# SEGMENTED, MULTIMODAL, INTERCITY PASSENGER DEMAND MODEL

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This report documents the specification, calibration, and performance of a segmented mathematical model developed to predict intercity travel by mode within and around the state of Michigan. The performance of different existing demand models is studied, and a model is formulated that uses income data and cost, time, and frequency of modal service to predict the travel volumes linking a wide range of city sizes. Model parameters are estimated by using a constrained-search calibration technique. Model performance is documented, and the sensitivity of this performance to changes in input data and calibration parameters is discussed.

•MATHEMATICAL models developed to predict intercity passenger demand have typically focused on travel between densely populated urban areas. Models developed and calibrated in this fashion generally fare poorly in predicting travel demand between sparsely populated areas and between a large city and a smaller urban area. Yet, statewide transportation planning entails the forecasting of traffic between cities of any size. This report describes the development of a segmented mathematical model designed to represent the demand for travel between cities of any size in Michigan.

## MODEL SPECIFICATION

### Range of Performance

Michigan covers an area of 58,216 square miles. Its populated areas range in size and type from isolated rural hamlets to the heavily industrialized Detroit area. An intercity passenger demand model designed for use in the state must be capable of predicting traffic by mode between cities of widely varying population densities separated by distances ranging from 50 to 600 miles. To assist in the formulation and calibration of a model having this capability, a set of 15 sample origin-destination pairs was selected to reflect the range of population-distance combinations existing in and around Michigan. These sample pairs are given in Table 1. The designations given in Table 1 are as follows:

| Item | Designation |
|---|---|
| Population | |
| 20,000 to 50,000 | Small |
| 200,000 to 1,000,000 | Medium |
| 2,000,000 to 5,000,000 | Large |
| Distance, miles | |
| 50 to 100 | Short |
| 150 to 250 | Medium |
| 400 to 600 | Long |
| City | |
| Alpena | ALP |
| Sault Sainte Marie | SSM |
| Houghton | HOU |
| Flint | FLI |
| Caro | CAR |

| Item | Designation |
|---|---|
| City | |
| Detroit | DET |
| Kalamazoo | KAL |
| Columbus (Ohio) | COL |
| Des Moines | DES |
| Chicago | CHI |
| Philadelphia | PHL |

## Performance of Existing Models

As a first step toward selecting a model for use in predicting Michigan intercity traffic, the 15 sample origin-destination pairs were used to test several existing unimodal and multimodal demand models. A list of the models is given in Table 2. Details regarding the structure of the models may be found in the indicated references. All of the models represent traffic between zones as a function of trip generation characteristics and some measure of interzonal impedance. As such, all of the models are descendants of the gravity model.

Table 3 gives the results of using each of the demand models to predict traffic between the city pairs. This table also gives actual measurements of intercity automobile traffic as compiled by the Michigan Department of State Highways in studies conducted between 1964 and 1968. A comparison of predicted and observed values shows that existing models generally cannot cope with the range of city sizes and distances to be found in Michigan. As might be expected, model 4, developed and calibrated specifically for use in the state, does the best job of reproducing actual traffic measurements, although it appears to overstate traffic between cities separated by short distances. Unfortunately, this model is limited to the prediction of automobile traffic.

The performance of the remaining models hardly can be termed promising. Models 1 and 2, both classic gravity models, perform poorly when uprooted from their places of calibration and applied to the range of city pairs existing in Michigan. Model 3, which woefully understates traffic, might profit slightly from a change of coefficients. Model 5, calibrated on the large cities of the Northeast Corridor, performs poorly in estimating traffic between the smaller Michigan cities.

The discrepancies between predicted and actual values given in Table 3 highlight the difficulty of predicting intercity passenger demand for a wide range of distances and city sizes. This difficulty is multiplied by the problem of designating modal preferences of passengers. No gravity model exists that can be pulled off the shelf and used with confidence to predict travel patterns in any arbitrary area. In this sense, the term gravity model, implying as it does an immutable law, is a misnomer. Isaac Newton himself might have had second thoughts about the validity of his gravity model had it been necessary to reformulate it for different masses and recalibrate it for different points on the earth's surface.

