# STRUCTURAL TRAVEL DEMAND MODELS: AN INTERCITY APPLICATION

John B. Peers and Michael Bevilacqua, Alan M. Voorhees and Associates, Inc.

Conventional sequential transportation models clearly have limitations as estimators of intercity travel demand. Despite their theoretical advantage, little work has been carried out in the full application of behavioral or "structural" models. Structural-model development is focused primarily on disaggregate models, particularly for modal split. This paper discusses the development of an alternative approach, that of developing a set of direct-demand models for estimating intercity transit travel for a Sacramento-Stockton-San Francisco Bay Area corridor study. A series of judgments are described that identify why structural models rather than sequential models were chosen and why direct-demand models rather than probabalistic-choice models were used. The methodology of calibration, including variable selection and equation development, validation, and forecasting, is outlined. Emphasis is placed on the trade-offs to be made among policy responsiveness, accuracy, and the practical problems of developing and using such forecasting tools. The material has been oriented toward the planner-engineer faced with the practical issues of selecting and using intercity travel demand forecasting procedures.

•ENGINEERS and planners in transportation forecasting have become more aware recently of the changing and searching questions that they are required to answer. They also are aware that existing modeling techniques, particularly the best known models forming the sequential decision-making process, have severe shortcomings in their abilities to answer these questions (1). In the planning of the 1950s and 1960s, the emphasis was on building new transportation facilities, which were nearly always highways, to maintain or improve existing levels of service and to match a long-term demand forecast. The major restraint on such plans was the budget. Large quantities of money, particularly the Highway Trust Fund, were set aside for rural and urban freeway facilities. The physical structure had been anticipated, and concern was on the size of structures in terms of the number of freeway lanes and capacities at intersections.

For a transportation corridor study between Sacramento, Stockton, and the San Francisco Bay Area, concerns were with the development of a staged plan for transportation (specifically transit) improvement. Putting all the findings in a format that could be understood by many people rather than precisely understood by a few also was necessary. The clients for the study, the California Department of Transportation, the California State Senate, and the U.S. Department of Transportation, reinforced the need for general understanding. In addition, the clients wanted to know what kind of assumptions were included when patronage estimates were made, whether the assumptions (such as parking or fare costs or frequency of service) were open to public policy change, and what effect such changes would have on transit programs in terms of market response of riders and consequent financial costs and revenues.

In such an environment, to combine the benefits of the structural models with the advantages of logical behavioral relationships, responsiveness to differing assumptions of policy issues, and speed of turnaround when questions arose that required additional analysis clearly was mandated.

## PROBLEM OF CHOICE-MODELING DECISION

The history of travel forecasting has been one of successively more comprehensive attempts to move from models that simply project demand to those that provide a coherent representation and organization of the complex of consumer attitudes, behavior, and perceptions of service attributes that produce travel demand. The structure of such models should, in theory, permit them to respond to significant changes in the transportation service variables specified for the model regardless of whether the level of service associated with a specific model has been experienced previously.

A primary objective of the Sacramento-Stockton-San Francisco Bay Area corridor study was the assessment of the feasibility of alternative forms of transit systems and the evaluation of their impacts across a wide range of issues. In conjunction with this, the necessity to effectively forecast the possible demand for intercity travel became apparent. For most of the systems proposed for the corridor, no previous operational experience existed within this region from which data on travel characteristics could be monitored and collected. Therefore, if a model that could effectively estimate travel on these "new" systems was to be employed, the model had to be responsive to service as well as to user attributes. The underlying strategy associated with the estimation of the demand for intercity travel was to develop a series of models that established predictable relationships among physical systems, demographic characteristics, activity distributions, and travel behavior. Several specific criteria were defined in the effort to develop a demand-estimation tool that would have

1. The ability to incorporate a broadened range of such service characteristics of the transportation system;
2. The capability of incorporating responsiveness to nontransit events, such as gasoline price increases and speed limits, into its structure;
3. Transferability to other corridors; and
4. Both long-range and short-range usefulness not only as a planning tool but also as a link-specific design tool for new system improvements.

Conventional urban transportation models for estimating travel demand have a number of deficiencies that limit their validity and utility in estimating both travel behavior and patterns and the impact assessment of new transportation facilities and modes.

