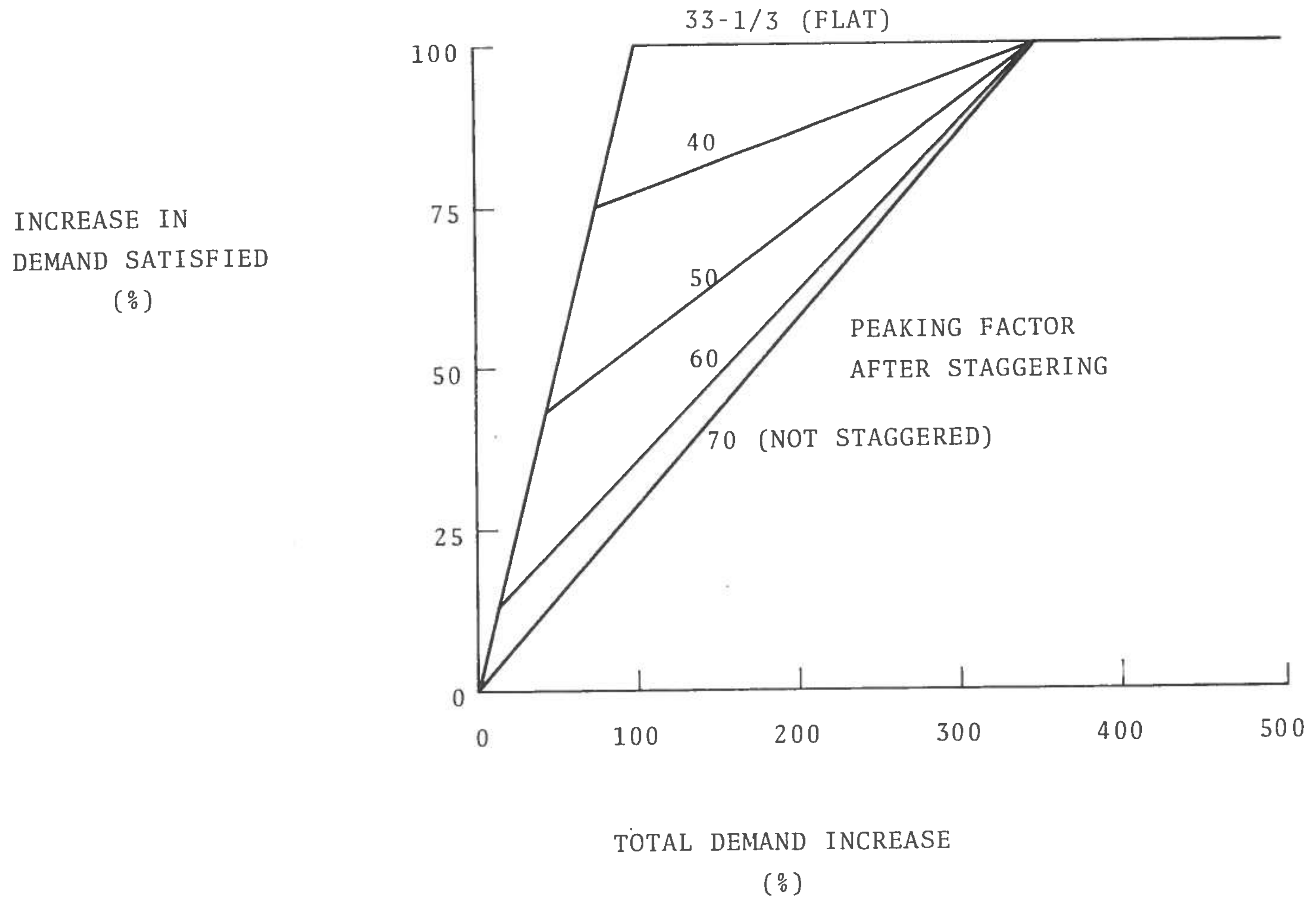


Figure 3-12. Demand Increase Satisfied (3-Hour Peak Period, Initial 70% Peaking Factor)

