Use of Density Function and Monte Carlo Simulation Techniques to Evaluate Policy Impacts on Travel Demand

FRED L. MANNERING AND IAN E. HARRINGTON

A modeling system is presented that is designed to evaluate the travel-related impacts of various energy contingency plans. The proposed modeling system uses constructed probability density functions and Monte Carlo simulation techniques in an effort to reduce overall data requirements and allow for ready adaptability to a number of alternative geographic areas. The resulting computer model provides for both an acceptable degree of accuracy and an inherent flexibility and thus represents a general improvement over comparable existing modeling techniques that possess the capability to forecast the impacts of energy contingency plans. To demonstrate the applicability of the computer model, a number of energy contingency alternatives were evaluated at the national level. These alternatives included speed-limit enforcement and reduction, a four-day work week, vehicle modifications, and plans involving household-based vehicle stickers and vehicle-based stickers. Model applications reveal that a relatively wide range of results, including potential reductions in fuel consumption, modal shifts, and income effects, is indicated by the enactment of these alternatives. The results presented in the study are intended for use only as guidelines in the selection of an appropriate contingency plan, and organizational, institutional, and implementation factors not explicitly addressed must also be considered. However, in terms of forecasting capability, the research indicates that travel demand forecasts can, in fact, be made with very modest data requirements.

Recent national concerns relating to the uncertainty of future energy supplies have generated the need to develop standby energy contingency plans in an effort to ease the consequences of potential fuel-supply interruptions. The primary objective of such plans is to equitably reduce the demand for fuel, thereby preventing or limiting the formation of queues at gasoline stations and other undesirable effects that result from a fuel shortage. Regrettably, analytic tools currently available for forecasting the reductions in fuel demand induced by alternative energy contingency plans are highly restrictive in terms of their data requirements and their regional transferability. Furthermore, existing analytic techniques often have methodological approaches that limit their applicability in evaluating the impacts of various energy contingency policies.

The purpose of this study is to develop a sound analytic framework specifically designed to address the issue of the evaluation of energy contingency plans. The proposed framework is designed to overcome the deficiencies of previous analytic efforts in this area and to provide a process that is readily adaptable to a variety of possible contingency planning applications.

This paper first presents a summary of the problem addressed in the study. The discussion is then directed toward the development of the modeling system, and the analytic techniques used are emphasized. The balance of the paper provides a number of sample applications of the modeling system in which the impacts of several energy contingency planning options are estimated.

THE PROBLEM

As shown in Figure 1, a fuel-supply shortage occurs when the available supply of gasoline falls below the current level of consumption (from Q_1 to Q_2). Because consumers thus wish to purchase more gasoline than is available, according to the basic economic laws of a competitive market, the value consumers place on the remaining supply will be increased (from P_1 to P_3) in order to distribute the scarce good.

Since price controls prevent the retail price of gasoline from rising freely to its shortage equilibrium level (P_3), the demand for gasoline at the preshortage pump price remains greater than the available supply, and consumers form queues at service stations in an attempt to obtain their desired share of the constrained supply. Thus, the cost to consumers of waiting in line replaces the increase in the retail price of gasoline in raising the price to its shortage equilibrium level. A major objective of contingency plans is to reduce the shortage equilibrium price and service-station queues by lowering the demand for gasoline at price P_1 from Q_1 toward Q_2.

Such a measure causes a shift in demand from D_1 to D_2, thus reducing the shortage equilibrium price of gasoline (the price at which consumers will want to purchase the Q_2 gal of gasoline that are available) from P_3 to P_2, and the net effect of the contingency measure is thus to move the point of market equilibrium from point D to point C.

MODEL OBJECTIVES

The primary objectives of the proposed modeling process can be classified into five broad categories:

