Estimation of Urban Passenger Travel Behavior: An Economic Demand Model

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•THIS paper describes an urban transportation demand model that has a number of attractive features in evaluating the effects of alternative transportation systems. The model is derived directly from the theory of consumer demand in the economic literature. [For a discussion of the theory of consumer behavior consult one of the standard intermediate texts on price theory, e.g., (1).]

To an economist, urban transportation is simply another commodity—in principle no different from any other good or service, although perhaps in practice far more complex and multi-faceted than other commodities. Thus, it is natural for an economist to approach the task of developing an urban transportation demand model in much the same way that he would attempt to model the demand for any commodity. (To be precise, transportation is a derived demand, and therefore the general approach would be the same as that for any other derived demand commodity.) In doing this, he is likely to draw on elements of the theory of consumer behavior. This body of economic theory has been tested with numerous empirical studies, including at least one study of intercity travel demand (2), and provides a well-founded basis for a model of urban travel demand.

This paper describes the urban passenger travel demand model we have developed based on economic theory. A discussion of the reasoning underlying the model leads to a presentation of the general specification of the model, including a description of the relevant variables, the mathematical form taken by the model, and the statistical techniques used in estimating its parameters. Empirical estimates of the model's parameters were obtained using data for Boston. In the final section, selected results are presented and their implications for transportation investment planning are discussed.

We feel that by taking a fresh view of travel demand and by approaching it from an economist's viewpoint we have developed a model that has several important advantages over the existing generation of demand models. Upon further consideration, and after exposure to a wider range of outside review and criticism, it may turn out that the differences between our approach and the extant travel demand models are neither important nor advantageous. We may be presenting, as it were, the same contents in a different package. At present we doubt this; the model seems to be conceptually sounder, a better tool for forecasting, and more useful in evaluating policy alternatives than the previous models that have been developed. To be sure, many of the elements of the model are familiar. This is not surprising since most of the variables used in investigating travel demand are likely to be relevant within the context of any particular model. In any event, approaching this problem from a new point of view can only enrich our knowledge, for if it results in important advantages, the state of the art is that much advanced, while if it only confirms what we already know, our confidence in the existing techniques can be that much stronger.

BACKGROUND

Since the model is to be used in evaluating transportation system alternatives, at the outset it is useful to consider what policy questions we would like to be able to explore with the model. The following are indicative of those that should clearly be included.

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What effect will increases in population, personal income, and car ownership have on travel demand and consequently on future traffic congestion? What effect would changes in travel time or cost have on total travel demand and on the demand for the various modes? What effect would changes in the spatial distribution of homes, jobs, and retail establishments have on future traffic flows?

To obtain a deeper level of understanding, we would also like to know whether travel demand is more sensitive to some policy variables than to others. For example, are out-of-pocket costs such as parking charges or toll fees more onerous to auto users than vehicle operating costs? Are transfer or access times more onerous to transit users than in-vehicle line-haul times? Are savings in costs more important to travelers than savings in time?

In approaching the problem of developing a model of urban travel demand, it is useful to begin with consideration of the individual. Although we are concerned with aggregates of people, their behavior can probably best be understood by considering the behavior of individual travelers. We would like to know what decisions the traveler faces in his travel behavior, and what factors influence these decisions.

The individual traveler has a set of choices to make. He must decide whether to make a trip at all, where to go, which route to take, which mode to use, and when to go. Each of these choices has an associated set of values and costs (in money and time) to the individual; the values themselves will vary with the trip purpose and sometimes with the time of day. On a moment's reflection, it is clear that these choices are not independent. The costs of the various modes influence not only the choice of mode but also the selection of destination and the determination of whether the trip should be made at all. For example, an improvement in the freeway system that reduces the travel time to the downtown area may not only divert shoppers from regional shopping centers to downtown and shift travelers from transit to auto, it may also stimulate an increase in the total number of shopping trips. Mounting congestion, on the other hand, may reduce the total number of shopping trips by making each trip more effective and well planned.

Similarly, the attractiveness of a destination may influence both the distribution of trips between destinations and the number of trips that are made. Rejuvenating the downtown area, for example, or building a new stadium or concert hall, may not only redistribute shopping, social, and recreational trips between zones; it may also draw housewives or families out of the home and thereby increase the total number of trips made.

These points may become clearer by considering the following extreme but useful example. A woman living on a relatively isolated coastal island may make very few trips to the mainland because of the time, cost, and general difficulty of making the trip. One would expect that each trip would be well planned and executed. There is little opportunity to "run out to the store" to get the item she forgot. On the other hand, a woman living a few doors from a shopping district may make a large number of trips without nearly as much care. If she forgets an item, the resulting cost and inconvenience are relatively minor.

Although the example is extreme, it spans a wide variety of circumstances that occur in real life. It illustrates the point that the alternatives available to individuals determine not only their selection of modes and destination zones, but also the total number of trips that they make. If conditions are favorable, the individual may make many trips; if all the available alternatives are poor, he may make few trips or even no trips at all. Because the value of the trip depends on its ultimate objective, we might expect shopping, personal business, social, and recreational trips to be more sensitive to these conditions than work trips. But the fact that trips made for the former purposes comprise a large and growing percentage of all trips makes it essential that we analyze the responsiveness of passenger travel demand to time and cost conditions. In most cities nonwork trips probably constitute the majority or close to the majority of trips.

