Transportation Policy Analysis Using a Combined Model of Travel Choice

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A combined model of travel demand is introduced to analyze the effects of new transportation policies on travel patterns. A brief discussion of the need for new forecasting procedures is followed by a description of the combined model's formulation. The procedure used to solve the combined model (i.e., to forecast travel demand) is then compared with a sequential modeling process currently used by planning agencies. Three scenarios representing possible policy results are analyzed in terms of their effects on different travel and network-related variables. The scenarios studied represent changes in transit fares, fuel costs, and land use changes that consider dispersed employment locations. Finally, research possibilities that could enhance the applicability of the combined model for various policy analyses are examined.

As a result of the 1990 Clean Air Act Amendments, greater attention is being focused on transportation policies for mitigating congestion and reducing total vehicle kilometers (miles) of travel. To design and evaluate alternative policies that will influence travel choices in the desired direction, it is necessary to model the effects of these policies in an accurate and consistent manner.

Transportation policy analysis traditionally has been performed using a sequential travel forecasting procedure, which involves the application of models for trip generation, trip distribution, mode split, and trip assignment. Increasingly, this procedure has proven deficient in several respects:

- The values of the variables used in the different models are inconsistent; in particular, travel times and costs used in the trip distribution and mode split models are not equal to those times and costs determined in the solution of the trip assignment model.
- The basis for forecasting travel choices, as defined in terms of variables and parameters, is inconsistent across the several models; for example, trip assignment is often based on travel times only, whereas mode split is based on a weighted combination of travel times and operating costs and fares.
- Evaluation of alternative policies using the sequential modeling process is complex and time consuming in that it is often not possible to produce results easily in the time frame decision makers desire. Moreover, the effects of these policies on travel patterns may not be clearly visible because of inconsistencies in the models.

The need for a new generation of forecasting procedures that take into account these deficiencies and provide a better basis for estimating travel choice has been expressed by various practitioners in the field (*1*). The purpose of this paper is to illustrate the application of a forecasting procedure that avoids these difficulties by combining the trip distribution, mode split, and trip assignment models into a single model and solution procedure. In this "combined" model, the same travel choice principles and relationships are incorporated as are used in the sequential procedure. By solving the problem as one model, however, the inconsistencies of the sequential procedure are eliminated, and model results are much easier to obtain.

In the paper, the formulation of a combined model and the procedure used to solve it are described. The results of solving the model for three scenarios representative of possible policy changes are then analyzed in terms of their impact on travel patterns and network-related variables. Finally, extensions of the model needed to facilitate its application in practice are discussed.

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DESCRIPTION OF MODEL AND SOLUTION PROCEDURE

Combined models are based on the assumption that travel choices should result in equilibrium or user optimal conditions of travel. Wardrop (*2*) defined equilibrium route choice conditions such that "the journey times on all the routes actually used are equal and less than those which would be experienced by a single vehicle on any unused route."

The concept of equilibrium has been widely accepted by practitioners with regard to traffic assignment or route choice. That is, given the number of trips between different origin-destination pairs, the resulting traffic is assigned iteratively to multiple sets of links or routes until all used routes between each origin-destination pair have equal travel times.

Most equilibrium or iterative traffic assignment models used in practice are applied to a given trip table that may be the result of earlier modeling steps involving trip distribution and mode choice. However, trip distribution (or destination choice) models and mode choice models also incorporate the interzonal travel costs as an important variable in determining travel choices. Because these models are applied before the traffic assignment model, the travel costs assumed for trip distribution and mode choice may in fact be quite different from the travel costs that result from the traffic assignment step. To be consistent, the travel choices that result from the route choice model must be equal to the travel costs used in the trip distribution and mode choice models.

To model true equilibrium conditions of travel, it is necessary, therefore, to feed back the travel costs that are determined as a result of the traffic assignment model to the trip distribution and mode choice models. The models must then be solved iteratively until the costs that are used to model trip distribution and mode choice are equal to the costs that result from the traffic assignment (or route choice) model. Such iterative procedures using the sequential models are rarely done in practice. The process itself can be time consuming, and the use of different variables to express travel costs in the different models leads to inconsistencies that make it harder to reach a solution with the desired properties.

In the combined models, the problems associated with the sequential models are overcome by

- Considering a common cost function to model the various travel choices, and
- Using an iterative solution procedure so that the final equilibrium travel conditions are a result of the destination, mode, and route choices, instead of just route choice.

In a combined model of travel choice, a trip maker's choices regarding destination, mode, and route are considered as part of a single decision-making process with user cost minimization the main criterion. The model is formulated as a minimization problem, with the objective function representing a generalized cost that is a weighted sum of the travel times and monetary costs associated with a trip. The objective function is subject to constraints with regard to nonnegativity of flow and flow conservation, in terms of trip origins, destinations, and route flows. Furthermore, in order to consider dispersion of choices from a strictly cost minimizing behavior, which might occur either because of imperfect knowledge on the part of the user or because of consideration of other factors, such as convenience and comfort, that are not accounted for in the model, a choice dispersion constraint is introduced. The dispersion constraint is derived from an entropy function that originally was defined as a measure of dispersion in information theory (*3*).

