MODAL-CHOICE MODEL FOR RELATING DEMAND TO INVESTMENT

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The development of a macromodel for modal choice is presented. The model relates investment to transit supply, supply to level of service, and level of service to demand. The model is developed at a city-wide level by using a simulation technique involving the analysis of 13 individual highway-transit system tests for a city of 3.5 million people. Land use activities are allocated on the basis of accessibility provided by both highway and transit systems. The generation of travel is sensitive to the level of service provided, and the distribution of trips is achieved by using weighted highway-transit skim trees and a standard gravity model. The modal-choice analysis employs a utilitarian model develped as part of a study of models calibrated for existing cities. The macromodel relates demand to mean travel-time difference and mean travel-cost difference between transit and highway for work and nonwork purposes for both peak and off-peak periods. The mean city-wide transit travel time is related to the supply of seat-miles of service per capita, and the highway travel time is related to capacity-miles of highway per capita. Transit supply is in turn related to the capital and operating costs of providing that service. In application, the model assumes a fixed level of highway supply and has as policy variables the absolute investment level in transit, the split of investment between bus or rail rapid transit and conventional bus transit, the transit fare, the split of service between peak and off-peak periods, and the parking cost.

•THERE IS a critical need in the urban transportation planning process for an analytical capability to permit the testing of multimodal and multiregional transportation-investment policies. In recognition of this need, the U.S Department of Transportation sponsored a series of studies aimed at improving that capability. One of these studies was the Transportation Resource Allocation Study that considered the quantity and the quality of the transportation system as well as the basic indicators of socioeconomic characteristics such as population and automobile ownership. In an earlier report, Kassoff and Gendell (1) described a process and travel-demand forecasting procedure to project future urbanized-area travel. This work has been further expanded in England by Lesley (2), who has attempted to establish a relation between the structure and operating performance of urban public transportation systems and the macroparameters of European cities.

This paper is concerned with the development of a modal-choice model that can be used to relate demand to investment on an urbanized-area basis. The model provides the planner with a simple analytical tool to estimate transit investment for a given demand, estimate transit demand for a given investment, or estimate the level of transit service for a given demand or investment.

In the development of this macromodel, a simulation approach was used. That is, the basic relations have been established by simulating the urban-activity characteristics for 2 large metropolitan areas, and an experimental design was developed to sketch feasible combinations of highway and transit levels of service for both areas based on the known theory of travel demand and urban activity. The reasons for adopting a simulation approach are as follows:

1. Supplying an adequate and consistent empirical data base across several urbanized areas is difficult;
2. Certain variables of concern (e.g., high levels of transit service) do not currently exist on a city-wide basis;
3. Sensitivities that emerge on a macrobasis can only be established through a microsimulation and then a city-wide summary; and
4. Interrelations among land use, transit, highway, and other policies for a metropolitan area make sensitivity testing very difficult.

EXPERIMENTAL DESIGN

The experimental design developed for the study is shown in Figure 1. The number of transportation alternatives (simulation tests) was set at 13, and the figure shows how these alternatives were developed to cover a wide range of highway and transit system service levels.

In each case, the design of the system was based on the characteristics of systems operating in, or proposed for, existing cities. A mix of transit systems is implied by the categories of conventional bus transit, bus rapid transit, and rail rapid transit because the operation of each system is dependent on supporting feeder and distribution systems.

Two base-year urban-activity patterns were developed in the study to simulate a range of existing cities. Specifically, patterns of central-city activity concentration and suburban-activity dispersion were tested. From an analysis of existing cities, each transportation system was matched with the urban-activity pattern to which it was most closely related, and as a result the 13 tests shown in Figure 1 were selected.

OPERATIONAL PROCEDURE

To provide inputs to the macromodel, an operational procedure was developed and applied to each of the 13 simulation tests shown in Figure 1. This procedure is shown in Figure 2, and basically it has involved the following major components.

1. The development of a procedure enabling the prediction of microutility modal-choice curve characteristics (3, 4) for a city, given a set of macroparameters describ- that city, involved a research study of the characteristics of existing microutility curves in order to relate those characteristics to the macroparameters of the city for which each model was developed. (For the aggregate transit percentages output from the study to be realistic, a modal-choice model that accurately reproduced the trip-maker's modal-choice decisions had to be utilized for each simulation test. Such models are usually developed and calibrated for individual cities on the basis of trip-interchange data. Because such data are not available for the simulated cities, it was necessary to develop a relation between the characteristics of microutility modal-choice models and aggregate city parameters.) A relation was developed between the microutility modal-choice curves calibrated for Los Angeles, Twin Cities, and Newcastle (England) and the mean city-wide automobile ownership stratified by the level of automobile ownership (5). The resulting family of curves provides the basis on which the microutility curve for different cities can be estimated directly from a knowledge of the mean automobile-ownership rate in the city.