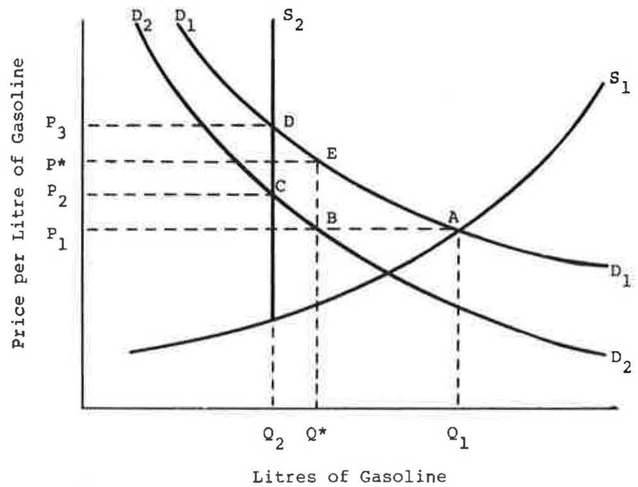
1. To develop a policy-sensitive model that is consistent with the supply-shortage framework presented above;
2. To provide the capability to forecast a wide range of travel demand information, including such factors as modal split, fuel consumption, vehicle miles of travel (VMT), and trip length;
3. To achieve an acceptable level of accuracy with minimal data requirements;
4. To incorporate an inherent flexibility so that the model can be easily adapted to a number of alternate geographic areas; and
5. To minimize model-run computer costs and generalize the program so that it can be implemented on most large-scale computational facilities.

Several existing modeling systems, most of which are discussed in some detail in an NCHRP report (1), were found to satisfy some of the objectives listed above. These models were generally judged to be inadequate for the intended application purposes of this study because they have relatively large data requirements, produce many related outputs that are of little interest in relation to the problem at hand, and use modeling components that are highly time and place specific.

Once the shortcomings of existing modeling approaches were considered, it was decided to develop a modeling procedure that would incorporate the applicable features of existing models and/or be based on newly calibrated models. The disaggregate approach, which includes the application of behavioral choice modeling techniques, was found to be most suitable.

Several problems do arise, however, in the use of disaggregate models. The large amounts of data needed for the calibration of disaggregate models

Figure 1. Effects of fuel-supply shortages and contingency measures on gasoline price and demand.



are not readily available. This implies that the use of existing calibrated models is necessary, and hence the results are subject to errors because of limits in model transferability. In addition, the problem of possible bias in aggregating resultant disaggregate forecasts arises.

After consideration of these arguments, it was decided to construct a modeling system based on a series of existing calibrated disaggregate models. This paper discusses the handling of the aforementioned problems with disaggregate models and explains precisely how these selected disaggregate models are incorporated into the overall modeling system.

MODELING APPROACH

The entire modeling approach is structured so as to be compatible with simulated data. The use of simulated data, derived from constructed probability density functions, offers several advantages over the use of collected data, including (a) easy adaptation to different geographic areas (i.e., a major data-collection effort is generally not needed when the modeling system is transferred), (b) less expense in terms of possible data collection and eventual computer-related costs, and (c) greatly reduced model implementation times.

Unfortunately, a number of disadvantages are associated with the use of simulated data, such as the fact that the assumed density functions are only approximations of actual density functions and the covariances between variables are difficult to account for. Despite these disadvantages, it was felt that the attractive features of the simulation approach provided a strong basis for its use. Furthermore, with the implementation of techniques directed toward limiting the impacts of the inherent disadvantages of the simulation approach, the overall accuracy of such an approach could be greatly enhanced.

Once the capabilities and limitations of disaggregate models and data simulation techniques were considered, the overall modeling system was designed to forecast policy-induced changes in factors such as (a) trip modal shares by trip type (work, shopping, and social-recreational), (b) VMT by trip type, (c) trip generation rates and trip lengths, (d) fuel consumption, and (e) effective fuel "shadow prices", defined here as the fuel pump price needed to clear the market under given shortfall and contingency plan combinations.

In addition to providing total "regional" values for the above factors, the model was designed to have the capacity to determine values for any arbitrary subset of the population (e.g., low-, middle-, and high-income groups). An overview of the resulting modeling system is shown in Figure 2.

As Figure 2 indicates, the system includes models for (a) carpool size, (b) work-trip modal choice, (c) shopping-trip generation, (d) social-recreational trip generation, (e) social-recreational trip destination and modal choice, and (f) shopping-trip destination and modal choice. All of the models, with the exception of the model for work-trip modal choice, were developed by Cambridge Systematics, Inc., for the Metropolitan Transportation Commission (MTC), by using data from a 1968 San Francisco home-interview travel survey (2,3). The work-trip modal-choice model was developed by Ben-Akiva and Atherton by using data from a 1968 Washington, D.C., travel survey. A more detailed explanation of these models is given elsewhere (2,4).

The models for work-trip modal choice, shopping-trip destination and modal choice, and social-recreational trip destination and modal choice are all random utility models of the multinomial logit form. Information relating to the calibration techniques and general properties of such logit models is well documented in several sources, most notably by Domencich and McFadden (5).