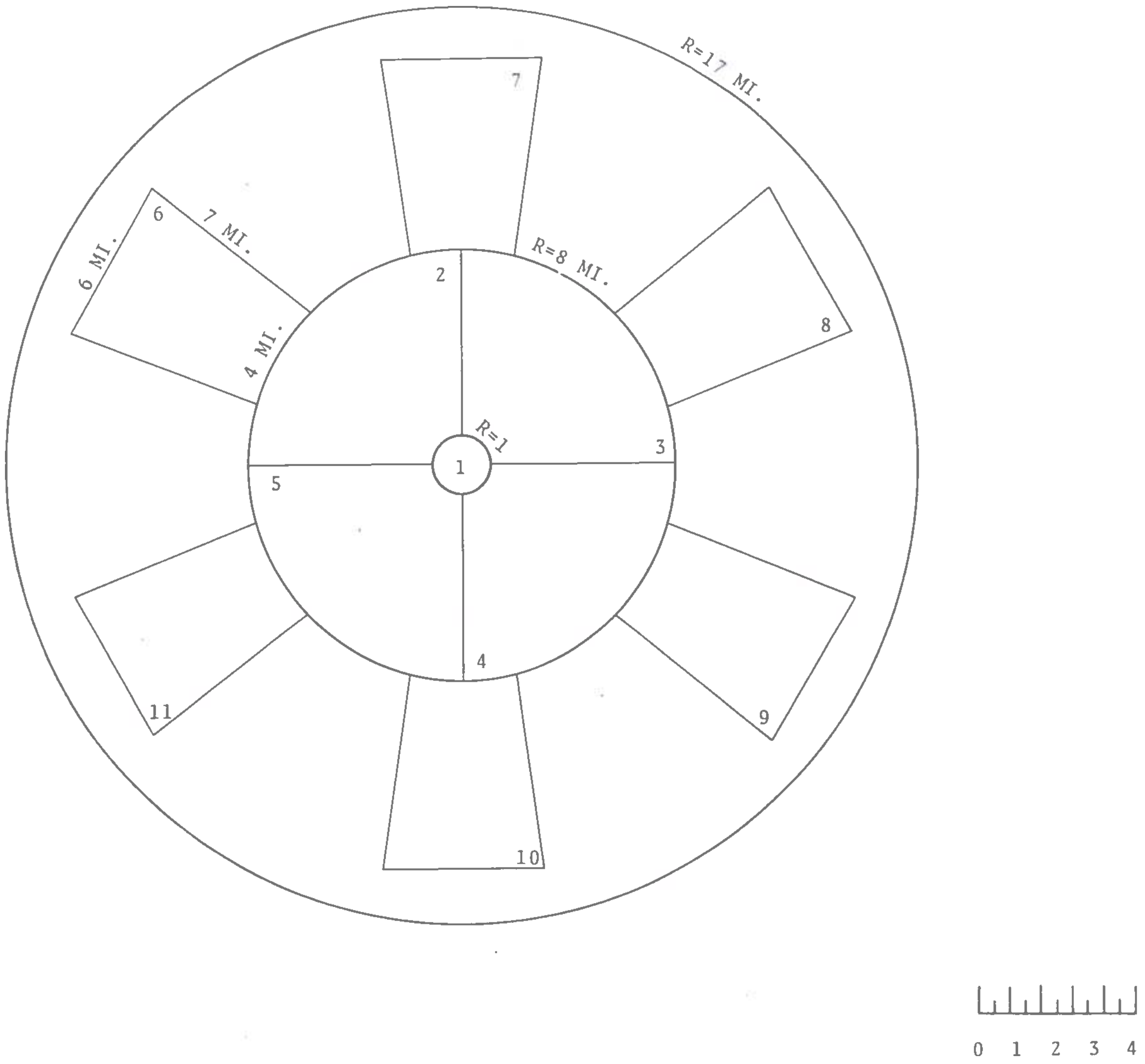


Figure 3-13. Plastictown

There are 22 different categories of origin-destination pairs, 12 of which are listed in Table 3-1. Trip volumes for remaining categories are too low for carpooling.

