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TRANSIT REQUIREMENTS FOR ACHIEVING LARGE REDUCTIONS IN LOS ANGELES AREA AUTOMOBILE TRAVEL

U.S. ENVIRONMENTAL PROTECTION AGENCY

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ABSTRACT

This paper describes the structure and application of a model for estimating aggregate supply characteristics of bus transit systems that are capable of carrying substantial fractions of the person trips in an urban area. Given the number and geographical distribution of trips that must be carried on transit, the model enables a range of transit options for carrying these trips to be developed. Each option is characterized by the number of buses it requires, the geographical area served by transit, the transit schedule frequency, the transit mode split that must be achieved in the transit service area, average transit travel time and cost per trip, and the average travel time and cost that would result if bus travelers used automobiles.

The model is applied to Los Angeles, California. The results indicate that large fractions of current person trips in Los Angeles can be carried on bus transit at a cost that is comparable to the cost of automobile travel and with an average travel time that exceeds average automobile travel time by 15 to 20 minutes. However, this requires bus fleets and transit mode splits that are quite large by current standards. For example, to carry 20 percent of person trips at a cost equal to the cost of automobile travel and with an average travel time 17 minutes greater than average automobile travel time, the transit system must have 9500 buses and must achieve a 45 percent mode split in the areas it serves.

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TRANSIT REQUIREMENTS FOR ACHIEVING LARGE REDUCTIONS IN LOS ANGELES AREA AUTOMOBILE TRAVEL

by

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The need to reduce air pollution, energy consumption, and traffic congestion caused by automobiles has stimulated widespread discussion of the feasibility and desirability of diverting large numbers of urban area automobile travelers to other modes. Much of this discussion has been concerned with issues of travel demand. The problem of identifying measures that are effective in reducing the demand for automobile travel has received particular attention. Several investigators (Ref. 1, 2, 3) have suggested that if suitable policies influencing travel demand were implemented, automobile travel in cities could be reduced by 20 to 30 percent. The reduction would be achieved mainly by diverting automobile drivers to transit and carpools. Traffic reductions of lesser but nonetheless impressive magnitudes already have been achieved in some cities through the implementation of policies to control the demand for automobile travel (Ref. 4, 5).

The problem of characterizing transit systems that could carry a large fraction of current urban area automobile trips has received less attention than demand-related issues. Transit system characteristics that might affect the feasibility of diverting large numbers of automobile users to transit include the number of transit vehicles required, the geographical area served by the transit system, the relative travel times of transit and automobile trips, the relative costs of transit and automobile service, and the mode split that the transit system must achieve. One possible reason for the relative neglect of these matters in the discussion of the feasibility of achieving large reductions in urban area automobile traffic is the lack of a methodology that would enable aggregate characteristics of transit systems that may be quite different from current systems to be estimated relatively quickly and inexpensively for use in policy planning. Techniques of the UTPS type tend to be too cumbersome, costly, and time consuming for use in policy planning. Simpler techniques frequently are used to compare the characteristics of alternative modes in a corridor (Ref. 6, 7, 8, 9), but these techniques have not been generalized for application to an entire urban area. A model developed by the RAND Corporation (Ref. 10) does enable aggregate characteristics of a regional transit system to be estimated quickly and inexpensively. However, this model assumes a uniform distribution of trip ends over the transit service area and, hence, does not reflect the spatial structure of travel demand.

This paper describes a model that was developed to estimate aggregate characteristics of bus transit systems capable of carrying substantial fractions of person trips -- and, by implication, automobile trips -- in the Los Angeles area. The model can be applied to other cities easily and removes some of the previously described methodological difficulties. Given the number and geographical distribution of trips that must be carried on the transit system, the model enables a range of transit options capable of carrying these trips to be developed. Each option is characterized by the number of transit vehicles it requires, the geographical area served by transit, the transit schedule frequency, the transit mode split that must be achieved in the transit service area, average transit and automobile travel times per trip, and average transit and automobile costs per trip. The model is based on a generalization of techniques that have been used in corridor-level comparisons of modal options (Ref. 6, 7, 8, 9). The model is not intended to provide information useful in the detailed design and evaluation of transit systems. Rather, it provides a relatively quick and inexpensive means of generating estimates of transit supply characteristics that can be used in forming preliminary assessments of the feasibility of proposals for reducing automobile travel in cities and in identifying options worthy of more detailed analysis.

In the following sections the structure of the model is described, and the results of its application to Los Angeles are presented. The sensitivity of the results to variations in input parameters and potential errors in structural assumptions is discussed. Finally, conclusions based on the Los Angeles results are presented, and limitations of the model that might be the topics of further research are discussed.

Structure of the Model

The structure of the model is described verbally in this section. The equations of the model are presented in Appendix A. Appendix B lists the model's inputs and outputs.

The model is similar in concept to the previously mentioned corridor models. Person trip volumes and transit mode splits are specified exogenously.

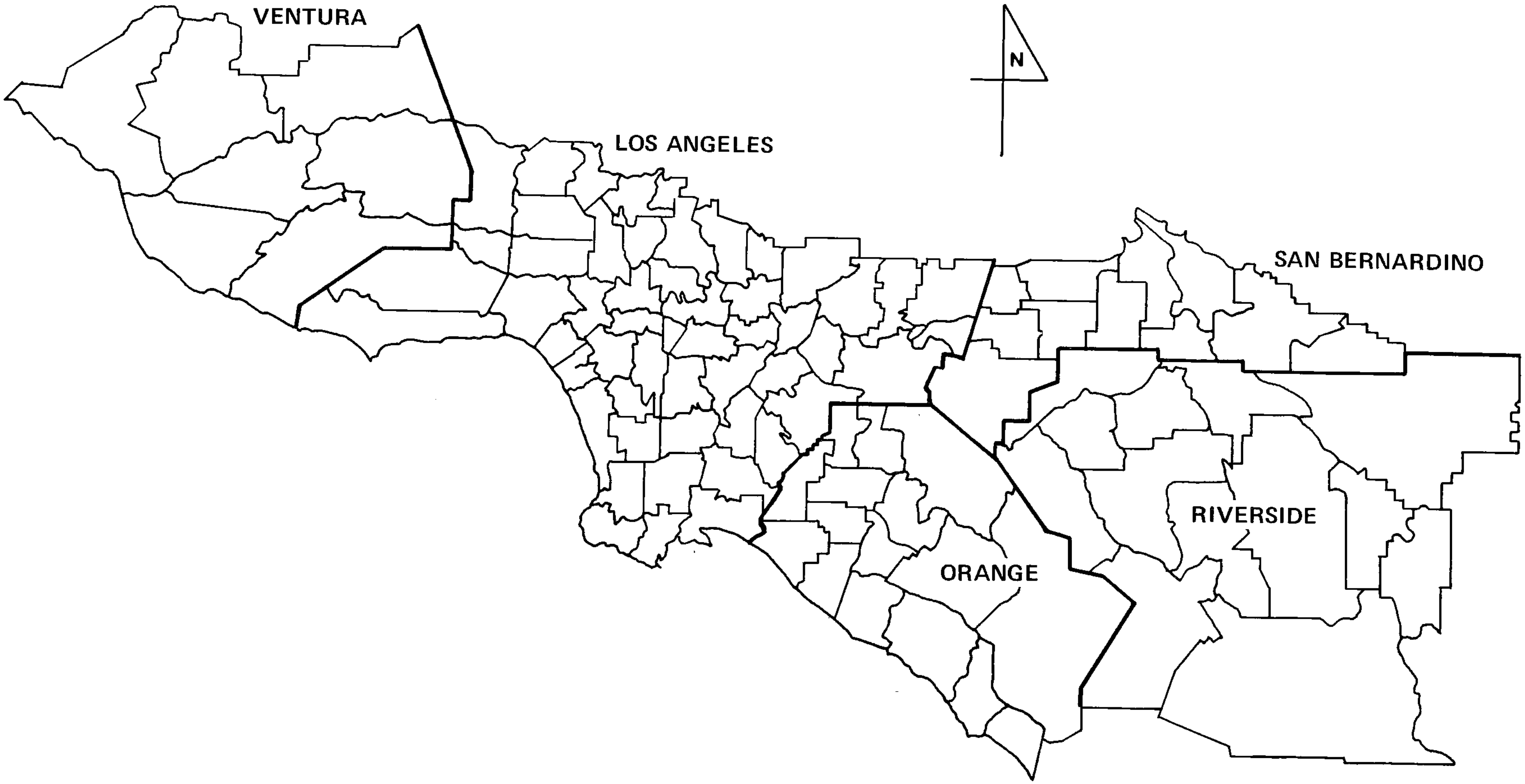
Bus service is provided in areas where the volume of person trips exceeds a specified threshold, and transit trips in these areas are assigned to bus routes on an idealized street network. Buses are assigned to the routes in sufficient quantities to both accommodate the demand for transit trips and achieve or exceed an exogenously specified minimum schedule frequency. Average transit travel time is computed from estimates of average walk and wait times, in-vehicle distances, and bus speeds. Average transit cost per trip is computed from estimates of the purchase prices of buses and auxiliary facilities, and from estimates of the relationship between bus miles (kilometers) traveled, bus hours of operation, and bus operating cost. The average travel time and cost per trip that would be incurred if all transit trips were carried in automobiles also are computed. Through repeated runs of the model using different levels of transit mode split, threshold trip volume for providing bus service in an area, and minimum schedule frequency, graphical and tabular relationships among the total number of transit trips, the transit service area, the transit mode split that must be achieved in the transit service area, transit schedule frequency, the number of buses needed, the average travel time for bus trips, the average travel times that would result if the same trips took place in automobiles, the average cost per bus trip, and the average cost per trip that would be incurred if the same trips took place in automobiles are developed. In general, there exists a continuum of transit options capable of carrying a specified proportion of person trips in a given urban area. The graphical and tabular relationships summarize the characteristics of these options.

The model is based on the traffic districts typically defined in urban area transportation surveys. In the Los Angeles application of the model, 100 such districts were used (Figure 1). The districts were defined in connection with the Los Angeles Regional Transportation Study (LARTS) and have a median area of 25 sq. mi. (64 sq. km.).

The demand for transit trips is developed from exogenously specified, district level person trip tables and exogenously specified transit mode split factors. The trip tables give the number of person trips per hour between each pair of districts according to trip purpose and time of day. The mode split factors give the fraction of trips of each purpose that will use transit if service is provided between their origin and destination districts. The mode split factors do not represent projections of the demand for transit travel. Rather, they are parameters of the model that are used to establish supply-side relationships between transit mode split and other characteristics of the transit system.

The person trip tables and mode split factors are combined to yield district level transit trip tables according to trip purpose and time of day. The tables for the various purposes at each time of day are further combined to yield district level tables specifying total transit trips per hour, according to time of day, that will take place between each pair of districts served by transit. These trip tables contain all the transit travel demand information supplied to the model. In the Los Angeles application, the trip purposes considered were work and non-work. The times of day considered were morning peak, afternoon peak, and off peak.

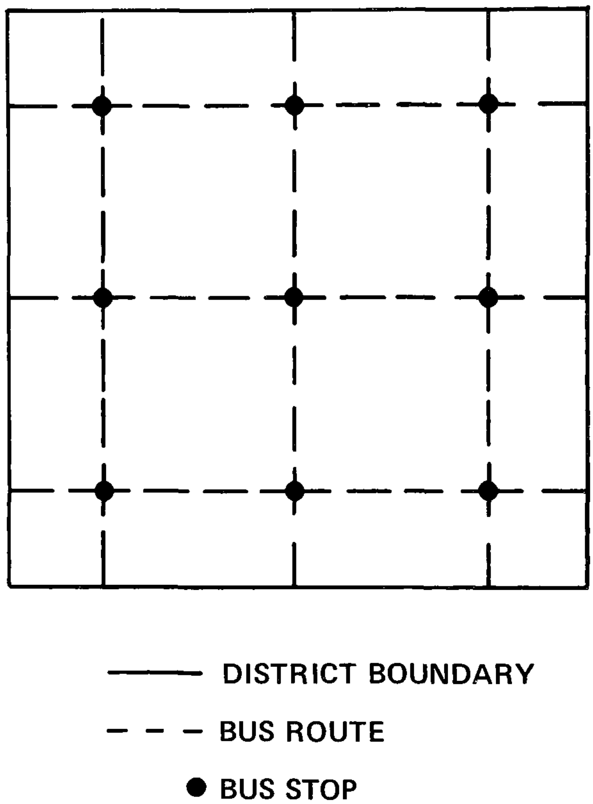
Figure 1 – DISTRICT MAP OF LOS ANGELES



A transit system that carries a substantial fraction of the trips in an urban area must serve suburban trips as well as CBD-oriented trips. Consequently, the model is designed to estimate the characteristics of transit systems that serve trips whose origins and destinations are diverse and spread over a large geographical area. The model provides two types of transit service: inter-district and intra-district. The inter-district service provides limited-stop, linehaul service for trips whose origins and destinations are in different districts. The intra-district service carries trips whose origins and destinations are in the same district. It also provides collection and distribution service for inter-district trips. This service design enables trips with widespread and diverse origins and destinations to be served. It also enables the model to use the geographically aggregated travel data normally available in urban area transportation surveys. However, the service design does not permit the optimization of bus service in high density corridors.