The approach usually taken in the analysis of urban travel demand separates the problem into elements of trip generation, attraction, distribution, assignment to routes, and modal split. As the foregoing discussion indicates, however, these choices are so intertwined that they are best treated as being made simultaneously rather than separately.

The separate treatment of these elements in the currently popular models has several related consequences. First, it results in the implicit assumption that the number of trips generated is independent of the performance of the transportation system. That is, it is assumed that changes in travel time or cost can influence the modal split or distribution of trips between zonal pairs, but cannot change the total number of trips generated. By assumption, the models assert that the policies implemented by transportation planners have no effect on the total number of trips made! While it is possible that changes in the transportation system will not affect trip generation, there is no good reason for making this assumption a priori. It seems better to avoid making this assumption altogether; we have everything to gain and nothing to lose by letting the question be settled through the results of empirical estimation.

Second, the separation of these elements could lead to improper measurement of the effect of the independent variables in the individual trip generation and attraction equations. To clarify this, recall the comparison of the woman on the coastal island with the woman living next to the shopping center. Assume that the woman on the coastal island has a large family, is relatively wealthy, and that the family has several autos, while the second family is moderate in size, relatively poor, and has one automobile. Other things the same, we would expect more shopping trips from the larger family with the higher income and greater number of autos. If the effect of car ownership or family size on trip generation were measured from these two observations, however, the opposite would appear to be true. The reason for this is, of course, that the time, cost, and related inconvenience of travel have been left out of the comparison, and their effects on travel behavior have been attributed to socioeconomic variables. As the example illustrates, improperly specifying the trip generation and attraction equations by omitting relevant variables may cause the effects of the variables actually included in the equations to be confounded with the effects of the omitted variables and consequently cause them to be improperly measured (3).

The next section describes how all these elements of choice can be represented in a single model. To the extent that the model can be made to represent the effects of each element of travel behavior, the model can provide answers to the significant policy questions posed. Furthermore, by incorporating the transportation system characteristics explicitly in the model, the planner can investigate the consequences of alternative designs on tripmaking behavior, facilitating the accomplishment of design objectives.

MODEL SPECIFICATION AND VARIABLES

Economic theory provides us with useful guidelines for specifying a demand model: first, because it identifies in a broad, general way the variables that influence demand; and second, because it specifies the general nature of the relationship between these variables and demand. The variables identified by the theory of consumer behavior as relevant in a study of demand are the price of the good or service being investigated, the prices of competing or complementary goods or services, and income.

For urban auto passenger demand the subject commodity has at least two prices that must be considered—automobile travel time and cost. The prices of competing goods are the times and costs of travel by the available transit modes. For transit passenger demand, of course, the prices of the subject commodity are transit cost and travel time, while the relevant prices of substitutes are the times and costs of travel by auto. For auto, the prices of complementary goods are parking charges, toll fees, and the walking time to and from the car. For transit, they are the times and costs of access to and from the transit station.

Economic theory tells us that demand will be negatively related to the prices of the subject commodity and positively related to the prices of substitutes. Demand will be negatively related to the prices of complements.

The relevant income variables include both the incomes of individuals (or households) in the urban area and various measures of output of the activities that attract trips. Demand for most goods is positively related to the incomes of the individuals in the market for the good or service. However, this need not be so, and there are examples of goods for which the demand decreases as income goes up. People substitute a more desirable commodity for the good in question as their incomes rise. For instance, the demand for cheaper cuts of meat may decrease with a rise in incomes because people shift to more expensive cuts of meat.

The need for measures of output of the activities that attract trips stems from transportation's role as a derived demand commodity. That is, transportation is usually not desired for its own sake but rather because it enables the traveler to satisfy another demand such as shopping, work, or personal business. Thus, some measure of the level of operations in the activity from which the demand for transportation is derived is needed in the transportation demand function. This requires disaggregating the trips by trip purpose and specifying the relevant measure of activity for each trip purpose—sales, employment, etc. These measures of activity are the usual attraction variables. All else equal, we expect the demand for transportation to be positively related to the level of operations of the activities served by transportation.

The foregoing variables are the appropriate ones to measure individual demand behavior. Aggregate demand will, of course, be positively related to the number of individuals in the market and often will depend as well on various socioeconomic characteristics of these individuals, such as age, occupation, family size, and ethnic background.