In addition, the model for carpool size is of a conventional linear regression form, whereas the trip-generation models assume a nonlinear regression form. The models for both shopping and social-recreational trip generation provide for an interaction with transportation level of service by including the natural logarithm of the denominator of the respective destination/modal-choice model as an independent variable. The variable is referred to as the log sum of a logit model and represents the expected value of the maximum utility of the destination/modal-choice set.

SIMULATION TECHNIQUES

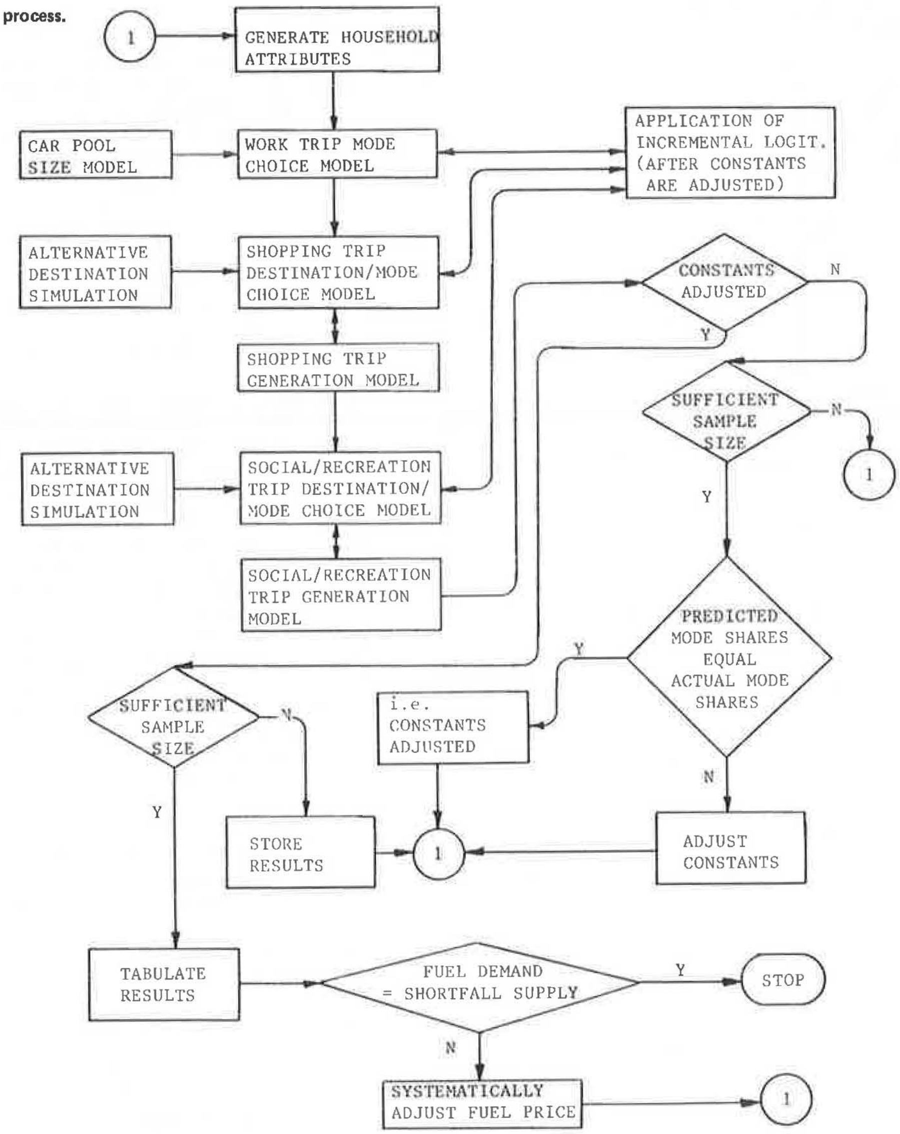
The use of simulation techniques serves two basic purposes: (a) to reduce aggregation bias and (b) to provide the desired level of forecasting detail. A summary of the simulation techniques developed for use in this study is presented in the following sections.

Aggregation Bias

Since disaggregate models provide information only on household-level decisions, the issue of expanding the results to represent aggregate values must be addressed. The potential for aggregation bias arises from two sources: (a) the nonhomogeneity of the population and (b) the fact that the choice probabilities in disaggregate logit models are nonlinear. Aggregation bias can be completely eliminated by simply summing or averaging the individual choice probabilities of the entire population being considered. Unfortunately, the data requirements for such an approach are unrealistically large, since the complete multivariate distribution of explanatory variables is required. To overcome this problem, a number of techniques have been proposed as a means of approximating the true distribution of explanatory variables in the population. These distribution estimation techniques include (a) enumeration, (b) density functions, (c) distribution moments, and (d) classification. More information on distribution estimation techniques is given by Koppelman (6) and Reid (7).