A model (see Appendix B-2) was devised to determine whether, for each of the 22 different O-D pairs, it was possible for the commuters making that trip to join carpools. Because of the assumptions behind the formula, if *any* commuters making a given kind of trip could join a carpool, then *all* the commuters making that trip could join a carpool.

The model is based on the number of auto commuters making the trip, the density of such commuters at the origin of the trip, and the density at the destination of the trip. The model divides the region of origin of the trip and region of destination of the trip into square grid cells of a specified size. It is assumed that two commuters can form a carpool if:

1. They live in a common origin grid cell.
2. They work in a common destination grid cell.
3. The difference in their departure times for work is less than a specified time interval (assumed here to be 1/4 hour).

The size of the grid cell depends on whether it is an origin or destination grid cell and on their locations. The areas of the grid cells used were the following:

Region	Size of Origin Grid Cell (sq. miles)	Size of Destination Grid Cell (sq. miles)
Central Business District	0.5	0.25
Inner Area	2.0	0.50
Outer Area	4.0	1.00

The origin grid cell areas were established based on available information regarding how far apart carpool members live, in sectors of varying population density. Destination grid cell areas were set rather arbitrarily, since traditionally most carpools

TABLE 3-1. ORIGIN-DESTINATION PAIR CATEGORIES

Trip Description	Example of Trip Region of Origin*	 Region of Destination*	Trip Code
CBD Trips			
1. Within Central Business District (CBD)	1	1	C-C
2. From CBD to Inner Area	1	2	C-I
3. From Inner Area to CBD	2	1	I-C
4. From CBD to Outer Area	6	1	C-O
5. From Outer Area to CBD	1	6	O-C
Trips Within Inner Area			
6. Within One Region	2	2	I-I/S
7. From One Region to an Adjacent Region	2	3	I-I/A
8. From One Region to Opposite Region	2	4	I-I/C
Trips Among Outer Regions			
9. Within One Region	6	6	O-O/S
10. From One Region to Closest Neighbor	6	7	O-O/A
11. From One Region to 2nd Closest Neighbor	6	8	O-O/B
12. From One Region to Opposite Region	6	9	O-O/C

Note: There are also trip categories between the outer and inner areas, ten types in all, but there is no possibility of forming carpools here because of the small number of auto commuters making the trip.

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*Number refer to regions - see Figure 3-13.

have had a single destination. However, it was felt that, in estimating the *potential* for carpooling, the destination could be a sector. The destination cell area was set so that dropping off one or two passengers would not take more than five minutes.

The first step in the analysis was to determine the potential for carpools in an hour, given the number of work trips occurring during that hour. The fraction of the day's traffic contained in the morning commuting period for Plastictown was 19 percent. A varying fraction of the morning commuter traffic was assigned to a single hour. It was assumed that this fraction was the same for each O-D pair category.

Table 3-2 shows whether it is possible to form carpools for each type of trip during a given hour, depending on the fraction of trips occurring during that hour. It can be seen that if the peak hour contains between 53% and 100% of all morning auto commuter trips, carpools can be formed for 6 of the 22 categories. At 53% it becomes impossible to form carpools for trips within a sector of the inner area. As the percentage continues to drop, other categories are eliminated and the total number of possible carpoolers drops.

The results contain the effect of the following two variables on the potential for carpooling:

1) Length of commuting period; three values were used: 2 hours, 3 hours, and 4 hours.

2) Proportion of commuter traffic in the peak hour. This percentage was varied from 25% to 90%.

