Travel Demand and Estimation of Energy Consumption by a Constrained Model

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A new model based on a theory of consumer behavior has been developed to aid transportation policy analysis. The model assumes that travelers attempt to maximize their spatial and economic opportunities, represented by the total daily travel distance, subject to constraints of time and money. The constraints are not identical for all travelers but depend on such factors as socioeconomic characteristics and transportation system supply. In this basic optimization model, travelers choose the number of trips, trip distances, and car-ownership levels by trip purpose and mode shares. All of these choices are determined through a feedback solution mechanism. Both urban and interurban travel can be treated by the model, although investigation of the interurban model has just begun. The model is useful for the analysis of policies that affect all travel decisions, such as increases in energy prices. It can treat the trade-offs travelers will make among their various trips and their decision to own cars. A simple analysis of the effect of raising fuel prices has shown that travelers will reduce their total amount of interurban travel and shift their mode shares. The energy savings from these responses appear to come mainly from the reduction in travel distance and only minimally from a switch to energy-efficient modes.

Estimation of the energy consumed by travel for alternative scenarios is totally dependent on the available travel demand models, whose purpose is to predict travel behavior under a wide range of assumed conditions. One major problem associated with most of the available models is that their submodels deal with each travel component separately (such as trip generation by purpose, trip distribution, and mode choice). Even when all equations are solved simultaneously, the feedback between the travel components (such as between trip rate and trip distance) is not defined explicitly, and the models tend to be open-ended in the sense that the outputs are not constrained.

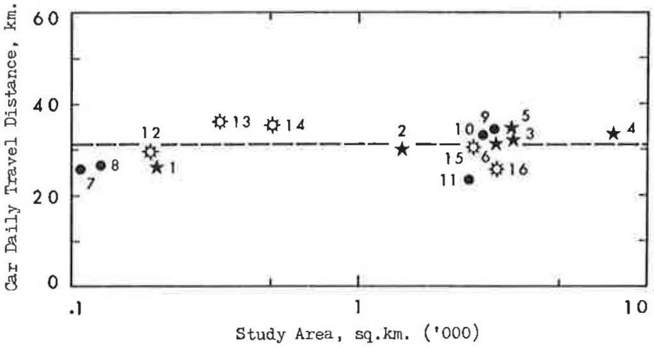
Models based on microeconomics of consumer behavior under explicit constraints of travel budgets appear to be both more true to reality and more versatile in application. One such new model is described in this paper, and examples of its application to both urban and interurban travel conditions are presented and discussed.

URBAN TRAVEL

A car, on the average, travels the same daily travel distance in a wide range of cities in both developed and developing countries (1). Figure 1 shows the daily travel distance per average car versus city size in the United States, Europe, and developing countries, as detailed in Table 1.

Car ownership levels tend to be lower in large, compact cities than in small, dispersed cities. The principal reason for this is the higher costs of car travel in the larger cities; the available cars still travel, on the average, the same daily distances in most cities. Hence, when all urban travel is considered collectively, it appears that gasoline savings from higher travel costs can accrue primarily from fewer cars and from energy-efficient

Figure 1. Car daily travel distance versus study area.



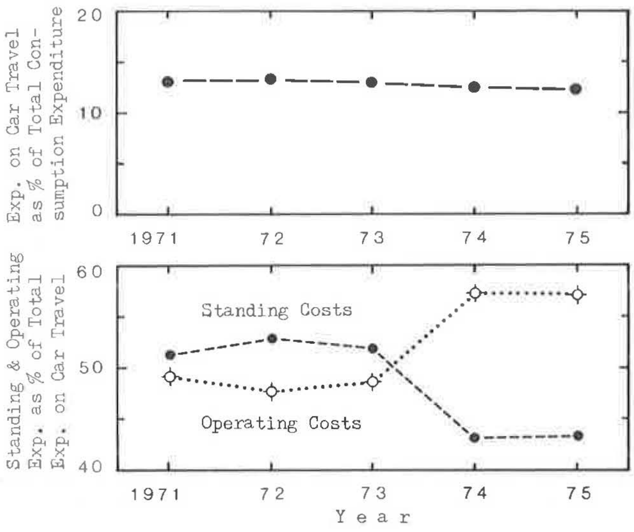
Note: 1 = Monroe, 2 = Orlando, 3 = Cincinnati, 4 = Twin Cities, 5 = Washington, 6 = Philadelphia, 7 = Kingston Upon Hull, 8 = Belfast, 9 = Nuremberg, 10 = Copenhagen, 11 = London, 12 = Tel Aviv, 13 = Kuala Lumpur, 14 = Singapore, 15 = Bogota, 16 = Bangkok.

Table 1. Car travel characteristics in selected cities.

Location	Year	Population	Area (km^2)	Cars per 100 Persons	Trip Rate	Trip Distribution	Total Daily Travel Distribution	Speed (km/h)
United States								
Monroe	1965	96 530	200	32.8	5.79	4.51	26.1	37.1
Orlando	1965	355 620	1400	38.6	4.33	6.92	30.0	42.8
Cincinnati	1965	1 391 870	3495	34.8	3.63	8.85	32.1	38.8
Twin Cities	1970	1 874 380	7680	38.3	4.12	8.19	33.7	39.3
Washington	1968	2 558 100	3410	39.8	3.28	10.59	34.7	40.7
Philadelphia	1960	3 812 460	3040	28.5	3.96	7.88	31.2	NA
Europe								
Kingston upon Hull	1967	344 890	107	12.5	6.25	4.15	25.9	36.0
Belfast	1966	504 620	127	12.8	5.63	4.65	26.2	32.4
Nuremberg	1975	1 160 000	3000	28.3	3.07	11.20	34.4	39.2
Copenhagen	1967	1 707 000	2760	20.1	4.21	7.91	33.3	45.0
London	1962	8 826 620	2450	14.1	3.27	7.18	23.5	31.3
Developing countries								
Tel Aviv	1965	817 000	190	4.9	7.28	4.09	29.8	27.0
Kuala Lumpur	1973	912 490	337	7.2	6.78	5.36	36.3	25.9
Singapore	1968	1 536 000	518	4.1	5.03	7.03	35.4	33.2
Bogota	1969	2 339 600	2520	2.4	4.55	6.76	30.8	22.5
Bangkok	1972	4 067 000	3100	4.3	3.50	7.40	25.9	19.5

Note: Data relate to internal-internal travel by cars registered in the metropolitan area, derived from the comprehensive transportation study reports.

Figure 2. Expenditures on car travel as a percentage of total consumption expenditure and proportions of standing and operating costs of car travel, U.S. total 1971-1975.



cars rather than from shorter travel distance per available car.