The equivalent optimization problem is to minimize the following expression:

$$\frac{R}{N}\gamma_1 \sum_a \int_0^{v_a} c_a(x)dx + \frac{1}{N}\gamma_2 \sum_a \int_0^{v_a} k_a(x)dx + \gamma_3 \sum_i \sum_j P_{ijh} w_{ijh} + \gamma_1 \sum_i \sum_j P_{ijt} c_{ijt} + \gamma_2 \sum_i \sum_j P_{ijt} k_{ijt} + \gamma_3 \sum_i \sum_j P_{ijt} w_{ijt} + \gamma_4 \sum_i \sum_j P_{ijt} \quad (1)$$

The constraints are as follows:

$$\sum_{r \in R_{ij}} f_r = P_{ijh} N/R + T_{ij} \quad (2)$$

$$\sum_j \sum_m P_{ijm} = \overline{P}_i \quad (3)$$

$$\sum_i \sum_m P_{ijm} = \overline{P}_j \quad (4)$$

$$-\sum_i \sum_j \sum_m P_{ijm} \ln \frac{P_{ijm}}{\overline{P}_i \overline{P}_j} \geq S \quad (5)$$

$$f_r \geq 0 \quad (6)$$

where

$$v_a = \sum_i \sum_j \sum_{r \in R_{ij}} f_r \delta_r^a \quad (7)$$

The terms used in the preceding expressions are defined as follows:

N = total number of trips/hr,
v_a = total flow of vehicles on Link a,
c_a = in-vehicle travel time function that increases with link flow,
k_a = automobile operating cost function that increases with link flow,
R = automobile occupancy factor (persons/vehicle),
R_{ij} = set of highway routes between Zones i and j,
T_{ij} = number of truck trips/hr in automobile equivalent units,
f_r = total vehicle flow on Route r (vehicles/hr),
δ_r^a = 1 if Link a belongs to Route r and 0 otherwise,
$\overline{P}_i$ = fixed proportion of trips originating from Zone i,
$\overline{P}_j$ = fixed proportion of trips terminating at Zone j,
P_{ijm} = proportion of person trips by Mode m between Zones i and j,
P_{ijh} = proportion of automobile person trips between Zones i and j,
P_{ijt} = proportion of transit person trips between Zones i and j,
w_{ijh} = out-of-vehicle travel time for automobile trips between Zones i and j,
w_{ijt} = out-of-vehicle travel time for transit trips between Zones i and j,
c_{ijt} = in-vehicle transit travel time between Zones i and j,
k_{ijt} = transit fare between Zones i and j, and
S = observed dispersion of choices.

γ_1, γ_2, and γ_3 are the weights for the three cost components considered: in-vehicle travel time, operating cost or fare, and out-of-vehicle travel time; γ_4 is the estimated transit bias. This last term in the objective function is considered part of the transit cost. These weights are found by calibrating the model to represent the relative importance of the associated travel costs in determining travel choices for a particular region. Operating costs are expressed in terms of the average cost per vehicle, whereas times are stated per person.

The solution to the minimization problem defined above results in traffic flow conditions that are equivalent to the equilibrium flow conditions as defined by Wardrop. The equation to determine the interzonal automobile costs, u_{ij}, is derived from the optimality conditions of the model as a weighted sum of the link flow dependent travel times and operating costs and may be written as

$$u_{ij} = \gamma_1 \sum_a c_a(v_a)\,\delta_r^a + \frac{\gamma_2}{R} \sum_a k_a(v_a)\,\delta_r^a \quad (8)$$

For routes that are not used for a given zone pair, the cost on that route will be not less than u_{ij}, in accordance with Wardrop's definition. This result may also be derived directly from the optimality conditions of the model.

The generalized cost of travel by automobile between a zone pair, *i-j*, is a weighted sum of the travel time, operating cost, and parking cost associated with the trip and is given by the following equation:

$$c_{ijh} = u_{ij} + \frac{\gamma_2}{R} p_j + \frac{\gamma_3}{R} w_{ijh} \quad (9)$$

The generalized cost of travel by transit is given by a similar equation as

$$c_{ijt} = \gamma_1 c_{ijt} + \gamma_2 k_{ijt} + \gamma_3 w_{ijt} + \gamma_4 \quad (10)$$

Travel times and costs for transit are taken from a fixed matrix of travel times and fares on the basis of the minimum paths between each zone pair. The equation to determine the proportion of trips between Zones i and j by Mode m is also derived from the optimality conditions as a function of these generalized costs:

$$P_{ijm} = A_i \overline{P}_i B_j \overline{P}_j \exp(-\mu c_{ijm}) \quad (11)$$

where c_{ijm} is the generalized cost of travel between Zones i and j by Mode m. We may interpret A_i and B_j as the balancing factors for trip productions and attractions to satisfy the constraints on flow conservation defined on $\overline{P}_i$, the fixed proportion of trips originating from Zone i, and $\overline{P}_j$, the fixed proportion of trips terminating at Zone j. Thus, the origin-destination and modal choices are specified as direct functions of the proportion of trips leaving origin zones and entering destination zones and inverse functions of the interzonal generalized mode costs. The equations for the interzonal trip costs and proportions, as derived from the optimality conditions of the model, are used to find a solution to the model in an iterative procedure discussed below.