In view of the objectives of this study, it was

Figure 2. Overview of modeling process.



determined that a hybrid technique of distribution estimation would be most suitable. The estimation technique eventually developed relies heavily on the density-function approach and uses classification techniques as a means of approximating the joint distributions of key variables. It is assumed that the variables have multivariate normal distributions. Unfortunately, the number of data needed to construct the necessary distribution, which requires an approximation of the true variance-covariance matrix, tends to be prohibitively large. To overcome this problem, and thereby satisfy the study objective of minimal data requirements, univariate normal distributions were used along with a classification procedure that provides for a covariance between critical variables.

The data needed to construct univariate normal distributions are generally readily available to local and state agencies, since all that is needed is the appropriate means and variances. When the necessary data are obtained, the issue of continuous variables (such as income and residential density) and discrete variables (such as automobile ownership and licensed drivers per household) must be addressed. In the current study, all variables are initially assumed to be continuous, and discrete values are determined, where appropriate, from the constructed continuous distributions by transforming the distribution to provide only integer values. The univariate normal distributions are often truncated to eliminate the possibility of negative or "unrealistic" values.

The classification procedure used to approximate the covariance between critical variables comprises two steps: (a) separating the population into nearly homogeneous subsets by using influential variables, such as income, as a basis, and (b) constructing univariate normal distributions of critical variables for each subset of the population. The use of this procedure provides an approximation of the true multivariate distribution through the application of a number of univariate distributions. The finer the classifications used, the more accurate is the approximation of the underlying multivariate distribution. Regrettably, since fineness of classification greatly increases data requirements, a trade-off must be made between accuracy and data needs.

The application of the classification technique generates a multicentered multivariate normal distribution, which cannot be illustrated here because of space requirements. This resulting distribution can, however, provide an efficient approximation to the true multivariate distribution depending on the level of classification and the number of univariate distributions constructed from such classifications.

In addition to the type of density functions described above, some dummy variables (taking values of zero or one), such as government worker and central-business-district destination, were estimated simply by assuming a uniform distribution and an appropriate probability.

In the current study, the distributions were constructed on the basis of national data provided in a number of sources (8-11). These distributions are presented elsewhere (12).

Aggregation Procedure

The constructed distribution of explanatory variables can now be used in conjunction with the disaggregate models described earlier to provide aggregate forecasts. As mentioned previously, aggregate predictions can be obtained directly by summing or averaging the choice probabilities for all individuals in the population (i.e., complete enumeration). This procedure can be represented in integral form as follows:

$$C_i = \int_x g^i(x)\, h(x)\, dx \quad (1)$$

where

C_i = share of the population selecting alternative i,
$g^i(x)$ = representation of the specification of the choice model, and
$h(x)$ = distribution of model variables for the total population.

When the exact distribution of model variables is known, the above integration produces the same results as complete enumeration. However, since the distribution of variables in this study is only an approximation of the true distribution, the results are likely to differ from the complete enumeration case, although this difference can be expected to be tolerably small.

With the specification of the choice models known and the distribution of variables constructed, it now becomes necessary to evaluate the above integral to obtain aggregate results. The procedure used for this evaluation is a Monte Carlo integration technique. This technique uses the constructed density functions to generate pseudo households and the results of subsequent applications of the disaggregate models are summed to approximate the actual integral value. Such an explicit integration technique can be readily applied on many computer systems. The accuracy to which the actual integral is approximated is obviously directly related to the number of pseudo households generated. Experience with the model has shown that 500-1000 households are generally sufficient to provide an acceptable level of accuracy.

In summary, the aggregation technique presented above provides (a) efficient use of available data, (b) an acceptable level of forecasting accuracy, (c) an inexpensive and theoretically sound approach, (d) easy adaptability to different geographic areas, and (e) the ability to predict separate results for selected population subsets (e.g., change in VMT for low-, middle-, and high-income groups).

Alternative Destination Simulation

The destination/modal-choice models for shopping trips and social-recreational trips estimate the probabilities of selecting a specified mode for trips to a number of alternative destinations. The available modes in these models are automobile and transit, and in the analysis 10 alternative destinations are provided for each pseudo household (i.e., the total number of choice alternatives is 20). Each alternative destination has specific characteristics assigned to it, such as distance from trip origin and retail employment density. These characteristics are assigned by using density functions (constructed from the data sources referred to above) and the Monte Carlo procedure. Such an assignment permits the determination of the expected change in trip length induced by an applied policy option. The technique accounts for the ability of households to satisfy shopping and social-recreational trip demands at a number of alternate locations.