Rapid and extensive increases in car travel costs, like those caused by Organization of Petroleum Exporting Countries (OPEC) policies, do not imply an immediate reduction in the number of cars. The mechanism is more subtle and extends over a period of time. For instance, car-owning households tend to allocate to car travel a relatively stable proportion of their disposable income; any significant change in such an allocation will affect other money allocations, such as for housing, food, and medical care, that are not as easy to change as travel expenditures. Thus, when the costs of car travel increase suddenly, such as during 1974 and 1979, households are faced with several options. They can (a) reduce the number of cars, (b) reduce the daily travel distance per car, or (c) travel the same distance per available car as before but save on other aspects of car travel costs. Households, on the average, prefer a combination of the last two options in the short run, and add the first option for the long run. For instance, as can be seen in Figure 2 (1), the extensive increase in gasoline prices during 1973-1974 resulted in a substantial increase in expenditures on car operating costs, with a simultaneous and compensatory decrease in expenditures for fixed car costs; however, the proportion of income allocated to total car travel (urban and interurban) remained practically unchanged, at about 12.6 percent of the total consumption expenditure. The decrease in the fixed-cost expenditures was achieved mainly by a decrease in the rate of car replacement; thus millions of cars were unsold (until inflation caught up with gasoline prices). The same patterns were also observed in the United Kingdom (2).

One apparent implication of these observations is that, generally speaking, ownership of a car is justified only above a certain threshold of desired car use. Detailed analyses suggest that the minimum threshold is about 15 car-passenger-km/day for the first car and about 55 car-passenger-km/day for the second car per household (3). These values may explain the relatively stable average daily travel distance per car within metropolitan areas, as shown in Figure 1.

Another implication of the above observations is that, if car operating costs continue to increase incessantly, a point must be reached where households would either have to give up the use of their cars or would have to spend more than 12-13 percent of their income in order to travel the observed average distance per car. Indeed, the proportion of expenditure on urban car travel in many countries is much higher than in the United States and accounts for up to 25 percent of income in cities of some developing countries, although cars still travel, on the average, about 30 km/day within the urban areas.

The expenditure proportion on car travel is critical for the economy of a country. A compensatory change within a stable expenditure on car travel (as shown in Figure 2) can severely affect the automotive industry and have effects that spill over to some other sectors of the economy; however, a real increase in the expenditure on car travel may result in a rearrangement of all the money allocations to all other goods and services. Hence, the level of car operating costs after which the proportion of expenditure on car travel starts to increase is critical for the entire economy. Unfortunately, little is known about this subject, since most travel demand models deal with the time and money expenditure per trip and ignore the possible implications of the total travel expenditures, aggregated for all trips per household per day, on travel behavior.

A different approach to travel behavior, which takes into account the total expenditures on travel, is presented below. Although this approach is still in its development stages, it already shows some promising insights into the mechanism of travel behavior.

THE UNIFIED MECHANISM OF TRAVEL APPROACH

The new approach to travel behavior is called the unified mechanism of travel (UMOT). It was first conceptualized for the World Bank and further developed for the U.S. Department of Transportation and the Federal Republic of Germany Ministry of Transport (3). It is based on the assumption that the daily mean expenditures on travel per traveler and per household, in time and money, display predictable regularities that can be attributed to such factors as the socioeconomic characteristics of the household, the transport system supply, and the urban structure. When these regularities are found to be transferable both between cities and over time in a country, then these expenditures can be regarded as travel budgets. Furthermore, under certain conditions, these travel budgets may be applied as constraints on travel behavior. There is now an increasing amount of evidence to suggest that travel time and money expenditures do, indeed, display predictable regularities (4-8).

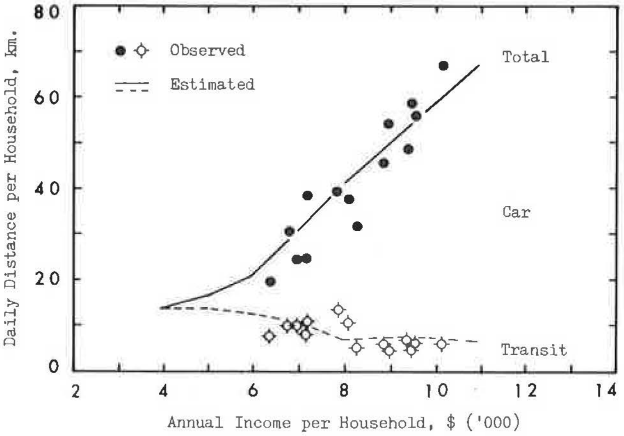
One useful way of applying travel budgets as constraints is within the microeconomic theory of consumer behavior, where consumer utilities are maximized under explicit constraints. In UMOT, the utility of the spatial and economic opportunities to which a person travels, which are conveniently represented by the average daily travel distance, is maximized under the explicit constraints of time and money budgets allocated to travel. As is common in economics, UMOT considers an average traveler who is representative of a group that has similar socioeconomic and locational characteristics.

The constraints in the UMOT process are not absolute constants, but can vary with exogenous (and endogenous) factors. For instance, the daily travel time budget per traveler is a function of speed, and the daily travel money budget per household is a function of such factors as urban structure, income,

Table 2. Summary of estimated travel demand per household by income for the average weekday, Washington, D.C., 1968.

				Car			Transit			
Annual Income ($)	Cars per Household	Travel Money ($)	Travel Time (h)	Door-to-Door Speed (km/h)	Cost per Kilometer ($/km)	Daily Travel Distance (km)	Door-to-Door Speed (km/h)	Cost per Kilometer ($/km)	Daily Travel Distance (km)	Total Distance (km)
4 000		0.51	2.02	13.5	0.104	0.02	6.8	0.037	13.63	13.65
5 000	0.1	0.75	2.02	15.0	0.096	2.39	7.5	0.037	13.96	16.35
6 000	0.35	1.24	2.09	16.0	0.092	8.40	8.0	0.037	12.52	20.92
7 000	0.71	2.01	2.20	19.0	0.081	19.74	9.5	0.037	11.02	30.76
8 000	1.02	2.82	2.29	21.0	0.075	34.14	10.5	0.037	6.97	41.11
9 000	1.29	3.17	2.41	24.0	0.068	42.38	12.0	0.037	7.73	50.11
10 000	1.54	3.53	2.53	26.0	0.064	50.81	13.0	0.037	7.45	58.26
11 000	1.76	3.88	2.63	28.0	0.060	60.59	14.0	0.037	6.56	67.15

Figure 3. Estimated and observed daily travel distances per household, by mode, versus income for Washington, D.C., 1968.



and car ownership. Constraints that vary with speed or level of car ownership require an iterative process for solving the utility-maximization equations.