The model is essentially a 3-dimensional surface, as shown in Figure 3, for each level of automobile ownership. However, because only mean automobile-ownership rates were predicted for the simulated cities, the model was aggregated over levels of automobile ownership for use in the study by using a unique relation between mean automobile ownership and the percentage of households in each ownership group.

2. The development of realistic urban-activity patterns and transportation system alternatives to use as input to the simulation study was achieved from an extensive analysis of existing cities and resulted in the development of 2 base-year distributions of population and employment representing a highly concentrated city typical of older cities and a more dispersed automobile-oriented city. Those cities were matched against the transportation systems as shown in Figure 1. Base-year distributions of

Figure 1. Experimental design.

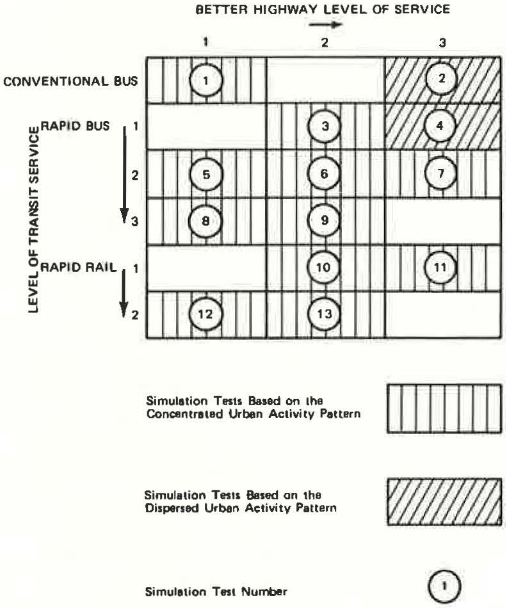


Figure 2. Operational procedure for development of variables for macromodel for modal choice.

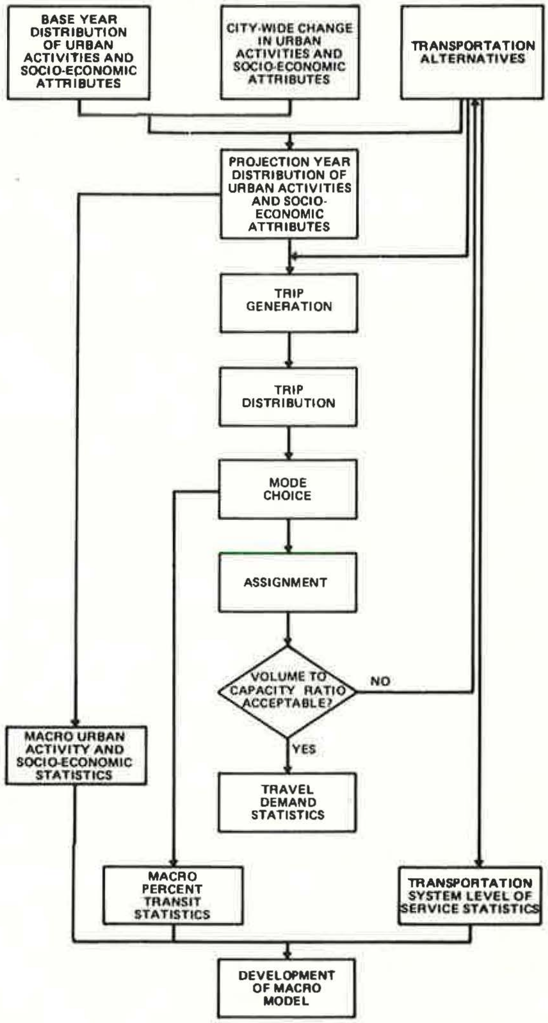


Figure 3. Three-dimensional surface of micromodel for modal choice.

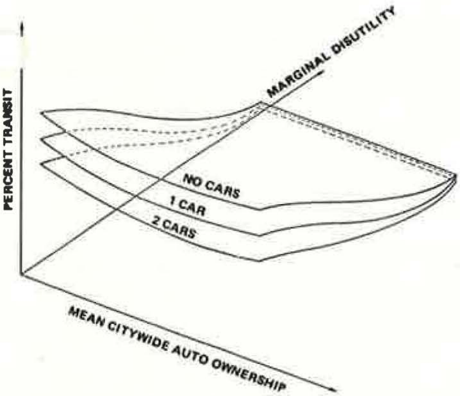


Table 1. City-wide variables generated by each simulation test for input to macromodel.