## Model Selection

The ability to reproduce observed travel data with a reasonable degree of fidelity for the range of city sizes and separations encountered in Michigan was but one of the criteria considered in selecting an intercity demand model. In addition to this important consideration, it was desired that the model have the following attributes: simplicity, sound theoretical structure, and ability to reflect the intermodal consequences of system changes. Because each of the tested models failed to reproduce modal preferences for the range of sample city sizes, the selection process centered on these additional attributes. Once a model having these attributes was identified, an attempt was made to extend its range of applicability to include the city sizes of interest in Michigan.

A review of existing intercity demand models led to the selection of the basic model developed by McLynn (5), modified by the National Bureau of Standards (6), and summarized by the Northeast Corridor Transportation Project (7). The variables con-

**Table 1. Sample origin-destination city pairs.**

| City Size | Distance Short | Medium | Long |
|---|---|---|---|
| Small to small | ALP-SSM | SSM-HOU | |
| Small to medium | ALP-FLI | SSM-FLI | |
| Small to large | CAR-DET | SSM-DET | HOU-DET |
| Medium to medium | FLI-KAL | FLI-COL | FLI-DES |
| Medium to large | FLI-DET | FLI-CHI | FLI-PHL |
| Large to large | | DET-CHI | DET-PHL |

**Table 2. Models used to test city pairs.**

| Model | Developer | Calibration Area | Modal-Split Capability | Reference |
|---|---|---|---|---|
| 1 | Unknown | Detroit | Single | 1 |
| 2 | Stanford Research Institute | California | Multiple | 2 |
| 3 | Wilbur Smith | Illinois | Single | 3 |
| 4 | Arthur D. Little | Michigan | Single | 4 |
| 5 | Office of High Speed Ground Transportation, U. S. Department of Transportation | Northeast Corridor | Multiple | 5 |

**Table 3. Demand model predictions of daily 1-way person trips by automobile.**

| City Pair | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Actual Traffic |
|---|---|---|---|---|---|---|
| ALP-SSM | 1 | 2 | 1 | 22 | 0 | 19 |
| SSM-HOU | 0 | 1 | 0 | 7 | 0 | 11 |
| ALP-FLI | 4 | 17 | 2 | 29 | 1 | 27 |
| SSM-FLI | 1 | 6 | 0 | 14 | 1 | 51 |
| CAR-DET | 280 | 1,837 | 138 | 910 | 51 | 660 |
| SSM-DET | 8 | 46 | 0 | 62 | 4 | 274 |
| HOU-DET | 3 | 15 | 0 | 60 | 1 | 62 |
| FLI-KAL | 56 | 327 | 31 | 78 | 29 | 58 |
| FLI-COL | 37 | 231 | 1 | n. a. | 33 | 16 |
| FLI-DES | 2 | 8 | 0 | n. a. | 2 | 3 |
| FLI-DET | 7,021 | 59,378 | 1,302 | 24,859 | 2,877 | 14,600 |
| FLI-CHI | 262 | 2,032 | 1 | 127 | 148 | 77 |
| FLI-PHL | 22 | 151 | 0 | n. a. | 14 | 5 |
| DET-CHI | 2,635 | 25,732 | 2 | 597 | 1,391 | 775 |
| DET-PHL | 279 | 2,461 | 0 | n. a. | 161 | 74 |

Note: 1960 population data were used.

sidered by the model in determining the traffic by a mode m between origin-destination pair (i, j) are identified as follows:

$t_m$ = total (i to j) travel time for the mth mode, hours;
$c_m$ = total (i to j) out-of-pocket per capita cost, dollars;
$f_m$ = frequency of (i to j) service, trips per day; and
F = number of families with annual incomes exceeding \$10,000 (families $\times 10^{-5}$) in the SMSA or county of the origin or destination city.