These ideas are incorporated in the following equation, which is a general expression for the urban transportation demand model that we have developed:

$$N(i, j, i \mid P_0, M_0) = \phi\, [\underline{S}(i \mid P_0), \underline{A}(j \mid P_0), \underline{T}(i, j, i \mid P_0, M_0), \underline{C}(i, j, i \mid P_0, M_0), \underline{T}(i, j, i \mid P_0, M_\alpha), \underline{C}(i, j, i \mid P_0, M_\alpha)]$$

where

$N(i, j, i \mid P_0, M_0)$ = the number of round trips between origin i and destination j for purpose P_0 by mode M_0;

$\underline{S}(i \mid P_0)$ = vector of socioeconomic characteristics appropriate to purpose P_0 describing the travelers residing in zone i;

$\underline{A}(j \mid P_0)$ = vector of socioeconomic and land-use characteristics describing the level of activity appropriate to purpose P_0 in destination zone j;

$\underline{T}(i, j, i \mid P_0, M_0)$ = vector of travel time components for the round trip from origin i to destination j for purpose P_0 by mode M_0;

$\underline{C}(i, j, i \mid P_0, M_0)$ = vector of travel cost components for the round trip between origin i and destination j for purpose P_0 by mode M_0;

$\underline{T}(i, j, i \mid P_0, M_\alpha)$ = vector of travel time components for the round trip between origin i and destination j for purpose P_0 by each of the alternative modes ($\alpha = 1, \ldots, n$); and

$\underline{C}(i, j, i \mid P_0, M_\alpha)$ = vector of travel cost components for the round trip between origin i and destination j for purpose P_0 by each of the alternative modes ($\alpha = 1, \ldots, n$).

In words, the equation says that the number of directed round trips between any zonal pair for a given purpose and mode is a function simultaneously of the number of individuals (or households) in the origin zone and their socioeconomic characteristics, the appropriate level of activity and other relevant socioeconomic and land-use characteristics in the destination zone, together with the round-trip travel times and costs of the subject mode as well as those of competing modes. Times and costs of complementary services are included in the vectors of times and costs of the subject mode because they are also negatively related to demand and because it is often difficult in practice to distinguish the characteristics of the subject mode from those of its complementary services. There is an equation for each trip purpose and each mode.

Notice that the dependent variable is the interzonal round trip. It is the interzonal trip because, first, this is the quantity of interest rather than the number of trips generated or attracted by a zone; and second, as discussed earlier, the simultaneity of the decisions about whether to make a trip at all, where to go, and which mode to use require that the socioeconomic characteristics of the origin and destination zones be considered together, along with the trip times and costs required to travel between that specific zonal pair. This necessitates examination of zonal-pair combinations.

It is preferable to analyze the round trip because time and cost conditions on both legs of the trip are considered by the traveler in making his trip decisions. Moreover, it is clear that the return trip selection of mode depends on the modal choice made for the outbound trip, and the destination of the return trip depends on the origin of the outbound trip.

The choice of when to travel (i.e., which hour of the day) is not reflected in the foregoing model. This choice was omitted, not because it is unimportant, but rather because it substantially increases the size and complexity of the model. If the day is disaggregated only into its peak and off-peak components, the number of equations is doubled and the number of variables almost doubled. The number of equations is doubled because separate equations are needed for the peak and off-peak times of day, and the number of variables is almost doubled because separate peak and off-peak variables are needed for each travel time and cost variable. Because of the time and budget limitations of the study, it was not possible to consider a model of this size and complexity, so a simple heuristic device was developed to take account of the choice of time of day.

The model allows for consideration of a number of transit modes. In this study, all transit modes were aggregated into a single heterogeneous mode. This was not done by choice but rather because data were available only for the single heterogeneous mode within the time limitation of the study.

The independent variables include the usual socioeconomic and land-use variables used in the current models to measure trip generation and attraction and at the same time include the system performance variables used to measure the times and costs to the traveler of making the trip by each of the alternative modes.

The socioeconomic and land-use variables tested in this study are straightforward and conventional, and need not be described in detail here. They include population and population density (i.e., population per acre), personal income, car ownership, employment and employment density for relevant industry groups, etc.

Since the system variables are the likely policy variables, they require and deserve lengthier comment. First, because in the view of the user all components of the trip probably contribute to its inconvenience, total door-to-door travel time and cost must be examined rather than only line-haul costs or times. Second, because travelers may react differently to different components of travel time and cost, it is desirable to disaggregate the times and costs into their component parts. Answers to the policy questions listed earlier can only be obtained by disaggregating travel costs and times.

The travel time by transit consists of a walk or drive to the station, the wait at the platform, the line-haul time, the time consumed in any transfers that have to be made, the walk from the terminating station to the final destination, and a component we choose to call schedule delay. The schedule delay is any additional time that may be incurred because the arrival time allowed by the transit schedule may differ from the traveler's preferred arrival time. (If he has a 9:30 appointment, for example, and the nearest transit arrival time is 9:00, the traveler has a 30-minute schedule delay.)

Similarly, the travel time by auto consists of the walk to the auto, the line-haul time, the parking time, the walk from the parking place to the destination, and the schedule delay. (If the auto traveler must leave early to get a parking place, for example, he suffers a schedule delay. Schedule delay for automobile also results from high congestion and queuing situations requiring trip-makers to arrive early in order to make their appointments.)

For automobile trips, the travel costs consist of vehicle operating costs, toll charges, and parking fees. The costs of transit trips include both transit fares and any costs incurred in traveling to or from the transit stations.

When the different components of time and cost are taken as separate explanatory variables, it may be possible to bring the effect of policy actions into much sharper focus. The non-line-haul portions of transit travel time, for example, may be far more onerous than the line-haul time. Auto out-of-pocket costs such as tolls and parking charges are more visible and therefore may be more onerous to the driver than vehicle operating costs. The relationships expressed in the model should reflect these evaluations by the traveler because the estimated responses to the onerous portions of the travel time will be greater than those for the less objectionable segments of the trip.