1. The estimated number of trips produced by a household is typically not sensitive to the quality of service provided by the transportation system. Accordingly, conventional models show travel demand as being insensitive to service whether there are 1, 2, or 3 transportation modes available and whether the transport facilities available are continually overloaded or are continually free-flowing. As a consequence, no direct mechanism exists in the demand-estimation process to deal with latent or induced travel demand or to reflect transportation system quality or transportation pricing effects.
2. Most conventional models are sequential and involve 4 step functions in estimating demand: trip generation, trip distribution, modal choice, and route assignment. The sequence in which these functions are carried out predetermines the underlying behavioral rationale and presupposes a travel-decision process that is not substantiated with factual behavioral research.
3. Too many conventional models are derived from empirical data-fitting without taking account of any underlying theoretical foundations or behavioral hypotheses. Consequently, their behavioral properties are suspect and their utility for travel-demand forecasting or policy analysis under differing conditions and constraints is highly unsatisfactory.
4. Many conventional models lack any direct expression of public policy variables in their formulation. As a result, their use and value in planning analysis are restricted substantially.
5. The lack of fundamental theory and behavioral properties underlying most conventional models, as well as their failure to incorporate policy sensitivity, makes the

transferability of most models highly dubious. This means that the model relationships developed for that area can seldom be translated for use in other urban areas; it also means that the issue of "new mode" or facilities introduced into an urban- or intercity-corridor setting poses a serious problem for conventional models because of their behavioral deficiencies and questionable forecasting reliability. The record to date in widely varying patronage projections for the new system is ample evidence of this problem.

The first 4 of these limitations could not be readily accepted for the intercity-corridor study. Such features as the identification of causal relationships between trip making and user and system attributes and the ability to express the decision to travel as a simultaneous function of mode, destination, and route made it clear that structural models should be selected as the most effective technique for satisfying intercity-travel requirements.

The terms behavioral and structural are commonly interchanged freely in modeling. Structural models that can be specified so that they relate the decision to travel to the characteristics of the trip maker can be considered behavioral (2).

## STRUCTURAL MODEL ALTERNATIVES

Structural models can be separated into 2 distinct classes: direct demand and probabilistic choice. Direct-demand models estimate travel demand by origin, destination, and mode with a single equation (3). Probabilistic-choice models estimate the probability of choosing 1 alternative from a set of available alternatives (4). More specifically, the probabilistic-choice model potentially estimates the probability or likelihood of a traveler's making a trip conditional on 6 decisions—frequency of trip, destination, mode, time of day, choice of route, and purpose—or on a subset of these 6 decisions. These probabilities are evaluated on a per-person or per-household level. To determine the absolute number of trips within each category, one must multiply this function by the total number of households or persons at the origin zone.

The decision to choose the aggregate direct-demand model to estimate future travel demand in the Sacramento-Stockton-San Francisco Bay Area corridor was based on several issues including the availability and requirements for data, experience of model use, special features of each model, and subsequent costs in time and money.

Data requirements perhaps constitute the foremost constraint to the development of a probabilistic-choice model. Both direct-demand and probabilistic-choice models can be calibrated with either aggregate or disaggregate data. It is accepted that modal split, or market share, is a function of socioeconomic indicators such as income. It follows that probabilistic-choice models, which define market share, respond best to market-segmented, or disaggregate, data. This presents several problems. Existing travel information as compiled by the origin-destination surveys conducted in the 1960s generally is not in a format that is compatible with the calibration of disaggregate models. Therefore, expending significant efforts to reformat the data becomes necessary. In most cases, and in this study, the time required for the compilation of base-year household data to obtain information on choice of mode, frequency of travel, choice of destination, time of day, choice of route, and purpose precluded pursuing this course. In the corridor study, the option of using market segmentation that stratified the data by income class, household-ownership category, and household size was considered to minimize base-year data reformatting; however, it would have been necessary to calibrate 90 models for the transit mode alone (5 purposes × 3 household sizes × 3 income classes × 2 household-ownership categories). In contrast to this, it was estimated that only 5 direct-demand models for transit need be calibrated.

In addition to base-year data format needs and the number of models requiring calibration, there is the issue of aggregate or disaggregate modeling in the future year. Estimating future-year population and employment to produce reasonable and reliable results is difficult. Reliable techniques have not been devised by which reasonable estimates can be expected for substratifications of population and employment. To obtain such figures would require the application of extrapolated "factors" that, in turn, are highly vulnerable to error. The suggestion is that, the higher the level of disaggregation is, the less reliable the data become.