The intra-district service operates within districts and on rectilinear routes (Figure 2). The spacing between parallel routes and between stops along a route is equal to an exogenously specified maximum distance that travelers must walk at each end of a bus trip. For reasons that will be described later, this walk distance was set equal to 0.5 mi. (0.8 km.) in the Los Angeles application. An intra-district vehicle begins its route at a district boundary and proceeds along the route to the opposite district boundary, making stops along the way to load and unload passengers. When the vehicle reaches the end of its route, it turns around and traverses the

Figure 2 — SCHEMATIC DIAGRAM OF INTRA - DISTRICT SERVICE

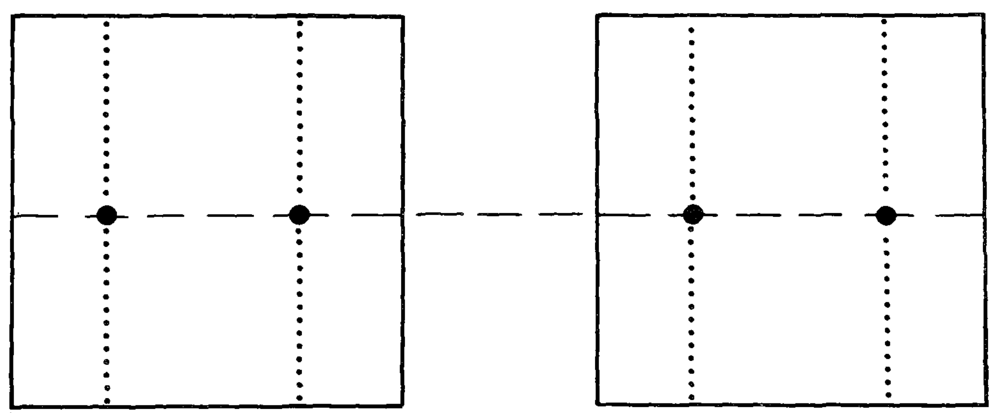


route in the opposite direction, again making stops along the way. The vehicle continues this back-and-forth movement along its route throughout the service period. When in motion, buses move at exogenously specified automobile speeds. However, buses lose time at stops due to the loading and unloading of passengers, acceleration, and deceleration. Buses also lose time when turning around at the ends of their routes.

The street network on which intra-district vehicles are assumed to operate is a square grid with a grid spacing equal to the maximum walk distance. The average one-way length of an intra-district bus route on this network is equal to the square root of the area of the district. Significant differences between the geometry of real street networks and the idealized network geometry used in the model will cause errors in the model's results. The likely magnitudes of these errors are discussed in the section on sensitivity analysis.

The structure of the inter-district service is illustrated in Figure 3. The service between two districts i and j operates as follows. An inter-district vehicle begins its route at a boundary of district i. It proceeds across district i, making stops to load inter-district passengers at stations whose spacing along the route is exogenously specified. No passengers are unloaded along this portion of the route. The stations serve as points of transfer between intra-district and inter-district vehicles, and each intra-district vehicle detours from its route as necessary to serve the nearest inter-district station. After loading passengers at the last station in district i, the inter-district vehicle proceeds non-stop to the boundary of district j. It then traverses district j, making stops at stations to unload but not to load passengers. When it reaches the last station in

Figure 3 – SCHEMATIC DIAGRAM OF INTER - DISTRICT SERVICE



——— DISTRICT BOUNDARY

– – – INTER - DISTRICT BUS ROUTE

● INTER - DISTRICT TRANSFER STATION

········ INTERSECTING INTRA - DISTRICT BUS ROUTES district j, the vehicle reverses its route and returns to district i, stopping at stations in district j to load passengers and at stations in district i to unload passengers. The vehicle continues to travel back-and-forth between districts i and j throughout the service period. When in motion, the inter-district buses move at the same speeds as automobiles. However, the buses lose time at stops and in turning around at the ends of their routes.

An inter-district bus operating between two districts i and j uses the same square-grid street network as intra-district vehicles on the portions of its route that are inside districts i and j. The model does not contain a network representation for the portion of the route between districts i and j. Inter-district route lengths and bus speeds are determined from exogenously specified automobile distances and speeds. The length of a bus route between two districts is equal to the automobile distance between the district centroids plus the distances on the square-grid network between the district centroids and the district boundaries. The speed of an inter-district bus is the centroid-to-centroid automobile speed adjusted for time lost at bus stops.

An intra-district bus traveler walks to the nearest intra-district bus stop, waits for a bus, and boards the first bus that arrives. If the traveler's destination is within the maximum walk distance of the route he has boarded, he rides to the stop nearest his destination, alights from the bus, and walks to the destination. Otherwise, the traveler must make at most one transfer to a route that serves his destination. The traveler walks an average distance equal to half the maximum walk distance at each end of his trip. The corresponding average walk time is computed from this distance and an exogenously specified walk speed. The traveler waits before boarding each vehicle he rides for a period whose average duration is half the headway of intra-district vehicles in his district. If a transfer is needed, the traveler spends additional time moving between bus stops at the transfer point. This transfer time is specified exogenously.

In-vehicle distances and transfer frequencies for intra-district travelers are estimated by assuming that the intra-district trip density is uniform within a district. Thus, the number of trips between a point x in a district and a point y in the same district is assumed to be the same for all points x and y in the district. The trip densities vary between districts, depending on the trip volumes specified in the transit trip table and on the district areas. The uniform density assumption implies that the average intra-district traveler has an in-vehicle distance equal to two-thirds of the average intra-district route length in his district. The average in-vehicle travel time of an intra-district traveler is the automobile travel time required to traverse this distance plus the time the intra-district bus spends at stops while traveling along two-thirds of its route. The average number of transfers per intra-district trip depends on district size. In the Los Angeles application, there were an average of 0.8 transfers per intra-district trip.

An inter-district traveler walks to the nearest intra-district bus stop, boards an intra-district bus, and travels to an inter-district transfer station. There, he transfers to an inter-district bus and rides to a transfer station in his destination district. He then transfers to another intra-district bus, rides to the stop nearest his destination, and walks from the bus stop to his destination. An inter-district traveler must make two transfers. At each end of his trip he walks an average distance equal to half the maximum walk distance. The corresponding walk time is computed from this distance and the average walk speed. The traveler's average total waiting time is the sum of half the headway of intra-district vehicles in his origin district, half the headway of inter-district vehicles operating between his origin and destination districts, and half the headway of intra-district vehicles in his destination district. The traveler spends exogenously specified additional time moving between platforms at the transfer stations.

It is assumed that the ends of the trips between two districts i and j are uniformly distributed within the districts. Hence, a traveler between districts i and j travels on a district i intra-district bus an average distance equal to one quarter of the district i intra-district route length. He travels an equivalent distance on a district j intra-district bus. He travels on an inter-district bus an average distance equal to the distance between the centroids of districts i and j. The average in-vehicle travel times for inter-district travelers are computed from these in-vehicle distances, automobile speeds within and between districts, and the time buses spend at stops.

The model averages the walk, wait and transfer, in-vehicle, and total travel times of all individual travelers in the transit service area, thereby producing average transit travel times. The average travel time that would result if all of the transit trips took place in automobiles is computed from exogenous automobile travel time data.

Bus schedule frequencies vary across routes and time periods (e.g., morning peak, afternoon peak, off peak), depending on passenger flows. The passenger flow during a particular time period at the maximum load point of a bus route is developed from the transit trip table for the time period, the assumed distribution of trip ends within districts, and the square-grid network geometry. The flow at the maximum load point of a route divided by bus capacity yields the minimum bus schedule frequency needed to carry the flow on the route during the time period. The schedule frequency on the route during the time period is set equal to this value or an exogenously specified minimum schedule frequency, whichever is larger. The reciprocal of the resulting schedule frequency equals the bus headway that is used in computing wait times.

The schedule frequencies together with the previously described assumptions concerning route lengths, stop spacings, and bus speeds enable the number of buses needed during each time period to be computed. In addition, bus hours of operation and bus miles (kilometers) traveled are computed for each time period. The total bus fleet size is set equal to the largest number of vehicles needed in any time period plus five percent for spare vehicles. Bus hours of operation and bus miles (kilometers) traveled are summed over time periods to obtain total bus hours of operation and bus miles (kilometers) traveled per service day.

The geographical area served by the bus system remains constant throughout the day and is determined by the average daily volumes of person trips on potential bus routes. Intra-district service is provided on potential intra-district routes where the average daily volume of person trips exceeds an exogenously specified threshold. Inter-district service is provided on potential inter-district routes where the average daily volume of person trips exceeds the same threshhold, subject to the condition that the routes connect districts in which intra-district service is provided. The latter condition is imposed because the intra-district service performs passenger collection and distribution for the inter-district service. The provision of bus service only on potential routes that have sufficiently large trip volumes enables the model to take advantage of the tendency of transit service to be cheaper per trip in high-volume corridors than in low volume ones.

Bus costs evaluated by the model include bus operating costs and the capital costs of buses, yards and shops for buses, and inter-district stations. The cost that would be incurred if transit passengers used automobiles includes automobile capital and operating costs. Buses and automobiles are assumed to operate on existing roadways. Hence, roadway costs are not included in the model. In computing automobile capital costs it is assumed that households owning two or more cars will dispose of one car if transit service is available for the work trip of one or more household members. In computing automobile operating costs, it is assumed that average automobile occupancies by trip purpose have exogenously specified values that may exceed one person per car. All costs are expressed in 1974 dollars. Capital costs are annualized with a discount rate of 10 percent per year. Capital costs per service day are computed from the annualized costs assuming a 255-day service year. Capital costs per trip are computed by dividing the capital costs per service day by the number of transit passengers per day.

The capital costs and service lives used in the Los Angeles application of the model are shown in Table 1. Automobile operating cost was assumed to be \$0.08 per vehicle mile (\$0.05 per vehicle kilometer, Ref. 11). Bus operating cost was computed using an equation derived from a cost estimating algorithm obtained from the Southern California Rapid Transit District. The equation is

(1) $C = 0.246M + 12.43H$

where C = Bus operating cost (\$/day)

M = Bus miles traveled per day (1 mi. = 1.6 km.)

H = Bus hours of operation per day.

Bus and automobile operating costs per trip were computed by dividing the daily bus and automobile operating costs by total daily transit trips.

The exogenous variables of the model define the demand for transit trips, the transit service policies, and the operating characteristics associated with a transit option. The model computes the total transit trips, fleet size, average transit and automobile travel times, and average transit and automobile costs per trip for the transit option defined by the exogenous variables. By changing the values of the exogenous variables, the aggregate characteristics of a range of transit options serving various levels of demand with various service policies and operating characteristics can be estimated. In the Los Angeles application of the model, the transit mode split factors, threshold trip volume for providing service on a potential bus route, and minimum intra-district schedule frequency were treated as policy variables. The other exogenous variables were treated as fixed

TABLE 1 - CAPITAL COSTS AND SERVICE LIVES

	Capital Cost[a]	Service Life
Bus[b]	$53,000	15 Yr.
Automobile[c]	$ 3,400	10 Yr.
Inter-district Station[d]	$300,000 per berth	25 Yr.
Yards and Shops[b]	$14,500 per bus	25 Yr.

a. Costs are in 1974 dollars

b. Source: Ref. 8. Assumes 50-passenger seating capacity.

c. Source: Ref. 11

d. Source: Ref. 12. It is assumed that each berth can accommodate up to 1300 inter-district passengers per hour (Ref. 13).

parameters. The values of the policy variables were changed between runs of the model, whereas the values of the fixed parameters stayed constant. Through a series of runs, using different values of the policy variables, graphical and tabular relationships between total transit trips, the transit service area, the mode split to transit that must be achieved in the transit service area, fleet size, schedule frequency, average travel times, and average travel costs were developed. These relationships are discussed further in the next section.

Application of the Model to Los Angeles

The Los Angeles application is based on travel data obtained from the Los Angeles Area Transportation Study (LARTS). District level person trip tables, automobile occupancies, automobile travel times, and automobile travel distances were developed from the LARTS data. Automobile speeds and the speeds of buses while in motion were computed by dividing automobile travel distances by automobile travel times. It was assumed that each automobile trip incurs a terminal time of 5 minutes in addition to the LARTS travel time. This terminal time was not included in the speed computations.

Transit service was provided during three periods of the day: morning peak (6 AM - 9 AM), afternoon peak (3 PM - 6 PM) and off peak (9 AM - 3 PM and 6 PM - 8 PM). Collectively, these three periods account for 88 percent of daily person trips in the Los Angeles area. No service was provided between 8 PM and 6 AM.

As explained earlier, all of the model's exogenous variables except the transit mode split factors, the trip threshold for providing bus service on a route, and the minimum intra-district schedule frequency were treated as fixed parameters. The values that were assigned to the parameters not developed from LARTS data are shown in Table 2. The maximum walk distance was set at 0.5 mi. (0.8 km.) as the result of a series of experiments with the model indicating that the 0.5 mi. (0.8 km.) distance tends to minimize both average passenger travel time and a weighted travel disutility equal to in-vehicle travel time plus two times out-of-vehicle travel time. Shorter maximum walk distances increase the number of bus stops per route. Other things being equal, this reduces both schedule frequencies and average bus speeds. The resulting increases in wait and in-vehicle times negate the beneficial effect of the reduced walk distance. With maximum walk distances greater than 0.5 mi. (0.8 km.), the increase in walk time is not fully compensated by improved bus speeds and schedule frequencies.

The relationship between total transit trips, transit service area, mode split to transit in the transit service area, fleet size, minimum schedule frequency, average travel time, and average travel cost that was developed by repeatedly running the model with different values of the policy variables is shown in Table 3 and Figure 4. Additional results of the model are presented in Appendix C. In both the table and the figure, the total number of transit trips is expressed as a percentage of total 6 AM - 8 PM person trips in the Los Angeles area. Transit service area is defined by the trip threshold for providing service on a potential bus route. Maps of the service areas corresponding to various threshold values are shown in Appendix C. Travel times and travel costs respectively are

TABLE 2 - PARAMETERS OF THE MODEL[a]

Parameter	Value
Maximum walk distance at each end of bus trip	0.5 mi.
Walk Speed	3 mi./hr.
Bus Capacity	50 passengers
Minimum schedule frequency for inter-district buses	5 per hour
Distance between inter-district stations	1 mi.
Bus turnaround time	1 min.
Time lost by buses at each stop	0.6 min.[b]
Time passengers spend moving between platforms at transfer points	1 min.

a. 1 mi. = 1.6 km

b. Assumes passengers board and alight through separate double-width doors with an average of 15 passengers boarding per stop (Ref. 13).

expressed as the difference between average transit travel times and costs per trip and the average times and costs per trip that would result if all transit trips took place in automobiles. Automobile travel times and costs per trip typically are in the ranges 17-19 min. and $0.40-$0.50 respectively, depending on the geographical coverage of the transit system.

The transit mode splits in Table 3 and Figure 4 represent the mode splits that must be achieved in the transit service area if the indicated travel times, travel costs and transit trip volumes are to be achieved. They are not projections of the mode splits that would result from the implementation of the various options. The mode splits are averages over all trip purposes. The travel times, travel costs, and fleet sizes for each value of the mode split have been averaged over a range of ratios of work trip to non-work trip mode split. The effects of variations in this ratio are discussed in the section on sensitivity analysis.