It should be noted that, since the modeling system used in this study considers only short-term effects, possible changes in residential and workplace location are not considered. Hence, trip distances to alternative shopping and social-recreational destinations and work-trip lengths remain constant.

Model Transferability

The disaggregate models used in this analysis were calibrated by using various data sources; hence, the issue of applying these models to different geographic areas must be considered. A number of studies have been undertaken to evaluate the potential transferability of disaggregate models, most notably the study by Atherton and Ben-Akiva (13). That study concluded that the transferability of model coefficients relating to variables such as income and travel time was justified on theoretical grounds and empirical evidence. However, no theoretical basis was found to exist for the transferring of model constant terms, since by definition such terms capture a wide range of miscellaneous factors that affect the choice process and that can be expected to vary considerably between geographic areas.

In light of these findings, a procedure was used to systematically adjust the model constant terms before the application of the disaggregate models to the study region (the remaining nonconstant model coefficients are assumed to be perfectly transferable). This procedure consists of two steps: (a) generating a sample of pseudo households from the constructed density functions and applying the Monte Carlo integration procedure to estimate aggregate values and (b) comparison of the aggregate values calculated above with the actual observed regional values. (If differences in these values exist, appropriately revise the constant terms and repeat the process.) The application of this process provides a basis for minimizing errors that result from the transferability assumption and provides for ready adaptability of the overall modeling system to alternate geographic areas. In addition, to limit computer memory costs, the impacts of alternative policy options are evaluated for each pseudo household during the Monte Carlo aggregation procedure by applying the incremental logit model (14). This avoids the reapplication of the complete logit model, since subsequent recalculation of systematic utilities is not necessary.

Shadow Price

The model also has provisions for calculating the "shadow price" of gasoline for any combination of supply shortage and contingency measures. The procedure used to estimate this price, which is illustrated in Figure 1, can be described as follows.

First, determine the change in the demand for fuel at price P_1 that results from implementing the contingency measure ($Q_1 - Q^*$). Then, compare the estimated drop in fuel demand at price P_1 with the extent of the supply reduction ($Q_1 - Q_2$). If they are equal, P_2 equals P_1. However, if, as in most instances, the demand reduction does not equal the cut in supply, P_2 will not equal P_1. In this case, the price of gasoline is thus systematically adjusted from P_1 (using an iterative procedure) until the postmeasure demand for gasoline (on curve D_2) is equal to the constrained supply (Q_2). The price at this point is P_2, which is defined as the gasoline shadow price.

MODEL APPLICATIONS

The model described in this paper has been applied to several contingency-measure and supply-shortage scenarios in order to illustrate some of its capabilities and to evaluate the effectiveness of various contingency measures. In addition to estimating the reduction in demand expected from the measures, their net effects on travel and fuel consumption are also evaluated, all at the national level.

Since the net effect of a contingency measure is estimated by comparing the changes it produces in the equilibrium price of gasoline and the distribution of consumption and travel with those changes produced by a supply shortage, the characteristics of points C and D in Figure 1 should be compared to obtain an estimate of a measure's net effect. However, still referring to Figure 1, although the changes occurring between points A and D are readily estimated by the computer model (by increasing the fuel price from P_1 to P_3), estimating the changes between points A and C is costly because of the high computational requirements. As a result, a more cost-effective proportionality technique that does not significantly sacrifice accuracy is developed and used to measure the net effects.

Assuming that the price elasticities of demand curves D_1 and D_2 are equal, it can be shown that the proportional changes in desired fuel consumption and travel between points B and C would equal the proportional changes between points E and D. Therefore, the proportional differences between the characteristics of points C and D are equal to the proportional differences between the characteristics of points B and E. Since the changes produced by the measures discussed here are relatively small, the price elasticity of demand is not likely to change significantly; so the net effect of a contingency measure is thus estimated by comparing the changes between points A and B with the changes between points A and E.

While the changes between points A and B are estimated by the model, the price of fuel at point E(P^*) must be estimated so that the model can estimate the changes between points A and E. Thus, again assuming curves D_1 and D_2 have equivalent price elasticities, P^* can be estimated as follows:

$$P^* = (P_3/P_2)P_1 \quad (2)$$

Following is a discussion of the application of the model to five contingency measures and the results obtained. However, this discussion must be prefaced by a brief review of the expected impacts of a supply shortage if no contingency measures are implemented.