	System Characteristics		
Component	Highway	Transit	Urban Activity Characteristics
Demand[a]	Number of trips Vehicle-miles	Percentage of transit work trips Percentage of transit nonwork trips Percentage of transit total trips Passenger-miles	Population and population density (CBD, central city, and suburbs) Manufacturing employment and manufacturing employment density (CBD, central city, and suburbs) Office employment and office employment density (CBD, central city, and suburbs) Population following employment and population following employment density (CBD, central city, suburbs) Mean income Mean automobile ownership
Level of service[a]	Mean run time Mean travel cost (running costs and parking costs) Mean speed Mean trip length	Mean walk time Mean wait time Mean run time Mean fare Mean speed Mean trip length	
Supply	Arterial miles Freeway miles Highway miles Arterial lane-miles Freeway lane-miles Highway lane-miles Capacity-miles	Fleet size[a] (number of buses and number of rail cars) Miles of private right-of-way Route-miles Number of rapid transit stations Seat-miles[a]	
Investment		Capital costs (guideway and rolling stock) Daily operating costs (labor and other)	

[a]Stratified by peak and off-peak period.

mean zonal income, automobile ownership, parking costs, and transit fares were established for both cities. [The distibution of mean zonal income was calculated from 1968 in-house data for Cleveland (6). Automobile-ownership rates were calculated from a relation among income, transit level of service, and automobile ownership developed for Memphis, Tennessee. Base-year zonal parking costs were developed from a procedure used in the Washington Metropolitan Area Transit Authority study (7), and zonal transit fares were developed from in-house data and library research material.]

3. The application of urban-activity, trip-generation, trip-distribution, modal-choice, and trip-assignment models to each simulation test developed inputs to the macromodel. Initially, distributions of population, employment by type, and income were allocated to the simulated city zones to produce the base-year patterns of concentrated and dispersed urban activity (which in each case had a base-year population of 2.5 million and a labor force of 900,000). At the same time, the 13 simulation tests shown in Figure 1 were devised, and the respective highway and transit systems were developed. Peak and off-peak highway and transit skim trees were then built for each test, and a composite skim tree was developed and weighted in terms of work and nonwork trips, peak and off-peak trips, and highway and transit trips. The projected city-wide increases in population and employment by type were then distributed to zones on this composite skim tree by using a simple activity-allocation model (8). [A projection period of 20 years from a 1970 base year was assumed in the study. Both simulated cities were assumed to have the same growth in population and employment, and growth was based on the mean projections for the 40 largest urbanized areas in the United States during the period 1970-1990 (8).]

It was also necessary to project the zonal increase in income and automobile ownership. In the case of income, however, a literature survey indicated that little information was available on changes in the spatial distribution of income over time. A simple model was, therefore, developed to allocate the total city-wide increase in income to zones. The mean city-wide increase in income was based on the Cleveland study projections (8), and this total was allocated to zones in proportion to each zone's population growth during the projection period relative to the city-wide population growth and to each zone's base-year mean income relative to the city-wide base-year mean income.

Automobile-ownership rates for the projection were developed by applying the 1990 zonal income projections to the base-year relation established among income, transit level of service, and automobile ownership.

The 1990 distributions of activity and socioeconomic characteristics were then used to forecast trip-generation rates [which were sensitive to the level of service provided (9)] for home-based work, home-based nonwork, and non-home-based trips. So that they would be consistent with the 1990 projected distributions of activity, socioeconomic characteristics, parking costs, and transit fares, the composite skim trees were updated. The 1990 trip productions and attractions, composite skim trees, and F-factor curves (10) were used, and the gravity model was run for each of the following trip purposes associated with each test: home-based work, home-based nonwork, and non-home-based.

Trip tables were then combined into the categories of work and nonwork trips and factored to provide peak and off-peak trip tables. The resulting 4 tables were split into automobile and transit trip tables by using the micromodel described previously and shown in Figure 3, and the trips were loaded onto the highway and transit networks.

The reasonableness of the assumptions made about the volume to capacity relations was tested by using a standard equilibrium approach to check the output highway speeds against the initially assumed highway speeds using capacity restraint. If the output speeds were significantly at variance with the initially assumed speeds, the output speeds were adopted, and the entire procedure was reiterated for that particular simulation test. If the initially assumed speeds were within an acceptable range of the output speeds, the highway assignments were adopted.

Transit trips were then assigned to the transit network; for those tests having more than 1 transit mode, the assignment to a specific mode was made on the basis of relative modal capacity.

4. The parameters describing each simulated city test were spatially aggregated, and the relations between those parameters and the city-wide percentage of transit usage were developed after the simulation tests were complete. Table 1 gives the parameters that were generated and considered as possible variables for the macromodel.

THE MACROMODEL FOR MODAL CHOICE

The variables from the simulation tests given in Table 1 were used to develop city-wide relations of transit supply and investment, level of service and supply, and demand and level of service. Alternative combinations of variables were tried for each of the 3 components of the macromodel in an attempt to develop a model that was both conceptually sound and statistically accurate. The final relations established for each of the components of the model are now presented.