In our empirical research, travel time and cost were disaggregated into the following components: auto in-vehicle time, auto out-of-vehicle time, transit line-haul time, transit excess time, auto line-haul costs, auto out-of-pocket costs, transit line-haul costs, and transit excess costs. These variables are defined in Appendix A.

BEHAVIORAL ASSUMPTIONS AND MATHEMATICAL FORMS

Three basic mathematical forms of the model were tested: logarithmic, linear, and mixed log and linear. Each of these forms can be described in terms of the behavioral assumptions implied. The logarithmic model assumes that equal relative changes in travel times and costs evoke equal responses in travel demand. Thus it assumes, for example, that a housewife will curtail her trips to the supermarket by the same percentage amount whether her travel costs have increased from 10 to 11 cents or from 10 to 11 dollars.

The linear model, on the other hand, focuses on absolute changes. Its shortcoming is that it assumes that reducing a two-hour trip by, say, 10 minutes is as important as reducing a 20-minute trip by 10 minutes.

We generally prefer the mixed form to either the pure log or linear forms because, by including both linear and logarithmic terms for each variable, the effects of both relative and absolute changes in the variable are measured. Because of its greater generality, the mixed log and linear form has been tested for each equation in the model. This procedure provides empirical evidence on whether absolute or relative changes in each variable are important or whether both are important. The difficulty with the mixed form is that the linear and logarithmic values of a variable are closely correlated (i.e., are collinear). This makes estimation of the separate parameters difficult.

In interpreting the results of our empirical research and in comparing the estimated model parameters with our prior notions of traveler behavior, it is useful to introduce the concept of demand elasticity. For our travel demand model, elasticity is the percentage change in the number of trips demanded for a given purpose and mode in response to a one percent change in one of the variables giving rise to travel demand, assuming all other explanatory variables in the equation are held constant.[1] This is a particularly useful concept for comparing the sensitivity of travel demand to changes in a number of explanatory variables because elasticity is dimensionless. Thus, comparisons are not confused by the particular units in which the variables are expressed.

By convention, an elasticity of less than unity (in absolute value) is called inelastic, and one that is greater than unity (in absolute value) is called elastic. In the former case a given change in an explanatory variable results in a less than proportionate change in demand, while in the latter case the change in demand is greater than proportionate. It is also conventional to call the elasticities with respect to the variables for the subject mode direct elasticities, and the elasticities with respect to the variables for competing modes cross-elasticities. We shall employ this terminology in the remainder of the discussion.

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[1]Elasticity is precisely defined as

$$\eta_x = \frac{\partial N/N}{\partial x/x} = \frac{x}{N}\frac{\partial N}{\partial x}$$

where η_x is the elasticity of travel demand, N, with respect to variable x. It should be noted that, in general, the elasticity is not equivalent to the coefficients in a regression equation. The elasticity expresses a ratio of relative changes while, for example, the coefficient in a linear model expresses a ratio of unit changes. The latter ratio is dependent on the choice of units—minutes vs hours, for example—while the former ratio is independent of the units selected.

TABLE 1

ALTERNATIVE MATHEMATICAL FORMS OF THE MODEL

Model Form	Elasticity	Form Estimated
Logarithmic		
$N = KX^{\alpha}$	α	$\ln N = \ln K + \alpha \ln X$
Linear		
$N = K + \alpha X$	$\alpha \frac{X}{N}$	$N = K + \alpha X$
Mixed log and linear		
$N = KX^{\alpha} e^{\beta X}$	$\alpha + \beta X$	$\ln N = \ln K + \alpha \ln X + \beta X$
$N = K + \alpha \ln X + \beta X$	$\frac{\alpha + \beta X}{N}$	$N = K + \alpha \ln X + \beta X$

N = dependent variable,
X = independent variable,
K, α, β = parameters to be estimated.

Other things equal, we expect the elasticities with respect to the times and costs of travel by the subject mode (the direct elasticities) to be negative. Thus, we expect more trips by a given mode the less the cost and inconvenience of travel by that mode. The elasticities with respect to the travel times and costs of competing modes (the cross-elasticities) should be positive. We expect more trips by a given mode the greater the cost and inconvenience of travel by alternative modes.

The relationship between the model parameters and elasticities for each model form is given in Table 1. The log model implies that the elasticities are constant over the entire range of the variables. The log model is the single case where the elasticities are equal to the coefficients. The linear model implies that the elasticity depends on the level of the variable and accordingly it varies continuously as the level of the variable changes. In the mixed form of the model, the elasticity has both a constant and a variable term.

ESTIMATION TECHNIQUE

The model was estimated by means of constrained multiple regression analysis. This method of estimation consists of estimating parameters by minimizing the sum of squared deviations as with ordinary least squares but performing this minimization while satisfying certain prespecified conditions derived from a priori information. The constrained least squares regression technique used in this study states the problem as an equivalent quadratic programming problem.

One reason for the use of constrained regression analysis is related to the problem of unequal zone sizes. Since zones cannot generally be selected to be of equal size (expressed in terms of either area or population), the model must account for differences, particularly with respect to population. Thus a zone with twice as many people, other things being equal, is likely to produce roughly twice as many trips.