Fuel-Supply Shortage

A fuel-supply shortage of 7 percent is represented by determining the shortfall equilibrium price (P_3 in Figure 1) through an iterative procedure that consists of changing the price of gasoline until the amount of gasoline normally consumed at that price equals the constrained supply. Assuming a 7 percent shortage in supply and an initial price (P_1) of \$0.32/L, P_3 is estimated to be \$0.46. This permits the estimation of P^* for each contingency-measure scenario under these assumptions, once the shadow price (P_2) resulting from the measure's implementation has been estimated (Equation 2).

Using the increase in price of gasoline from P_1 to P_3 to represent the supply shortage, the model indicates larger impacts on shopping and social-recreational trips than on work trips, since households desire to maintain their normal commuting practices. The majority of the reduction in shopping-trip VMT results from changes in trip length as households satisfy trip demands by selecting closer alternative destinations. A much smaller portion of the reduction in shopping-trip VMT is attributable to modal shifts and trip generation rates. The induced modal shifts and decreases in trip generation rates for social-recreational trips have a much larger effect on VMT reduction than was observed with the reduction in shopping-trip VMT. This results from the fact that the social-recreational trips generally have a greater sensitivity to utility function cost components.

Contingency Measures

Reduction of Travel Speed

In the first scenario, two speed-limit plan alternatives are analyzed. These alternatives can be summarized as follows: (a) Compliance with the 55-mile/h speed limit is increased from the current 42 percent (based on 1977 Highway Statistics) to 70 percent, and (b) the maximum speed limit is reduced from 55 to 50 miles/h, with a 42 percent compliance level.

The most difficult problem encountered in considering such changes in speed limits and/or compliance is the estimation of future vehicle speed distributions. For the purposes of this analysis, the existing speeds were assumed to have a profile that could be approximated by a truncated normal distribution. On the basis of this normality assumption and existing speed data, an average speed of 56.5 miles/h and a standard deviation of 5.5 were selected as normal speeds on 55-mile/h roads. Under alternative 1, it was assumed that (a) vehicles currently traveling at speeds less than 55 miles/h will be unaffected and (b) those vehicles currently traveling at speeds in excess of 55 miles/h will not reduce their speeds to less than 55 miles/h. An appropriate "mean average speed drop" was selected to ensure that 70 percent of the simulated vehicle-speed observations had speeds at or less than 55 miles/h. For alternative 2, it was assumed that (a) vehicles currently traveling at speeds less than 50 miles/h would not be affected, (b) vehicles traveling at speeds between 50 and 55 miles/h would reduce their speeds to 50 miles/h, and (c) vehicles traveling at speeds in excess of 55 miles/h would reduce their speed by an average of 5 miles/h.

It is estimated that 47.2 percent of all automobile VMT is on roads with 55-mile/h speed limits. Unfortunately, the percentage of VMT on 55-mile/h roads by trip type is not readily available. It is unreasonable to suggest, for example, that shopping trips, which have average lengths of about 5 miles,

Table 1. Estimated effects of contingency measures.

Category	Measure	Change (%) Speed Reduction Alt. 1	Speed Reduction Alt. 2	Four-Day Work Week	Household Sticker Weekend	Household Sticker Weekday
Total change	VMT by trip type					
	Work	-[a]	-[a]	-11.6	-2.8	-10.3
	Shopping	-2.0	-5.0	-0.5	-3.0	-3.9
	Social-recreational	-1.0	-2.5	-2.9	-4.6	-1.6
	Work-trip modal share					
	Drive alone	-[a]	-[a]	+1.9	-4.7	-18.0
	Shared ride	-[a]	-[a]	-5.0	+11.3	+43.2
	Transit	-[a]	-[a]	-6.5	+11.0	+39.2
	Average automobile trip length					
	Shopping	-1.7	-4.3	+0.3	-[a]	-[a]
	Social-recreational	-0.4	-0.9	+1.0	-[a]	-[a]
	Total fuel consumption	-1.5	-3.4	-5.9	-3.4	-5.7
Net change[b]	VMT by trip type					
	Work	+0.2	+0.4	-11.0	-2.4	-9.7
	Shopping	-[a]	-1.1	+5.5	+0.9	+4.0
	Social-recreational	+2.2	+3.7	+6.4	+1.6	+5.7
	Work-trip modal share					
	Drive alone	+0.3	+0.6	+2.9	-4.1	-17.0
	Shared ride	-0.5	-1.1	-7.7	+10.2	+41.5
	Transit	-1.6	-3.1	-11.3	+7.9	+34.4
	Shadow price of gasoline	-8.6	-15.1	-21.6	-15.2	-21.4