The application of explicit constraints is a powerful tool because the constraints eliminate the need for much of the coefficient calibration of conventional models. Thus, once the constraints and unit costs of all alternative modes are known, the model produces estimates of such travel characteristics as daily travel distance, modal share, and car ownership, with almost no estimation of coefficients.

An additional advantage of applying constraints as the driving mechanism of choice making is that it allows the calculation of all the travel characteristics in a consistent equilibrium. For instance, application of the travel-distance-maximization process under the time and money constraints results in the demand for travel distance by each mode. The demand for car travel distance generates car ownership required to satisfy the demand; the interaction between the estimated number of cars and a given road network results in new unit costs of travel, which are fed back into the travel demand phase; and the process is repeated by iterations until equilibrium between travel demand and system supply is reached. One aspect of the robustness of the model is that, although all travel components interact with each other, the outputs converge rapidly to the observed values.

The use of average daily travel distance to represent travel utility has additional advantages. The conventional approach is to attribute utility to the trip purpose at the trip destination. There are, however, several practical difficulties with such an approach; for instance, trips are linked in various ways and, hence, different definitions and treatments of trip linkage can result in different trip rates. Furthermore, the definition of linkages affects modeling of trip purposes, distance, time, and cost, as well as modal shares.

On the other hand, the only travel component unaffected by definitions of trip linkage is the total daily travel distance, which is invariant for any combination of trip rates, trip distances, trip times, and trip costs. The same invariance also applies to the total daily travel time and money expenditures.

Note further that the daily travel distance is also a measure of the potential accessibility to various destinations, within which trip rates and trip distances can be traded off. Thus, the daily travel utility is still attributed to the combination of trip purposes at the trip ends, but it is measured by the daily travel distance.

Perhaps the best way of explaining the characteristics of UMOT is to present an example.

Example with Two Modes

Table 2 details the observed daily travel time and money expenditures per average household, stratified by income, as derived from the 1968 comprehensive home-interview survey in Washington, D.C. The table also details results from UMOT of the estimated maximum daily travel distance, by two major modes, that can be generated by the given unit costs within the constraints of travel budgets. (The travel time budget per household increases with income primarily because the number of daily travelers per household increases with household income, but the daily travel budget per traveler shows a negligible variation with income.)

Figure 3 shows the estimated travel distance per household by mode as continuous curves and the observed values as dots. The fit between the estimated and the observed values is encouraging, especially since the estimated values were not calibrated to the observed values of trip characteristics but were derived only from the observed travel budgets and unit costs of travel, and theoretical relationships were dictated by the utility model of the UMOT process (3).

The data in Table 2 can also be expressed in a different way, as shown in Figure 4. The diagram details the daily travel distance per household that can be generated by each of the two major modes if each travel budget is observed separately for different income levels (i.e., by dividing each budget by the unit cost of each mode). Since the faster mode is usually the more expensive, the travel distances that can be realized when both modes are available are expected to be within the shaded area in Figure 4. This area includes those values of maximum travel distance that can be generated by

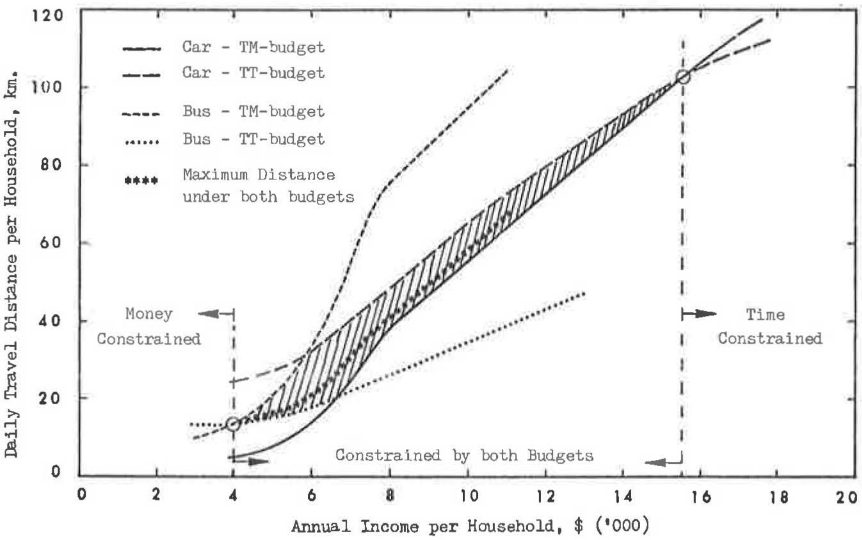


Figure 4. Maximum daily travel distance per average household versus household annual income for Washington, D.C., 1968.

using combinations of the available modes. Indeed, the observed travel distance per representative household follows the curve that represents the maximum distance under the constraints. Hence, the shaded area represents the choice set for modal shares (measured by distances, not trips).

The figure also shows that households that have an annual 1968 income within the $5000-$15 000 range will use both travel budgets in trade-offs to achieve maximum travel benefits (i.e., in this case maximum travel distance). There are cases, however, where one budget alone is binding. For instance, representative households below an annual 1968 income of approximately $4000 are constrained in travel choices by money expenditures alone and, therefore, have a practical choice of the transit mode only. Representative households above an annual 1968 income of approximately $15 500, on the other hand, are constrained by time expenditure alone and thus are expected to prefer the speedier mode, namely, car only. (These results would be modified, of course, if system supply was considered to vary by household location. For instance, high-income travelers located in high-density areas might still choose some transit due to slow car speeds and relatively better transit service.) Such cases analytically operationalize the planning concepts of mode choice and captive riders on particular modes.

The simple relationships in Figure 4 also suggest what possible shifts in modal choices are to be expected if travel conditions change. For example, increases in the unit cost of car travel will lower the car travel money (TM) curve and result in (a) a wider choice set, (b) an increase in bus travel, and (c) a decrease in total daily travel distance. The last result is of considerable importance because it suggests that modal changes are not only unilateral transfers (as usually is the case when mode choice is based on trips), since travel distance may be gained or lost, depending on the direction of transfer.

Observed Variations

The last point to note at this stage is that the link between the above aggregate examples and the behavior of an individual household is the variation in the observed values of travel time and money budgets around their mean values for each socioeconomic group. The causes for such variations are many and varied, and they can be grouped under four principal classes:

1. Socioeconomic differences such as income, age, profession, and sex of the travelers; since summary tables cannot capture all the possible stratifications of such characteristics, part of the variations can be attributed to real differences between the travelers.
2. Taste differences such as mode preference, which may be affected by personal considerations of safety and convenience; conventional surveys usually do not capture the reasons for such personal preferences.
3. Daily differences in travel for each traveler; this may be greater than the variations between different travelers during one day; hence, a weekly travel diary should be preferred over a one-day survey.
4. Sampling, coding, and processing differences that may introduce errors into the data.