These variables can be used to define the modified demand model by the following relations:

$$w_m = \begin{cases} a_m t_m^{\alpha(1)} \; c_m^{\alpha(2)} \; [1 - \exp(-Kf_m)]^{\alpha(3)} & \text{for } m \neq \text{automobile} \\ t_m^{\alpha(4)} \; (c_m/1.7)^{\alpha(5)} & \text{for } m = \text{automobile} \end{cases} \qquad (1)$$

$$W = \sum_m w_m \qquad (2)$$

$$D = \begin{cases} \beta(0)(F_i F_j)^{\beta(1)} \; W^{\beta(2)} & \text{for } F_i F_j > G \\ \beta'(0)(F_i F_j)^{\beta'(1)} \; W^{\beta(2)} & \text{for } F_i F_j \leq G \end{cases} \qquad (3)$$

$$D_m = Dw_m/W \qquad (4)$$

The terms $w_m$ and W may be regarded as modal conductance and total (i to j) conductance respectively. $D_m$ and D are daily one-directional modal (i to j) demand and total (i to j) demand respectively (measured in persons).

So that the model could be adapted to the wide range of city sizes of interest in Michigan transportation studies, the demand model was segmented as indicated in Eq. 3. Thus, city pairs having population products $F_i F_j$ below a specified value G received a treatment different from that received by city pairs having larger population products.

## Data Development

In the calibration of the demand model, numerical values were assigned to each of the model's parameters, and the effect of each assigned value on the model's ability to reproduce actual travel data was observed. The basic demand data used in this calibration process consisted of observed 1-way travel volumes by air, rail, bus, and automobile between each of 20 origin-destination pairs for the base year 1967. The 20 origin-destination pairs were the 15 city pairs given in Table 1 and the following 5 additional pairs: Detroit-Cleveland (CLE), Detroit-Pittsburgh (PIT), Detroit-Milwaukee (MIL), Flint-Cleveland, and Flint-Milwaukee. These pairs were added to broaden the data base and to place additional emphasis on travel between larger cities.

The cost, time, and frequency of common carrier service between each pair of cities were obtained from published schedules, and access times and costs were computed for each city. In the calculation of automobile costs and times, operating costs of 4 cents/mile were assumed and average speeds of 60, 30, and 15 mph were associated with freeways, arterials, and local streets. An average automobile occupancy of 1.7 persons/vehicle was assumed. Census data from 1960 were extrapolated to 1967 in the estimation of the number of families in each origin or destination zone having a real income exceeding \$10,000/year.

Calibration Technique

Attempts to use a series of log-linear regression analyses to calibrate the model formulated in Eqs. 1 through 4 proved unsuccessful. Part of the explanation for this lack of success may be traced to the failure of the log-linear regression format to deal adequately with the range of city sizes under consideration.

In lieu of regression analysis, the Michigan intercity passenger demand model was calibrated by means of a constrained-search technique. Through a combination of past experience and a knowledge of the model's structure, upper and lower bounds were set on acceptable values of each model parameter. A limited search was undertaken within those constraints for the combination of parameters that minimized a series of error functions describing model performance. The parameter bounds and error functions used in this constrained-search calibration process are described below.

Parameter Bounds—The following logical bounds were imposed on the model parameters in advance of the calibration process:

$$0 \le \beta'(0) \le \beta(0)$$

$$0 \le \beta'(1) \le \beta(1) \le 1.1$$

$$0 \le \beta(2) \le 1$$

$$-5 \le \alpha(j) \le 0; \; j = 1, 2, 4, 5$$

$$\alpha(3) = 0.3247$$

$$K = 0.12$$

$$0 \le a_m \le 5$$

The model's consistency of behavior was ensured by imposing a positive or a negative constraint on each parameter. In addition, the positively constrained parameters $\beta'(1)$, $\beta(1)$, and $\beta(2)$ each had logical upper bounds. Experience with gravity models has shown that the exponent $\beta(1)$ associated with the population product rarely exceeds 1.1. Were this exponent to be higher, population increases would have a disproportionate effect on predicted travel demand. Furthermore, the exponent $\beta'(1)$ associated with small-city pairs cannot exceed the large-city exponent $\beta(1)$. This relation is indicated by empirical data relating intercity travel to population product for the sample city pairs.