Figure 4 constitutes a nomograph of the Los Angeles application of the model. The use of the nomograph is illustrated by the dashed lines in the figure. The nomograph is entered on the horizonal axis of Figure 4a by specifying the percentage of daily 6 AM - 8 PM person trips that the transit system must carry. The vertical axis indicates the required mode split to transit in the transit service area as a function of the relative travel times and costs of transit and automobile trips. The dashed line in Figure 4a illustrates a case in which 20 percent of 6 AM - 8 PM trips are to be carried on transit at an average transit cost per trip equal to the average automobile cost and an average transit travel time that exceeds the average automobile travel time by 17 minutes. A transit mode split of 45 percent is required in the service area. This mode split is projected onto

TABLE 3 - CHARACTERISTICS OF LOS ANGELES TRANSIT OPTIONS[a]

Option No.	N	C	T	FL	MS	V	F
1	10	0	15	2350	61	3500	16
2	10	0	17	2100	38	4000	11
3	10	0	20	2000	28	3000	8
4	10	0.10	15	2200	48	5000	17
5	10	0.10	17	2050	31	4500	12
6	20	0	15	2100	68	7000	17
7	20	0	17	1700	45	9500	11
8	20	0	20	1450	33	7500	8
9	20	0.10	15	1950	55	8500	19
10	20	0.10	17	1650	38	9000	13
11	30	0	15	1850	76	11000	17
12	30	0	17	1275	52	14000	13
13	30	0	20	750	39	15000	9
14	30	0.10	15	1675	63	13000	21
15	30	0.10	17	1125	46	15000	14
16	50	0	15	1500	90	18000	18
17	50	0	17	750	65	23000	14
18	50	0	20	225	53	28000	9
19	50	0.10	15	1250	77	23000	24
20	50	0.10	17	475	60	27000	16

(Footnote on next page)

TABLE 3 (cont'd)

a. Notation:

N= Percentage of daily 6 AM - 8 PM trips using transit

C= Difference between average transit and automobile costs per trip ($).

T= Difference between average transit and automobile travel times (minutes)

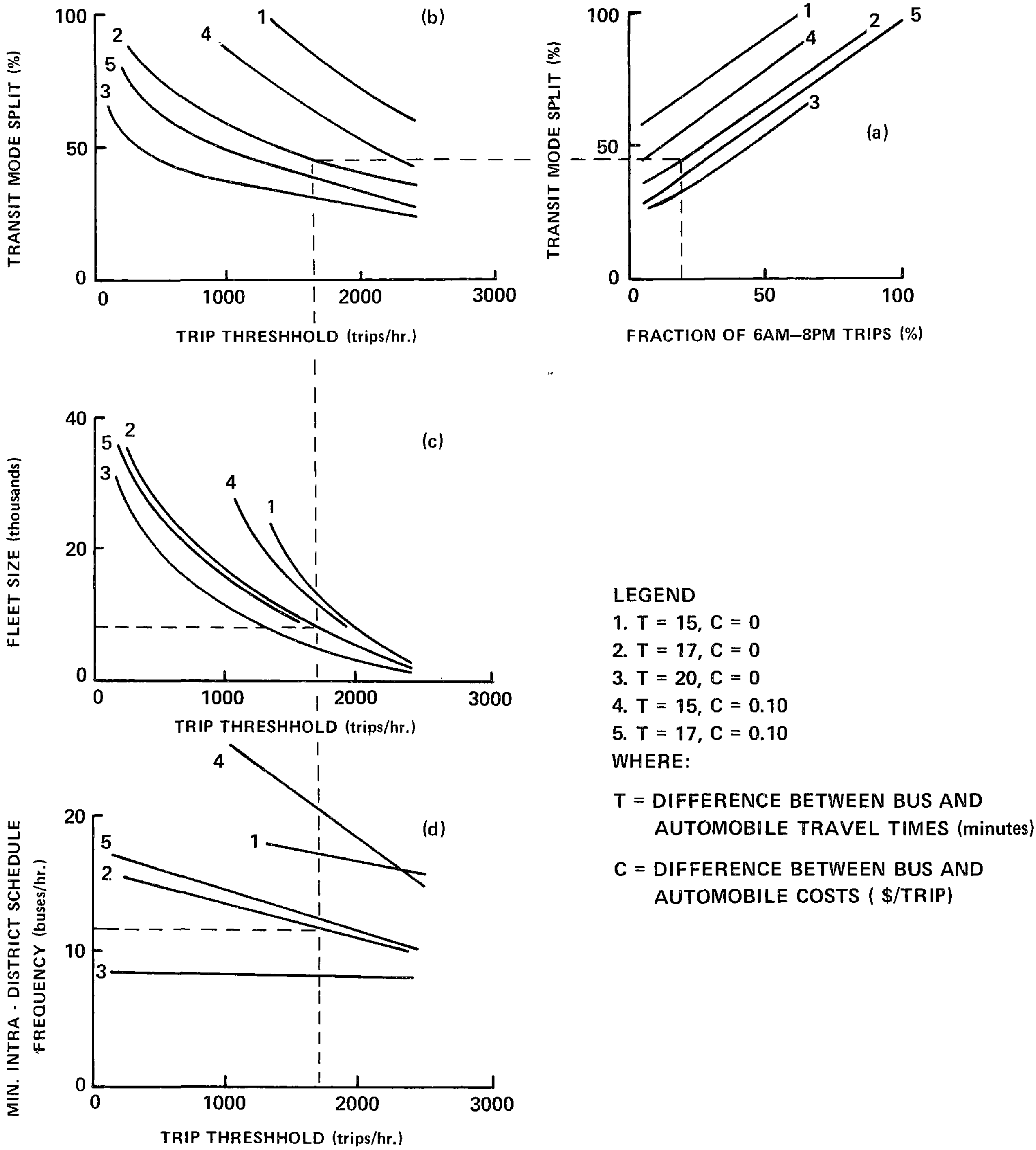
FL= Threshold volume to provide service on a potential transit route (person trips/hr.)

MS= Transit mode split that must be achieved in the transit service area (%)

V= Fleet size

F= Minimum schedule frequency on intra-district routes (buses per hour).

Figure 4 – NOMOGRAPH OF LOS ANGELES RESULTS



the vertical axis of Figure 4b, which gives threshold trip volume as a function of mode split, travel time, and travel cost. In the example under consideration, the figure indicates that service should be provided on potential bus routes where the average volume of person trips equals or exceeds 1700 trips per hour. This volume is projected into Figure 4c, which gives fleet size as a function of threshold volume, travel time, and travel cost. In this example, 9500 vehicles are needed. Finally, the threshold volume is projected into Figure 4d, which gives the minimum intra-district schedule frequency as a function of threshold volume, travel time, and travel cost. In this example, the frequency is 11 buses per hour. Summarizing these results, to carry 20 percent of 6 AM - 8 PM person trips on transit at a cost equal to the cost of automobile travel and with an average travel time exceeding the automobile travel time by 17 minutes, transit service must be provided on potential routes where the average volume of person trips equals or exceeds 1700 trips per hour. The transit system must carry 45 percent of person trips on these routes. A bus fleet of 9500 vehicles is needed. The schedule frequency on each intra-district route should be set at the value needed to accommodate the flow on the route or at 11 buses per hour, whichever is larger. The same results also are presented as option 7 in Table 3.

The Los Angeles results of the model are qualitatively reasonable. The average bus operating cost is roughly $1.00 per vehicle mile ($0.60 per vehicle kilometer). Bus operating cost is roughly 85 percent of total bus cost. Average bus speeds are 21 mi./hr. (34 km./hr.) for inter-district buses and 15 mi/hr. (24 km/hr.) for intra-district buses. The high speed of inter-district buses is a consequence of their limited-stop operation. The speed of intra-district buses reflects an assumption that passengers board and alight through separate double-width doors (see Table 2). If conventional boarding and alighting through single-width doors with non-prepayment of fares had been assumed, intra-district bus speeds of 10-12 mi./hr. (16-19 km/hr.) would have been obtained.

Increasing the number of trips that transit must carry while keeping relative transit and automobile travel times and costs constant requires increasing both the size of the transit service area (i.e., decreasing the threshold trip volume) and the transit mode split in the service area. Although the number of transit trips could be increased by increasing mode split without changing the size of the service area, the required increase in mode split would be greater than the increase that is needed when the service area is expanded, and travel times and costs would not stay constant.

Increasing the number of transit trips at constant relative travel times and costs also requires increasing the fleet size and the minimum intra-district schedule frequency. The fleet size increases because the transit system must serve a larger geographical area and larger ridership. The minimum schedule frequency increases because the structure of the Los Angeles districts and the geographical distribution of trips among districts are such that the average district size tends to increase as the service area expands. This increases the average number of bus stops per route and reduces the average bus speed. The resulting increase in in-vehicle time must be compensated by a reduction in wait time to maintain a constant difference between transit and automobile travel times. Wait time is reduced by increasing the minimum schedule frequency.

When total transit patronage is held constant, reducing transit cost at constant travel time and reducing travel time at constant cost require increasing both the threshold trip volume for providing transit service and the transit mode split in the service area. This reflects the tendency of transit to be most efficient in high density corridors and at high mode splits. The increase in threshold trip volume and corresponding decrease in the size of the service area tends to reduce the required fleet size, other things being equal. However, this tendency is counteracted to a greater or lesser extent by the increase in average passenger flow per bus route that occurs when the service area decreases while total ridership stays constant. Thus, reducing travel time or cost at constant ridership sometimes increases the required fleet size and sometimes decreases it.

The Table 3 results show that it is possible to carry a substantial fraction of Los Angeles person trips on bus transit at a cost per trip that is comparable to the cost of automobile travel and with average travel times that are within 15 to 20 minutes of automobile travel times. However, this requires bus fleets and transit mode splits that are quite large by current standards. The fleet and mode split requirements are discussed further below. Although it is not shown in Table 3, the difference between bus and automobile costs increases rapidly as the difference between bus and automobile travel times decreases from 15 minutes. With the bus service policies assumed in the model, bus travel times that exceed automobile travel times by less than roughly 12 minutes are not possible.

The bus fleets required to carry 10 or more percent of Los Angeles trips with the travel times and costs shown in Table 3 are large and roughly proportional in size to the number of trips carried in buses. A fleet of 3000 to 5000 buses, depending on operating policies, is needed to carry 10 percent of 6 AM - 8 PM trips. To carry 20 percent of 6 AM - 8 PM trips, a fleet of 7000 to 9500 buses is needed. The current Los Angeles bus fleet has approximately 2500 vehicles and carries roughly 3 percent of daily trips.

High transit mode splits are needed to achieve the travel times and costs shown in Table 3. When 10 percent of daily trips are carried by transit, 28 to 61 percent of the trips in the transit service area must use transit if an average transit travel time within 15 to 20 minutes of the average automobile travel time and a cost of transit travel comparable to the cost of automobile travel are to be achieved. The required mode split to transit increases as the fraction of daily trips using transit increases. All-day mode splits to transit exceeding 28 percent are found in some European cities. In the United States, transit mode splits of 28 percent or more usually are experienced only during peak periods. Achieving the transit ridership levels and travel times shown in Table 3 with mode splits below the tabulated values would substantially increase the average cost of transit trips. For example, if the mode split to transit in the transit service area were 15 percent, then transit travel would be at least twice as costly as automobile travel, depending on transit operating policies.

The transit service described in Table 3 has a minimum schedule frequency on intra-district routes of 8 to 24 buses per hour, depending on ridership and operating policies. This minimum frequency range applies to suburban routes as well as central-area routes. Schedule frequencies equalling or exceeding these values are common in the central areas of U. S. cities, particularly during peak periods, but are not normal in suburban areas.

Sensitivity Analysis

The sensitivity of the model to small errors in exogenous parameters and structural idealizations was evaluated using transit option 7 in Table 3. In the analysis of the model's sensitivity to changes in exogenous parameters, the policy variables (i.e., threshold trip volume for provision of service on potential bus routes, transit mode split in the transit service area, and minimum schedule frequency on intra-district routes) were held constant, and the changes in travel time, travel frequency, and fleet size caused by a 10 percent change in each of several parameters were computed. The results are shown in Table 4. Travel costs are most sensitive to changes in bus and automobile operating costs and automobile trip lengths. A 10 percent change in any of these parameters causes a $0.03 per trip change in the difference between bus and automobile costs. The difference between bus and automobile travel times is most sensitive to changes in automobile travel time, bus speeds, and the walk speed. Ten percent changes in these quantities cause one to two minute changes in the difference between bus and automobile travel times. Fleet size is most sensitive to bus speeds and the time buses lose at stops. Ten percent changes in these parameters cause fleet size to change by 300 to 500 vehicles.

TABLE 4 - RESPONSE OF MODEL TO TEN PERCENT CHANGES IN EXTERNAL PARAMETERS

Parameter	Change In: Bus Cost -Auto Cost ($/Trip)	Bus Time -Auto Time (Minutes)	Fleet Size
Bus Operating Cost	0.03	0	0
Bus Capital Cost	0.004	0	0
Yard and Shop Cost	0.001	0	0
Cost of Stations	0.001	0	0
Auto Operating Cost	0.03	0	0
Auto Capital Cost	0.01	0	0
Walk Speed	0	0.9	0
Bus Speeds	0.02	1	500
Time buses spend at stops	0.01	0.6	300
Time passengers spend moving between platforms at transfer points	0	0.1	0
Bus turnaround time	0.002	0	40
Ratio of work trip to non-work trip mode split	0.008	0.009	40
Auto Travel Times	0	2	0
Auto Travel Distances	0.03	0	0

The structural idealizations tested in the sensitivity analysis are the square-grid intra-district street network and the uniform distribution of trips within districts. The square network geometry used in the model tends to minimize the average lengths of bus routes, other things being equal. The effect of non-square network geometry was simulated by increasing the lengths of the intra-district portions of bus routes in the model by 10 percent. This caused a $0.03 per trip increase in the difference between the costs of bus and automobile travel, a one minute increase in the difference between bus and automobile travel times, and a 600 vehicle increase in fleet size. These changes are similar in magnitude to the changes caused by 10 percent variations in bus operating costs, bus speeds, and automobile travel times.