We may consider the problem from another point of view. Suppose we have a model to describe the number of trips from adjacent zones A and B, having similar characteristics, to another zone, C. Let us define a new zone, A′, which is the geographic zone encompassed by zones A and B. The models should predict the same number of trips from A′ to C as the number of trips from A to C plus the number of trips from B to C. This will only be the case if the model is homogeneous in the first degree with respect to the variables describing zone size. Since it is necessary for the model to behave in this way, parameters associated with the zone size-related variables must be made to behave appropriately in the constrained regression formula. This was done by constraining the demand elasticity with respect to the size variables to be unity.

The main problem, however, requiring prespecified conditions on the values of the estimated parameters is collinearity. In this study collinearity can be attributed either to the form of the model or to the nature of the variables. As an example of the first case, a model that contains both the linear and the logarithmic forms of a variable is necessarily subject to some degree of collinearity. The second case of collinearity occurs when trip behavior is independently influenced by two variables which show a close relationship to each other, either structurally or spuriously. Modal choice may, for instance, depend on car ownership as well as income of the trip-makers. The structural collinearity results because car ownership itself is related to income. Because of the statistical problems resulting from collinearity, it is very difficult to assess the individual effect of collinear variables unless some additional information is provided. It is often possible to specify the sign or reasonable ranges of a parameter from a priori knowledge or economic theory. The expected signs of the elasticities with respect to the system performance variables were described earlier. Constrained regression allows the analyst to take advantage of this information. In such a case, this information regarding a variable is explicitly taken into account by constraining the corresponding parameters; it then becomes possible to estimate the individual effect of the collinear variable.

Constrained regression was used to treat collinearity by imposing appropriate sign constraints on the direct elasticities and cross-elasticities of the system variables. This a priori specification of the parameter signs is an application of the economic theory of demand.

DISCUSSION OF EMPIRICAL RESULTS

The parameters for the model were estimated using data for the Boston metropolitan area. Although equations were estimated for several additional trip purposes, we have selected work and shopping trips to illustrate the application of these models. It is important to emphasize the illustrative nature of these results. The empirical work suffered from all of the normal handicaps, such as lack of time and funds for a full exploration, but in addition was dependent on input data that were never intended for this model.

Perhaps the most serious limitation in the available data was the fact that transit trips represent all non-auto trips whether they are commuter rail, subway, or bus. The heterogeneous nature of the transit mode made it extremely difficult to obtain estimates for the parameters associated with the transit variables. Since most research in urban travel is oriented toward highway transportation, it is not surprising that the existing transit data are less carefully compiled than the auto data, but this practice severely inhibits research on transit demand, and because of the interdependencies of auto and transit demand makes research on auto demand more difficult.

Tables 2 and 3 give the elasticities of demand for auto and transit work and shopping trips with respect to each component of travel time and travel cost. The complete auto

TABLE 2

ELASTICITIES OF PASSENGER TRAVEL DEMAND WITH RESPECT TO THE COMPONENTS OF TRAVEL TIME

Trip Purpose	R^2	Auto Trips			
		Direct Elasticities		Cross-Elasticities	
		Auto In-Vehicle	Auto Out-of-Vehicle	Transit Line-Haul	Transit Excess
Work	.41	-.82	-1.437	0	.373
Shopping	.55	-1.02	-1.440	.0950	0
		Transit Trips			
Trip Purpose	R^2	Direct Elasticities		Cross-Elasticities	
		Transit Line-Haul	Transit Excess	Auto In-Vehicle	Auto Out-of-Vehicle
Work	.35	-.39	-.709	0	0
Shopping	.63	-.593[a]		0	0

[a]The available shopping transit trip sample was unsuitable for estimating elasticities for the disaggregated time components.

TABLE 3

ELASTICITIES OF PASSENGER TRAVEL DEMAND WITH RESPECT TO THE COMPONENTS OF TRAVEL COST

Trip Purpose	Auto Trips			
	Direct Elasticities		Cross-Elasticities	
	Auto Line-Haul	Auto Out-of-Pocket	Transit Line-Haul	Transit Excess
Work	-.494	-.071	.138	0
Shopping	-.878	-1.65	0	0

Trip Purpose	Transit Trips			
	Direct Elasticities		Cross-Elasticities	
	Transit Line-Haul	Transit Excess	Auto Line-Haul	Auto Out-of-Pocket
Work	-.09	-.100	0	0
Shopping	-.323[a]		0	0

[a]The available shopping transit trip sample was unsuitable for estimating elasticities for the disaggregated cost components.

and transit work and shopping demand equations from which these elasticities were computed are given in Appendix B. The elasticities in the tables were calculated at the mean value of the variables. In general, the elasticities vary depending on the levels of the variables because the variables are usually expressed in both linear and logarithmic form.

Let us first consider travel time. The results indicate that for auto work trips demand is inelastic with respect to auto in-vehicle time, while auto shopping trips are unitary elastic with respect to auto in-vehicle time. This result is not surprising, since the greater urgency of the work trip would lead one to expect the elasticity of demand for work trips to be less than that for shopping trips.