Supply and Level of Investment

Figures 4 and 5 show the relations that were developed between transit supply and level of investment. Transit supply (measured in terms of rapid transit seat-miles) is highly correlated with both capital costs and operating costs on a per capita basis. The number of seats per vehicle was based on the characteristics of existing transit systems (11), and it was estimated that each bus had 50 seats, each rail car had 80 seats, and each train had 6 rail cars in the peak period and 3 in the off-peak period.

For each system test, capital costs were developed for both rolling stock and guideways by using 1968 Washington Metropolitan Area Transit Authority unit cost figures (12). Guideway costs were made up of the type of line construction (e.g., subway, arterial, or grade construction for rail systems) and of station costs, which included the cost of providing parking facilities. Rolling-stock costs were calculated per vehicle for buses and rail cars, and operating costs were calculated (from the same source as capital costs) for conventional buses, rapid transit buses, feeder buses, and rapid transit rail cars on a daily basis.

Level of Service and Supply

Because the demand component of the macromodel was developed to deal with both peak- and off-peak-period travel, it was necessary to develop peak and off-peak relations between the level of service and supply variables. (Peak and off-peak level-of-service measures were then input into the demand component of the model.)

Figure 6 shows the peak-period model developed to relate transit-travel time to rapid transit seat-miles per capita. As shown in the figure, there are distinct relations for bus-oriented systems and rail-oriented systems. The model indicates that the level of service provided by rapid transit bus-oriented systems is very sensitive to changes in the level of supply over a comparatively narrow range of supply. In contrast, the model shows that the changes that can be brought about in the level of service for rail-oriented systems by varying the level of supply are of a small magnitude, although the supply of rapid transit seat-miles is greater and covers a wider range. Figures 4 and 5 show that both capital and operating costs of rail-oriented systems tested are higher than those of bus-oriented systems. The implication is, therefore, that, for a given increase in investment, the bus-oriented systems are more cost effective in terms of providing an improved peak-period level of service than are rail-oriented systems. (This conclusion relates to the experiment described in this paper. It is not meant as a general conclusion for all metropolitan areas.)

For the off-peak period, little correlation was found to exist between off-peak level of service and supply variables in absolute terms. However, when a ratio relation was developed, a strong correlation was found to exist between the off-peak to peak ratio of transit-travel time and the off-peak to peak ratio of total system seat-miles per hour. This model, stratified by highway level of service (expressed in terms of capacity-miles of highway per capita), is shown in Figure 7. The stratification by highway level of service is significant. It implies that different levels of off-peak service can be provided for a given level of off-peak supply, depending on the quality of the highway system.

Figure 4. Rapid transit seat-miles per capita versus capital costs per capita.

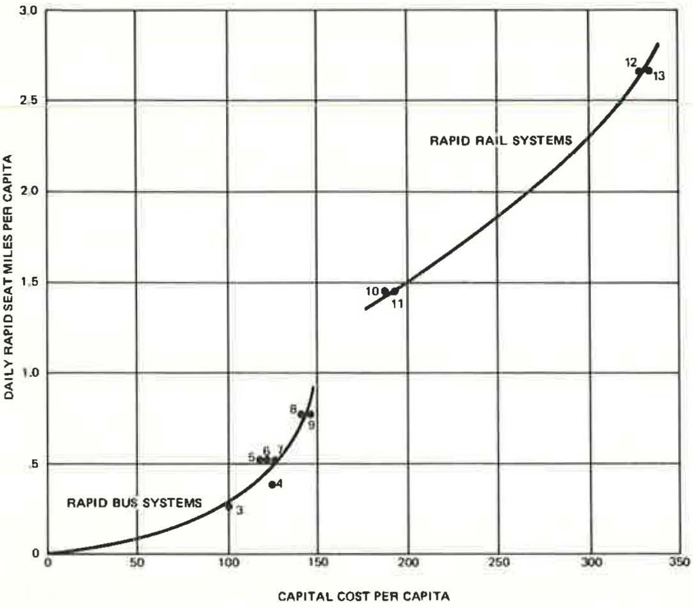


Figure 5. Rapid transit seat-miles per capita versus daily operating costs per capita.