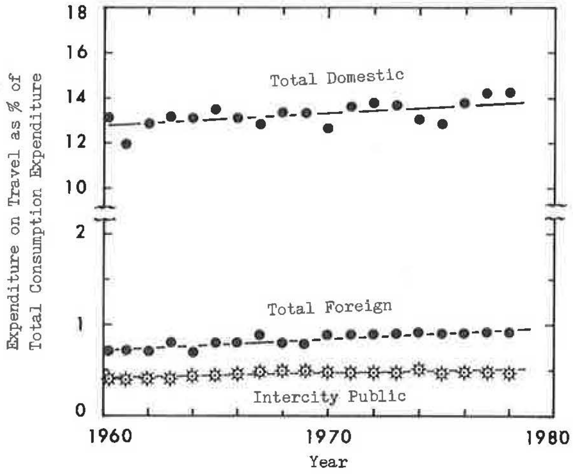
Detailed analyses of travel time budgets in a wide range of cities in both developed and developing countries suggest a rather large coefficient of variation (standard deviation over the mean) of about 0.6. Interestingly, this value was found to be quite similar both between different cities and within each city for different stratifications of travelers. The same stability between cities and between groups of households within each city was also noted for the variation in the total travel distance per household, which suggests that the same stability also applies to the travel money budget (3). Thus, the expected behavior of an individual household that belongs to a certain socioeconomic segment can be expressed in probabilistic terms based on the group's mean values of the travel time and money budgets and the variations about their mean values.

The use of constraints in travel demand models can be appreciated best when applied to interurban travel, where differences between modes can be more pronounced (say, car versus airplane) than in urban travel, and trip distances are not confined by the boundaries of an urban study area.

INTERURBAN TRAVEL

The literature on interurban travel demand models is vast, and the reader is referred to the following summary reports: a comparative evaluation of seven models, developed in the Northeast Corridor Transportation Project (9); alternative demand functions for abstract transportation models (10); airline

Figure 5. Expenditure on total domestic, foreign, and intercity public travel as a percentage of total U.S. consumption expenditure, 1960-1978.



passenger forecasting (11,12); intercity rail passenger forecasting (13); and European intercity passenger transport (14).

All currently operational interurban models, like urban models, have to be calibrated to the observed travel choices that they are required to estimate, and their validity hinges on their ability to reproduce the choices to which they were fitted. The UMOT process, on the other hand, is based on the constraints under which travel choices are made, and the predicted travel choices are then compared with the observed choices for the model's validation.

The inputs required for the UMOT process are as follows:

1. Time and money budgets allocated to interurban travel by households of different population segments and
2. Operational characteristics of the modes, assumed in our case to be three--car, train, and airplane.

The amount of data on the time and money budgets that households allocate to their urban travel is rapidly increasing, but a lot of data have not yet been summarized for interurban travel. An important aspect of this data void is that we do not know for sure that stable interurban budgets exist for individual households, although the money expenditures on interurban travel display remarkable regularities over time at the aggregate level, as can be seen in Figure 5 (15). Therefore, the following examples can be regarded as sensitivity tests for the interurban UMOT process, where interurban travel is generated under a wide range of assumed money and time budgets. The results are then examined to assess the reasonableness of the model.

For the simulations detailed below, the range of the money budgets is limited to \$20-\$200, and the range of the daily time budgets is 2.00-6.25 h (120-375 min). Note that the travel money and time budgets are not allocated to travelers who have specific incomes or other socioeconomic characteristics. Such an allocation still awaits data from actual surveys. Furthermore, in the following simulations no assumptions are made about the frequency of travel (e.g., a traveler could either spend \$50 on each of four trips during a certain period or spend \$200 on one trip). Thus, the simulations deal with a range of trips, without specification about their frequency per traveler.

The matching of time budgets to money budgets of travelers is based on the reasonable assumption that there is an increasing reluctance to spend more time on interurban travel as money expenditures increase, with an upper limit of about 8-10 h during one day. Thus, the travel time budget is assumed to increase with money budgets at decreasing rates, following a decreasing marginal utility trend, which expresses known trends of the value of travel time. This assumption differs from the situation for urban areas, where the daily travel time budget per average traveler shows little variation.

Three modes are considered here: automobile, rail, and airplane. With the inclusion of the modes' access and egress times, the range of travel time budgets that could be reasonably matched to each money budget came out to be relatively narrow. This then leads to the result that changes to the travel time or travel money budget change the choice set. For instance, reduction of the travel money budget for a given travel time budget reduces the choice set from three modes, through two modes, to only one mode. Such boundaries of the time and money budgets, which determine the choice set, are an important finding of the UMOT process, and they are of special importance for mode-choice analyses.

The operational characteristics of the three modes are detailed in the table below, based on actual travel experience from late 1978 to early 1979. The operational characteristics of automobile and train are kept constant, but the speed of air travel is regarded as a function of travel distance, and makes allowance for the time for climb and descent. The costs are based on travel costs in the Northeast Corridor of the United States during 1978.

Characteristic	Car	Train	Airplane
Network average speed (km/h)	90	100	600-700
Cost (\$/km)	0.120	0.070	0.110
Access and egress time (min)		40	90
Access and egress cost (\$)		3	12

Trip characteristics for one traveler after one iteration under various time and money constraints are given in Table 3. Because of the access-egress costs in terms of time and money, the unit trip time and cost depend on distance and, therefore, the exercises have to be iterated:

1. The first run of the UMOT process is based only on the networks' unit costs and
2. The iteration is carried out on the basis of the generated travel distances by mode that result from the first run and the addition of the access-egress times and costs, which affect the new costs and, hence, also the new travel distances.

Basic Results

Application of the UMOT travel-distance maximization process results in the following outputs:

1. Total travel distance by using the available modes within the travel time and money budgets and, as a result, simultaneous mode shares;
2. Allocation of travel time and money to each mode and, therefore, the expected revenue for the operators of the public modes; and
3. Average travel speed.

All modes in the simulations are considered to be equally attractive to travelers; personal tastes and preferences for a specific mode are disregarded.

Table 3 summarizes the unit costs and outputs,

Table 3. Estimation of travel under money and time constraints for one traveler after one iteration.