Experience and competition by destination and mode also were important issues. With regard to experience, an additional disadvantage associated with the development of probabilistic-choice models is that there is practically no production experience in their development and application as predictive models. Although a maximum-likelihood technique for the calibration of probabilistic-choice models has been developed, there have been limited opportunities to apply and test the results of this procedure. Until recently, most probabilistic-choice models, developed as operational rather than research tools, have been used as modal-split or explanatory models (5).

An advantage of the probabilistic-choice model is its sensitivity to competing activities and competing systems. The problem of competing activities has been partially overcome by the proper specification of the direct-demand model, that is, by the expression of the attraction variables in a form that represents the market share as opposed to the magnitude. The ability of direct-demand models to respond to alternative-mode system changes depends to a large extent on the ability to include a comprehensive set of alternative-mode system variables in the model. This could be achieved for transit models in the corridor study.

Having considered the problems associated with assembling base-year disaggregate data, the significantly increased effort implied by calibrating and estimating 90 models, the forecasting of market-segmented data, and the inadequate production-oriented experience of probabalistic-choice models, we decided that an aggregate direct-demand modeling procedure would be the most feasible approach to pursue. We decided to calibrate less precise models with good forecast data rather than to define highly refined models with forecast data of questionable reliability.

## DIRECT-DEMAND MODELS

Direct-demand models can be specified as either modal-abstract models or modal-specific models. The primary advantage of a modal-abstract model is that only 1 equation is necessary to estimate travel demand (6). This is particularly advantageous when one is estimating demands for new modes that are not in operation or for which there are no existing prototypes. The primary disadvantage associated with developing a modal-abstract model, however, is that it requires that each alternative mode be described by a single set of variables. The selection of a set of attributes that can effectively represent the wide range of system features characterizing different modes can present a major problem because homogenizing attributes means the loss of model responsiveness to policy changes. Further, the ability to identify cross elasticities becomes impaired. An attempt was made, however, to calibrate a set of modal-abstract models; it was unsuccessful because of data inadequacies.

Modal-specific models require separate formulation of generically different modal forms. Although it may be possible to develop separate models for automobile, bus, rail, and airplane modes, the distinction generally is limited to automobile and transit. The separate formulation of models by mode provides the opportunity to achieve the maximum flexibility in model specification. Furthermore, by modal-specific modeling, those intrinsic qualities associated with the automobile, such as privacy and convenience, as well as those associated with transit, will be reflected in the model calibration. Given the provision for greater system and user sensitivity that is afforded by modal-specific models, we decided to adopt these functional forms (that is, automobile and transit) in the development of the direct-demand models.

It was necessary to determine which model form would be best suited for the intercity application. Various mathematical forms have been suggested and applied in the development of previous demand models. Basically, there are 3 forms (with respect to the variables) that the model function can assume: linear, nonlinear, and mixed. The nonlinear form includes product forms of powers and exponentials. The decision to choose one form over the other is more pragmatic than theoretical. Relatively little research has been conducted to assess the influences of model form on the performance of the model. However, several observations can be made with respect to the most reasonable form for a model. From an examination of the function one can see that the dependent variable in nonlinear models is much more responsive to a given change in an independent variable than it is in linear models. In addition, travel data do not support the idea that trip makers behave in a manner that is responsive to changes in individual causal variables that have been arranged in a linear function. Finally, nonlinear functions have been shown to be more effective in describing observed tripmaking behavior. Although the issue cannot be definitively resolved, we found that a mixed-form model provided the necessary versatility and fitted the survey data best.

## MODEL CALIBRATION

Before calibration could begin, the data for calibration had to be developed. The prime source of trip data was the Bay Area Transportation Study (BATS) files, developed from home-interview surveys taken in 1965. The data required reformatting into zone data a 123-zone system covering the San Francisco Bay Area, Sacramento, and Stockton. Ninety zones were included in the Bay Area. For the base year, the highway network was derived from California Department of Transportation data. Four transit networks were coded for the base transit system, 1 pair for off-peak travel and 1 pair for peak travel. Each pair had 1 network for public transit access and walk connectors to the transit facilities. The second network had only private automobile access to the transit facilities. Production-zone socioeconomic data related to households were developed by using expanded home-interview data in the Bay Area from BATS and in the Sacramento and Stockton areas from the equivalent home-interview data collected in 1967 and 1968. The attraction-zone socioeconomic data related to employment categories were developed from surveys that were conducted in conjunction with the home-interview surveys.