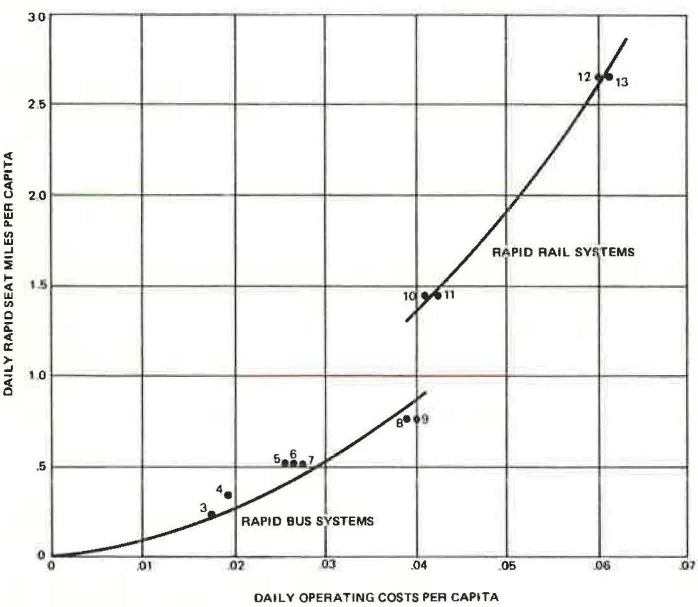


Figure 6. Peak-period transit travel time versus peak-period rapid transit seat-miles per capita.

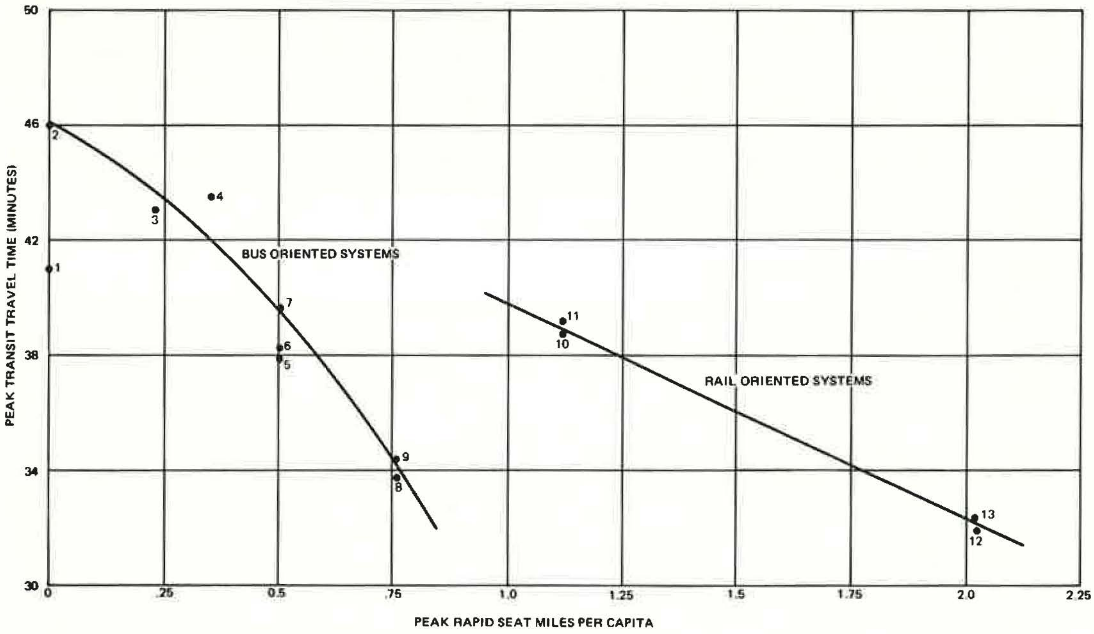
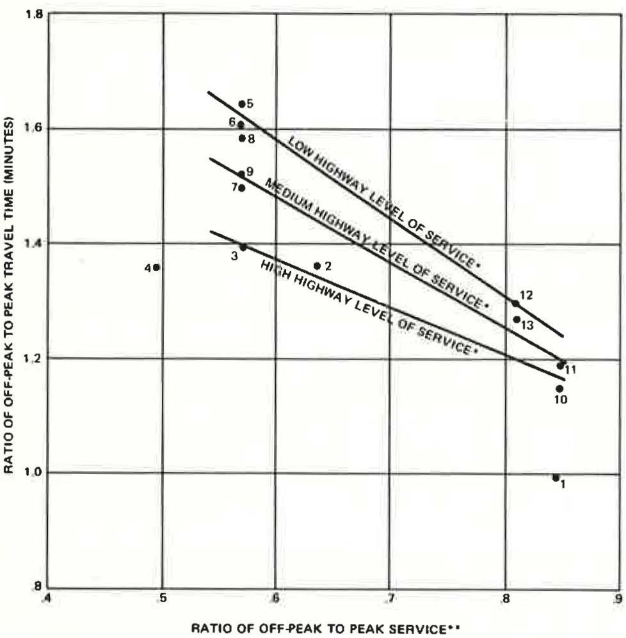


Figure 7. Ratio of off-peak to peak-period travel time versus ratio of off-peak to peak-period seat-miles per hour.