		Travel Budget					
Characteristic	Mode	\$20, 120 min	\$50, 240 min	\$75, 300 min	\$100, 330 min	\$150, 360 min	\$200, 375 min
Unit costs[a]							
Money (\$/km)	Car	0.120	0.120	0.120	0.120	0.120	0.120
	Train	0.092	0.084	0.082	0.082	0.083	0.085
	Air	0.426	0.183	0.146	0.132	0.122	0.118
Time (min/km)	Car	0.667	0.667	0.667	0.667	0.667	0.667
	Train	0.896	0.781	0.763	0.763	0.772	0.794
	Air	2.468	0.645	0.373	0.261	0.176	0.146
Travel distance (km)	Car	85	109	134	143	142	121
	Train	18	76	107	118	113	95
	Air	19	166	341	554	1013	1509
Total		122	351	582	815	1267	1725
Modal split by distance (%)	Car	69.7	31.0	23.1	17.6	11.2	7.0
	Train	14.7	21.7	18.4	14.4	8.9	5.5
	Air	15.6	47.3	58.5	68.0	79.9	87.5
Average door-to-door speed (km/h)		61	88	116	148	211	276

[a] Final, after iteration.

Figure 6. Travel distance per traveler by mode versus expenditures on travel by use of UMOT process.

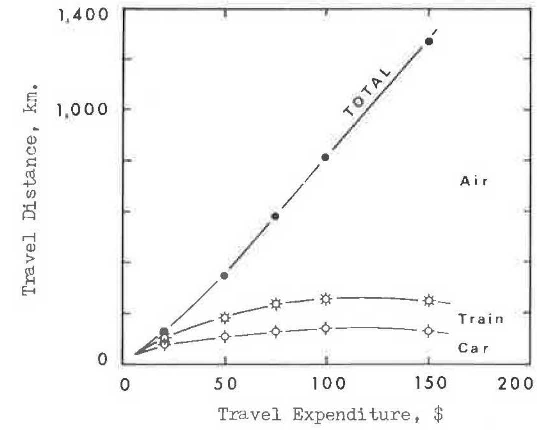
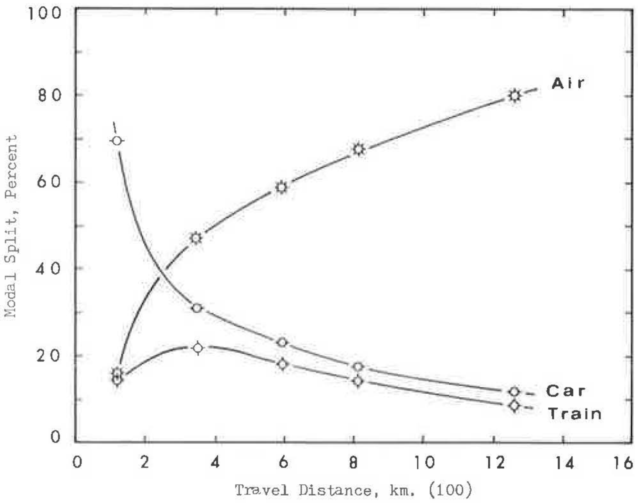


Figure 7. Modal split per traveler versus travel distance by use of UMOT process.



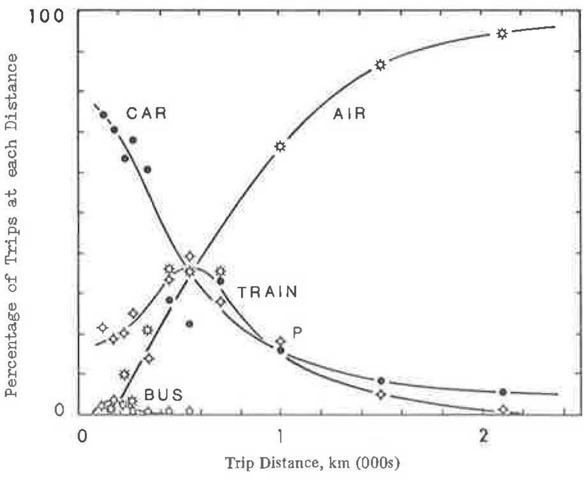
and Figure 6 shows the maximum travel distance, by mode and total, that can be generated within the travel budgets after one iteration.

There is nothing unusual in Figure 6, but if the proportions of travel distance by mode are related to the total travel distance, a remarkable transformation takes place, as shown in Figure 7, which is the well-known relationship of trip modal split versus trip distance. An example of this relationship is shown in Figure 8 (14).

The last result is of special interest for the understanding of travel behavior. The proportion of trip modal split by trip distance is an observed relationship to which other models are calibrated. In the UMOT process, on the other hand, it is an output from a model of behavior; thus a behavioral rationale is suggested for the observed relationship. The units of measurements in Figures 7 and 8 are different; nonetheless, the travel behavior clearly follows the same trends, namely (a) the choice of the automobile mode decreases monotonically with travel distance, (b) the choice of the air mode increases monotonically with travel distance, and (c) the choice of the train mode increases with travel distance up to a maximum value, after which it declines.

The UMOT process can be used for different trip purposes (such as business and nonbusiness) by as-

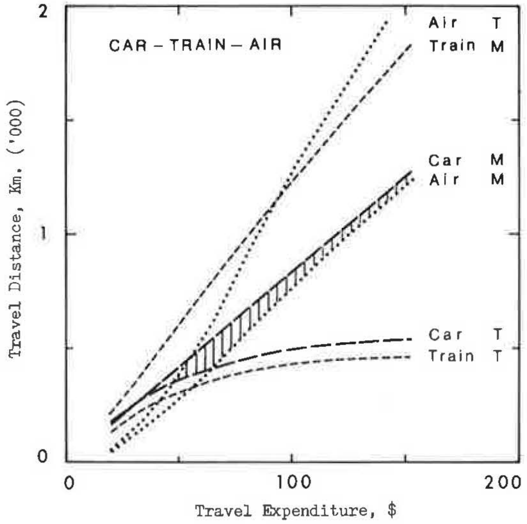
Figure 8. Trip modal split by trip distance for business trips in European inter-city travel.



suming different ratios between the travel money and time budgets (i.e., different values of travel time). The results show the same general relationships, with slight shifts. For instance, the observed relationships for business trips display a stronger preference for air mode than for automobile and train modes at each trip distance. The same pattern is also generated by the UMOT process when the value of travel time is increased. However, the importance of the UMOT process is that it can predict the behavior of travelers with minimal dependence on the available observations, and hence it can be used to predict travel behavior beyond the range of observations with more assurance than can calibrated models.