Consideration of the conductance exponent $\beta(2)$ shows that the value of this exponent cannot exceed unity. Otherwise, a decrease in the time or cost of travel by 1 mode could cause corresponding increases in travel by competing modes. This can be shown by considering that, for small changes in time or cost, demand changes may be expressed as a function of the partial derivative of demand with respect to the changing variable. If the cost $c_m$ of travel by mode m between 2 cities were to be changed, the effect on a competing mode n can be represented as follows:

$$\Delta D_n = (\partial D_n/\partial c_m)\Delta c_m$$
$$\Delta D_n = [\alpha(2)/c_m][\beta(2) - 1] D_n (w_m/W)\Delta c_m \qquad (5)$$

where $\Delta D_n$ represents a small change in demand $D_n$ for a competing mode n, and $\Delta c_m$ represents a small change in cost $c_m$. Thus, the intermodal effects predicted by the proposed demand model will remain consistent only as long as $\beta(2) \le 1$.

Model consistency also demands that the modal conductance exponents $\alpha(1)$, $\alpha(2)$, $\alpha(4)$, and $\alpha(5)$, associated with time and cost, be negative. If these exponents are allowed to become too large, however, small changes of time or cost will have a disproportionate effect on demand. If $\alpha(2) \le -5$, for example, sensitivity analysis shows that a 10 percent decrease in the cost of mode m could cause more than a 50 percent increase in the demand for that mode. Accordingly, a lower limit of -5 was placed on exponents $\alpha(1)$, $\alpha(2)$, $\alpha(3)$, and $\alpha(4)$ to forestall such unlikely results.

In calibrating his basic demand model, McLynn (5) empirically set K = 0.12. This value was used in the segmented model, as was the McLynn-calibrated value $\alpha(3)$ = 0.3247. An upper limit of 5 was placed on the common carrier conductance multiplier $a_m$, because it was felt that larger values of $a_m$ would create unrealistic imbalances between common carrier traffic and automobile traffic.

Error Functions—As the parameter values were varied within the established bounds, different error functions were computed and monitored to determine the overall effect of each parameter on the demand model's ability to reproduce observed travel data. These error functions reflected (a) the square root of the sum of the squares of the differences between calculated and observed modal travel values; (b) the sum of the absolute values of the difference between calculated and observed modal travel values; and (c) the number of calculated travel values that fell outside a predetermined range surrounding the observed value. Range settings within 10, 25, and 50 percent of the observed demand were monitored in the calibration process.

Calibration Procedures—In the calibration of the segmented demand model, attention was first directed toward the determination of the parameters $\beta(0)$ and $\beta(1)$, which were associated with larger-city pairs. Once these parameters were fixed, the search for $\beta'(0)$ and $\beta'(1)$ was undertaken. In the case of larger-city pairs, the constrained-search calibration procedure followed the steps outlined below.

1. Set $\beta(0) = a_m = 1$;
2. Select values for $\beta(1)$ and $\beta(2)$;
3. Select values for $\alpha(1)$, $\alpha(2)$, $\alpha(4)$, and $\alpha(5)$;
4. Compute $D_{mj}$ for each city pair;
5. Compute error functions;
6. Adjust $a_m$ to approximate modal-split proportions;
7. Adjust $\beta(0)$ to minimize error functions; and
8. Return to step 3 and try another combination of $\alpha(i)$, repeat until no further improvement in the error functions appears possible for the combination of $\beta(1)$ and $\beta(2)$ selected in step 2, and then try another combination of $\beta(1)$ and $\beta(2)$.

In the actual calibration process, $\beta(1)$ and $\beta(2)$ were varied in increments of 0.1 until a combination was found that appeared to fit the observed travel data associated with large-city pairs. At this point, $\beta(0)$, $\beta(1)$, and $\beta(2)$ were fixed, and a search was undertaken for appropriate values of $\beta'(0)$ and $\beta'(1)$.