* Highway Capacity Miles Per Capita

LOW LEVEL OF SERVICE .415 CMS/PERSON
MEDIUM LEVEL OF SERVICE .622 CMS/PERSON
HIGH LEVEL OF SERVICE .864 CMS/PERSON

Capacity miles = $\sum_i$ (capacity of each link (i) x length of link in miles)

**Service measured in Seat Miles Per Hour

Perhaps more important, it indicates that, to provide the same level of off-peak service, cities with poorer highway systems require a higher level of supply than cities with good highway systems. Third, the relation also makes explicit the effect of different levels of highway investment (and hence supply) on the existing level of off-peak transit service.

Inasmuch as the demand component of the macromodel was based on a level-of-service difference variable (transit minus highway) for both peak and off-peak periods, relations were developed to provide the highway level of service inputs to the demand model. These relations are shown in Figures 8 and 9 for the peak and off-peak periods respectively. In each case, highway-travel time was found to be highly correlated with the supply of capacity-miles of highway per capita.

Demand and Level of Service

Of the alternative combinations of macroparameters that were used in the development of a relation between transit demand and level of service, it was found that travel-time and travel-cost differences (transit minus highway) best accounted for the variations in transit demand. Figures 10, 11, 12, and 13 show the 4 demand models developed to estimate transit usage for work and nonwork purposes in the peak and off-peak periods. The initial relations were developed at a 10-cent cost difference, and the sensitivity of demand was later tested against the range of cost differences shown in these 4 figures.

The relations developed here between demand and level of service are significant for several reasons. For a given travel-cost difference, the demand models make it possible to identify the effects that changes in transit-travel time (brought about by specifying different levels of investment and mixes of transit supply) have on demand. These effects can be stratified by time of day (peak and off-peak) and by trip purpose (work and nonwork). Similarly, the effects that changes in transit-travel cost have on demand can also be identified for a given travel-time difference. This is achieved by varying the transit-fare policy, and again the effects would be stratified by time of day and type of trip.

Alternatively, the demand models could indicate the effects that different levels of highway supply (measured in terms of changes in highway travel time) and highway cost (measured in terms of changes in parking cost policies) have on demand.

IMPLICATIONS

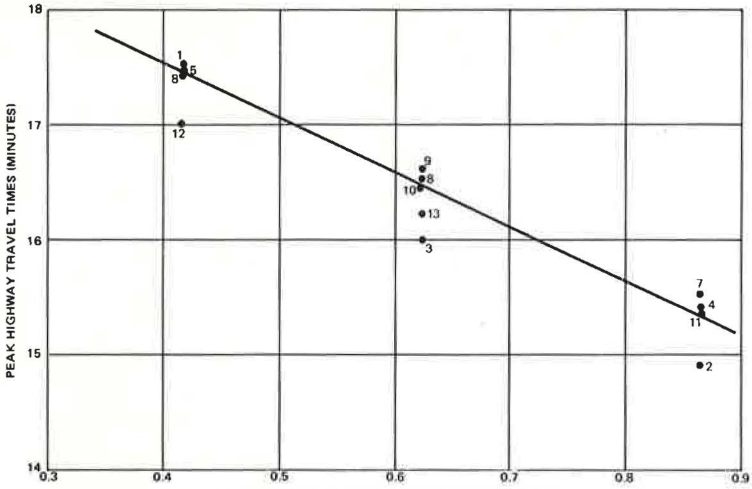
The macromodel for modal choice presented in this paper would have considerable application in multimodal and multiregional transportation-investment planning. It can be utilized to test alternative transit-investment policies across cities. For a given level of investment, a measure of supply in terms of rapid transit seat-miles per capita can be used to determine the level of transit service for that level of investment. From a prespecified highway supply, the highway level of service can be determined. Knowing both the highway and transit levels of service, one can estimate the percentage of transit trips.

The model can also be applied incrementally to predict the likely increase in transit patronage that would result from alternative investment policies for existing systems or to estimate the usage that would result in investing in new systems. It, therefore, provides a capability and analytical link that previously required a considerable elapsed time and computer cost to obtain. It is not a panacea, however, and should be considered as an initial rather than a final screening process when a wide range of transit-investment policies is examined.

The components of the model offer flexibility to the analyst. For a constant investment, for example, differing systems mixes of total, peak, and off-peak rail rapid and bus rapid transit supply can be specified, and the sensitivity of total transit demand can be ascertained. In addition, the model allows alternative fare and parking policies to be examined.