The Evans algorithm (*4*), based on the partial linearization technique, is used to solve the model. The steps involved in using the Evans algorithm to find a solution to the combined model may be summarized as follows:

Step 0 (initialization). Find initial trip proportions P_{ijm} and link flows v_a using an all-or-nothing assignment based on zero flow link costs.

Step 1. Update link costs on the basis of the new flows, v_a.

Step 2. Find new minimal-cost routes on the basis of costs from Step 1 and compute new generalized costs on the basis of these routes.

Step 3. Find the feasible descent direction as follows. First, compute new travel demands or trip proportions, Q_{ijm}, using the new generalized cost values:

$$Q_{ijm} = A_i \overline{P}_i B_j \overline{P}_j \exp(-\mu C_{ijm}) \quad (12)$$

and solve for A_i and B_j. Second, compute link flows, w_a, by assigning these new travel demands to new minimal-cost routes.

Step 4. Conduct line search; find an optimal step size λ such that if x represents the current solution (P_{ijm} and v_a) and y represents the subproblem or new solution (Q_{ijm} and w_a), then $x' = x + \lambda(y - x)$ minimizes the objective function value.

Step 5. Update the trip proportions, P_{ijm}, and link flows, v_a, using the step size λ such that $P'_{ijm} = (1 - \lambda)P_{ijm} + \lambda Q_{ijm}$ and $v'_a = (1 - \lambda)v_a + \lambda w_a$. The costs based on the updated link flows are then used to find a new subproblem solution at Step 2. Steps 2 to 5 are repeated until a stipulated convergence criterion is satisfied. About 20 iterations of the algorithm were sufficient to find a solution within 0.5 percent of the true optimal solution corresponding to the desired equilibrium of origin-destination, mode, and route choice.

In the equilibrium traffic assignment model used in the sequential modeling process, the link flows are assigned iteratively until travel costs for all used routes between a given zone pair are approximately equal. However, no attempt is made to update the trip matrices for the new travel costs. In the combined model, the trip matrices are updated for every iteration of the link flow assignment by calculating new trip proportions, Q_{ijm}, corresponding to updated link flows, w_a. Thus, the combined model solves a larger problem than the equilibrium traffic assignment model. Whereas the equilibrium traffic assignment model solves for the equilibrium travel conditions by reassigning only the link flows, the combined model solves for the same equilibrium conditions by both reassigning the link flows and revising the corresponding trip matrices. The solution procedure used in the combined model is compared with the sequential solution procedure in Figure 1.

The first formulation of a combined model was made in 1956 by Beckmann et al. (*5*), about the same time that the sequential procedure was conceived. This kind of formulation was specialized for the trip distribution model that was used by Evans in the sequential procedure in 1973. Evans proposed an algorithm for solving the model as well as proving that the solution converges to the desired conditions outlined above. The combined model, including trip distribution, mode, and route choice, was first implemented in 1982 on a network of realistic size for the Chicago region by Boyce et al. (*6*). Development and implementation of similar models for the northeastern Illinois region, based on a sketch planning network and zone system, have been the subject of ongoing research efforts involving the staff and faculty of the University of Illinois at Chicago and the Chicago Area Transportation Study. This paper is based in part on a report by Boyce et al. (*7*) [see also Boyce et al. (*8*)].

The data used for the analysis reported here are for 1980 from the Chicago region. A sketch planning or aggregated zone system and

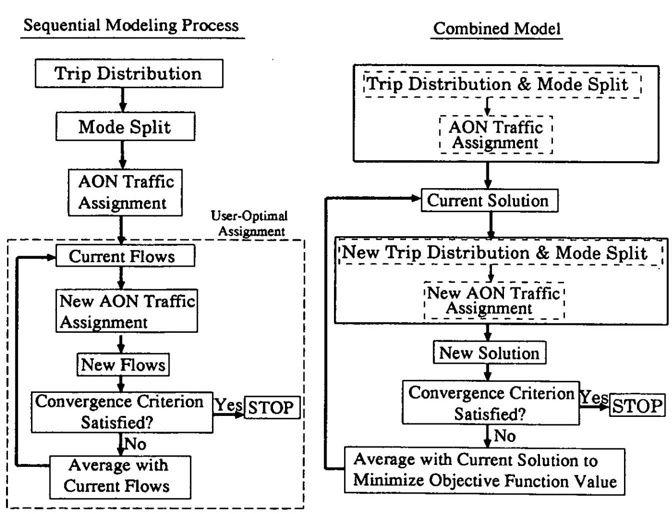

FIGURE 1 Comparison of solution procedures.

network was used in the analysis. The zone system, which includes 317 zones, is shown in Figure 2. The highway network has 2,902 links. The transit network is represented by a fixed matrix of travel times and fares.