[a]No change or insignificant change. [b]In comparison with do-nothing alternative.

will have the same percentage of VMT on 55-mile/h roads as social-recreational trips, which have average trip lengths of about 12 miles, since access to such roads is a fixed distance that will make up a larger portion of the total shopping-trip length than the social-recreational trip length. To account for this fact, the 47.2 percent of VMT on all roads was appropriately adjusted to account for trip type by applying a trip-length proportionality technique. Furthermore, it was assumed that the percentage of VMT on 55-mile/h roads would be normally distributed about the mean for the trip type with a specified standard deviation. This allows a realistic variance among households and trip destination alternatives.

The resulting estimates of the effects of the two alternative measures on normal travel and consumption patterns are given in Table 1. The impact of the two alternatives on work-trip VMT is negligible due to the inflexibility of the work trip in the short- and medium-range time periods. Furthermore, the decrease in automobile operating costs and the increase in travel time essentially offset each other so that no significant modal shift occurs.

Shopping trips were found to be the most sensitive trip type in both of the alternatives tested. This results from the fact that time is a relatively more important consideration on shopping trips than it is on social-recreational trips or work trips. In addition, shopping-trip generation, destination, and modal selection are more responsive to increases in time than to decreases in operating costs and, as a result, significant reductions in VMT occur. The majority of this decrease was attributable to decreases in average trip length as households selected shopping destinations closer to home.

Social-recreational trips also made significant contributions to the overall decrease in VMT. In this case, a much smaller portion of the VMT reduction is attributable to decreases in trip length and, consequently, decreases in trip generation and modal shifts play a more important role.

The total reductions in fuel consumption of 1.5 and 3.4 percent for alternatives 1 and 2, respectively, largely result from a decreased VMT attributable to increased travel times, although increases in vehicle fuel efficiency still make a substantial contribution to these totals. Both of the alternatives tested indicate that high-income groups are invariably more sensitive to speed-limit changes, since they experience significantly greater reductions in VMT.

In summary, the net effects of these measures, given in Table 1, include considerable reductions in the shadow price of gasoline, net increases in VMT for all trip types (particularly social-recreational trips), and a disproportionate effect on high-income households.

Four-Day Work Week

The second scenario evaluates the impacts of the implementation of a four-day work week. To apply this policy option, it is first necessary to estimate the extent of compliance with such a plan. The assumption of 100 percent compliance is clearly unrealistic, since the nature of a number of jobs makes at least a five-day schedule necessary. As a result of such factors, a compliance level of 63 percent was selected, which is consistent with compliance estimates made in a previous study (15). If it is further assumed that the average reduction in weekday work-trip travel will be 20 percent among complying individuals (with a reduction from five- to four-day work weeks), then a 12.6 percent reduction in work travel would be expected (with 63 percent compliance), providing that no modal shifts occur.

Representation of the four-day-work-week plan in the modeling system was achieved by appropriately adjusting (a) the automobile-availability variables; (b) the employment-density variable in the models for work, shopping, and social-recreational trips; and (c) the number-of-worker variables. The adjustment procedure for the automobile-availability variable was to randomly select 12.6 percent of the household sample to represent those household individuals who were in compliance with the work plan and were not making work trips on the selected work day. For both shopping and social-recreational trips, the automobile-availability variables of these selected households were increased by the number of vehicles no longer being used for work trips and the number-of-worker variables were adjusted accordingly. A subsample of households was randomly chosen to represent those households that are in compliance with the plan but happen to be making work trips on the selected work day. For these households, the automobile-availability variable of the work-trip model was increased by 20 percent of the vehicles normally available for work trips. This increase reflects the fact that many shopping and social-recreational trip demands are now satisfied during the nonwork days and so such trip types do not compete as much for available automobiles during work days; hence, there is an effective increase in work-trip automobile availability.