## Calibration Results

The calibration process given above resulted in the identification of the following parameter values:

$$a_m = \begin{cases} 1.5 & \text{for } m = \text{air} \\ 0.75 & \text{for } m = \text{bus, rail} \end{cases}$$

$$\alpha(1) = \alpha(2) = -1.5$$

$$\alpha(3) = 0.3247;\ K = 0.12$$

$$\alpha(4) = \alpha(5) = -1.8$$

$$\beta(0) = 25{,}000;\ \beta'(0) = 2{,}500$$

$$\beta(1) = 1.0;\ \beta'(1) = 0.1$$

$$\beta(2) = 0.9$$

$$G = 0.075$$

Table 4 gives a comparison of the demand calculated through the use of the parameters and the observed travel between each of the 20 city pairs. Although the overall agreement between calculated and observed values is satisfactory, the demand model severely understates travel between a city pair consisting of 1 small city and 1 large city. The reason for this understatement is shown clearly in Figure 1, where normalized demand is plotted as a function of population product. Normalized demand is defined as follows:

$$D_{normalized} = D/W^{\beta(2)}$$

This normalization process removes the effect of travel impedance from the demand term so that the resulting normalized demand should be a piece-wise log-linear function of the trip attraction measure, the income product $F_iF_j$. Figure 1 shows that the normalized demand between all city pairs except Sault Sainte Marie-Detroit, Houghton-Detroit, Sault Sainte Marie-Flint, and Caro-Detroit clusters closely about the log-linear form defined by the calibration process. It would appear to be impossible to use the chosen model effectively to represent travel between each of these 4 city pairs without destroying the model's ability to reproduce the remainder of Michigan's intercity traffic. There seems to be nothing within the framework of the mathematical model to explain, for instance, why automobile traffic between Detroit and Sault Sainte Marie should be nearly double the combined traffic between Detroit and the larger, closer cities of Pittsburgh and Milwaukee.

In addition to highlighting data inconsistencies, Figure 1 clearly shows the need for segmenting the Michigan intercity demand model. The data points plotted in this figure make it plain that a single log-linear function cannot reflect travel demand between city pairs of all sizes.

## MODEL SENSITIVITY

### Effect of Variable Changes

One test of the soundness of a demand model is its ability to behave logically in the face of changes in input variables. Because the Michigan intercity passenger demand model is a closed-form mathematical expression, its sensitivity to variable changes may be determined analytically. The first partial derivative of demand with respect to each input variable, $\partial D/\partial V$, provides a measure of this sensitivity and, by inference, also provides a measure of the impact of each variable on intercity demand.

The value of $\partial D/\partial V$ associated with each model input variable was computed and used to assess the effects of small (10 percent) changes in each variable on model demand and total intercity travel. Table 5 gives the results of this assessment. For large-city pairs, a 10 percent increase in the number of families in 1 city earning more than $10,000/year will increase travel demand by 10 percent across all modes. For small cities, an equivalent percentage increase will result in only a 1 percent increase in total travel. Although these differences in the modeled effect of population changes may be valid for extremely large cities and extremely small cities, it is illogical to expect such dichotomous behavior in the case of medium-sized cities. The abrupt transition from a 1 percent to a 10 percent increase in travel experienced when the income product $F_iF_j$ exceeds $G = 0.075$ might be smoothed by replacing the segmented demand model with a continous function.

The effects of small changes in the model input variables, time, cost, and frequency, vary with the importance of the individual mode in intercity travel. If mode m dominates intercity travel (i.e., if $w_m/W$ is nearly unity for mode m), the effects of modal changes on total intercity demand are maximized. Conversely, small changes in infrequently used modes (modes for which $w_m/W$ is vanishingly small) will have slight effect on total intercity demand.

Data given in Table 5 show that a 10 percent increase in the cost of travel by common carrier between 2 cities might cause a decrease of 13.5 percent in the total travel demand between those cities if common carrier is the prevalent mode of intercity travel.