Table 3-3 shows the percent of auto commuters who can join pools for each configuration of commuter period length and peak hour percentage. The data are plotted in Figure 3-14. It can be seen that the number of potential carpools is determined primarily by the proportion of traffic in the peak hour. It makes little difference whether the remaining traffic is split up among one, two, or three hours. Carpool potential appears to be especially sensitive to the percent of trips in the peak hour in the range

TABLE 3-2. POSSIBILITY OF FORMING CARPOOLS FOR EACH O-D PAIR CATEGORY IN PEAK HOUR AS A FUNCTION OF PEAKING FACTOR

Pair Category	Percent of Work Trips in Peak Hour			
	53-100	49-53	15-49	10-15
C-C	X	X	X	
C-I				
I-C	X	X	X	X
C-O				
O-C	X	X	X	
I-I/S	X			
I-I/A				
I-I/C				
O-O/S	X	X	X	X
O-O/A	X	X		
O-O/B				
O-O/C				

"X" - INDICATES CARPOOLS CAN BE FORMED

TABLE 3-3. PERCENT OF AUTO COMMUTERS WHO CAN JOIN CARPOOLS BY LENGTH OF COMMUTING PERIOD AND PERCENTAGE OF WORK TRIPS IN PEAK HOUR

Percent of Work Trips In Peak Hour	Length of Commuting Period		
	4 hr	3 hr.	2 hr.
25	32%		
33	32%	32%	
40	32%	32%	
50	35%	35%	38%
60	44%	45%	45%
70	46%	47%	47%
80		49%	50%
90			51%