The data available for use in calibration included 14 household statistics; 3 automobile-service statistics (walk time, in-vehicle time, total cost per car trip); 8 transit-mode statistics for automobile access by submode; 7 transit-mode statistics for nonautomobile access by submode; 10 destination-zone statistics (mainly subsets of employment data); and 4 subsets of trip data for the classes of purpose (home-based work, shop, other, and non-home-based trips).

The first step of the calibration process was that of attempting to find and identify causal variables. Sample statistics of zone means were listed, and a correlation matrix of variables, including the log and exponential forms of the variables, was developed for identifying correlations between independent variables and trips, the dependent variable. Each variable also was plotted against trips. The matrix and plots were reviewed to produce the best set of variables in their best forms for explaining the variance of trip making. In addition, it was necessary to check for levels of independence or low correlation between independent variables. Constraints were applied to some variables, for example, to a relationship between in-vehicle transit time and out-of-vehicle transit time. This was required because the path-builder algorithm requires weighted values of out-of-vehicle travel time to calculate the minimum time paths. The constraint applied to the model variables, therefore, maintained this minimum-path practice by replacing the 2 variables in-vehicle and out-of-vehicle time by 1 variable:

$$QLT + 2.5\,QXT \qquad (1)$$

where

QLT = transit line time, and
QXT = transit out-of-vehicle time.

## INITIAL MODEL SELECTION

Because an array of variables was known that satisfied the 2 criteria of (a) being strongly correlated with the dependent variable, trip making or demand, and (b) maintaining orthogonality among the exogenous variables, a series of models was produced by using these variables and a nonlinear regression program specifically adopted for this study. The primary virtue of using a nonlinear regression program for estimating the models was that it obviated the need to transform the dependent variables into a linear form. This process of using linear transformations, which is a requirement when applying standard linear regression programs, introduces bias in parameter estimation. The application of a nonlinear regression means that techniques such as restraining variables with reasonable limits need no longer be applied. As a result, the use of nonlinear regression was a significant improvement over standard estimation procedures.

The final set of variables used in specifying the transit models was divided into 3 groups: extensive variables, intensive variables, and system variables. The extensive variables are as follows:

1. Residential population;
2. Employment, by type;
3. Workers; and
4. Locations, magnitude, and net density according to "alternative futures" of moderate northern regional growth with environmental constraints versus slow, southern, dispersed regional growth (current trends).

The intensive variables are as follows:

1. Persons per household,
2. Income per household and income per worker,
3. Cars per household and cars per worker, and
4. Employment per acre (hectometer$^2$).

The system variables are as follows:

1. Automobile speeds (travel time),
2. Automobile out-of-pocket costs,
3. Transit speed (travel time for feeder and line-haul),
4. Transit costs (for feeder and line-haul),
5. Walking and waiting time,
6. Parking costs,
7. Service frequency (peak and off-peak),
8. Terminals per station locations, and
9. Mode and service path.

For each set of models, 4 major statistics were developed that compared the synthesized trips with surveyed data:

1. Error mean,
2. Absolute error mean,
3. Error mean squared, and
4. Coefficient of determination $r^2$.

It was important to ensure that all the variables open to policy action and variation, such as parking pricing or fare structure, were included wherever possible in the models. In some cases this meant accepting one model form over a better fitting model because the better fitting model did not include these important variables. Many techniques were used to analyze and compare the different models produced by this process. However, the most important single criterion was judgment. Because the models selected had to make sense, relationships implied by their structure and parameters had to be reasonable.

An initial set of models was calibrated by using a sample set of data taken from half of the surveyed information. A second set of models was subsequently calibrated for the entire surveyed data. Both sets of models were nearly identical. The 5 transit models developed covered the following:

1. Home-to-work trips by transit,
2. Home-to-work trips by automobile,
3. Home-to-shop trips,
4. Other home-based trips, and
5. Non-home-based trips.