**Table 4. Calculated and observed values.**

| City Pair | Air Cal. | Air Obs. | Rail Cal. | Rail Obs. | Bus Cal. | Bus Obs. | Automobile Cal. | Automobile Obs. | Total Cal. | Total Obs. |
|---|---|---|---|---|---|---|---|---|---|---|
| ALP-SSM | 0 | 0 | 0 | 0 | 0 | 1 | 14 | 19 | 14 | 20 |
| SSM-HOU | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 11 | 3 | 11 |
| ALP-FLI | 0 | 0 | 0 | 0 | 2 | 2 | 13 | 27 | 15 | 29 |
| SSM-FLI | 0 | 0 | 0 | 0 | 1 | 5 | 3 | 51 | 4 | 56 |
| CAR-DET | 3 | 0 | 0 | 0 | 4 | 20 | 70 | 660 | 76 | 680 |
| SSM-DET | 1 | 5 | 0 | 0 | 1 | 10 | 3 | 274 | 4 | 289 |
| HOU-DET | 1 | 7 | 0 | 0 | 0 | 0 | 1 | 62 | 1 | 69 |
| FLI-KAL | 0 | 0 | 3 | 3 | 14 | 25 | 60 | 58 | 77 | 86 |
| FLI-COL | 4 | 0 | 1 | 2 | 1 | 2 | 13 | 16 | 19 | 20 |
| FLI-DES | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 3 | 2 | 5 |
| FLI-DET | 51 | 9 | 55 | 30 | 269 | 250 | 4,096 | 4,618 | 4,470 | 4,907 |
| FLI-CHI | 29 | 31 | 4 | 5 | 9 | 20 | 59 | 77 | 101 | 133 |
| FLI-PHL | 14 | 4 | 0 | 0 | 1 | 2 | 2 | 5 | 18 | 11 |
| DET-CHI | 660 | 631 | 97 | 80 | 149 | 150 | 802 | 775 | 1,708 | 1,636 |
| DET-PHL | 155 | 251 | 5 | 5 | 19 | 20 | 40 | 74 | 220 | 350 |
| DET-CLE | 332 | 137 | 41 | 3 | 94 | 25 | 650 | 572 | 1,117 | 737 |
| DET-PIT | 188 | 139 | 34 | 2 | 62 | 10 | 127 | 103 | 411 | 254 |
| DET-MIL | 115 | 134 | 16 | 2 | 28 | 10 | 42 | 41 | 202 | 187 |
| FLI-CLE | 25 | 9 | 0 | 1 | 4 | 4 | 26 | 22 | 55 | 36 |
| FLI-MIL | 3 | 3 | 1 | 0 | 2 | 1 | 4 | 4 | 10 | 8 |