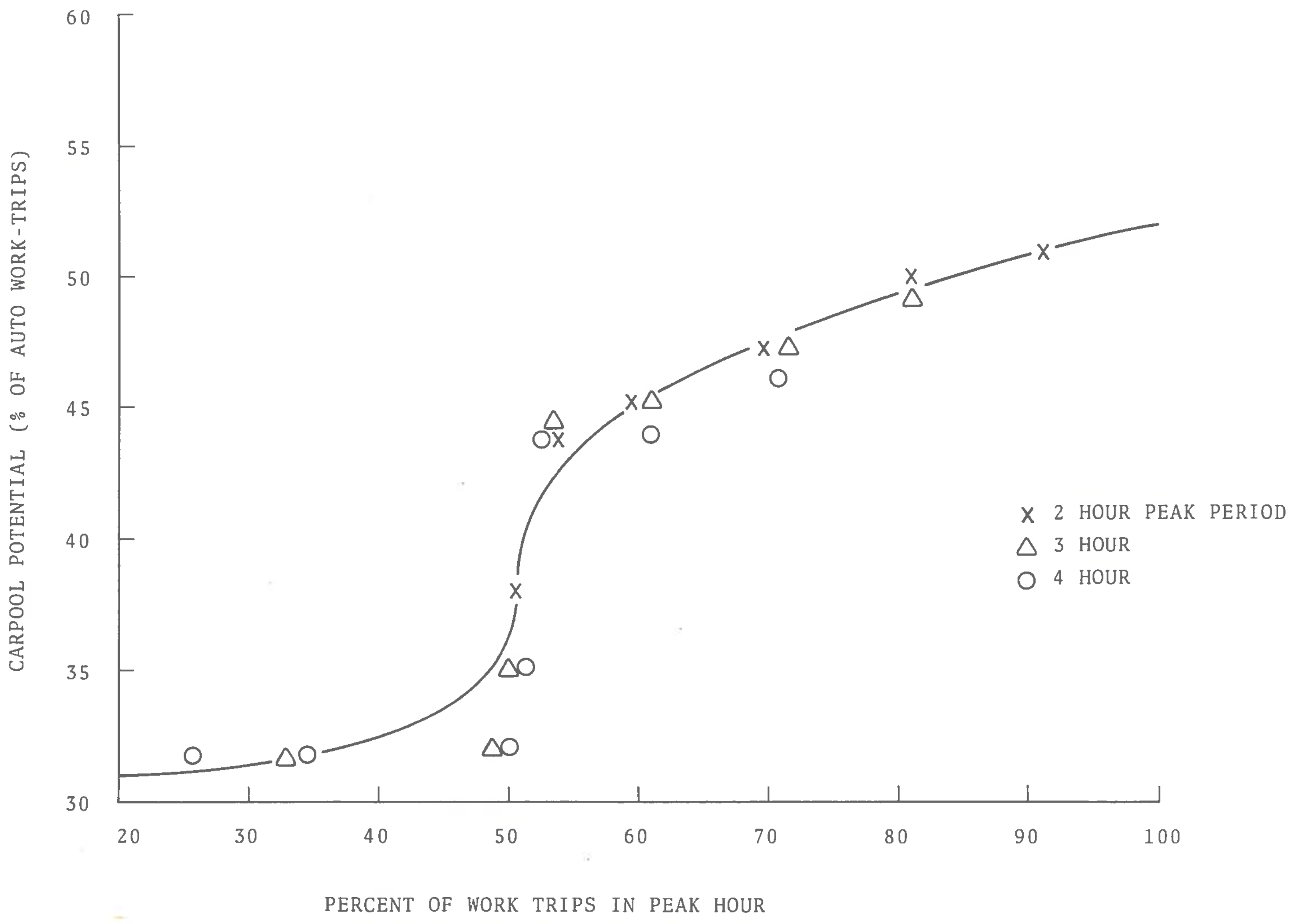


Figure 3-14. Effect of Staggering Work Hours on Carpool Potential

45 to 60 percent. Outside of that range, small changes in the peaking factor have relatively small effects on the number of potential carpools.

The reason for this result can be seen by referring to Table 3-2. In the range 15 to 49 percent of the peak period trips occurring during the peak hour, only one of the five O-D pair categories is eliminated. This reflects the high level of work trips to the core area for the four remaining categories. In other words, extending the peak period did not decrease the trip density enough to bring the number of trips in the grid cell below the minimum level established as a criterion for carpooling for those four trip types.

3.4 COMPARISON OF EFFECTS ON CARPOOLING AND TRANSIT UTILIZATION

Although effects of staggering work hours on carpool potential and on potential transit utilization are not strictly comparable, some insights can be gained by a case example. If the percent of travel in the peak hour is reduced from 60 to 45 percent (the most sensitive region for carpooling potential -- see Figure 3-16), the percent of auto work trips that can potentially carpool drops from 45 to 34 percent for a relative decrease of about one fourth. For a three-hour peak period, the same decrease in peaking results in the percent of new transit demand that can be accommodated rising from 40 to 67 percent (up to the capacity limit), or a relative increase of over three fifths.

It has been shown that staggering work hours in terms of spreading the peak period without changing the peak hour percentage has little effect on carpooling potential. However, the potential additional peak period capacity of a transit system is directly proportional to the number of nonpeak hours in the peak period and is therefore significantly affected by the length of the peak period.

In general, it appears that the benefits of staggering work hours to potential transit utilization may outweigh the detrimental effects on the potential for carpooling. This conclusion may be significant in that a recent survey of about 700 commuters at DOT's Transportation System Center which examined possible responses to various incentives and disincentives to auto commuting (such as gas rationing, high gas prices, high parking fees) revealed the following:

- Of those commuters who indicated a possible interest in carpooling, only about half would carpool; the other half would as likely switch to public transit in response to disincentives.
- Of those commuters who indicated no interest in carpooling, those who would consider switching mode in response to disincentives opted for public transit.

4. CONCLUSIONS

4.1 REDUCTION OF BUS ROUTE LENGTHS

Little, if any, energy savings due to decreasing auto miles are possible by relocating bus route terminal points for express bus service since no decrease in auto miles travelled are achieved. However, for multistop services a relocation may be worthwhile if appropriate conditions for such a move can be found. For circumstances in which an approximately uniform bus passenger trip density is exhibited, auto person mile savings are directly proportional to the reduction in bus route length. For trip densities increasing toward the CBD, relative savings increase out of proportion to the route length reduction. For decreasing trip densities, relative savings are less than proportional to the reduction in bus route length. For reductions of about ten percent or more, the auto-person mile savings may represent a significant fraction of the original miles travelled.

4.2 STAGGERING WORK HOURS

1) The maximum potential increase in transit passengers varies linearly with the peak percentage of travel, but without staggering of trip times, this maximum may be difficult to achieve where high peaking exists. Staggering has the effect of greatly increasing the fraction of desired demand that can be satisfied.