Non-uniformities in the distribution of trips within districts would cause passenger flows on bus routes and in-vehicle travel times to differ from the flows and travel times computed in the model, assuming that transit routes and service policies remain unchanged. The signs of the differences could be either positive or negative, depending on the nature of the non-uniformities. To simulate the effects of non-uniform trip distributions, passenger flows on bus routes and in-vehicle travel times were increased 10 percent over their normal values. Transit routes and service policies were not changed. This caused a $0.001 per trip increase in the difference between bus and automobile travel costs, a 2 minute increase in the difference between bus and automobile travel times, and a 70 vehicle increase in fleet size. The changes in cost and fleet size are negligible. This is because most of the buses in the transit option tested operate with excess passenger capacity. The change in travel time is similar in magnitude to the changes caused by 10 percent variations in walk speed, bus speeds, and automobile travel times.

Conclusions

The results presented here suggest that to achieve the diversion of a large fraction of Los Angeles automobile travelers to bus transit, transit schedule frequencies and mode splits must be maintained system-wide and all day at levels that normally are experienced in U. S. cities only during peak periods and in central areas. Depending on the fraction of travelers that use transit, substantial increases in the bus fleet size may be needed.

The model upon which these conclusions are based is inexpensive to use and readily applicable to other cities. The results the model produces are qualitatively reasonable and do not seem highly sensitive to the model's structual idealizations. However, the model has some significant limitations. The model's reliance on exogenously specified trip tables and mode split factors is, perhaps, its most serious weakness. The implementation of policies to achieve high transit mode splits undoubtedly would change the magnitude and geographical distribution of travel demand, as well as travelers' mode choices. The effects of such changes on transit system characteristics and the interactions between system characteristics and travel demand are not treated by the model and are not reflected in the results presented here.

Another limitation of the model is that it treats only one service concept: fixed route, fixed schedule service with separate collection/

distribution and linehaul vehicles. Moreover, this service concept is evaluated using district level aggregate travel data. Other service concepts, such as various forms of paratransit, and integrated service in high density corridors, might be less costly or time consuming under some circumstances. Improvements in transit performance also might be achieved through the use of system designs that reflect sub-district variations in the spatial distribution of trips.

A third limitation of the model is that it is static. Transportation changes of the magnitudes needed to divert large numbers of automobile travelers to transit will take many years to implement. During the implementation period, travel demand, the supply of roadway facilities, and the costs of travel by bus and automobile among other factors, are likely to change in ways that depend, in part, on transportation policy. However, the model assumes that all factors influencing transportation system characteristics have fixed values. The effects of long-term changes in these factors caused by transportation policy or exogenous influences are not treated.

ACKNOWLEDGEMENT

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APPENDIX A

Equations of the Model

Notation

** Signifies that non-integer values are to be rounded upward to the next highest integer.

A(I) = Square root of area of district I.

W = Maximum walk distance

W(I) = Maximum walk distance in district I.

NP(I,J) = Average number of person trips per hour from district I to district J. The average is over the service day.

FL = Trip threshold for providing service on a potential bus route.

Z = Set of districts in which intra-district service is provided

Z(I) = Set of districts J ($J \neq I$) such that inter-district service is provided between J and I.

LR (I,J) = Length of bus route between districts I and J. I=J signifies an intra-district route.

D(I,J) = Highway distance between the centroids of districts I and J ($I \neq J$).

T(I,J) = Automobile travel time between the centroids of districts I and J ($I \neq J$) excluding terminal time.

DS = Maximum distance between stations on inter-district routes

DS(I) = Average distance between stations on inter-district routes in district I

S(I,J) = Number of stops on route between districts I and J. I=J signifies intra-district route.

TVEH(I,J) = One-way bus travel time between the ends of route connecting districts I and J. I=J signifies intra-district route.

V(I,J) = Non-stop bus speed on route connecting districts I and J. I=J signifies intra-district route

TS = Time a bus spends accelerating, decelerating, and loading and unloading passengers at a stop.

TRND(I,J) = Round trip bus travel time on route between districts I and J. I=J signifies intra-district route.

TEX = Bus turnaround time at the end of a route.

N(I,J) = Transit passenger trips per hour from district I to district J during a time period.*

MN(I,J) = Major direction transit passenger trips per hour on route between districts I and J ($I \neq J$) during a time period. MN(I,I) is total inter-district transit trips per hour into or out of district I during a time period, whichever is larger.

R(I,J) = Bus round trips per hour during a time period on route between districts I and J. I=J signifies an intra-district route.

C1 = Passenger capacity of inter-district bus.

F1 = Minimum schedule frequency for inter-district buses.

VEH(I,J) = Vehicles required during a time period on route between districts I and J ($I \neq J$). VEH(I,I) is total intra-district vehicles needed in district I during a time period.

F(I,J) = Bus schedule frequency during a time period on route between districts I and J. I=J signifies intra-district route.

BMT(I,J) = Bus miles (kilometers) traveled per hour during a time period on route between districts I and J ($I \neq J$). BMT (I,I) signifies miles (kilometers) traveled on all intra-district routes in district I.

BHT(I,J) = Bus hours of operation per clock hour during a time period on route connecting districts I and J ($I \neq J$). BHT(I,I) refers to the total of all intra-district routes in district I.

T(I) = Average automobile travel time for trips in district I, excluding terminal time.

D(I) = Average highway distance for trips in district I.

C2 = Passenger capacity of intra-district bus.

F2 = Minimum schedule frequency on intra-district bus routes.

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*Time period refers to periods of the day, such as AM peak, off peak, PM peak.

FLOW(I) = Maximum bus passenger flow (in passengers per hour) during a time period on intra-district routes in district I.

VW = Average walk speed

TPASS(I,J) = Average passenger door-to-door travel time for bus travel between districts I and J during a time period. I=J signifies intra-district travel in district I.

TTR = Time required for a passenger to move between bus platforms at a transfer point.

TPASS = Average bus passenger door-to-door travel time during a time period.

N1 = Total inter-district bus passenger trips per hour during a time period.

N2 = Total intra-district bus passenger trips per hour during a time period.

N = Total bus passenger trips per hour during a time period.

VEH = Total buses in operation during a time period.

BMT = Total bus miles (kilometers) traveled per hour during a time period.

BHT = Total bus hours of operation per clock hour during a time period.

VEHH(I) = Total buses in operation during time period I.

BMTH(I) = Total bus miles (kilometers) traveled per hour during time period I.

BHTH(I) = Total bus hours of operation per clock hour during time period I.

H(I) = Number of hours in time period I.

NH(I) = Total bus passenger trips per hour during time period I.

TPASSH(I) = Average bus passenger door-to-door travel time in time period I.

DTPASS = All-day average bus passenger door-to-door travel time.

TC(I,J) = Average automobile door-to-door travel time between districts I and J, including terminal time.

TC = Average door-to-door travel time during a time period that bus travelers would experience if they used cars.

FLEET = Bus fleet size

DBMT = Daily bus miles (kilometers) traveled.

DBHT = Daily bus hours of operation

DC(I,J) = Average automobile travel distance between districts I and J.

AVMT = Automobile vehicle miles (kilometers) traveled per hour during a time period that bus travelers would cause if they used cars.

OCC = Automobile occupancy during a time period.

TCH(I) = Average door-to-door travel time during time period I that bus travelers would experience if they used cars.

DTC = Daily average door-to-door travel time of bus travelers if they use cars.

AVMTH(I) = Average automobile vehicle miles (kilometers) traveled per hour during time period I that bus travelers would cause if they used cars.

DAVMT = Daily automobile vehicle miles (kilometers) traveled that would be caused if bus travelers used cars.

P = Transit mode split of work trips in the transit service area.

WT(I) = Work trips per hour using transit in time period I.

Defining the Transit Service Area

$$W(I) = A(I) / [A(I)/W] **$$

$$Z(I) = \{J \neq I \mid NP(I,J) + NP(J,I) \geq FL,\ I,\ J \in Z\}$$

$$Z = \{I \mid W(I)\ [NP(I,I) + 0.5 \sum_{J \in Z(I)} (NP(I,J) + NP(J,I))]\ /A(I) \geq FL\}$$

The expression on the left-hand side of the inequality defining Z is the sum of hourly trips originating and terminating along an intra-district route, originating along the route and terminating elsewhere inside or outside the district, and originating elsewhere and terminating along the route.

Characteristics of Inter-district Service

The following equations apply only to district pairs I,J ($I \neq J$) such that $J \in Z(I)$. The equations apply separately to each time period modeled.

LR(I,J) = D(I,J) + 0.5 [A(I) + A(J)]

DS(I) = A(I)/ [A(I)/DS]**

S(I,J) = A(I)/DS(I) + A(J) /DS(J)

V(I,J) = D(I,J)/T(I,J)

TVEH(I,J) = LR(I,J)/V(I,J) + S(I,J) *TS

TRND(I,J) = TRND(J,I) = TVEH(I,J) + TVEH(J,I) + TEX

MN(I,J) = MN(J,I) = MAX [N(I,J), N(J,I)]

R(I,J) = R(J,I) = MAX [MN(I,J) /C1, F1]

VEH(I,J) = VEH(J,I) = [R(I,J)*TRND (I,J)]**

F(I,J) = F(J,I) = R(I,J)

BMT(I,J) = BMT(J,I) = VEH(I,J)* [LR(I,J) + LR(J,I)] /TRND (I,J)

BHT(I,J) = BHT(J,I) = VEH(I,J)

<u>Characteristics of Intra-District Service</u>

The following equations apply only to districts in the set Z. The equations apply separately to each time period modeled.

$$MN(I,I) = MAX \left[\sum_{J \in Z(I)} N(I,J), \sum_{J \in Z(I)} N(J,I) \right]$$

$$FLOW(I) = W(I) \, [N(I,I) + MN(I,I)]/4.0 \, A(I)$$

FLOW(I) is the maximum flow along a bus route caused by the combination of trips originating and terminating on the route, originating on the route and terminating elsewhere, and originating elsewhere and terminating on the route.

$$LR(I,I) = A(I) + 0.5 \, DS(I)$$

$$S(I,I) = 1 + A(I)/W(I)$$

$$V(I,I) = D(I)/T(I)$$

$$TVEH(I,I) = LR(I,I)/V(I,I) + S(I,I)*TS$$

$$TRND(I,I) = 2[TVEH(I,I) + TEX]$$

$$RCORR(I,I) = MAX \, [FLOW(I)/C2, F2]$$

$$F(I,I) = RCORR(I,I)$$

$$VEH(I,I) = 2A(I)*[RCORR \, (I,I)*TRND(I,I)]**/W(I)$$

$$BMT(I,I) = 2 \, VEH(I,I)*LR(I,I)/TRND(I,I)$$

$$BHT(I,I) = VEH(I,I)$$

Transit Passenger Travel Time

The following equations apply separately to each time period modeled. The equations apply only to districts I and J in the transit service area.

$$\begin{aligned}TPASS(I,J) = {} & [W(I) + W(J)]/2VW \\ & + 0.5[1/F(I,I) + 1/F(I,J) + 1/F(J,J)] \\ & + 2\ TTR + 0.5\ S(I,J)*TS + D(I,J)/V(I,J) \\ & + [A(I) + DS(I)]\ /4V(I,I) + TS \\ & + A(I)*\ TS/4W(I) + [A(J) + DS(J)]\ /4V(J,J) \\ & + A(J)*TS/4W(J),\ I \neq J\end{aligned}$$

The first term in TPASS(I,J) is walk time. The second and third terms are wait and transfer time. The fourth and fifth terms are time in inter-district vehicles. The last terms are time in intra-district vehicles in the districts of origin and destination.

$$\begin{aligned}TPASS(I,I) = {} & W(I)/VW + [1-W(I)/A(I)]\ /F(I,I) \\ & + [1-2W(I)/A(I)]\ TTR \\ & + [2A(I)/3 + 0.5\ DS(I)]\ /V(I,I) \\ & + TS*[2A(I)/3W(I) + 1]\end{aligned}$$

The first term in TPASS(I,I) is walk time. The second term is wait time and reflects the proportion of intra-district bus passengers making a transfer. This proportion is [1-2W(I)/A(I)]. The third term is the average time passengers spend moving between platforms during transfers. The last two terms are in-vehicle time, including the time required for a bus stop at an inter-district station.

$$N1 = \sum_{I} \sum_{J \in Z(I)} N(I,J)$$

$$N2 = \sum_{I \in Z} N(I,I)$$

$$N = N1 + N2$$

$$TPASS = [\sum_{I} \sum_{J \in Z(I)} N(I,J)*TPASS(I,J) + \sum_{I \in Z} N(I,I)*TPASS(I,I)]\ /N$$

Total Transit System

The following equations apply to each time period K separately.

$$VEH = \sum_{I \epsilon Z} [VEH(I,I) + 0.5 \sum_{J \epsilon Z(I)} VEH(I,J)]$$

$$BMT = \sum_{I \epsilon Z} H(K)[BMT(I,I) + 0.5 \sum_{J \epsilon Z(I)} BMT(I,J)]$$

$$BHT = \sum_{I \epsilon Z} H(K)[BHT(I,I) + 0.5 \sum_{J \epsilon Z(I)} BHT(I,J)]$$

The following equations are for service in all time periods

$$FLEET = 1.05 \text{ MAX } [VEHH(I)]$$

$$DBMT = \sum H(I)*BMTH(I)$$

$$DBHT = \sum H(I)*BHTH(I)$$

$$DTPASS = \sum [H(I)*NH(I)*TPASSH(I)]/ \sum [H(I)*NH(I)]$$

The Automobile System

The following equations apply separately to each time period modeled.

$$TC = \sum_{I \in Z} [N(I,I)*TC(I,I) + \sum_{J \in Z(I)} N(I,J)*TC(I,J)]/[N1 + N2]$$

$$AVMT = \sum_{I \in Z} [N(I,I)*DC(I,I) + \sum_{J \in Z(I)} N(I,J)*DC(I,J)]/OCC$$

The following equations are for service in all time periods.

$$DTC = \sum H(I)*NH(I)*TCH(I)/ \sum H(I)*NH(I)$$

$$DAVMT = \sum H(I)*AVMTH(I)$$

Los Angeles Cost Equations

DAILY BUS OPERATING COST = \$0.246 DBMT + \$12.43 DBHT

BUS CAPITAL COST PER DAY = \$4.53 FLEET

INTER-DISTRICT STATION COST PER DAY

= \$0.40 [MAX N1 OVER ALL TIME PERIODS]