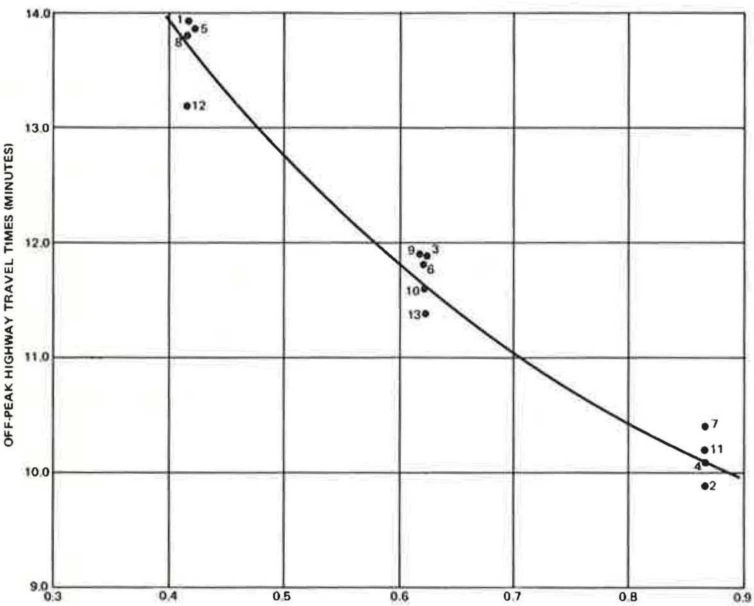
The user, however, should be careful that results are properly interpreted in analysis of transit-investment policies. The model is a guide for checking aggregate demand, supply, and level of service characteristics. It is not a substitute for microanalyses that are needed to determine the economic, social, and environmental effects of transit-investment policies for different groups of the regional community.

Figure 8. Peak-period highway travel time versus highway capacity-miles per capita.



*Capacity miles = $\sum_i$ (capacity of each link (i) x length of link in miles)

Figure 9. Off-peak-period highway travel time versus highway capacity-miles per capita.



*Capacity miles = $\sum_i$ (capacity of each link (i) x length of link in miles)

Figure 10. Peak-period work trips by transit (percent) versus peak-period travel time and cost difference.

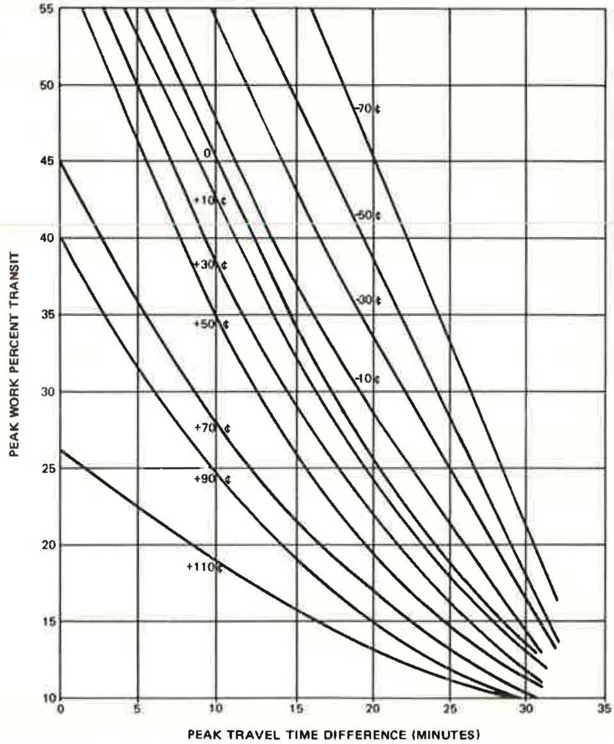
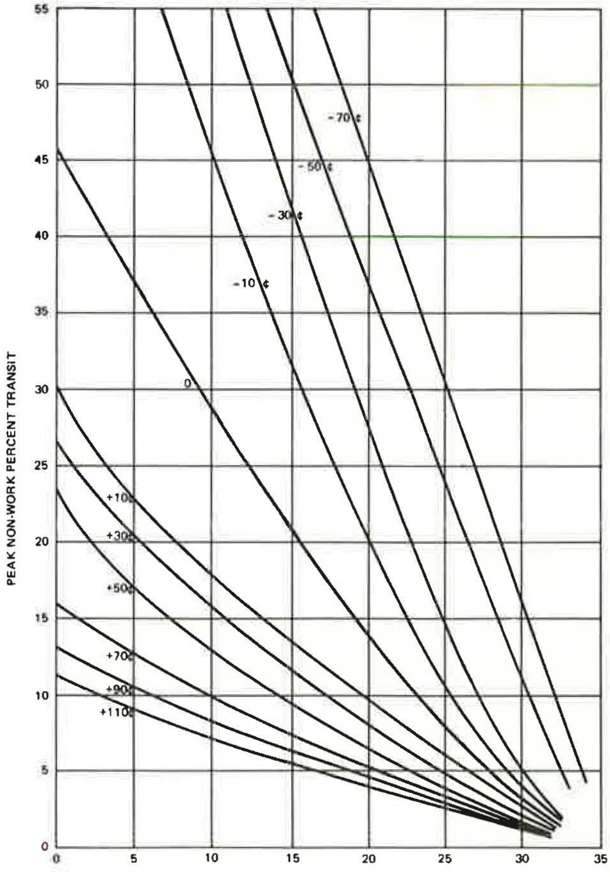
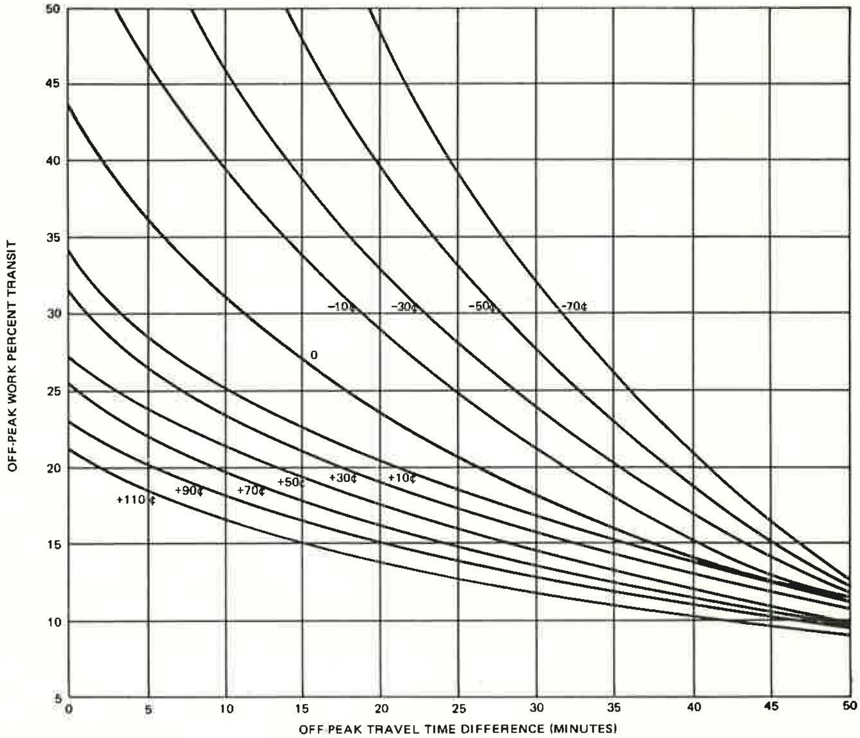