The potential for carpooling, based on commonality of origin, destination, and time, is highly sensitive to the proportion of peak period travel occurring in the peak hour. As this fraction increases, areawide carpooling potential increases up to the limiting case where all work trips occur in a peak hour.

2) Carpool potential is less sensitive to the length of the peak period than to the fraction of work trips in the peak hour. However, since transit fleet capacity is assumed to be sized according to the peak hour demands and therefore underutilized during the nonpeak hours, the length of the peak period *is* significant relative to accommodating transit demand increases.

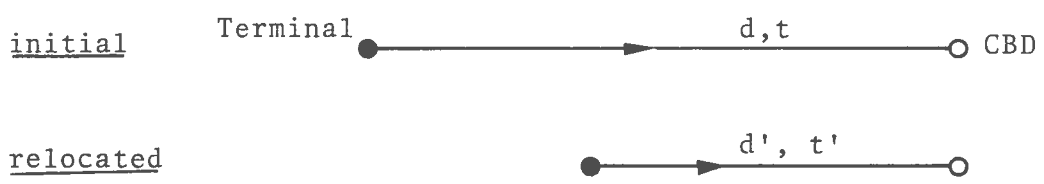
3) If there is no staggering, the only increases in transit demand that can be satisfied occur in the nonpeak hours. Staggering has the effect of enabling the transit system to serve some or all of the demand increase uniformly across the peak period.

The effects of staggering work hours on carpool potential are felt first by those in sectors where the density of work trips is low and travel patterns are diffuse. The number of zones where carpooling is possible decreases with staggered work hours and extended peak until only the inner, densely populated zones, or those zones with trips primarily focused on downtown destinations are remaining as candidates for any degree of carpooling.

4) Overall, it appears that the benefits of staggering work hours to potential transit utilization outweigh the detrimental effects on carpooling potential.

APPENDIX A
MATHEMATICAL DERIVATION OF CASE 1

Express Bus Service



d = initial route length

t = initial round trip time

d' = new route length

t' = new round trip time

When the terminal point is relocated, each bus can make t/t' more round trips. If the system initially carried p passengers, then it can now carry tp/t' passengers, or an increase of (t/t' - 1)p passengers. The additional miles required for the original passengers is

$$p\ (d - d')$$

The reduction in miles due to new passengers is

$$\left(\frac{t}{t'} - 1\right)(p)\ (d')$$

Net decrease in miles is the difference

$$\left(\frac{t}{t'} - 1\right)(p)\ (d') - p(d - d')$$

If we assume that

$$\frac{t}{t'} = \frac{d}{d'}$$

then the net decrease

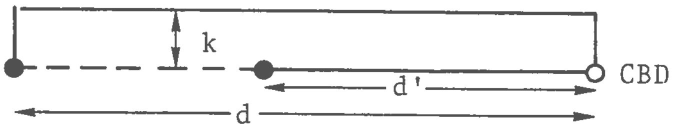
$$\left(\frac{d}{d'} - 1\right) (p)\ (d') - p(d - d')$$

is identically zero.

APPENDIX B

MATHEMATICAL DERIVATION OF CASE 2

Multistop Service, Uniform Trip Density
(See Appendix A for General Definitions)



Trip Density = k trips per route mile

Number of original passengers affected by relocation

$$= k(d - d')$$

Average number of increased miles for affected passengers

$$= \frac{d - d'}{2}$$

Therefore total additional miles required

$$= \frac{k}{2}(d - d')^2 \qquad (1)$$

Total passengers initially carried

$$= kd$$

Increase in passenger capacity

$$= \left(\frac{t}{t'} - 1\right) kd = \frac{(d - d')}{d'} kd \qquad (2)$$

Of the new passengers, a fraction $\frac{(d - d')}{d}$ (those originating outside the relocated terminal) will each reduce travel by d' miles. The remaining $\frac{d'}{d}$ (those originating inside the relocated terminal radius) will reduce travel an average $\frac{d'}{2}$ miles. Therefore the weight average reduced mileage is

$$d' \frac{(d - d')}{d} + \frac{(d')}{2} \frac{(d')}{d} \qquad (3)$$

Therefore the total reduced mileage is the product of (2) and (3):

$$\frac{(d - d')}{d} kd \left[\frac{d' (d - d')}{d} + \frac{(d')}{2} \frac{(d')}{d} \right] \tag{4}$$