DESCRIPTION OF SCENARIOS

Three policy changes represented by varying transit fares, fuel costs, and land use densities are considered. The monetary cost of travel is an important factor influencing travel choices. Both transit fares and automobile fuel costs may vary as a result of policy changes. To analyze the effects of those costs on travel patterns, both transit fares and gasoline prices are varied by multiplying the base year values by factors ranging from 0.25 to 3.0. The change in gasoline prices will affect only the cost of trips by automobile and does not affect transit trip costs.

Changes in land use variables are restricted to the consideration of changes in employment location. Work trip destinations are used to represent the availability of employment in different areas. The scenario examined here is the relocation of employment from the central business district (CBD) to the suburbs. Thus, work trip destinations in the CBD zone in the base data are reallocated to 11 suburban zones. The number of trips redistributed from the CBD varies from 0 to 44,000 out of the total 139,000 CBD destinations in the peak hour.

Six measures are selected to evaluate each scenario: mode choice, average trip length, total and congested vehicle kilometers (miles) of travel, average travel time, and average generalized cost of travel. Congested vehicle kilometers (miles) are the total vehicle kilometers (miles) on all links with flow exceeding capacity. Each of these scenarios is analyzed in detail in the following sections.

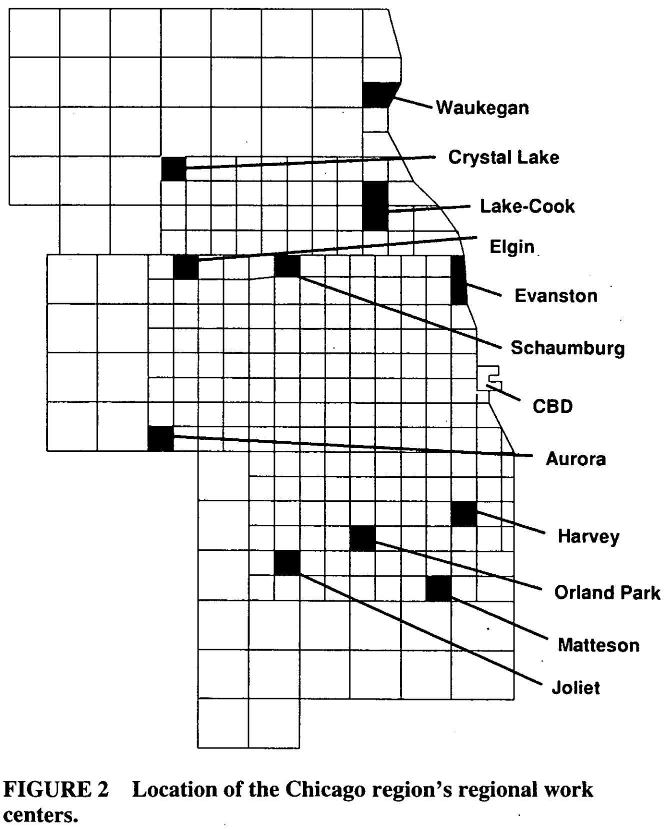

FIGURE 2 Location of the Chicago region's regional work centers.

EFFECTS OF VARYING TRANSIT FARES

The effects on each of the output variables considered of varying transit fares are shown in Figures 3 and 4 and may be summarized as follows.

Mode Choice

As transit fares increase, the relative attractiveness of transit compared with the automobile decreases. Thus, we find a decrease in the proportion of trips by transit and a corresponding increase in the proportion of trips by automobile. The effect is nonlinear, however, because the increase in automobile trips also results in increased automobile travel times, thereby reducing the attractiveness of the automobile.

Trip Length

As shown in Figure 3, an increase in transit fares is marked by a decrease in the average trip length for both modes, transit and automobile. Therefore, as transit fares are increased from low to higher values, there is a tendency for shorter trips to shift to automobile, resulting in a decrease in the average trip length for automobile. Increased costs associated with transit trips lead to a decrease in the average trip length for this mode as well. In addition, as the highway network becomes congested, the average length of transit trips reaches a stable minimum of about 14.5 km (8.7 mi).

Travel Time

The decrease in the average trip length for transit is accompanied by a decrease in the average travel time. On the other hand, as the number of trips by automobile increases as a result of the shifting of some trips from transit, there is an increase in the number of automobiles on the network to accommodate these trips, resulting in a reduction in the average speed on the network. Thus, slower speeds on the network result in an increase in the average travel time for automobile trips, despite a decrease in the average trip length.