The generic form of all the models was:

$$(\pi_1 P_1 + \pi_2 P_2)\,(\alpha_1 A_1 + \alpha_2 A_2)\; Z_1^{\xi_1} Z_2^{\xi_2} X_1^{\Theta_1} X_2^{\Theta_2} e^{\phi_1 X_1} e^{\phi_2 X_2}$$

where

$P_1$, $P_2$, $A_1$, and $A_2$ = extensive production and attraction variables describing zone size (such as zone populations, employment, and workers);
$Z_1$ and $Z_2$ = intensive production and attraction variables such as cars per worker and retail jobs per area;
$X_1$ and $X_2$ = interchange service variables by mode such as in-vehicle time, out-of-vehicle time, and out-of-pocket costs; and
$\pi$, $\alpha$, $\xi$, $\Theta$, and $\phi$ = model parameters.

## MODEL VALIDATION

The models had been calibrated entirely on base-year data (1965) for the Bay Area only. Even though the Bay Area includes most of the zones and socioeconomic activity, there was a requirement to validate the synthesized trips against corridor travel. At the beginning of the study, some effort had gone into surveying intercity travel for both highways and transit (bus) modes. No corridor travel data for transit travelers were available from the BATS files because transit travelers traveling outside the Bay Area had been recorded only to the transit terminals—airport, bus terminals, and railroad stations.

Interchange pairs along the corridor, particularly those with one end outside the BATS area, were compared for synthesized trips from 1965 socioeconomic data and the 1973 surveys plus some data from the Greyhound Bus Company files and the California Division of Highways annual vehicle counts. Trip-length distributions for survey and synthesized trips also were compared. When we amended the constant for each model for each 5-min interval of weighted trip length, the synthesized trips and surveyed trips maintained close relationships for both trip-length-frequency curves and specific corridor interchanges. Finally a stepwise approach was taken to forecast trips by using future socioeconomic data and future transit and highway networks. Initially, the 1995 networks were used together with 1965 socioeconomic data to produce trip tables. Total trips plus major interchanges along the corridors were inspected to see the effect of the presence of an upgraded set of transit networks. Then the 1965 networks were used together with 1995 socioeconomic data to produce trip tables. Again the total trips and the corridor movements were inspected. Two problems became clear from these analyses. One related to maintaining as linear the extensive variables in the models; the other related to large increases in trips due to increased income. The extensive variables defining zone population, employment, and subsets of population and employment always were kept linear; that is, they were kept in a power-product form without exponents other than unity. The maintenance of this linearity was an important condition because the models were independent of zone size and potentially were more transferable to different zone sizes within the study area or elsewhere. The result of this decision, together with the inclusion of both production (population) and attraction (employment) variables in the model, was that, where, for example, both population and employment doubled, the total number of trips increased 4-fold. To overcome this problem, the attraction variables had to be normalized in each model. This was accomplished by replacing the extensive attraction variable by a new variable that reflected the relative increase in the attraction activity. As a result, the models also became sensitive to the notion of market share; that is, if a large number of attractions were to be added to one zone, then the market share of attractions would increase for that zone and the interchanges between the origin zone and that zone would increase relative to the unchanged zones.

The income issue was a problem mainly because the future income was forecast to increase substantially. Average incomes per household at zone levels in 1965 ranged from \$4,700 to \$13,800. For 1995, estimated average incomes measured in real terms ranged from \$11,700 to \$35,000. A number of the models were highly elastic with respect to increases in income. Work trips for automobile access and shopping trips, for example, had exponents 2.0 and 1.9. That the models become steadily more unstable as the data stray farther from the base-year ranges is accepted. For future data, constraining income values to reduce the effect of this potentially explosive variable was necessary.

In summary, the calibration, validation, and forecasting of the models were developed in 4 steps:

1. Development of calibration data for trips, socioeconomic data, and networks;
2. Development of equations;
3. Validation against corridor movement; and
4. Cautious manipulation of the models to produce future forecast trip tables.

Each step took considerable levels of both time and effort, but for the transit models each step was carried out successfully.

## MODEL APPLICATION

On completion of the calibration and validation stages, we produced a final set of transit models. The specifications of these models are given in Tables 1 through 5. The dependent variable in all of these models is 1-way transit trips. The coefficients of determination and forms of the models are given in Table 6. K is the constant in all of the forms. All of the models yielded reasonable $r^2$ values. The work-purpose models were the best correlated models with $r^2$ values of 0.65 and 0.72 for the public-transportation-access and automobile-access models respectively. The remaining purposes had lower correlations. However, in terms of total transit trip making, the effective $r^2$ value is better than these values might imply because of the dominance of work trips. A weighted average of the $r^2$ by purpose and percentage of intercity transit trips by purpose will yield an effective $r^2$ value of 0.64 for the total trip demand.