Therefore the next decrease in mileage is the difference between (4) and (1), which reduces to

$$\frac{k}{2} d (d - d')$$

Substituting

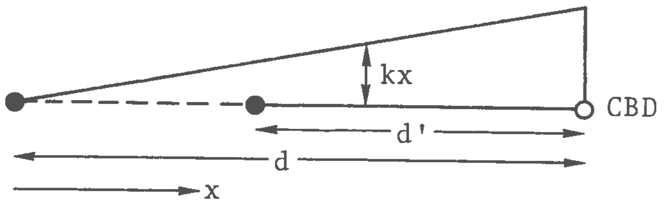
$r = \frac{d'}{d}$, we have $$\frac{k}{2} d^2 (1 - r) \tag{5}$$

Equation (5) is plotted in Figure 2 as a function of r for three values of d and for a trip density of 100 (k - 100).

APPENDIX C

MATHEMATICAL DERIVATION OF CASE 3

Multistop Service, Increasing Trip Density
(See Appendix A for General Definitions)



Trip Density = kx trips per route mile
where x = distance from original terminal

Number of original passengers affected by relocation

$$= \frac{k\ (d - d')^2}{2}$$

Average number of increased miles for affected passengers

$$= \frac{d - d'}{3}$$

Therefore total additional miles required

$$= \frac{k\ (d - d)^3}{6} \qquad (1)$$

Total passengers initially carried

$$= \frac{kd^2}{2}$$

Increase in passenger capacity

$$= \left(\frac{t}{t'} - 1\right) \frac{kd^2}{2} = \frac{(d - d')}{d'} \frac{kd^2}{2} \qquad (2)$$

Of the new passengers, a fraction $(d - d')^2/d^2$ (those originating outside the relocated terminal) will each reduce travel by d' miles. The remaining $d^2 - (d - d')^2/d^2$ (those originating within the relocated terminal radius) will reduce travel an average mileage of

$$\frac{d' (3d - 2d')}{3(2d - d')}$$

Therefore the weighted average reduced mileage is

$$d' \frac{(d - d')^2}{d^2} + \left[\frac{d' (3d - 2d')}{3 (2d - d')}\right] \left[\frac{d^2 - (d - d')^2}{d^2}\right] \tag{3}$$

Therefore the total reduced mileage is the product of (2) and (3)

$$\left\{\frac{(d - d')}{d'} \frac{(kd^2)}{2}\right\} \left\{d' \frac{(d - d')^2}{d^2} + \frac{d' (3d - 2d')}{3 (2d - d')} \frac{d^2 - (d - d')^2}{d^2}\right\} \tag{4}$$

Therefore the net decrease in mileage is the difference between (4) and (1), which, after substituting $r = \frac{d'}{d}$, reduces to

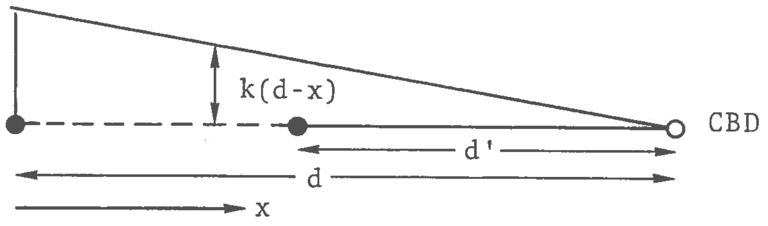
$$\frac{kd^3 (1 - r)}{6} \left[2(1 - r)^2 + \frac{3 - 2r}{3 (2-r)} (2 - 2r + r^2)\right] \tag{5}$$