DAILY YARD AND SHOP COST = \$6.25 FLEET

DAILY AUTOMOBILE OPERATING COST = \$0.08 DAVMT

DAILY AUTOMOBILE CAPITAL COST

$$= \$0.59\ P \sum H(I)*WT(I)$$

APPENDIX B

Inputs and Outputs of the Model

Inputs

Areas of districts

Average district-to-district automobile travel times

Average district-to-district highway distances

Average walk speed

Passenger capacity of inter-district buses

Passenger capacity of intra-district buses

Minimum inter-district schedule frequency

Minimum intra-district schedule frequency

Maximum walk distance

Time required for passengers to move between platforms at bus stops

Time buses spend at each stop

Maximum distance between inter-district stations

Bus turnaround time at the ends of routes

Automobile terminal time

Trip threshold to provide service on a potential bus route

Automobile occupancies by time period

Transit mode split factors by trip purpose

District level person trip tables by trip purpose and time of day

Cost estimating relationships

Outputs

The following outputs are provided for each time period:

Inter-district, intra-district, and total bus trips

Average door-to-door travel times for inter-district, intra-district and total bus passengers

Average wait and transfer times for inter-district, intra-district and total bus passengers

Average in-vehicle times for inter-district, intra-district, and total bus passengers

Components of inter-district, intra-district, and total passenger in-vehicle times attributable to bus stops

Inter-district, intra-district, and total buses in operation

Bus miles (kilometers) traveled by inter-district, intra-district, and all buses

Average door-to-door automobile travel times for inter-district, intra-district and all bus passengers

Automobile vehicle miles (kilometers) traveled that inter-district, intra-district, and all bus passengers would cause if they traveled by automobile

Operating costs of inter-district, intra-district, and all buses

Automobile operating costs that would be incurred if bus passengers traveled by car

The following outputs are provided for the entire service day:

Size of bus fleet

Bus operating cost

Bus capital cost

Cost of inter-district stations

Cost of yards and shops for buses

Total bus cost

Automobile operating costs that would be incurred if bus passengers traveled by car

Automobile capital cost that would be incurred if bus passengers traveled by car

Total automobile cost that would be incurred if bus passengers traveled by car

Bus trips

Average door-to-door travel time for bus passengers

Average door-to-door travel time for bus passengers if they travel by automobile

Listing of districts in which intra-district service is provided

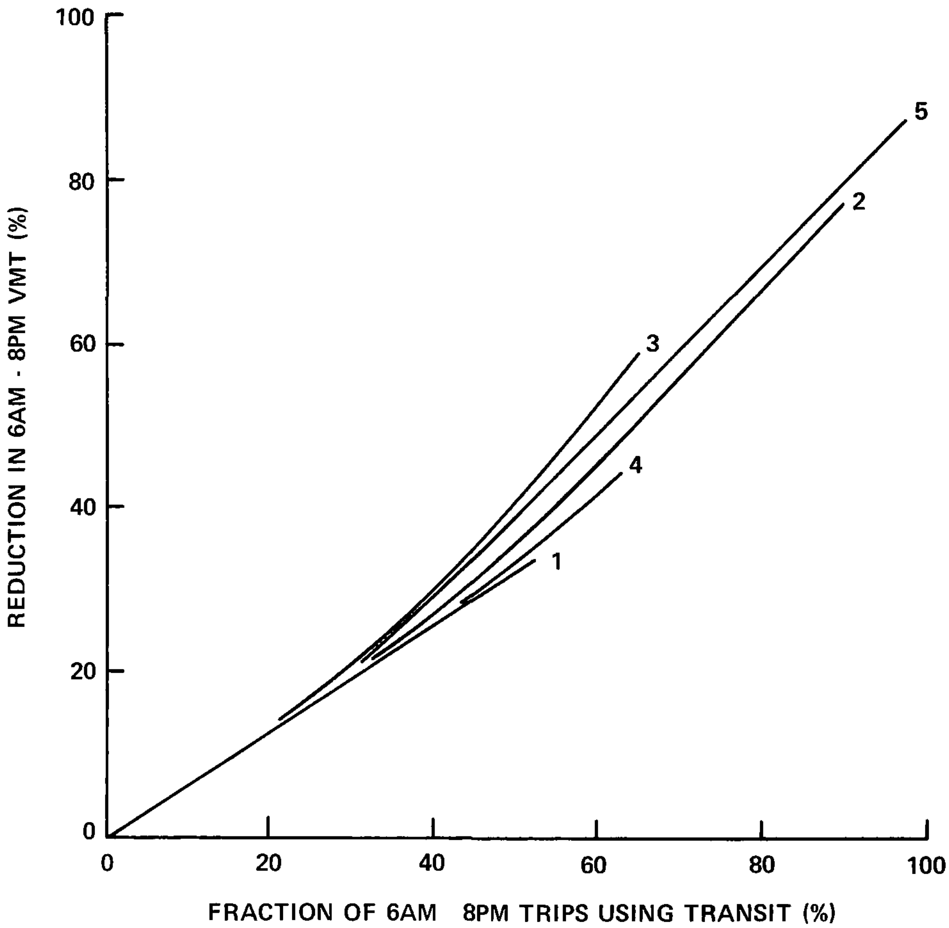
Listing of districts between which inter-district service is provided.

The cost outputs are expressed both as daily totals and as average values per trip.

APPENDIX C

Additional Los Angeles Results

Figure C 1 – REDUCTION IN 6AM - 8PM AUTOMOBILE VMT AS FUNCTION OF FRACTION OF 6AM - 8PM TRIPS USING TRANSIT

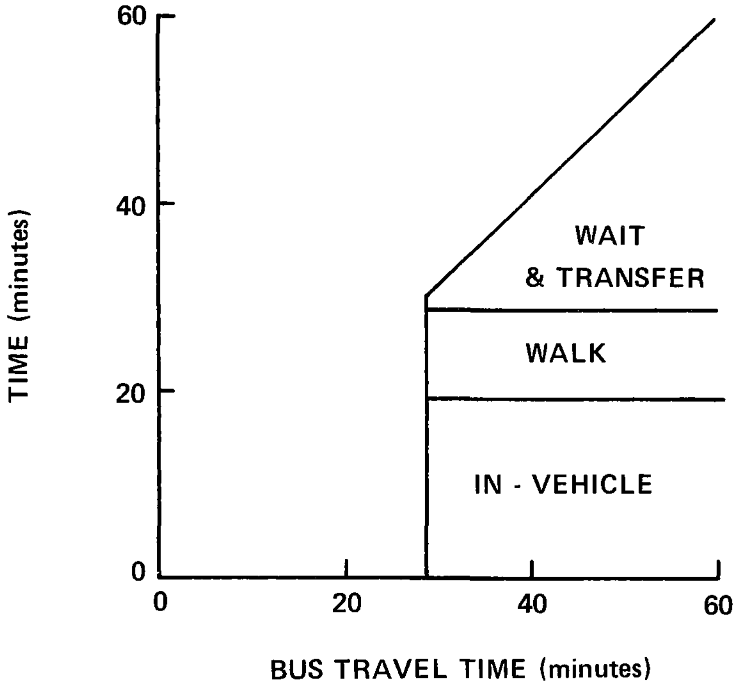


LEGEND

1. T = 15, C = 0
2. T = 17, C = 0
3. T = 20, C = 0
4. T = 15, C = 0.10
5. T = 17, C = 0.10

T = DIFFERENCE BETWEEN BUS AND AUTOMOBILE TRAVEL TIMES (minutes)
C = DIFFERENCE BETWEEN BUS AND AUTOMOBILE COSTS ($ PER TRIP)

Figure C 2 — COMPONENTS OF BUS TRAVEL TIME AND COST



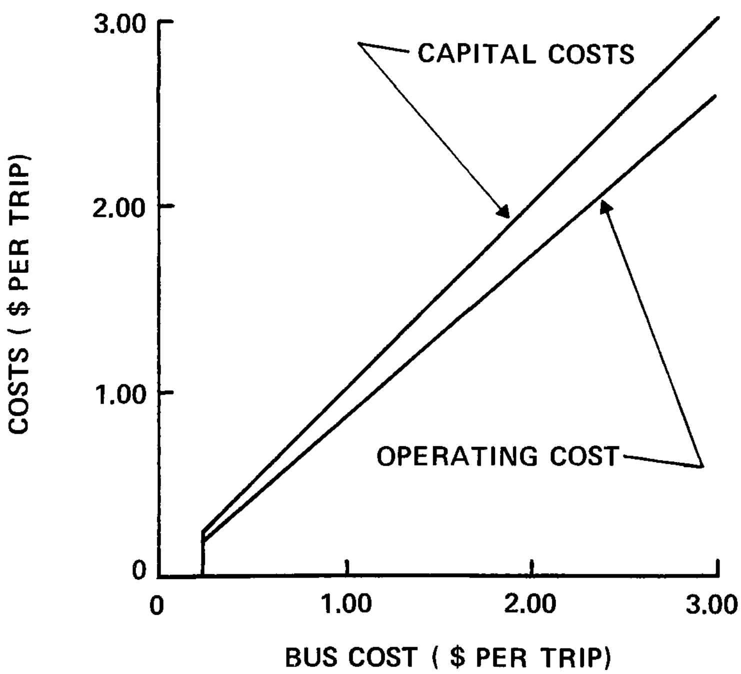
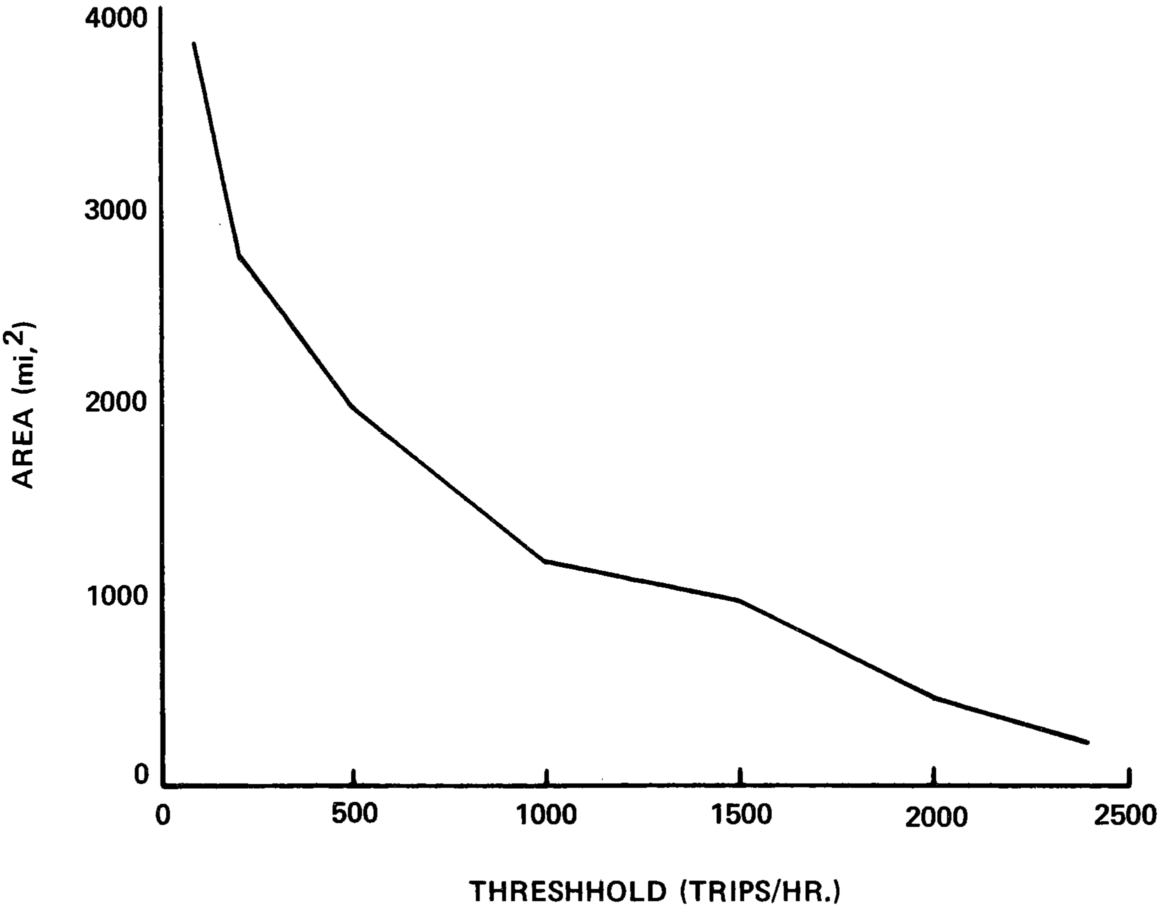