The transit and highway networks that would be employed in estimating future-year travel demand were developed at the same time as the transit models were developed. Seven distinct transit system alternatives were chosen to be analyzed. System technologies included express bus and conventional and high-speed rail options. For each of these systems, networks representing each of 3 access modes and 2 time periods were constructed. In all, 42 future-year transit networks were built. In addition, 1 future-year highway network was built.

With regard to the application of the transit models, approximately 84 distinct program packages were defined. These program packages were derived from combinations of the system line-haul alternative, the access mode, the line-haul fare, the access fare, and the demographic growth alternative. Additional program packages were derived from combinations of these independent corridor-specific program packages

**Table 1. Model for home-based work trips, public transportation access.**

| Variable | Description | Coefficient $a_y$ |
|---|---|---|
| $X_1$ | Automobile out-of-pocket cost/transit fare | 0.188 |
| $X_2$ | Income/worker at zone of origin | 0.564 |
| $X_3$ | Vehicles/worker at zone of origin | -1.494 |
| $X_4$ | Transit line time/(2.5 + transit wait time) | -1.355 |
| $X_5$ | Transit line time - automobile line time | -0.028 |
| $X_6$ | Automobile out-of-vehicle time | 0.275 |
| $X_7$ | Workers at zone of origin | — |
| $X_8$ | Jobs at zone of destination | — |

**Table 2. Model for home-based work trips, park-and-ride.**

| Variable | Description | Coefficient $a_y$ |
|---|---|---|
| $X_1$ | Transit fare | -1.137 |
| $X_2$ | Automobile out-of-pocket cost | 0.838 |
| $X_3$ | Income/household at zone of origin | 2.073 |
| $X_4$ | Vehicles/household at zone of origin | 3.864 |
| $X_5$ | Transit wait time + (transit line time/2.5) | -1.161 |
| $X_6$ | Automobile line time | 0.401 |
| $X_7$ | Automobile out-of-vehicle time | 1.806 |
| $X_8$ | Workers at zone of origin | — |
| $X_9$ | Jobs at zone of destination | — |

**Table 3. Model for home-based shopping trips.**

| Variable | Description | Coefficient $a_y$ |
|---|---|---|
| $X_1$ | Transit fare - automobile out-of-pocket cost | -0.0075 |
| $X_2$ | Transit wait time - automobile out-of-vehicle time | 0.0316 |
| $X_3$ | Income/household at zone of origin | 1.868 |
| $X_4$ | Persons/household at zone of origin | 3.839 |
| $X_5$ | Retail jobs/acre at zone of origin | 0.233 |
| $X_6$ | Vehicles/household at zone of origin | -2.479 |
| $X_7$ | Transit line time + (2.5 × transit wait time) | -1.619 |
| $X_8$ | Adults at zone of origin | — |
| $X_9$ | Retail job at zone of destination | — |

Note: 1 job/acre = 2.50 jobs/hm$^2$.

**Table 4. Model for home-based other trips.**

| Variable | Description | Coefficient $a_y$ |
|---|---|---|
| $X_1$ | Transit fare | -0.231 |
| $X_2$ | Income/household at zone of origin | -0.045 |
| $X_3$ | Automobile out-of-pocket cost - transit fare | 0.0046 |
| $X_4$ | Automobile line time | 0.0439 |
| $X_5$ | Automobile out-of-vehicle time | 0.0189 |
| $X_6$ | Transit line time + (2.5 × transit wait time) | -0.0238 |
| $X_7$ | Persons/household at zone of origin | 3.214 |
| $X_8$ | Vehicles/household at zone of origin | -1.537 |
| $X_9$ | Transit line time/(2.5 + transit wait time) | -2.27 |
| $X_{10}$ | Population at zone of destination | 0.00015 |
| $X_{11}$ | Service jobs at zone of destination | 0.00024 |
| $X_{12}$ | Population at zone of origin | — |