Equation (5) is plotted in Figure 4 as a function of r for three values of d and for an average trip density of 100. Values of k corresponding to this trip density are the following

d	k
20	10
10	20
5	40

APPENDIX D
MATHEMATICAL DERIVATION OF CASE 4

Multistop Service, Decreasing Trip Density
(See Appendix A for General Definitions)



Trip Density = $k(d - x)$ trips per route miles
where x = distance from original terminal

Number of original passengers affected by relocation

$$= \frac{k}{2}\left(d^2 - d'^2\right)$$

Average number of increased miles for affected passengers

$$= \frac{2d^2 - dd' - d'^2}{3(d + d')}$$

Therefore total additional miles required

$$= \frac{k}{2}\left(d^2 - d'^2\right)\frac{2d^2 - dd' - d'^2}{3(d + d')} = \frac{k}{6}(d - d')^2(2d + d') \qquad (1)$$

Total passengers initially carried

$$= \frac{kd^2}{2}$$

Increase in passenger capacity

$$= \left(\frac{t}{t'} - 1\right)\frac{kd^2}{2} = \frac{d - d'}{d'}\frac{(kd^2)}{2} \qquad (2)$$

Of the new passengers, a fraction $d^2 - d'^2/d^2$ (those originating outside of the relocated terminal) will each reduce travel by d' miles. The remaining d'^2/d^2 (those originating within the relocated terminal radius) will reduce travel an average of $\frac{2}{3}$ d' miles. Therefore the weighted average reduced mileage is

$$d' \frac{(d^2 - d'^2)}{d^2} + \frac{2}{3} d' \frac{(d'2)}{d^2} \tag{3}$$

Therefore the total reduced mileage is the product of (2) and (3)

$$\frac{(d - d')}{d'} \frac{(kd^2)}{2} \left[d' \frac{(d^2 - d'^2)}{d^2} + \frac{2}{3} d' \frac{(d'^2)}{d^2} \right] \tag{4}$$

Therefore the net decrease in mileage is the difference between (4) and (1), which reduces to

$$\frac{k}{6} (d - d') (d^2 + d')$$

Substituting

$$r = \frac{d'}{d}, \text{ we have } \qquad \frac{kd^3}{6} (1 - r^2) \tag{5}$$

Equation (5) is plotted in Figure 5 as a function of r for three values of d and for an average trip density of 100. Values of k corresponding to this trip density are the following:

d	k
20	10
10	20
5	40

APPENDIX E
CARPOOL POTENTIAL MODEL

The model for determining whether carpools can be formed for a given trip type in a given hour is:

$$n = \frac{(F)\ (o)\ (d)\ (t)\ (T_i)}{(O)\ (D)}$$

When $n \geq 2$, then two or more people are available for a carpool and a carpool can be formed. If $n < 2$, no carpool can be formed. Where:

n = the number of people available for a single carpool

F = the percentage of morning commuter trips made in the hour

o = the area of the origin grid cell

d = the area of the destination grid cell

O = the area of the region of origin

D = the area of the region of destination

t = maximum difference in departure time for work

T_i = the total number of trips in a given O-D pair category during the morning commuter period

APPENDIX F

MATHEMATICAL DERIVATION OF EFFECTS OF STAGGERING ON TRANSIT UTILIZATION

Let

p = percent of travel in the peak hour before staggering

p' = percent of travel in the peak hour after staggering ($p' \leq p$)

m = number of hours in the peak period before staggering

m' = number of hours in the peak period after staggering ($m' \geq m$)

The maximum total ridership that can be handled by an existing transit system expressed as a percentage of the original ridership is m p or a maximum <u>increase</u> satisfied of:

$$R_{max} = m'p - 100$$

The increase in total demand required to achieve the maximum satisfied is:

$$I_{min} = 100 \left(\frac{p}{\frac{100 - p'}{m' - 1}} - 1 \right)$$

$$= 100 \left(\frac{m'p - 100 - p + p'}{100 - p'} \right)$$