Figure C 3 – SIZE OF TRANSIT SERVICE AREA AS FUNCTION OF THRESHHOLD TRIP VOLUME



Maps of the Transit Service Areas for Three Threshold Trip Volumes

Figure C 4 – TRANSIT SERVICE AREA FOR 500 TRIP PER HOUR THRESHHOLD

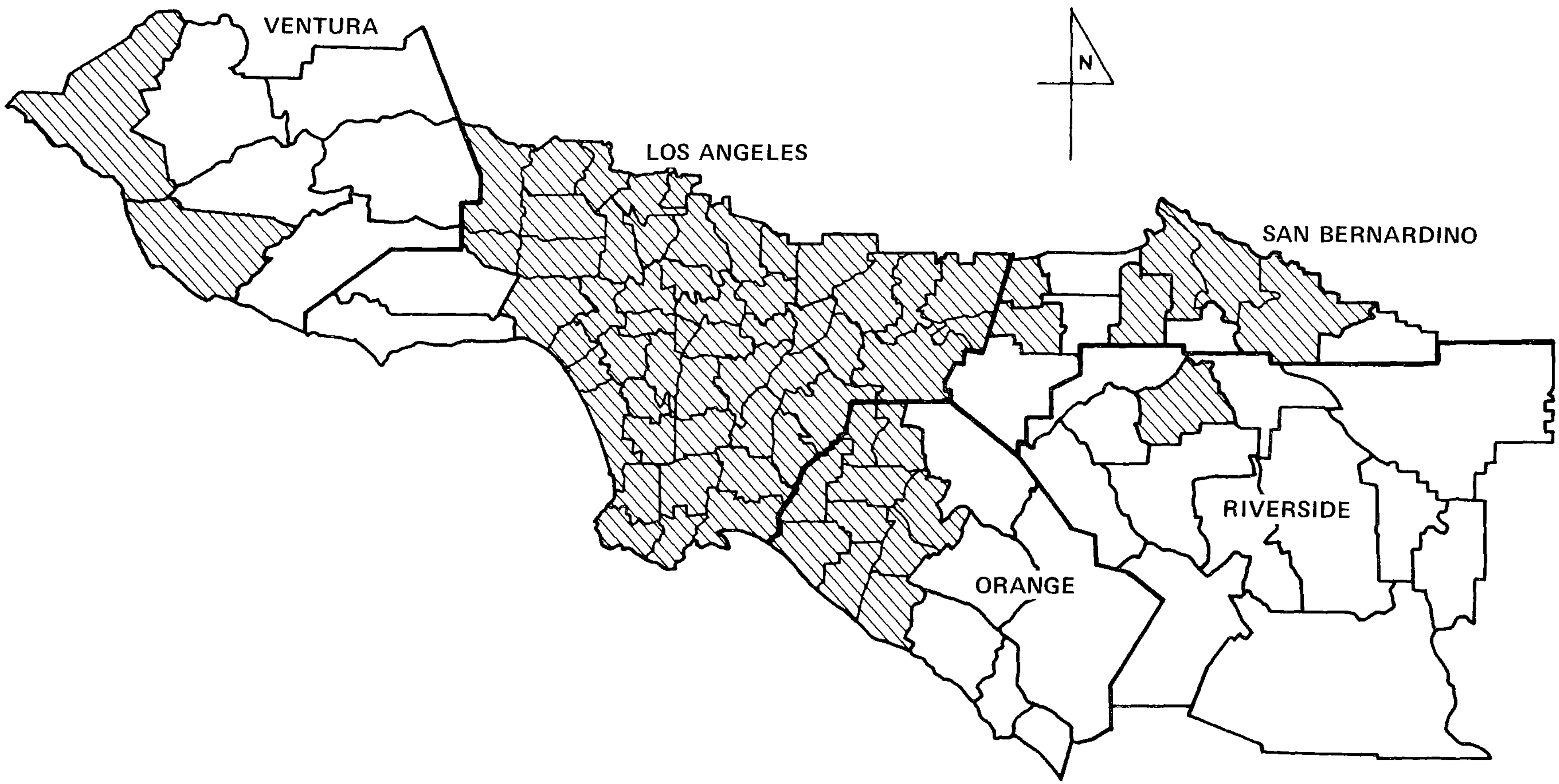


Figure C 5 – TRANSIT SERVICE AREA FOR 1500 TRIP PER HOUR THRESHHOLD

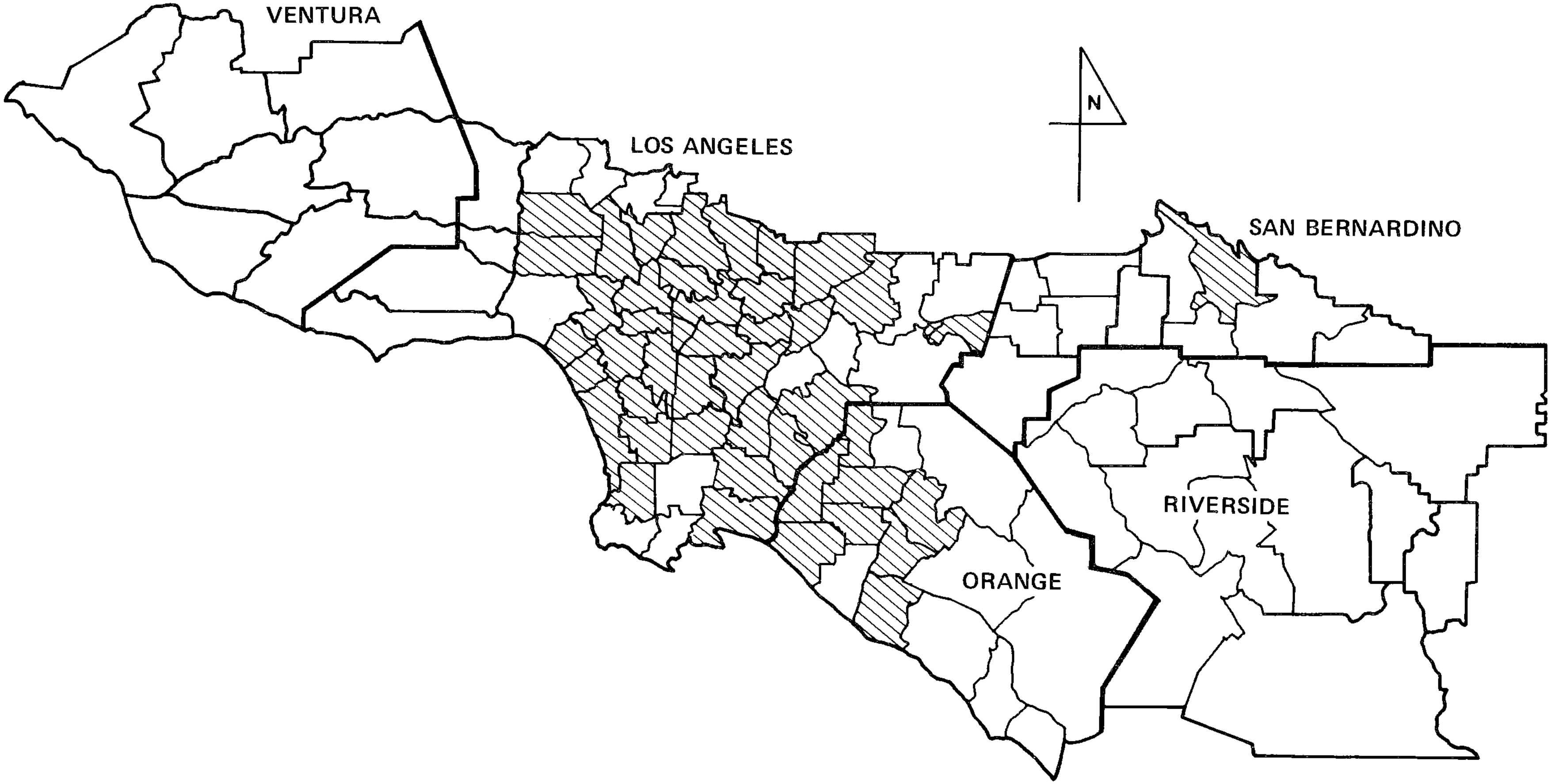
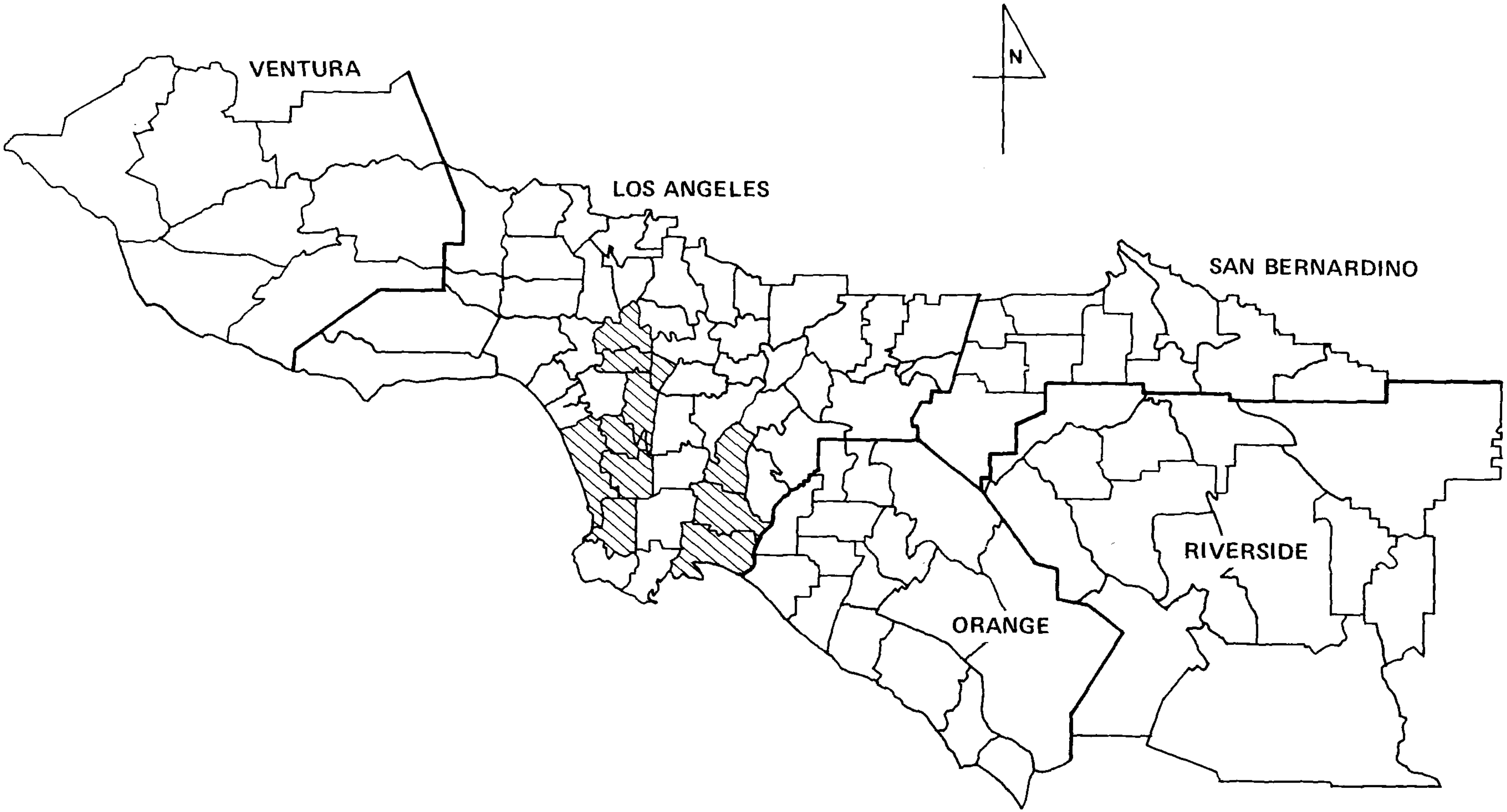


Figure C 6 – TRANSIT SERVICE AREA FOR 2400 TRIP PER HOUR THRESHHOLD



Relationships Between Travel Time, Travel Cost and Transit Mode Split for Three Threshold Trip Volumes

In the following figures, transit mode split, travel times, and travel costs have been averaged over a range of ratios of work trip to non-work trip mode split.