Congested Vehicle Kilometers (Miles)

As explained before, the increase in the number of automobile trips results in an increased number of automobiles on the network, leading to an increase in congested vehicle kilometers (miles) of travel.

Generalized Costs

The average generalized cost increases for both transit and automobile. In the case of the automobile, the increase may be attributed to longer travel times. For transit, although there is a decrease in the average travel time, the increase in transit fares results in an increase in the average generalized cost.

EFFECTS OF VARYING FUEL PRICES

The changes in trip characteristics due to an increase in fuel prices are shown in Figures 5 and 6. These effects may be summarized as follows.

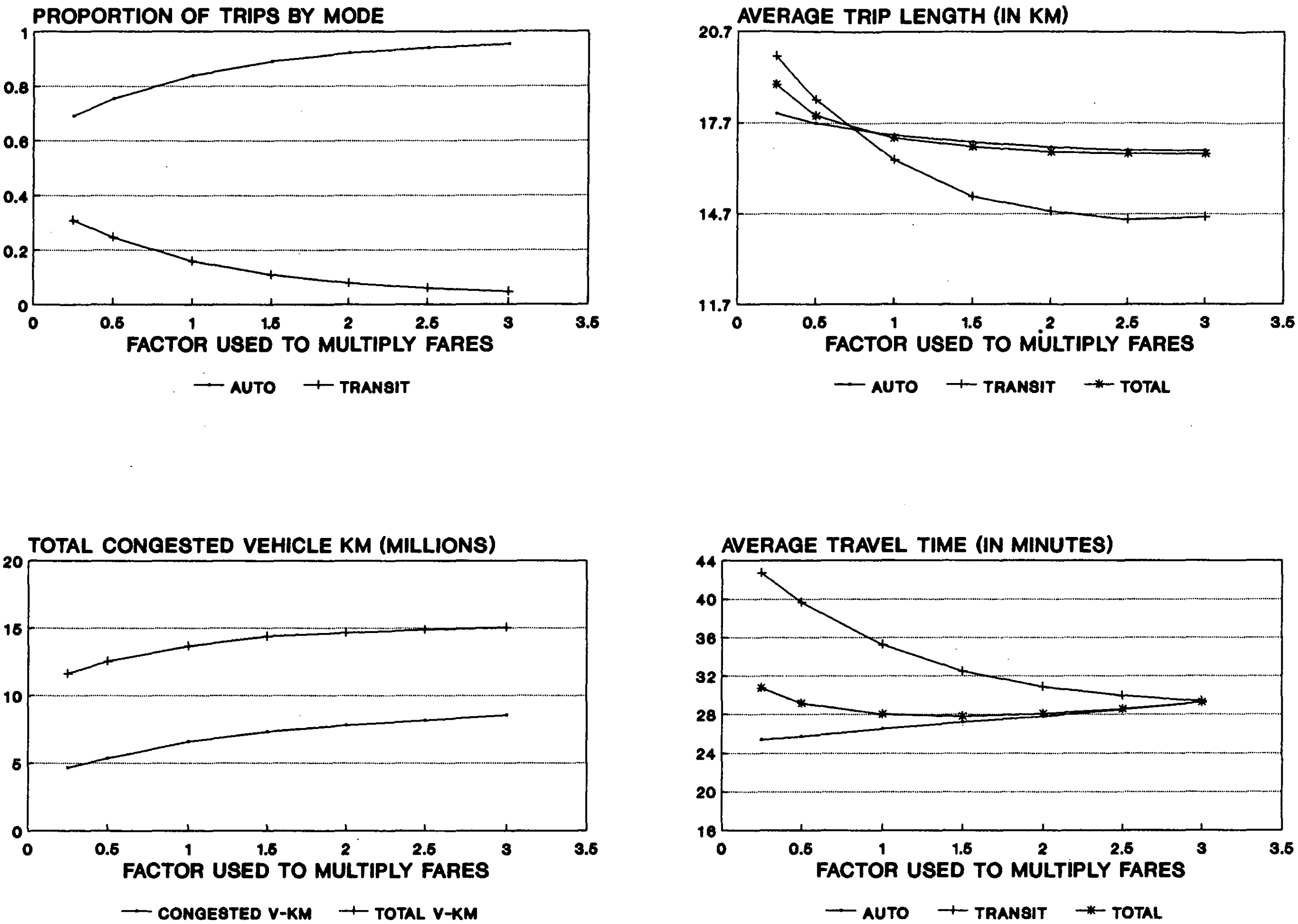

FIGURE 3 **Effect of varying transit fares.**

Mode Choice

As in the case of transit fares, an increase in fuel prices reduces the tendency to make trips by this mode and, accordingly, a decrease in the proportion of automobile trips may be observed. A corresponding increase in the proportion of transit trips may also be noted.