**Table 5. Model for non-home-based trips.**

| Variable | Description | Coefficient $a_y$ |
|---|---|---|
| $X_1$ | Transit fare | -1.352 |
| $X_2$ | Automobile out-of-pocket cost | 1.403 |
| $X_3$ | Transit line time/(2.5 + transit wait time) | -4.00 |
| $X_4$ | Automobile line time | 0.951 |
| $X_5$ | Automobile out-of-vehicle time | 0.184 |
| $X_6$ | Population at zone of origin | 0.00044 |
| $X_7$ | Jobs at zone of origin | 0.0002 |
| $X_8$ | Population at zone of destination | 0.00044 |
| $X_9$ | Jobs at zone of destination | 0.0002 |

(such as a rail system between the Bay Area and Sacramento combined with a bus system between the Bay Area and Stockton). Together, more than 100 program packages were described. Trip tables subsequently were estimated for approximately 40 selected program packages. The analyzed program packages were selected so that intercity travel demand for the remaining alternatives could be estimated by interpolation if desired.

As a final evaluation of the transit models, the 1995 rates for interzone transit-demand generation were compared to the rates observed in 1965. In both cases, the total number of interzone transit trips was compared to the area population. In 1965, the transit trip generation rate was 0.09 trip/person; in 1995, for the high-growth alternative, the rate increased to 0.12 to 0.16 trip/person depending on the program package analyzed. Because the interzone transit-trip totals are biased toward longer trips (shorter, intrazone trips are excluded), to expect generation rate to increase with the improvement of intercity transit is not unreasonable. The stability of these generation rates further substantiated the validity of the models and their demand estimates.

## RESPONSE TO ALTERNATIVE POLICIES

Sensitivity analysis is an important result of model development. The capability of the direct-demand models to respond accurately and quickly to alternative assumptions regarding the system and the user, and, therefore, to enable policymakers to see the effect of the policy alternatives they suggest, is a powerful feature. The response of the model to changes can be assessed by the analysis of the elasticities of the transit travel demand with respect to the components of the model. Elasticity can be defined as a dimensionless number that represents the percentage of change in the travel demand for a 1 percent change in any of the independent variables. In defining the elasticity, only 1 variable is changed and the others remain constant. By applying the concept of elasticities, we could analyze the sensitivity of the demand to ranges of the values of the system and user inputs. This technique is useful in analyzing the impact of various policy changes, such as increased fuel prices, decreased automobile speed, and increased transit service frequency on demand for transit travel.

Table 7 gives the elasticities derived for the household variables. Values for the system elasticities have not been shown because they are not always constant. In many cases, they are complex functions and have a meaning only within the context of a specific interchange movement.

As a result of the sensitivity analysis, several interesting relationships can be identified and generalized for the total intercity travel demand in the region.

1. The 30-year increase in corridor population between 1965 and 1995 represented by the low-growth alternative is equivalent to a 60 percent population increase causing a 60 percent increase in total regional transit demand. The moderate-growth alternative is equivalent to an 80 percent population increase causing an 80 percent increase in demand.
2. A 25 percent increase in income per household causes a 26 percent increase in transit demand for intercity travel.
3. A 25 percent increase in car ownership per household causes a 20 percent decrease in total transit trips with transit access, but a doubling of those transit trips with automobile access (mostly long trips).
4. A 100 percent increase in the current price of gas representing a 50 percent increase in out-of-pocket operating costs for automobile travel causes a 60 percent increase in total transit demand for long trips. A 200 percent change in the current downtown parking charge will have the same effect for downtown-oriented trips.
5. For long trips with a 40-min wait and transfer time (assuming that the 40 min is made up of 20 min of walk time and 20 min of wait time), a 50 percent reduction in headway will cause a 60 percent increase in demand. A 10-min reduction in wait time for long trips would produce a similar increase in demand. For shorter trips, this effect would be halved.