Figure C 7 – BUS TRAVEL TIME - AUTOMOBILE TRAVEL TIME VS.
BUS TRAVEL COST - AUTOMOBILE TRAVEL COST

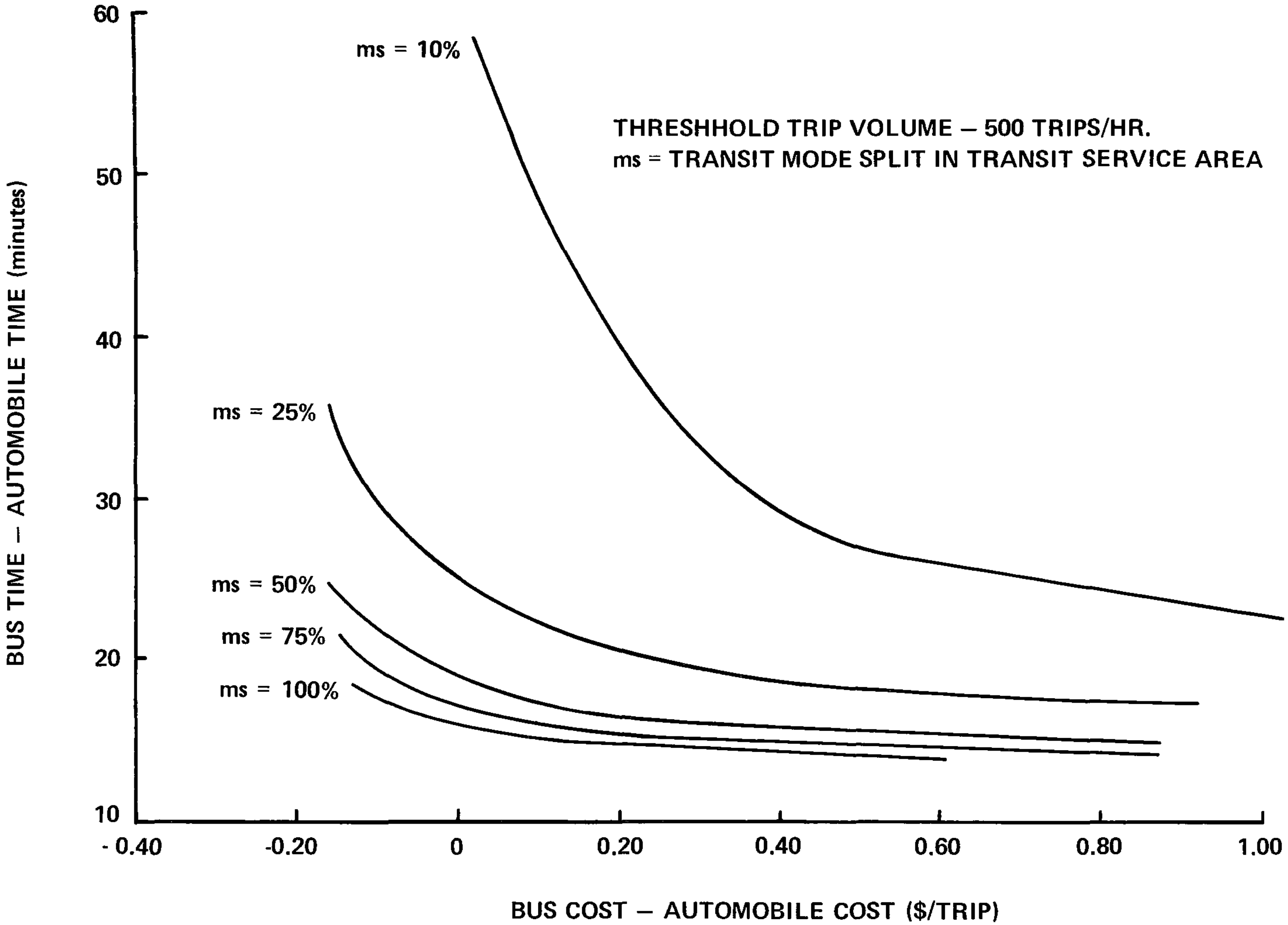


Figure C8 – BUS TRAVEL TIME - AUTOMOBILE TRAVEL TIME VS. TRANSIT MODE SPLIT

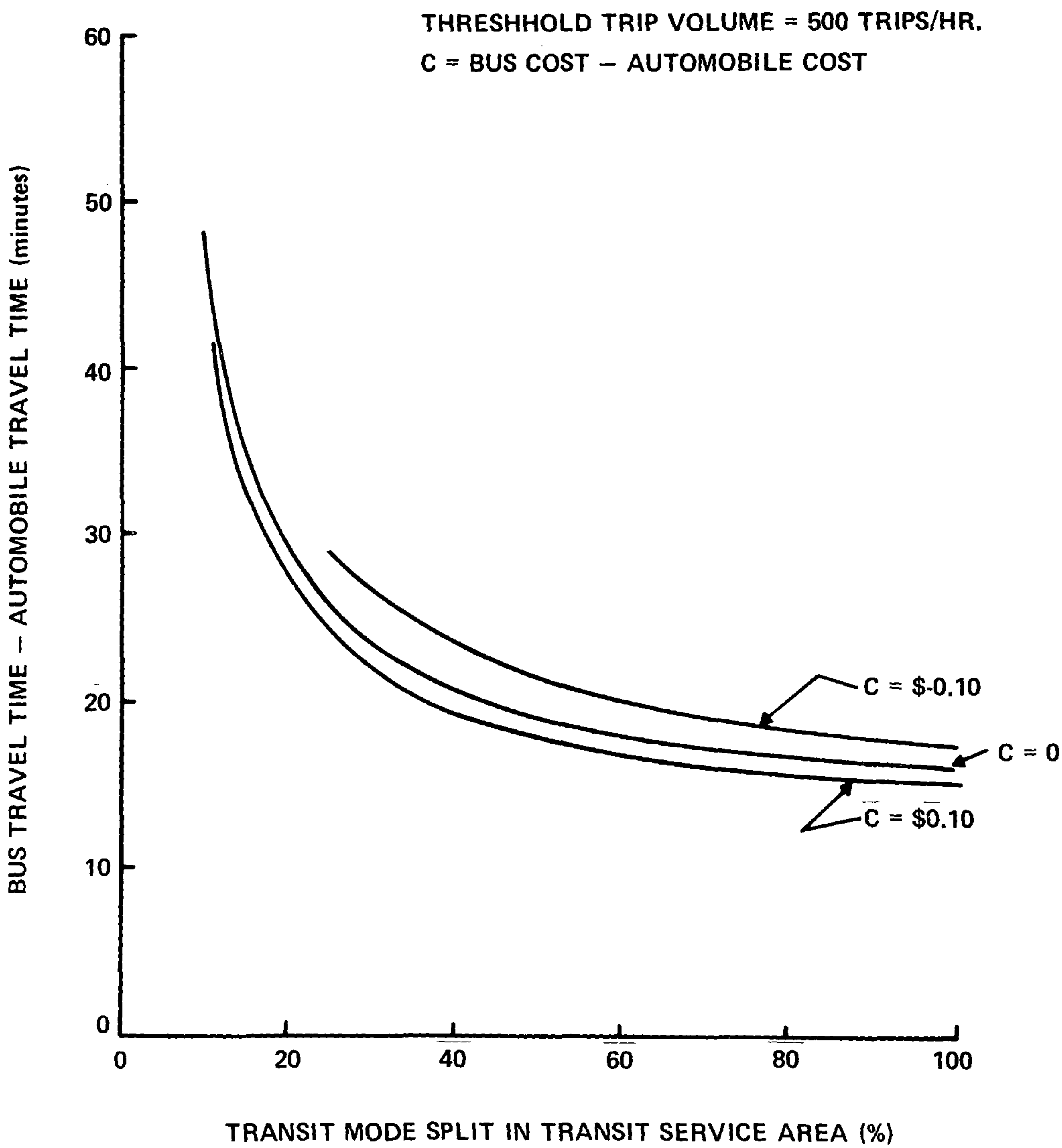


Figure C 9 — BUS COST - AUTOMOBILE COST
VS. TRANSIT MODE SPLIT

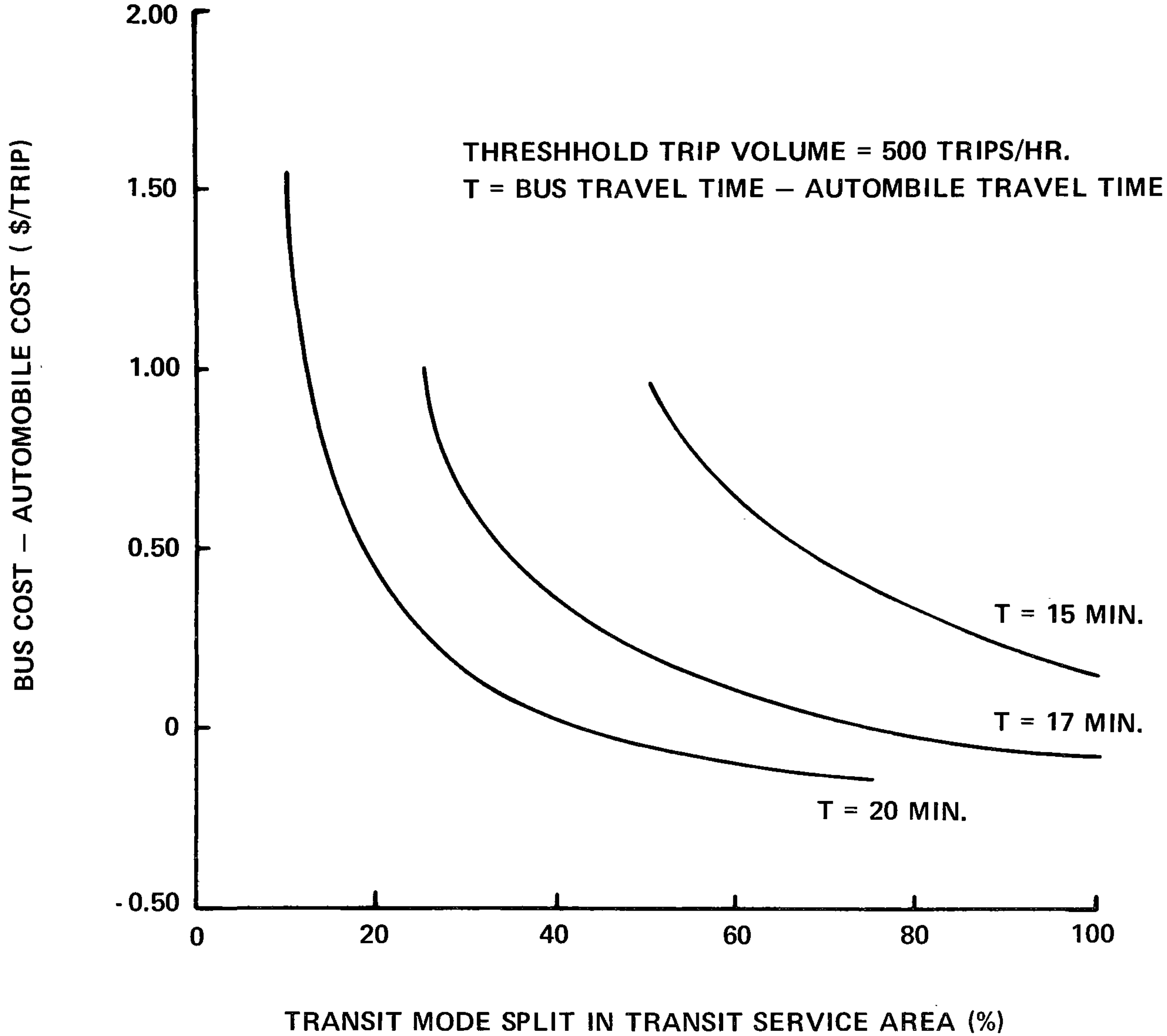


Figure C 10 — BUS TRAVEL TIME - AUTOMOBILE TRAVEL TIME VS.
BUS TRAVEL COST - AUTOMOBILE TRAVEL COST

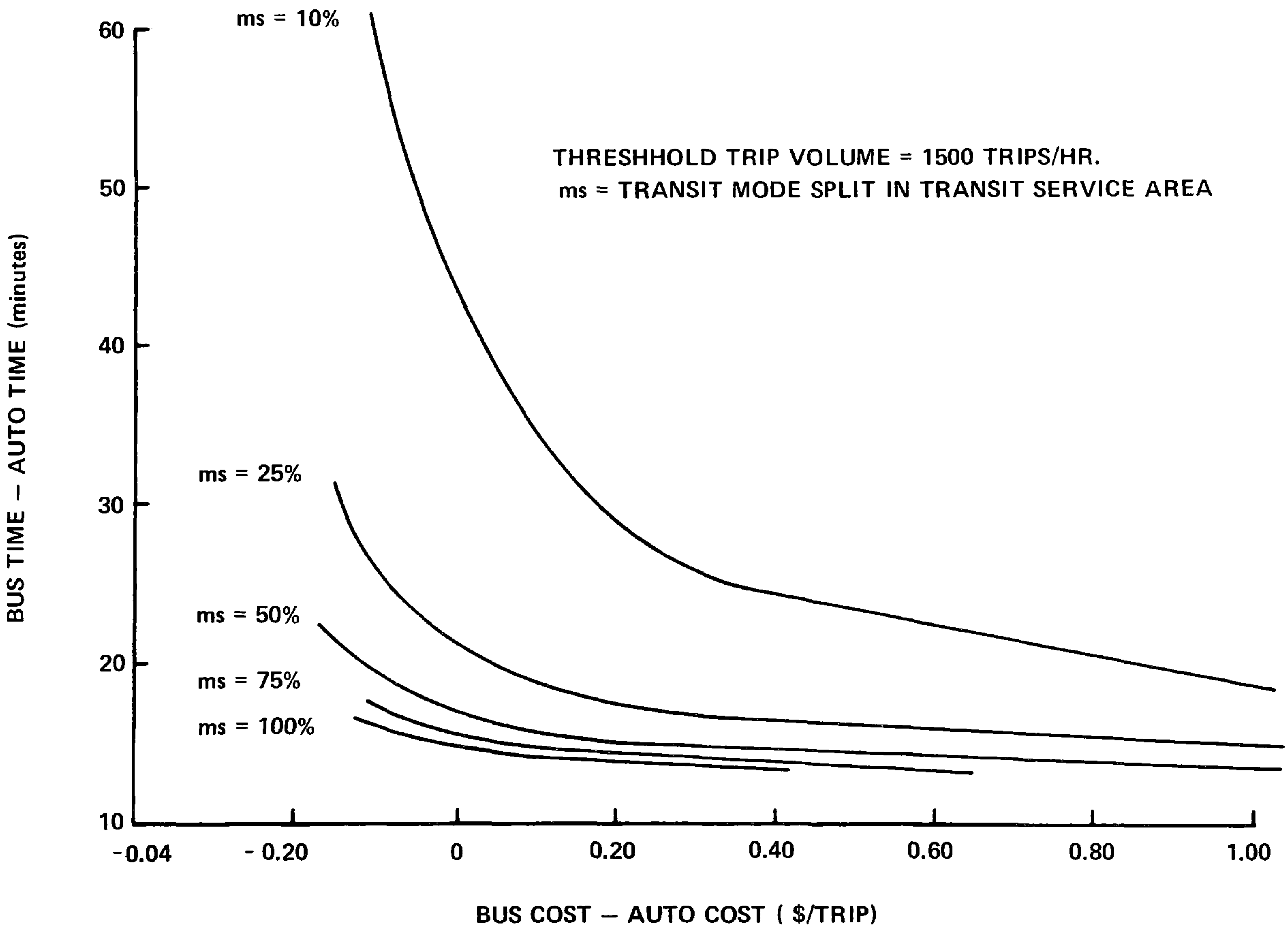