On the other hand, the elasticities of demand for both work and shopping trips with respect to out-of-vehicle times are nearly identical and substantially greater than the in-vehicle time elasticities. This result lends credence to the generally accepted hypothesis (although generally disregarded in extant models) that out-of-vehicle times are more onerous than in-vehicle times. This phenomenon helps to explain the popularity of the suburban industrial parks and shopping centers, where workers or shoppers can park near their final destinations.

Keeping in mind the problems of the transit data used to estimate the parameter of the system, it would appear that auto work trips are slightly sensitive to transit excess times, i.e., the time required to get to and from the transit system, to wait, or to transfer. All the other cross-elasticities are either zero or nearly so. This indicates that transit travel times do not strongly influence the amount of auto travel, and that the use of the auto mode is more a result of socioeconomic characteristics than of the comparative travel times by transit. (The zero values for these cross-elasticities should not be taken literally, of course. They are zero because the constraints were binding, not because they were estimated to be zero. Thus, they should be interpreted as a lack of empirical evidence in the sample of a positive cross-elasticity rather than as literally zero.)

These cross-elasticity estimates indicate that there is not much promise for reducing auto congestion by improving transit service. The results further indicate that improvement in transit excess travel time will be more consequential in this regard than improvement in transit line-haul times. Of course, the effects of major technological or organizational changes in the transit system cannot be readily inferred from the model as it has been estimated, but the magnitudes discovered may be significant at least for the direction of further research.

If we consider the effects of travel times on transit demand, we find the demand to be relatively inelastic with respect to the transit time components analyzed and, as with the auto results, the effect of excess time is substantially more pronounced than that of line-haul time. Unfortunately, sample considerations made it impossible to disaggregate the transit time components for shopping trips.

In the case of transit travel, all the cross-elasticities with respect to the auto time components turned out to be zero. This result is generally symmetric with the time cross-elasticities in the auto equations and reinforces our observation that the choice of mode is determined more by the socioeconomic characteristics of the traveler than by comparative travel times.

Let us now turn to the effects of travel costs on demand (Table 3). For auto trips, the effect of costs on travel demand appears to be substantially different for the two trip purposes. The demands for both work and shopping auto trips are inelastic with respect to line-haul travel costs (essentially the operating costs of an automobile), but work trips are much more inelastic than shopping trips with respect to this cost component.

When we examine the effect of out-of-pocket expenses (parking and tolls), the difference between the two trip purposes is far more pronounced. The demand for shopping trips is highly elastic with respect to out-of-pocket costs, while the demand for work trips is almost totally inelastic with respect to such costs. These results have some very interesting implications for evaluating an increase in tolls as a means of reducing congestion on a bridge or tunnel. The low elasticity for auto work trips suggests that an increase in tolls would have little effect on morning peak traffic because most of these trips are work trips. If the real problem is the afternoon peak, however, a toll increase may substantially reduce congestion because many of these trips are shopping trips.

It is interesting that shopping trips are consistently more sensitive than work trips to changes in the time and cost of auto travel.

The cross-elasticities of demand for auto trips with respect to transit cost components are, for all practical purposes, zero. We would not place a great deal of significance on the small value of the cross-elasticity with respect to transit line-haul costs for work trips.

Finally, the elasticities of demand with respect to costs for transit trips are highly inelastic and no cross-elasticities appear. This indicates that a decrease in transit fares would not substantially increase ridership and would only add to transit revenue difficulties. On the other hand, it implies that a fare increase would increase revenues because it would cause a less than proportionate drop in ridership.

In the preceding discussion we have drawn a variety of inferences about travel behavior. It is worth noting that it did not require extensive computer simulation to develop these observations; rather they were drawn directly from the model parameters. Many additional inferences about travel behavior could be made, but those already presented should be enough to illustrate the richness of the model in evaluating policy decisions, which is the primary purpose of this presentation. Perhaps the most important finding of the empirical results, however, is the lack of evidence of significant cross-relationships between auto and transit demands. The cross-elasticities for both time and cost are zero for almost all components, implying that socioeconomic factors rather than transportation system characteristics are the principal determinants of modal choice. All of these conclusions are, of course, subject to the qualifications stated earlier regarding the transit data and the sample, as well as to the statistical reliability of the estimates.

STATISTICAL RELIABILITY

In comparing the model presented here with those currently in use, some discussion is in order regarding the statistical reliability of the estimates. In particular, we often look at measures of goodness of fit such as the estimated coefficient of multiple determination (R^2) as an indication of the degree of success in explaining the variations in traffic movements in the base data. We are accustomed to finding very high levels of R^2 for trip generation and attraction equations, suggesting that a high proportion of traffic movements have been explained, but such levels may be extremely deceptive when our interest is in the origin/destination pattern of trips.

In our model the values of R^2 are substantially lower than those generally reported—the values in Table 2 range from 0.35 to 0.63. In comparing these correlation statistics with those generally reported, however, it is necessary to recognize that our results show the percentage of zone-to-zone traffic explained whereas the correlation statistics reported for conventional models relate only to the number of trips leaving or arriving in a zone. It is obviously more difficult to predict interzonal movements than the total number of trips leaving or arriving in a zone. Therefore, lower values of R^2 for our model are not surprising. It should also be pointed out that the values of R^2 obtained with these models are not unusual in economic cross section analysis.