Trip Length

An increase in fuel prices should suppress longer trips, and this result is reflected in the decrease in the average trip length for the automobile. However, there is a corresponding increase in the average trip length for transit, indicating that increasing fuel prices shifts longer trips to transit.

Travel Time

The increase in the average trip length for transit and the decrease in average trip length for automobile are associated with longer average travel times for transit and shorter ones for the automobile. Whereas the increase in transit travel times may be attributed to the increase in transit trip lengths only, in the case of the automobile, shorter travel times also result from an increase in speeds on the network as congestion decreases because of fewer automobile trips.

Congested Vehicle Kilometers (Miles)

As fuel prices increase, there is a corresponding decrease in automobile trips, which results in fewer automobiles on the network, thus decreasing congested vehicle kilometers (miles) of travel.

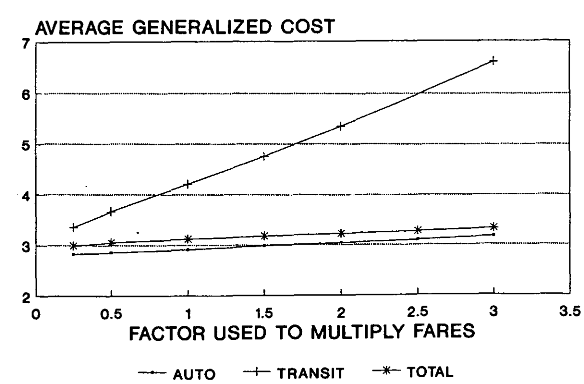

FIGURE 4 **Effect of transit fares on generalized cost.**

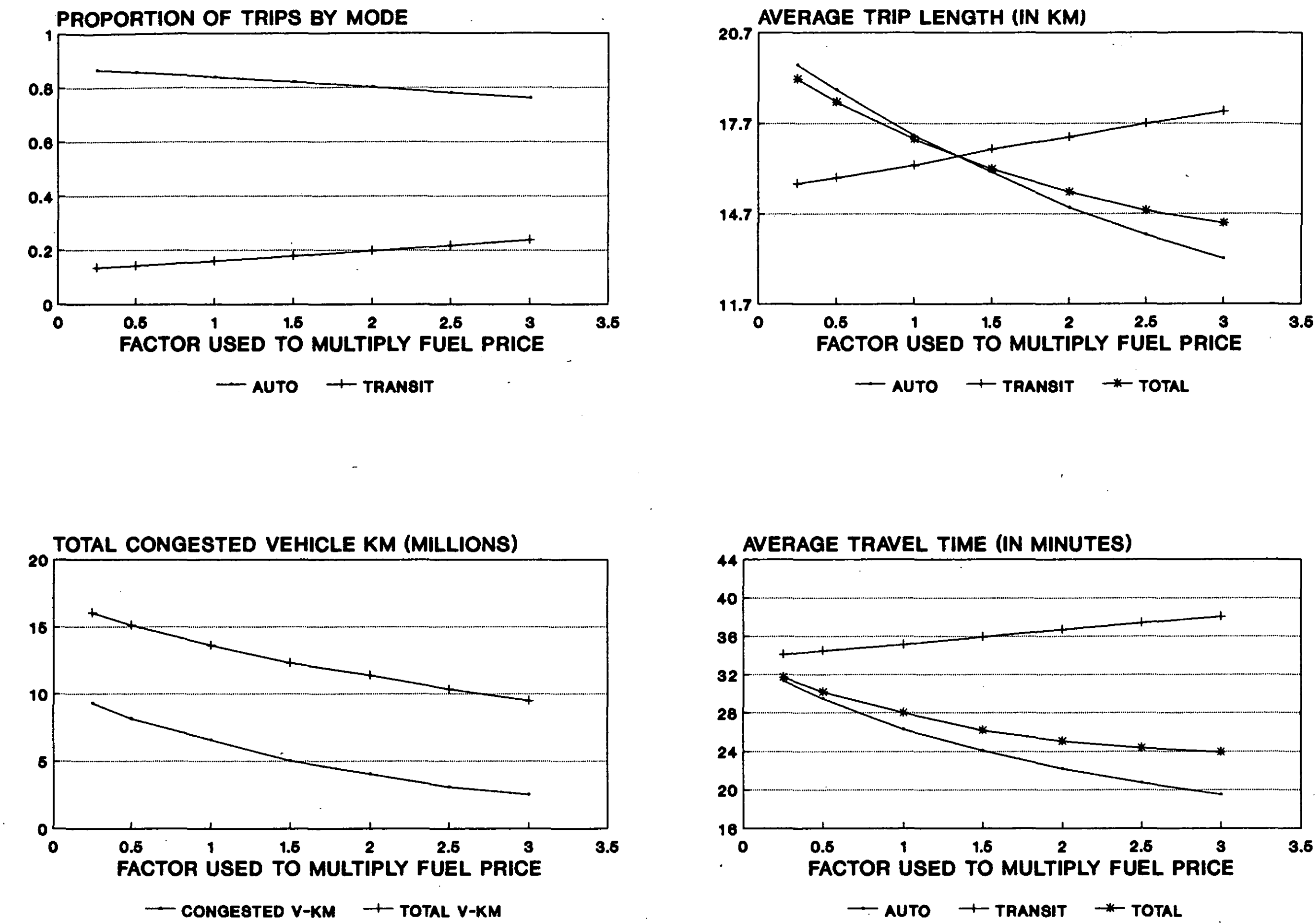

FIGURE 5 **Effect of varying fuel prices.**

Generalized Cost