For instance, the process can be used to estimate the demand for travel by a mode before the service is provided. As an example, the demand for air travel starts at relatively short travel distances, for example, 150 km in Figure 7. However, the absolute size of the demand may not justify the provision of air service for distances of less than, say, 250 km on economic grounds; thus the observed choice set for trips up to 250 km is reduced to two modes only--automobile and train. For this reason, the process is a powerful tool for estimating the potential demand for travel in situations where service is not yet provided.

Figure 9. Maximum daily travel distance per traveler under the travel money and time budgets for interurban travel by use of UMOT process.



The UMOT process can also define the choice set for any combination of modes, even for ones not yet introduced, if their operational characteristics are defined. If we refer to Table 3 and the same procedure described in Figure 4, it is possible to estimate the maximum travel distance by a mode, actual or assumed, within the travel time and money budgets. The results for the interurban case of three modes are shown in Figure 9. The UMOT process then estimates the mode shares within the shaded area that would result in the maximum travel distance.

Group Travel

It is well known from experience that the mode choice of travelers who travel as a group and share the same travel money budget (such as members of the same household) can be significantly different from the mode choice of a single traveler. The UMOT process can treat such cases readily. For example, if two travelers travel together, their money expenditures for train and air fares are often doubled. Therefore, their joint decision will affect not only choice of mode but also the total travel distance. Details of the analysis are given in Table 4 and shown in Figure 10.

The comparison between Figures 10 and 7 and their respective tables suggests the following:

1. A joint decision will affect both the mode choice and the total travel distance.
2. The effect of a joint decision differs, depending on the level of travel money budget (i.e., reflecting the level of income). For instance, at low travel money expenditures, the case of three modes reduces to a case of two modes; air travel is not even considered as a choice, as shown in Figure 10. This is an extremely important result for both travel modelers and policymakers, as the process can define the choice sets for different population segments and determine what population segments can

Table 4. Demand for interurban travel under money and time constraints for two travelers after one iteration.

		Travel Budget					
Characteristic	Mode	\$20, 110 min[a]	\$50, 240 min	\$75, 300 min	\$100, 330 min	\$150, 360 min	\$200, 375 min
Unit costs							
Money (\$/km)	Car		0.120	0.120	0.120	0.120	0.120
	Train		0.205	0.172	0.166	0.163	0.163
	Air		1.483	0.544	0.405	0.283	0.259
Time (min/km)	Car		0.667	0.667	0.667	0.667	0.667
	Train		1.030	0.814	0.772	0.754	0.753
	Air		4.837	1.316	0.792	0.330	0.234
Travel distance (km)	Car	167	165	174	164	181	177
	Train		87	133	142	159	157
	Air		8	57	140	361	590
Total		167	260	365	447	701	924
Modal split by distance (%)	Car	100	63.3	47.7	36.8	25.8	19.1
	Train		33.5	36.6	31.8	22.7	17.0
	Air		3.2	15.7	31.4	51.5	63.9
Average door-to-door speed (km/h)		90	65	73	81	117	148

[a] Degeneration to one mode at the lowest income level.

Figure 10. Modal split for two travelers sharing the same money expenditure versus travel distance by use of UMOT process.

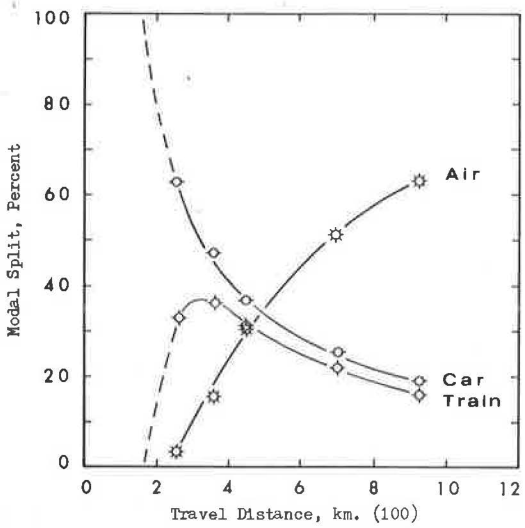


Table 5. Effect of increased train speed on travel demand for one traveler who has budgets of $100 and 330 min after one iteration.

		Train Speed		
Characteristic	Mode	100 km/h	200 km/h	Difference (%)
Travel distance (km)	Car	143	121	-15.4
	Train	118	215	+82.2
	Air	554	475	-14.3
Total		815	811	-0.5
Modal share	Car	17.6	15.0	-14.8
	Train	14.4	26.6	+84.0
	Air	68.0	58.5	-14.0

Table 6. Maximum travel distance for travel budgets of $100 and 330 min before and after car travel cost is increased by 25 percent and train and air fares are increased by 5 percent.

	Absolute Values (km)			Modal Shares (%)		
Mode	Before	After	Difference (%)	Before	After	Difference (%)
Car	143	151	+5.6	17.6	20.4	-2.8
Train	118	120	+1.7	14.5	16.2	+1.7
Air	554	469	-15.3	67.9	63.4	-4.5
Total	815	740	-9.2			

gain or lose from changes in travel costs and fares for each and all modes.

3. One possible way to attract more travelers to a public mode (trains, for example) is to start with discount fares for small groups of travelers that belong to one family (say a minimum of two or three) and to differentiate the discount by travel distance, namely to increase the discount with increasing trip distance. However, a close watch should be kept on such fares and discounts in relation to travel costs by other modes.

4. The value of travel time, which is currently derived from the observation of trade-offs between money and time expenditures for single trips, is not an intrinsic and fixed characteristic of travelers; the value may vary, depending on the number of travelers from the same household who make a joint decision.

Although these tentative indications, which result from simulations, appear to follow known trends, they still need careful assessment before they can be regarded as conclusive.

The UMOT process is also sensitive to changes in other components of the travel system.

Changes in System Supply

An increase in the travel speed of one mode can have a considerable effect on the use of all other modes. For example, a doubling of the operational speed of trains, say from 100 to 200 km/h, has specific expected effects on a traveler who has travel budgets of, say, $100 and 330 min, as detailed in Table 5. As can be seen, there is a marked shift to train travel, in both absolute and relative terms, which results in an increased demand for train travel of more than 80 percent. However, additional tests with this case suggest that such shifts to train travel are very sensitive to travel costs and that a relatively small increase in train fare (relative to the fares of other modes) can negate most of the benefits of increased speed.

The UMOT process can also predict travel behavior under extreme increases in gasoline prices or restrictions on automobile interurban speeds, since its validity is not dependent on calibrations to the observed travel characteristics. For example, the estimated effects of an increase of 25 percent in the total cost of car travel and an increase of 5 percent in train and air fares on the travel choices of a traveler who has travel budgets of $100 and 330 min (after one iteration) are detailed in Table 6.