**Figure 1. Normalized demand versus income product.**

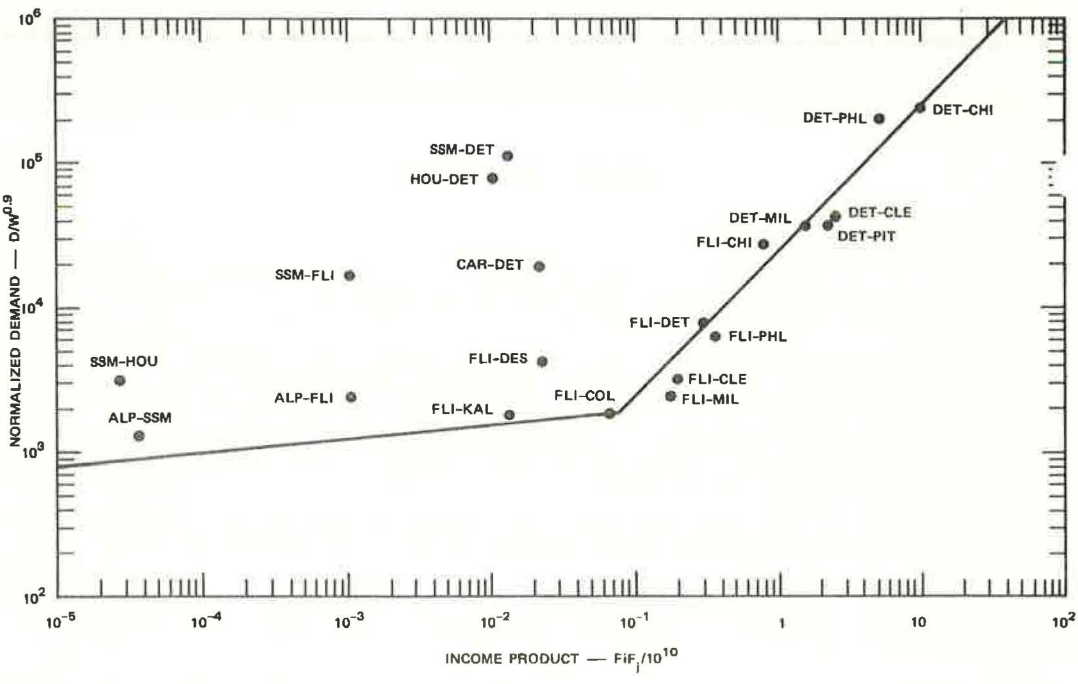


**Table 5. Model sensitivity to 10 percent increase in input variables.**

| Variable | Case | Change in Modal Demand (percent) Minimum | Change in Modal Demand (percent) Maximum | Change in Total Demand (percent) Minimum | Change in Total Demand (percent) Maximum |
|---|---|---|---|---|---|
| F | $F_iF_j > 0.075$ | 10.0 | 10.0 | 10.0 | 10.0 |
| | $F_iF_j \le 0.075$ | 1.0 | 1.0 | 1.0 | 1.0 |
| $t_m$ | m ≠ automobile | -13.5 | -15.0 | 0.0 | -13.5 |
| | m = automobile | -16.2 | -18.0 | 0.0 | -16.2 |
| $c_m$ | m ≠ automobile | -13.5 | -15.0 | 0.0 | -13.5 |
| | m = automobile | -16.2 | -18.0 | 0.0 | -16.2 |
| $f_m$ | m ≠ automobile | 0.0 | 3.9 | 0.0 | 2.6 |

If automobile is the prevalent mode of intercity travel, the effect of such a cost increase on total intercity travel would be negligible. The effect of the fare increase on travel via the affected mode would be a loss of between 13.5 and 15 percent of the mode's pre-increase travel volume. Similar ranges would be expected in the event of a 10 percent increase in travel time. These ranges are given in Table 5 along with the corresponding ranges for changes in the time and cost of automobile travel. The magnitude of these small changes does not appear to be unreasonable, and, thanks to the constraints imposed in the calibration procedure, the direction of change is proper.

Service frequency is the least effective of the input variables in terms of its ability to influence sizable demand changes. A 10 percent increase in common carrier service frequency can effect no more than a 3.9 percent in modal patronage and no more than a 2.6 percent increase in total intercity travel.

## Effect of Parameter Changes

Just as the effect of variable changes on predicted demand gives a measure of model reasonability, so the effect of parameter variations on demand gives a measure of model stability. If a small parameter change can drastically alter model output, the calibration procedure is complicated, and model validity may be suspect.

The effect of small parameter changes on total demand is quite complex and may depend on the relative impact of a mode on intercity travel; on the existing population product; on current levels of time, cost, and frequency; or on all of these factors. An evaluation of $\partial D/\partial P$, the first derivative of demand with respect to each model parameter, shows that the parameters whose changes have the greatest potential impact on demand are the time and cost components $\alpha(1)$, $\alpha(2)$, $\alpha(4)$, and $\alpha(5)$ and the conductance exponent $\beta(2)$.

The segmenting of the demand model buffers the effect of changes in the income exponent $\beta(1)$. Were it not for this segmentation, a 10 percent change in the parameter $\beta(1)$ could effect a 90 percent change in the demand calculated between a small-city pair. This buffering effect suggests that model stability and performance might be improved by similarly segmenting the model with respect to the conductance exponent $\beta(2)$. Such a segmentation would buffer the potentially pronounced effect of changes in the modal time and cost exponents.

## INDUCED AND DIVERTED DEMAND

When improvements in a single mode cause an incremental increase in the number of travelers using that mode, these travelers can be assumed to come from 1 of 2 sources: (a) other modes (diverted demand) or (b) the pool of potential travelers who currently are not included in the total intercity demand (induced demand). Thus, total modal increases are made up of travelers diverted from other modes and travelers induced to make the intercity journey for the first time (or more often). Although the calibrated demand model behaves logically in reproducing the overall impact of variable changes, numerical results of a number of model runs revealed that the model clearly overstates induced demand at the expense of diverted demand.