Table 6. Coefficients of determination and forms of models in Tables 1 through 5.

| Model | Table | $r^2$ | Form |
|---|---|---|---|
| Home-based work, public access | 1 | 0.65 | $\text{Trips}_{ij} = KX_1^{a_1}X_2^{a_2}X_3^{a_3}X_4^{a_4}e^{a_5X_5}X_6^{a_6}X_7X_8$ |
| Home-based work, park-and-ride | 2 | 0.72 | $\text{Trips}_{ij} = KX_1^{a_1}X_2^{a_2}X_3^{a_3}X_4^{a_4}X_5^{a_5}X_6^{a_6}X_7^{a_7}X_8X_9$ |
| Home-based shop | 3 | 0.43 | $\text{Trips}_{ij} = Ke^{(a_1X_1 - a_2X_2)}X_3^{a_3}X_4^{a_4}X_5^{a_5}X_6^{a_6}X_7^{a_7}X_8X_9$ |
| Home-based other | 4 | 0.47 | $\text{Trips}_{ij} = KX_1^{a_1}X_2^{a_2}e^{a_3X_3}e^{a_4X_4}e^{a_5X_5}e^{a_6X_6}X_7^{a_7}X_8^{a_8}X_9^{a_9}(a_{10}X_{10} + a_{11}X_{11})X_{12}$ |
| Non-home-based | 5 | 0.54 | $\text{Trips}_{ij} = KX_1^{a_1}X_2^{a_2}X_3^{a_3}X_4^{a_4}X_5^{a_5}(a_6X_6 + a_7X_7)(a_8X_8 + a_9X_9)$ |

Table 7. Elasticities for household variables.

| Trip Purpose | Persons/ Household | Income/ Household | Vehicles/ Household |
|---|---|---|---|
| Work, public access | N.A. | 0.56[a] | -1.49[b] |
| Work, park-and-ride | N.A. | 2.07 | 3.86 |
| Shop | 3.84 | 1.87 | -2.48 |
| Other | 3.21 | -0.05 | -1.54 |

Note: N.A. = not applicable.

[a] Income/worker. [b] Vehicles/worker.

6. For long trips (more than 1 hour), an automobile speed limit decrease from 65 to 55 mph (104 to 88 km/h) will cause a 45 percent increase in total transit demand. For short trips, the same change in automobile travel time will result in a 14 percent increase in transit demand.
7. A 50 percent decrease in transit block time, such as the difference between track-levitated vehicle and turbotrain between Oakland and Sacramento, will cause a 200 percent increase in transit demand.
8. An increase in total fares (access and line-haul) for a long trip, such as from San Francisco to Sacramento, from $5.00 to $10.00 will cause a 40 percent decrease in transit demand.

## SUMMARY

In the past few years, awareness of the limitations associated with the application of conventional sequential models (generation, distribution, and modal-split models) has been increasing. The structural models that have been recommended as replacements have covered a wide variety of model forms and calibration processes. Yet, despite the large number of alternative modeling choices made available, few studies attempted to use other than sequential models.

We feel that, at least in part, the lack of acceptance of structural models stems from a lack of a basic understanding of the features and applications of these models. For the intercity-corridor study in Northern California, we have found that a power-product, aggregate direct-demand model most successfully satisfied the objectives that were developed early in the study. These objectives included policy sensitivity and demand response to alternative transportation systems.

In the calibration of the direct-demand model, we found that the use of a nonlinear regression technique overcame many of the problems of variable transformations and constraints that have been encountered in previous studies. In addition, however, application of the model equations in the future still will require the careful, judgmental processes used in the sequential models. Particular attention needs to be paid when one attempts to estimate future demand by using future socioeconomic and system data that are outside the range of the base-year data.

Finally, the results of the modeling work provided an opportunity for a clear and useful dialogue between the technicians and the policymakers. As a result, the policymakers were afforded a technique by which they could test and assess the effects of a variety of alternate policy assumptions.

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## REFERENCES

1. D. Brand. Theory and Method in Land Use and Travel Forecasting. Department of City Planning, Harvard Univ., 1972.
2. T. J. Adler and J. A. Bottom. Formulation of Travel Demand Modelling Requirements. Department of Civil Engineering, Massachusetts Institute of Technology, 1973.
3. T. A. Domencich, G. Kraft, and J.-P. Valette. Estimation of Urban Passenger Travel Behavior: An Economic Demand Model. Highway Research Record 238, 1968, pp. 64-78.
4. D. Brand. Travel Demand Forecasting: Some Foundations and a Review. Department of City Planning, Harvard Univ., 1972.
5. M. E. Ben-Akiva. Passenger Transportation Demand Theory and Models. Department of Civil Engineering, Massachusetts Institute of Technology, 1972.
6. E. R. Ruiter. Analytical Structures. Special Rept. 143, 1972, pp. 178-205.