This table implies that the total travel distance is decreased by 9 percent. The modal demands by distance show the effects of two opposing forces: Increases in all travel costs, especially for car, reduce the total travel distance, but there is a shift to car travel when the average travel distance decreases (see Figure 7). Hence, contrary to conventional expectations, the end result is a slight increase in car travel distance. Trains also gain some travel, and airplanes lose most.

These results, obtained from hypothetical simulations, are unexpected but not necessarily wrong: Increases in travel costs are expected to reduce the travel distance of interurban trips and, hence, shift the shorter trips to car travel. The same results appear to be maintained even when the matching of time and money budgets is modified. More research on these results based on observed data will have to be carried out before final conclusions are reached.

Special care should be taken in the comparison of before and after mode shares in Table 6 because the common denominator, namely travel distance, changed. For instance, the conventional comparison suggests a decrease of 4.5 percentage points in air travel, but the air travel distance is estimated to decrease by 15.3 percentage points. Hence, calculations based on percentages may result in overestimation (or underestimation) of the actual travel, with possible grave consequences to the estimated revenues of public transport operators.

Additional Factors

Only travel money and time budgets have been considered up to now. However, additional factors that are difficult to identify and quantify, such as safety, comfort, personal preferences, personal handicaps, and their combinations, can affect travel choices. Furthermore, even the time and money budgets allocated to interurban travel by different population segments are not yet known. Moreover, more should also be known about business trips and the relationship between their money budgets (which are usually assigned to the firm and not to the household) and the socioeconomic characteristics of the travelers.

Although all the information required is not readily available, much of it can be derived from available data on interurban travel, and the rest may require additional, but limited, surveys. The point to note, however, is that data already available from surveys of urban and interurban travel, with the addition of simulations by the UMOT process, can be used to reduce the amount of required data.

The results of the above exercises can be used to good effect in clarifying a principal and urgent subject, namely the expected effects of changes in travel costs on the consumption of energy. One example of such possible effects is discussed below.

TRAVEL ENERGY CONSUMPTION

It is not directly evident from available observations how changes in travel costs affect the amount of interurban travel distance and, therefore, the amounts of energy required. There is, of course, some experience with such changes in selected cases, such as the effect of reduced air fares (including group fares and discount coupons) on air travel, but most of the studies deal with trips and not with the effects on travel distance. For energy consumption, however, the primary effects should be expressed by passenger travel distance, which is a direct output of the UMOT process.

Basic Assumptions

One example of UMOT's use in energy analysis is presented here. For simplification, the example is divided into two parts:

1. Derivation of the energy-consumption relationships for the urban and interurban cases detailed above and
2. Testing of the effect of increases in travel costs on interurban travel by one class of travelers.

The energy intensities of the relevant modes used in the exercises are detailed in the table below.

Mode	Btus per Passenger Kilometer	Occupancy Rate
Urban		
Automobile	3600	1.25
Compact automobile	2420	1.25
Bus	3000	12
Rail	2700	25/car
Interurban		
Automobile	1740	2.3
Bus	680	23
Rail	2050	17/car
Air, regular	4230	76
Air, wide-bodied	3360	138

Note that the values in the table above are averages and, depending on the source, may vary as much as ±50 percent. Furthermore, the intensity values given are based on specific passenger occupancy rates, which may not be applicable to all cases. This is why the emphasis in the following examples is on the trends of the resulting relationships and their possible implications to future research, rather than on their absolute values.

Results

Application of the interurban energy intensities to the examples detailed in Table 3 results in the estimated total energy consumption of each case, as summarized in Table 7. The average energy consumption per passenger kilometer is shown below:

Travel Budget	Energy Consumption (Btu/passenger-km)
$20, 120 min	2.17
$50, 240 min	2.99
$75, 300 min	3.25
$100, 330 min	3.48
$150, 360 min	3.76
$200, 375 min	3.94

As expected, energy consumption goes up with the expenditure of travel money, but this increase is actually composed of two different components: The first is an increase in total energy consumption due to an increase in travel distance, and the second is an increase in energy consumption due to a greater relative use of more energy-consuming modes, such as the airplane.

The upper diagram in Figure 11 shows the relationship between the energy consumption per passenger kilometer and the money expenditure (based on 1978-1979 travel costs) on an interurban trip. The lower diagram in Figure 11 shows the same estimated energy consumption versus 1968 household annual income for urban travel in Washington, D.C., based on Table 2 and the preceding text table. The similarity between the shape of the two diagrams adds credence to the results that the demand for high-energy-consuming modes increases with increasing money expenditures on travel (which are directly related to income), although at decreasing rates. The diagrams indicate the results of a shift from bus to automobile in the urban case of Washington, D.C., and from automobile and train to airplane in the interurban case.

One possible implication of these results is that efforts to save energy by encouraging travelers to shift from energy-consuming modes to energy-efficient modes, by such measures as increased travel costs or fares of the consuming modes, may result in the loss of mobility due to reduced travel distance and speed. This conclusion is best illustrated by referring to Table 6 and the preceding text table and calculating the energy consumption before and after the increase in travel costs--total travel distance decreased by 9.2 percent, but total energy consumption decreased by 12.0 percent. Thus, the increasing travel costs and the resulting modal shifts resulted in a 12.0 percent reduction in total energy consumption--9.2 percent due to decreasing travel distance and only 2.8 percent due to a shift to lower energy-consuming modes.

Application of the same process to the case of a $200 daily expenditure in Table 7 results in an even more extreme example: a reduction of 6.2 percent in total travel distance and a reduction of 7.1 percent in total energy consumption. That is, only 0.9 percent was saved by a modal shift, but 6.2 percent was saved by a reduction in travel distance.

By referring to Figure 11 it may also be concluded that, ironically enough, most of the energy savings by modal shifts will be realized at the lower end of travel money expenditures (i.e., for lower-income travelers in most cases). The total nationwide savings in travel energy consumption will then depend on the proportions of travelers at different income levels.

The above indications raise a crucial question: What is the loss to the economy of reduced inter-

Table 7. Energy consumption of interurban travel.