It is not unreasonable to believe that if values of R^2 were obtained for zone-to-zone trips for the existing models, they would be of lower magnitude than those found in our study, particularly if corrections are made for the number of degrees of freedom. The data used in this study, though not very satisfactory, are no worse than those used in other traffic demand studies and there is reason to believe they were used at least as efficiently in our model as they have been used in other demand models. This suggests that the amount of uncertainty in the estimates of interzonal traffic flows in the existing studies may be substantially higher than has generally been recognized.

Some of the high residual variability is likely to be due to inadequacies of the available data and to errors in specifying the model. As was pointed out earlier, readily available data had to be used and these data had not been compiled for use in estimating this type of model, and some variables considered important were not available. The heterogeneous transit trip was the most severe problem of the analysis. We anticipate that the home interview studies do provide a sound data base for the initial exploration of these models, but should be compiled somewhat differently for this application. When the testing opportunities of readily available data have been exhausted, some revision in the data collection process may be necessary to improve the estimates. Such revision should be premised on testing the hypotheses of the model and improving the quantitative estimates of the policy-oriented relationships.

While many mathematical forms of the model were tested in our empirical analysis, time did not permit an exhaustive study of these forms. Some revision of the form may also be useful in improving the results.

The high level of residual error in estimating the total choice mechanism (as opposed to a single aspect) should be regarded as a danger signal by the planner. The result implies high uncertainty in our predictions of the effects of changes in the transportation system. When account is taken of sampling errors and errors in predicting independent variables, in addition to the generally low correlation statistics, it is clear that the uncertainty in predicting origin and destination traffic movements is very great indeed. The planner must therefore be extremely cautious in his decisions and explicitly recognize that his evaluations are subject to this uncertainty.

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Appendix A

DEFINITIONS OF TIME AND COST VARIABLES USED IN THE ESTIMATION OF THE MODEL

Time Variables

Transit line-haul time = in-vehicle time spent in the principal transit mode.

Transit excess time = travel spent outside the principal transit mode. It includes time spent in auto, feeder bus, or walking to or from the principal transit mode. It is made up of the following components:

Travel time from origin to principal mode first station;
Waiting time at principal transit mode station;
Transfer time; and
Travel time from last principal mode station to destination.

Auto in-vehicle time = line-haul time from zone centroid to zone centroid plus parking time.

Auto out-of-vehicle time = walk-to-car time at origin of trip and time spent in walk from parking place to destination.

Cost Variables

Transit line-haul cost = fare paid on the principal transit mode.

Transit excess cost = money spent traveling to and from the principal transit mode.

Auto line-haul cost = operating cost of driving an automobile from the zone of origin to the zone of destination.

Auto out-of-pocket costs = tolls plus parking charges.

Appendix B

Tables B-1 through B-4 give the auto and transit work and shopping trip equations from which the elasticities in Tables 2 and 3 were computed. Table B-5 gives the means of the system variables.

TABLE B-1

AUTO WORK TRIPS

$$\text{Dependent variable} = \left\{ \frac{\text{Number of directed work round trips by auto}}{\left[\text{Employed labor force in zone of residence}\right] \times \left[\text{Employment in zone of work as a proportion of total employment in the region}\right]} \right\}$$

Independent variables:

Description	Coefficient
Constant	-31.0250
In-vehicle time—auto	*
ln (In-vehicle time—auto)	-1.7973
Out-of-vehicle time—auto	*
ln (Out-of-vehicle time—auto)	-3.1387
Line-haul time—transit	*
ln (line-haul time—transit)	*
Excess time—transit	*
ln (Excess time—transit)	.8153
Line-haul cost—auto	*
ln (Line-haul cost—auto)	-1.0793
Out-of-pocket costs—auto	*
ln (Out-of-pocket costs—auto)	-.1552
Line-haul cost—transit	*
ln (Line-haul costs—transit)	.3034
Excess cost—transit	*
ln (Excess cost—transit)	*
Median income of households and unrelated individuals in zone of residence	.0020
ln (Median income of households and unrelated individuals in zone of residence)	6.1168
Number of cars per capita in zone of residence	13.2677
ln (Number of cars per capita in zone of residence)	.0270
Employment density in zone of work	-.0063

Form of the model:

$$\frac{N}{Y} = \alpha X + \beta \ln X$$

$$\eta_X = \frac{\alpha X + \beta}{N} Y$$

where

η_X = elasticity of demand with respect to variable X

N = number of trips

X = independent variables

$$Y = \left[\text{employed labor force in zone of residence}\right] \times \left[\text{employment in zone of work as a proportion of total employment in the region}\right]$$

α, β = estimated parameters

*Variables introduced in the model which take a zero coefficient due to the use of the constrained regression technique.