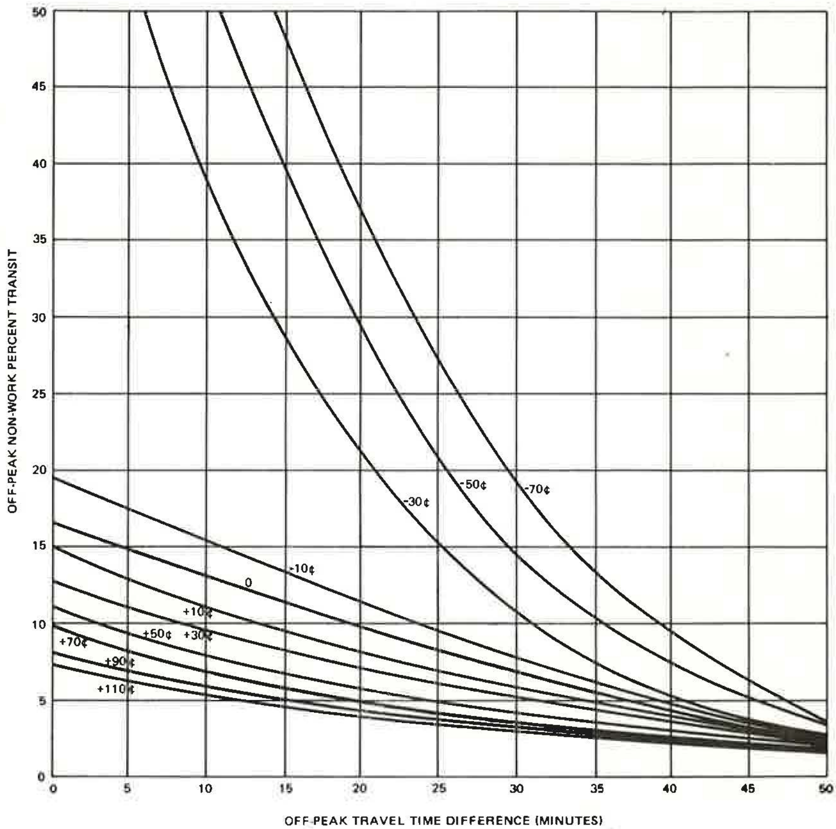
Figure 11. Peak-period nonwork trips by transit (percent) versus peak-period travel time and cost difference.



F[illegible] 12. Off-peak-period w[illegible] trips by transit (percent) versus off-peak-period travel time and cost difference.



Fi[illegible]e 13. Off-peak-period n[illegible]ork trips by transit (percent) versus off-peak-period travel time and cost difference.



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