	Travel Budget											
	$20, 120 min		$50, 240 min		$75, 300 min		$100, 330 min		$150, 360 min		$200, 375 min	
Mode	Distance (km)	Btu (000s)	Distance (km)	Btu (000s)	Distance (km)	Btu (000s)	Distance (km)	Btu (000s)	Distance (km)	Btu (000s)	Distance (km)	Btu (000s)
Car	85	148	106	190	134	233	143	249	142	247	121	211
Train	18	37	76	156	107	219	118	242	113	232	95	195
Air	19	80	166	702	341	1442	554	2343	1013	4285	1509	6383
Total	122	265	351	1048	582	1894	815	2834	1267	4764	1725	6789

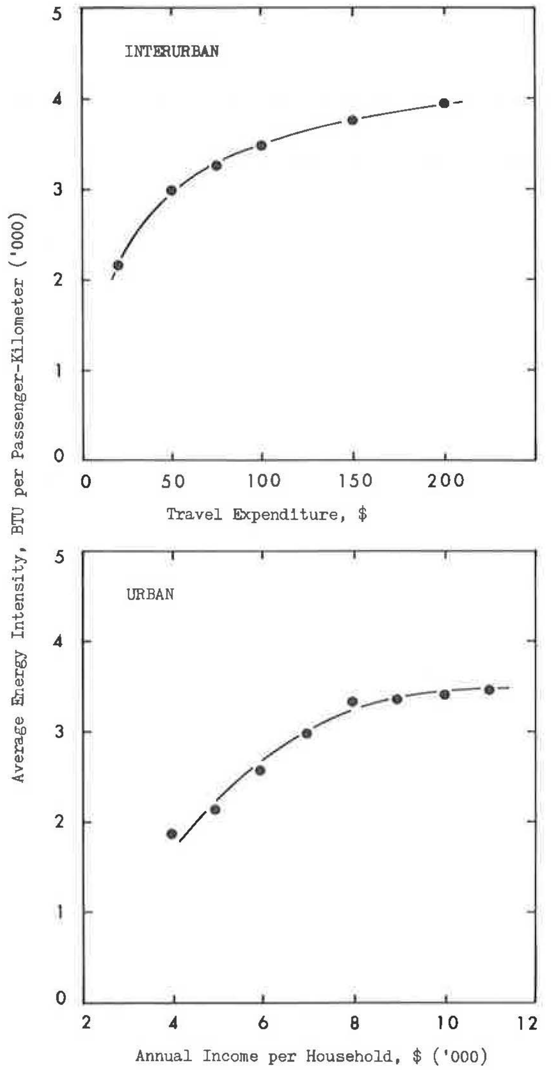


Figure 11. Average energy intensity per passenger kilometer versus travel expenditure and household income in Washington, D.C.

urban mobility versus the gain to the economy of the savings in energy consumption? Although no answer to this question is yet available, it is quite obvious that it is a prerequisite to any major policy decision about nationwide travel energy-consumption savings and their possible different effects on various population segments.

CONCLUSIONS

A new model has been developed to aid transportation planning and policy analysis. It is based on a theory of consumer behavior. It can be used to analyze urban, regional, or national levels of travel patterns and can be disaggregated so that subregions and several socioeconomic groups can be considered simultaneously. Variability in people's travel behavior is taken into account through the inclusion of variances or standard deviations for most of the estimated variables.

The UMOT model assumes that travelers attempt to maximize the utility they receive from activities away from home by maximizing the total number and variety of activities to which they travel. This optimization is represented in the model by the maximization of total travel distance. The maximization is constrained by both time and money allocated to travel. The constraints are not identical for all travelers but depend on such factors as socioeconomic characteristics, transportation system supply, and urban structure.

Within this basic optimization model, travelers choose the number of trips and trip distances by purposes, mode shares, and automobile ownership levels. All of these choices are determined in the model through a simple feedback solution mechanism; thus the model is a useful tool for policy analysis.

The UMOT process is especially useful for addressing policies that affect all travel decisions--for example, large increases in gasoline prices. In this type of situation, travelers will modify their mix of trips and destinations as well as, in the longer run, their decisions about car ownership.

When used to examine the energy implications of higher gasoline prices, UMOT indicates that travelers will reduce their total amount of interurban travel as well as shift their mode shares. The energy savings from these responses appear to come mainly from the reduction in travel and only minimally from a switch to energy-efficient modes. Further uses of UMOT can show which types of trips are affected most and the extent to which number of trips and trip distances are each changed.

The work on UMOT is in progess. More development is needed in several areas to make it fully useful for addressing energy and other policy-related issues. Investigations are to start on the existence of interurban travel budgets. The evidence for these budgets is not as extensive as that for urban budgets, even though the assumption of the existence of budgets gives results consistent with empirical research.

It is also important for energy-related studies that UMOT be expanded to consider the trade-offs between the travel budgets and other uses of time and money. It is important to determine the critical threshold of travel costs after which households will have to rearrange their time and money allocations to other goods and services, with possible implications to all segments of the economy.

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Assessment of the Wharton EFA Automobile Demand Model

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The Wharton EFA Automobile Demand Model was developed in 1976 by Wharton Econometric Forecasting Associates, Inc., for the Transportation Systems Center of the U.S. Department of Transportation. This stock-adjustment econometric model is a large-scale model of automobile demand. It has been used widely by federal agencies in policy analyses. However, no major analyses of the model were performed before it was applied and, in some instances, the model was used inappropriately. This paper reports the results of an analysis of the model performed by staff of the Highway Safety Research Institute's Policy Analysis Division at the University of Michigan. The structure of the model was examined. An attempt was made to reconstruct the key time-series equations of the model, the forecasting ability of the model was examined, and sensitivity testing was performed. Computer tapes of the model and data used in the analysis were obtained from the Transportation Systems Center. The analysis uncovered several major problems with the model. New-car sales are partitioned into size classes by using an unjustifiable approach, and some major policy variables (for example, gasoline price) are employed unrealistically in the model. These and other problems combine to seriously weaken the forecasting and policy analysis capabilities of the model. Because of this, policy analysts should use the model only with extreme caution.

The Wharton EFA Automobile Demand Model was developed in 1976 by Wharton Econometric Forecasting Associates, Inc., for the Transportation Systems Center (TSC), U.S. Department of Transportation (1). It is one of the prominent analytic tools that have been developed for policy analysis related to the motor vehicle transportation system.

This stock-adjustment model of automobile demand consists of a system of about 400 equations and 600 variables. It is designed to forecast prices of new cars, total and composition of demand for new cars in the United States, vehicle miles traveled, miles per gallon by size class, scrappage, and other output of importance to the automobile industry. To make such forecasts, the model requires a wide variety of exogenous input that may be categorized as automobile characteristic, economic activity, demographic, policy, and transportation mode data variables.

In addition to its use in forecasting, the model is intended for policy analysis. For this purpose, a proposed policy is decomposed into its effects on the input components of the model, principally price of fuel, automobile excise taxes, automobile production costs, and similar elements. Usually, two forecasts of the market are made--one in the absence of the proposed policy, the other with policy changes fully incorporated into the model. The difference between the two forecasts constitutes