An increase in fuel prices results in an increase in the average generalized cost for both modes considered. In the case of the automobile, the increase in fuel prices contributes to the increase in the average generalized cost, whereas the increase in the generalized cost associated with transit results from the increase in the average travel time for transit trips.

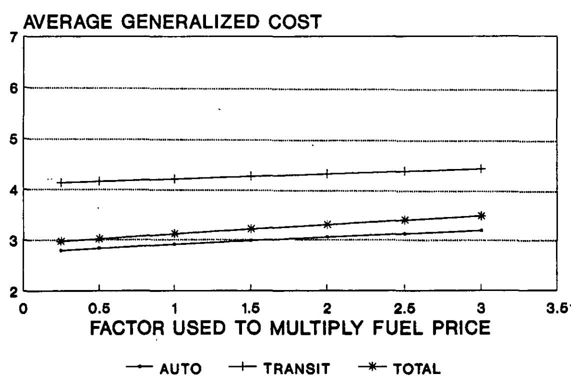

FIGURE 6 **Effect of varying fuel prices on generalized cost.**

EFFECTS OF VARYING EMPLOYMENT LOCATION

Locations of the regional centers to which trip destinations are shifted from the CBD are shown in Figure 2. The effects on travel choices of moving jobs to the suburbs are shown in Figures 7 and 8 and are discussed below.

Mode Choice

The decrease in transit trips may be attributed to the fact that workers employed outside the CBD are unable to use transit for their trip to work because the transit network for the Chicago region is designed to serve suburb-to-CBD trips rather than suburb-to-suburb trips. There is a corresponding increase in automobile trips.

Trip Length

Shifting employment from the CBD to suburban regional centers is marked by a decrease in the average trip length for both modes. In the suburban scenario, workers drive to work sites closer to their homes, thus decreasing the average trip length for both automobile and transit. Some of the long transit trips from the suburbs to the