Figure C 11 – BUS TRAVEL TIME - AUTOMOBILE TRAVEL TIME VS. TRANSIT MODE SPLIT

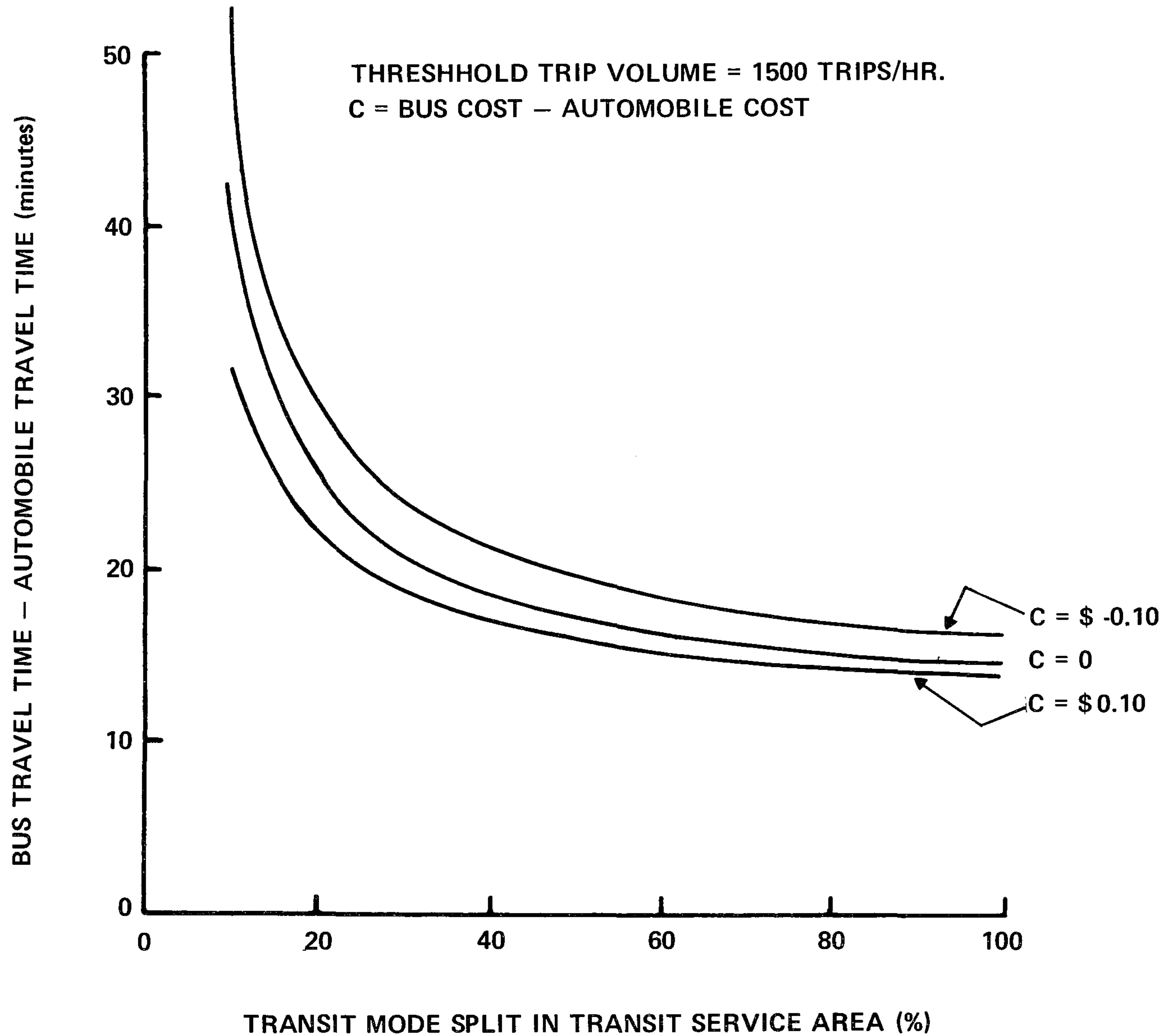


Figure C 12 — BUS COST - AUTOMOBILE COST
VS. TRANSIT MODE SPLIT

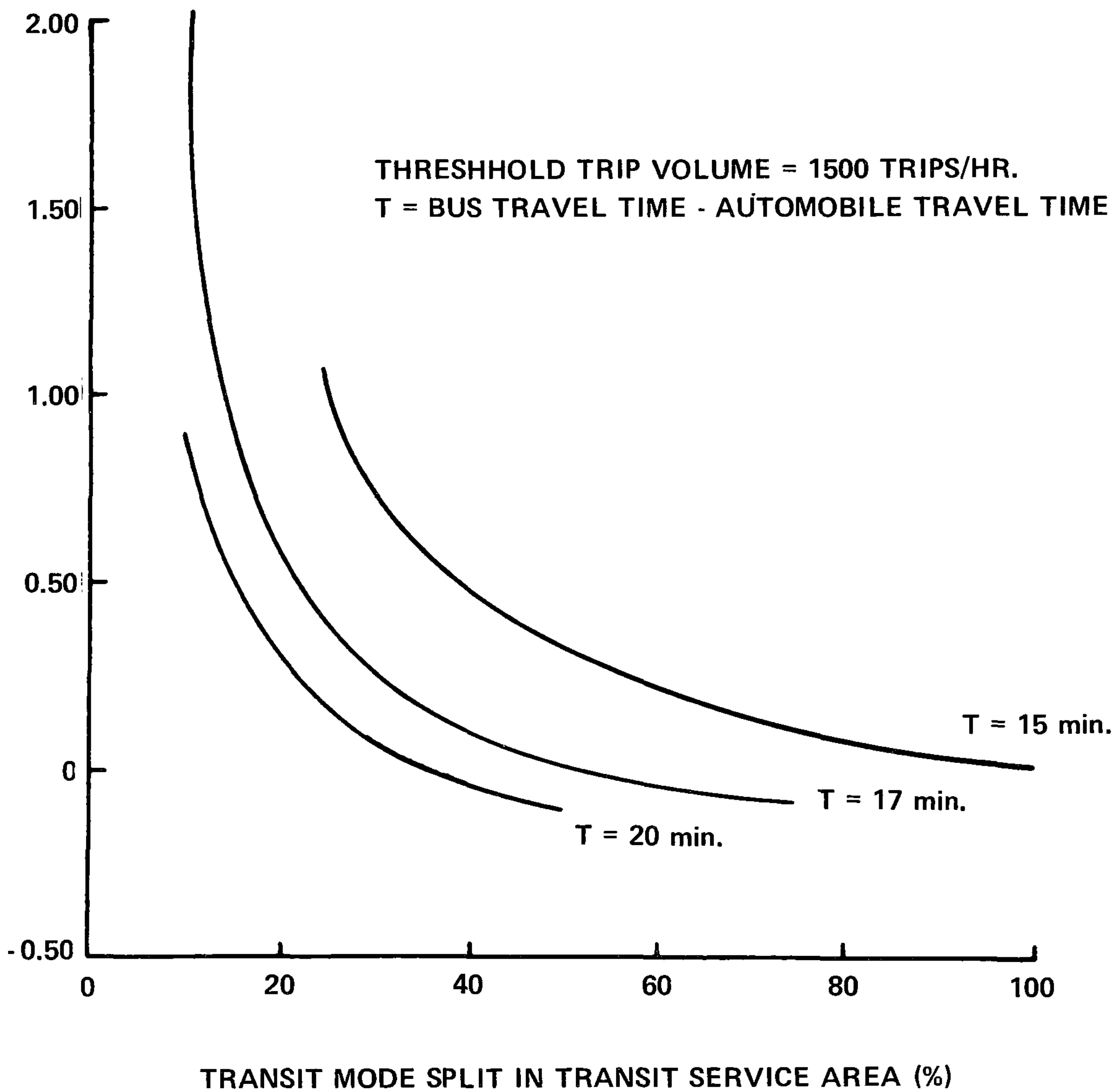


Figure C 13 — BUS TRAVEL TIME - AUTOMOBILE TRAVEL TIME VS. BUS TRAVEL COST - AUTOMOBILE TRAVEL COST

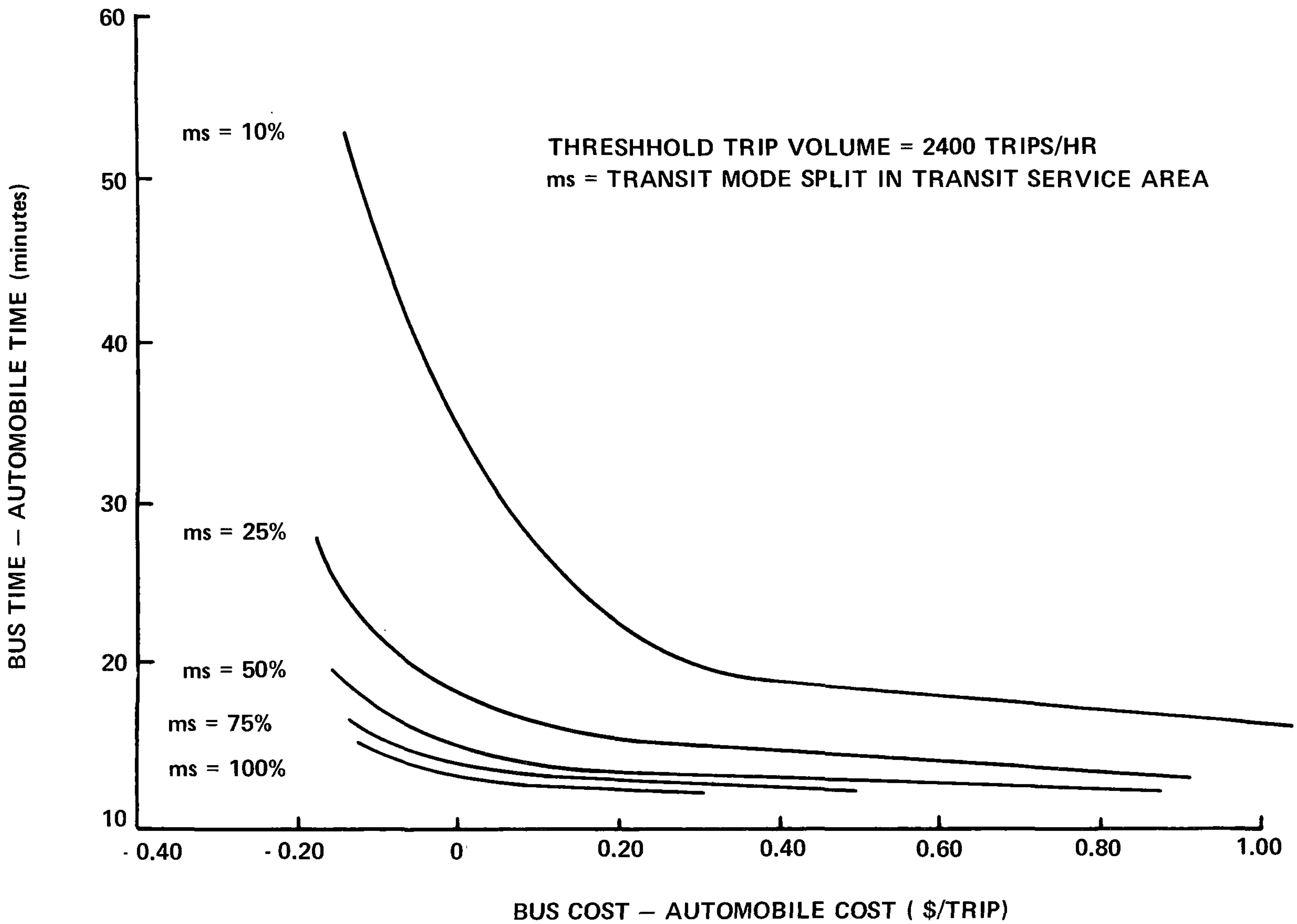


Figure C 14 – BUS TRAVEL TIME AUTOMOBILE TRAVEL TIME VS. TRANSIT MODE SPLIT

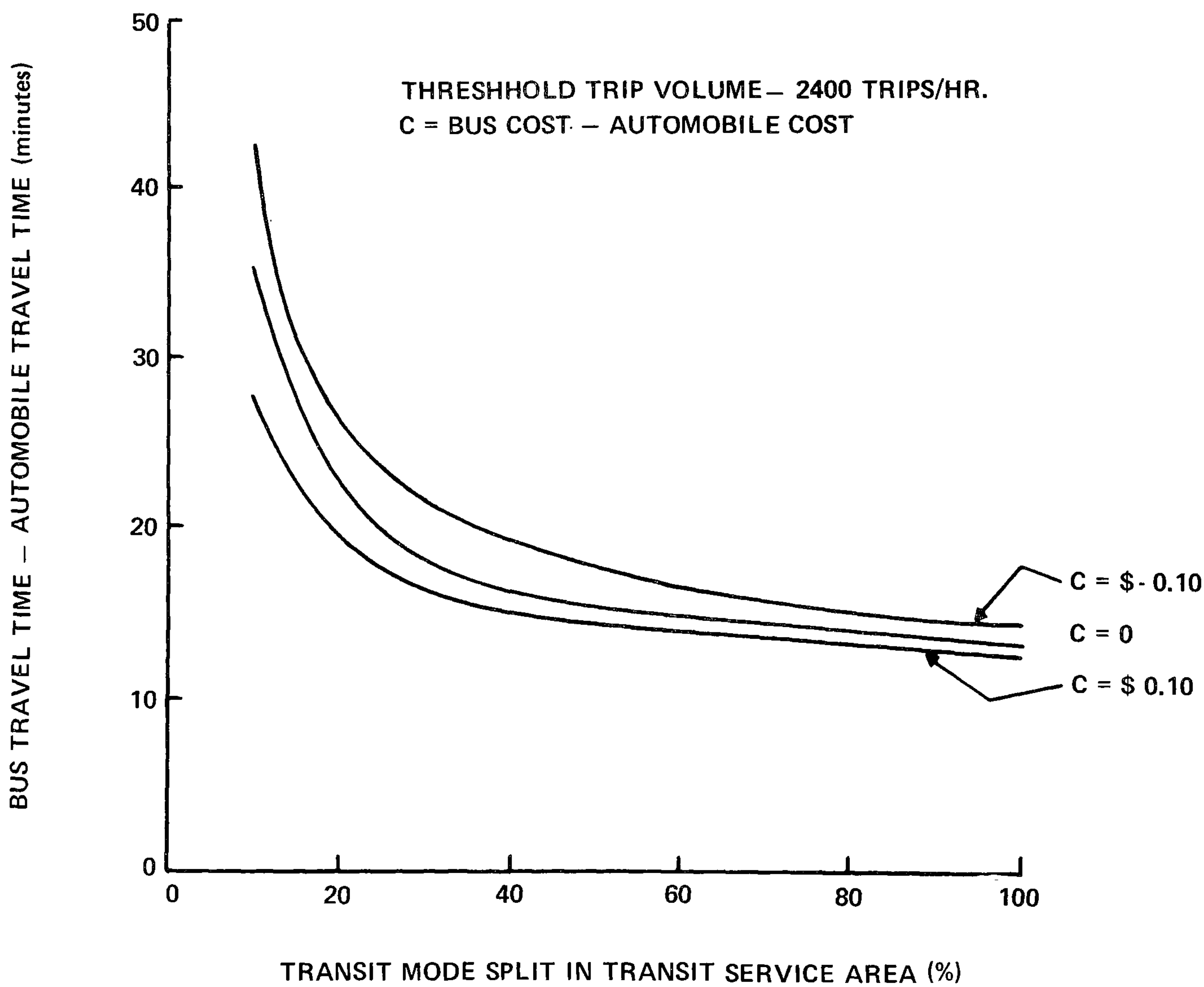


Figure C 15 — BUS COST   AUTOMOBILE COST VS. TRANSIT MODE SPLIT