TABLE B-2

AUTO SHOPPING TRIPS

Dependent variable = ln (Number of directed shopping round trips by auto)

Independent variables:

Description	Coefficient
Constant	-2.733324
In-vehicle time—auto	-.024824
ln (In-vehicle time—auto)	-.081710
Out-of-vehicle time—auto	*
ln (Out-of-vehicle time—auto)	-1.439808
Line-haul time—transit	*
ln (Line-haul time—transit)	.095003
Excess time—transit	*
ln (Excess time—transit)	*
Line-haul cost—auto	*
ln (Line-haul cost—auto)	-.878061
Out-of-pocket cost—auto	-.050591
ln (Out-of-pocket cost—auto)	-.853097
Line-haul cost—transit	*
ln (Line-haul cost—transit)	*
Excess cost—transit	*
ln (Excess cost—transit)	*
ln (Number of households in zone of residence)	1.000000
Number of persons per household in zone of residence	.583934
ln (Number of persons per households in zone of residence)	-3.048188
Median income of households and unrelated individuals	-.000029
ln (Median income of households and unrelated individuals)	.304834
Number of cars per capita in zone of residence	15.303761
ln (Number of cars per capita in zone of residence)	-2.341933
Density of employment in retail trade in zone of destination	.086956
ln (Density of employment in retail trade in zone of destination)	-.759571
ln (Employment in retail trade in zone of destination as a proportion of total regional employment in retail trade)	1.000000

Form of the model:

$$N = X^{\alpha} e^{\beta X}$$

$$\eta_X = \alpha + \beta X$$

where

η_X = elasticity of demand with respect to variable X

N = number of trips

X = independent variable

α, β = estimated parameters

*Variables introduced in the model which take a zero coefficient due to the use of the constrained regression technique.

TABLE B-3

TRANSIT WORK TRIPS

Dependent variable = ln (Number of directed work round trips by transit)

Independent variables:

Description	Coefficient
Constant	-12.158232
In-vehicle time—auto	*
ln (In-vehicle time—auto)	*
Out-of-vehicle time—auto	*
ln (Out-of-vehicle time—auto)	*
Line-haul time—transit	-0.005843
ln (Line-haul time—transit)	-0.190862
Excess time—transit	-.025288
ln (Excess time—transit)	.462262
Line-haul cost—auto	*
ln (Line-haul cost—auto)	*
Out-of-pocket costs—auto	*
ln (Out-of-pocket costs—auto)	*
Line-haul cost—transit	-0.002362
ln (Line-haul cost—transit)	.036214
Excess cost—transit	-.005095
ln (Excess cost—transit)	*
Number of cars per capita in zone of residence	1.777146
ln (Number of cars per capita in zone of residence)	-1.163856
ln (Median income of households and unrelated individuals in zone of residence)	1.144006
ln (Employed labor force in zone of residence)	1.000000
ln (Employment in zone of work as a proportion of total employment in region)	1.000000

Form of the model:

$$N = X^{\alpha} e^{\beta X}$$

$$\eta_X = \alpha + \beta X$$

where

η_X = elasticity of demand with respect to variable X

N = number of trips

X = independent variables

α, β = estimated parameters

*Variables introduced in the model which take a zero coefficient due to the use of the constrained regression technique.

TABLE B-4

TRANSIT SHOPPING TRIPS

Dependent variable = $\ln \left\{ \dfrac{\text{Number of directed shopping round trips by transit}}{\left[\begin{array}{l}\text{Number of households}\\ \text{in zone of residence}\end{array}\right] \times \left[\begin{array}{l}\text{Employment in retail trade}\\ \text{in zone of destination as a}\\ \text{proportion of employment}\\ \text{in retail trade in region}\end{array}\right]} \right\}$

Independent variables:

Description	Coefficient
Constant	-1.976884
ln (Total aggregated time—transit)	-.593240
ln (Total aggregated cost—transit)	-.323692
ln (Number of persons per household)	2.483299
ln (Median income of households in zone of residence)	-.048626
ln (Density of employment in retail trade)	.030759
ln (Employment in personal business activities in zone of destination as a proportion of employment in personal business in region)	-.739325

Form of the model: log/log

$$\frac{N}{Y} = X^{\alpha}$$

$$\eta_X = \alpha$$

where

η_X = elasticity of demand with respect to variable X

N = number of trips

X = independent variable

$Y = \left[\begin{array}{l}\text{number of households}\\ \text{in zone of residence}\end{array}\right] \times \left[\begin{array}{l}\text{employment in retail trade in zone of}\\ \text{destination as a proportion of total}\\ \text{employment in retail trade in region}\end{array}\right]$

α = estimated parameter

TABLE B-5

MEANS OF SYSTEM CHARACTERISTIC VARIABLES FOR INTERZONAL TRIPS IN THE BOSTON AREA

Description of Variable	Work Trips*		Shopping Trips
	Transit Sample	Auto Sample	(Single Sample)
Line-haul time—transit (minutes)	34.69	35.24	27.13
Excess time—transit (minutes)	46.84	52.58	47.76
In-vehicle time—auto (minutes)	54.43	49.73	37.15
Out-of-vehicle time—auto (minutes)	5.40	5.15	5.44
Line-haul cost—transit (cents)	56.06	51.69	48.95
Excess cost—transit (cents)	20.01	22.58	15.43
Line-haul cost—auto (cents)	36.88	34.32	20.70
Out-of-pocket cost—auto (cents)	18.31	8.35	16.35

*Separate samples were used for work trips by auto and by transit.