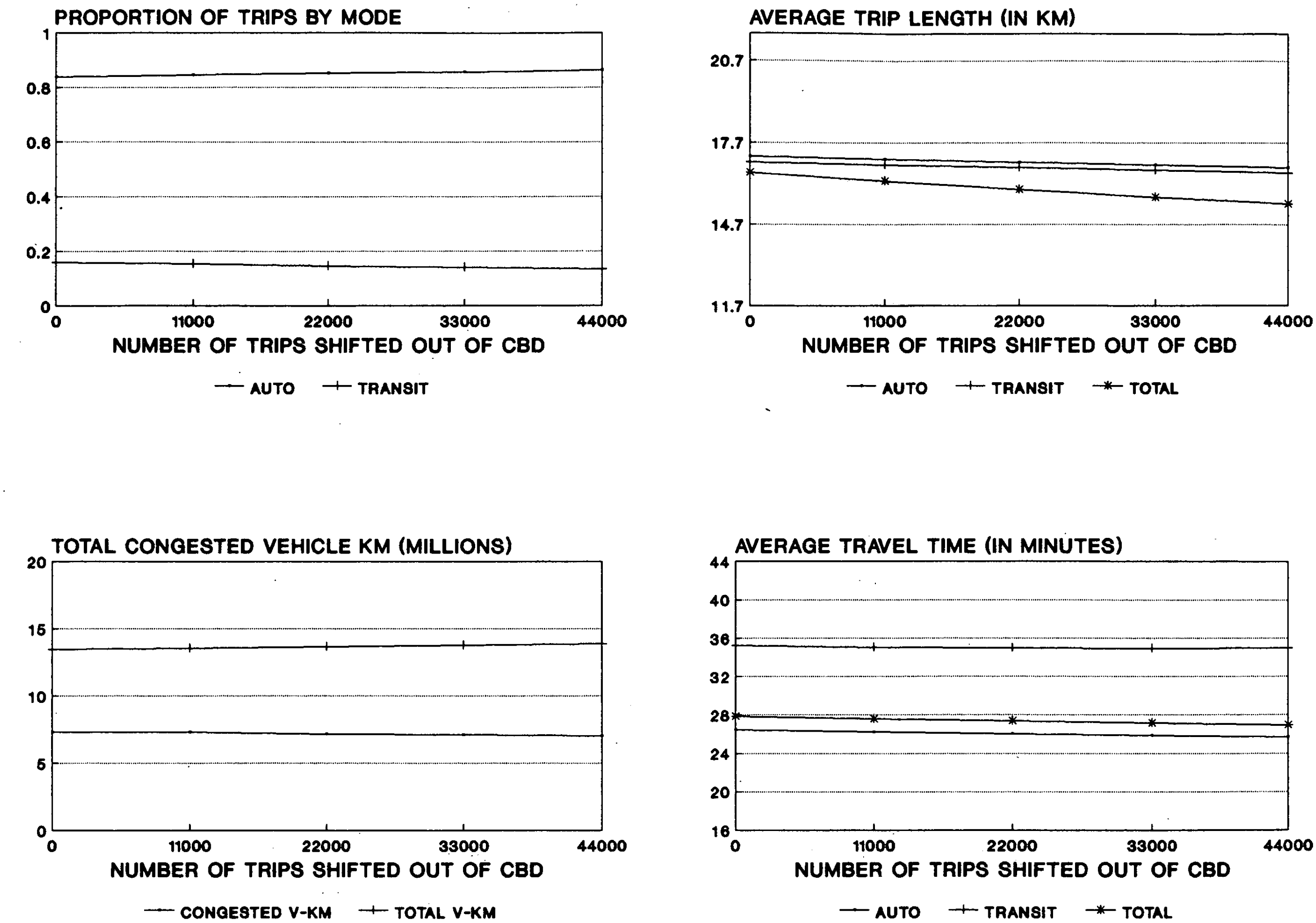

FIGURE 7 Effect of varying employment location.

CBD shift to automobile, resulting in a substantial decrease in transit trip length.

Travel Time

The increase in automobiles on the network is offset somewhat by the shorter distances those automobiles travel. Therefore, the average travel time for both automobile and transit decreases. The decrease in average travel time for transit is also a result of fewer workers bound for the CBD.

Congested Vehicle Kilometers (Miles)

Total vehicle kilometers (miles) traveled increase because of the larger percentage of automobiles on the network overall. However, congested vehicle kilometers (miles) decrease.

Generalized Cost

There is a decrease in the average generalized cost for both automobile and transit, which may be attributed in both cases to shorter work trips (i.e., decreased values of both travel times and monetary costs).

CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

The internal consistency with which travel costs and choices are determined in the combined model provides a better basis to analyze the effects and cross effects of varying costs on travel patterns. Moreover, the ease of applicability of the model enabled this analysis to be completed in a relatively short time. Much of the work in

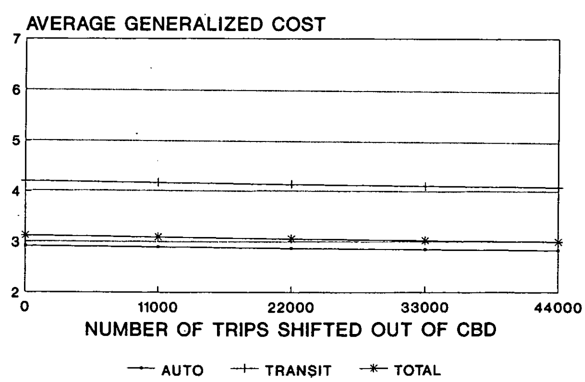

FIGURE 8 Effect of employment location on generalized cost.

developing the model, and subsequent solutions for calibration and analysis work with the model, was done using a CRAY supercomputer. In recent months, however, the model has been solved on a Sun SPARCstation 10 with 64 megabytes of memory at the Chicago Area Transportation Study (CATS). Solving the model at CATS for 20 iterations takes 45 min (i.e., 2.25 min per iteration). There is no doubt that rapid advances in desktop computing technology will make it much easier to use such models in the future.

There are still many possible extensions to the model in its present form that would widen its applicability. For instance, the model could be revised to enable one to predict variations in the overall trip rate and average automobile occupancy. Dispersion of travel choices from strictly cost-minimizing behavior occurs either because of differences in the perceived values of cost/time or consideration of factors not accounted for in the modeling process. Although the model in its present form accounts for choice dispersion in location and mode choices, further research could enable consideration of a similar dispersion measure for route choice.

At the present time, the model is solved by directly executing a source code written in FORTRAN. Further coding work, however, could make this model much more user friendly. Indeed, that should be one of the first steps taken to enhance the model's applicability in practical planning analyses. Another approach would be to solve the model using transportation planning software, such as the EMME/2 system.

It is clear that the planning profession needs to take a close look at present modeling methods and revise them to be more consistent. Obviously, the travel choice process does not consist of separate decisions with regard to destination, mode, and route. The interdependency of these choices, and the common costs considered, must be reflected in the modeling process. Planning agencies must incorporate relevant research findings into their modeling process to allow the models to represent more closely traveler response to real-life policy changes.

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