The reason for this overstatement becomes clear if the sources of incremental demand increases are investigated. Equation 5, repeated here for the sake of convenience, expresses the effect of an incremental cost change in mode m on a competing mode n.

$$\Delta D_n = [\alpha(2)/c_m][\beta(2) - 1](w_m/W) D_n \Delta c_m \quad \text{for } n \neq m$$

The effect of the cost change on the demand for service via mode m is as follows:

$$\Delta D_m = [\alpha(2)/c_m] D_m \{1 + (w_m/W)[\beta(2) - 1]\} \Delta c_m \tag{6}$$

Summing the expression given above across all modes gives the total intercity demand increment.

$$\Delta D = \Delta D_m + \sum_{n \neq m} \Delta D_n \qquad (7)$$

$$\Delta D = [\alpha(2)/c_m]\,\beta(2) D_m \Delta c_m \qquad (8)$$

In the case of a cost decrease, the constrained calibration procedure forces $\Delta D_m$ to be positive and $\Delta D_n$ to be negative. Hence, the total demand increment $\Delta D$ will represent the total induced demand. The ratio of induced demand to the incremental demand increase via mode m may be found as follows:

$$\Delta D/\Delta D_m = [\beta(2)] / \{1 + (w_m/W)\,[\beta(2) - 1]\} \qquad (9)$$

For the calibrated value of $\beta(2) = 0.9$, this ratio will vary from 0.9 to 1.0 as the ratio $w_m/W$ varies from 0 to 1. Thus, the induced demand component of traffic increases predicted by the intercity demand model will range between 90 and 100 percent. This is not a realistic state of affairs. The model's realism may be improved, however, by defining arbitrarily a more reasonable limit on induced demand and redistributing demand forecasts in accordance with this limit. A simple means of accomplishing this redistribution is to let

$$D_m = (D_0 + \gamma \Delta D)\,(w_m/W) \qquad (10)$$

where $D_0$ represents original intercity demand and $\gamma$ represents an arbitrary scaling factor ($0 \leq \gamma \leq 1$).

## FUTURE WORK

### Model Improvements

Future work to improve the accuracy and plausibility of the Michigan intercity demand model might profitably explore the following subjects: segmentation over distance; formulation of a continuous model; development of an induced demand correction factor; and investigation of the variation of parameter values over time.

Distance Segmentation—The possibility of segmenting the demand model as a function of distance by associating different values of $\beta(2)$ with different conductances has been noted already. The intercity highway traffic model designed for Michigan (4) was segmented in this fashion with good results. Such a segmentation would correct for the tendency of the current model to understate long-distance trips (more than 600 miles).

Continuous Model—Certain inconsistencies in model performance might be overcome by developing a continous demand model having the features of the segmented model. A continuous model having these features is shown below.

$$D = \beta(0)^{(1-s)}\,(F_i F_j)^{\{\beta(1) + s[\beta'(1) - \beta(1)]\}}\,\beta'(0)^s W^{\beta(2)} \qquad (11)$$

where $S = \exp[-\mu(F_i F_j) + \tau]$. The variables $\mu$ and $\tau$ are calibration constants, and the remaining model variables have the definitions stated in Eqs. 1, 2, and 4. SRI has achieved some success in calibrating the model of Eq. 11, but more experimentation is necessary before this model can replace the current segmented formulation. A similar continuous formulation could be employed to vary the parameter $\beta(2)$ for different intercity distances.

Induced Demand Correction Factor—Historical data regarding induced demand should be gathered in an effort to estimate the value of the parameter $\gamma$ used in Eq. 10 to correct for the model's tendency to overstate induced demand.

Time-Varying Parameters—If the functional form of the demand model is correct, it seems likely that parameter values will change with time. This supposition should be checked by calibrating the model at different points in time and attempting to explain and quantify any differences in the calibration parameters.

## Model Application

The true utility of the developed demand model is best tested by applying the model in the investigation of intercity transportation problems. In the course of SRI's Michigan studies, the model has been applied to the task of predicting potential air traffic from a proposed regional airport (8) and evaluating alternative high-speed rail routes between Detroit and Chicago (9). The model performed creditably in these tests. More such tests are needed to substantiate the model's current capability and to point the way toward future improvements.

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