Two approaches were used in making the employment-density adjustments:

1. For employment density at the work zone and for the retail and service employment densities in the residential zones, uniform reductions of 12.5 percent [selected on the basis of estimated work-force reductions (14)] were used to approximate the reductions in densities resulting from the closing of retail establishments.
2. For the retail employment densities of alternative shopping and social-recreational trip destinations, a random elimination technique was applied because the uniform adjustment approach would not provide for a realistic variability. The technique used randomly eliminates alternative destinations from the set of available destinations with an elimination probability of 0.125 for each shopping and social-recreational trip generated by the household. This technique attempts to capture the possibility that certain destinations will no longer be able to satisfy the trip demand due to store closings.

The application of the above assumptions resulted in the model outputs summarized in Table 1. The reduction in work-trip VMT is quite large, but it is noticeably less than the 12.6 percent reduction that would be expected on the basis of the compliance assumption described above. This apparent discrepancy results from induced modal shifts that arise from the effective increase in work-trip automobile availability among households with individuals who are in compliance with the plan and the decrease in work-trip-destination employment density, which decreases the attractiveness of the shared-ride option. The resultant modal shift consists of a mild increase in the drive-alone option and subsequent reductions in shared-ride and transit alternatives.

Both shopping and social-recreational trips showed decreases in total VMT. Such decreases are caused by rather large reductions in trip generation rates, since the overall attractiveness of trip making declines with reductions in effective employment densities. In fact, the reductions in trip generation rates were sufficiently large to overcome the effects of factors that tend to increase VMT, such as (a) modal shifts to automobile resulting from the additional automobile availability among households that are in compliance with the shorter work week, (b) an increased propensity to generate trips as the reduction in residential-zone employment densities decreases the probability of satisfying trip demands by making nonvehicle trips, and (c) the increase in average automobile trip lengths as households are forced to drive to different destinations to satisfy trip demands as the result of store closings.

The 5.9 percent overall reduction in fuel consumption indicates that the plan has considerable fuel-saving potential even with the modest compliance estimates used in this analysis. The resulting shadow price of $0.37/L represents only a small increase over the base price of $0.32/L. In addition, the implementation of the four-day work week was found to produce greater reductions in VMT among high-income households. This is due to the fact that lower-income households are more sensitive to changes in automobile availability, so much so that their greater sensitivity to reductions in employment densities is overcome.

In general, the four-day-work-week contingency plan appears to be quite effective in terms of reducing fuel demand. Furthermore, although the plan causes greater VMT reductions among high-income households, the differential impacts across income groups tend to be relatively small. The net effects of the plan (Table 1) are mainly to shift VMT from work trips to shopping and social-recreational travel and to shift work trips to the drive-alone mode.

Household-Sticker Plan

The third scenario evaluates the travel impact of a sticker plan that prohibits the use of all household vehicles for one day of the week. A major potential source of error in evaluating this plan is in estimating the number of households whose members will choose not to drive their vehicles on weekdays as opposed to weekends. Because of the significant differences in travel behavior between weekday and weekend trips, two alternatives were analyzed: One assumed that all households will select weekdays as those days in which their vehicles will not be driven, and the other assumed that all households select weekends. These two extreme cases will provide a range of likely consequences arising from the implementation of such a plan.

The representation of the plan in the modeling system is achieved by reducing the appropriate automobile-availability variable to zero in the models for shopping and social-recreational trips and to eliminate the drive-alone alternative in the work-trip modal-choice model. For the all-weekday alternative, it was assumed that the probability of selecting any given weekday is equal at 0.2, and households that did not have automobiles available on any given day were drawn at random. Furthermore, the fact that 90 percent of all work trips occur during weekdays and only 54 and 26 percent of shopping and social-recreational trips, respectively, occur during such days was also incorporated in the analysis (8,9). As a result, the all-weekday assumption would be expected to have less impact on the demand for shopping and social-recreational types of trips. In the case of the all-weekend alternative, the probability of a household selecting a given day was assumed equal at 0.5, and the amount of travel by trip type was also considered (10 percent of all work trips, 46 percent of shopping trips, and 74 percent of social-recreational trips). The results of model applications are given in Table 1.

The results indicate that substantial modal shifts are induced by the plan, including significant decreases in the use of the drive-alone mode, as would be expected. Naturally, the subsequent reduction in work-trip VMT is much larger for the all-weekday case because of the large proportion of weekday work trips. Changes in shopping and social-recreational trip VMT values result from reductions in trip generation rates and modal shifts. No change in automobile trip lengths is expected, since the representation of the plan by varying the automobile-availability variables does not affect the relative attractiveness of alternative destinations.

The reductions in total fuel consumption of 3.4 and 5.7 percent for the all-weekend and all-weekday alternatives, respectively, reflect the total range of fuel savings that can be expected from the implementation of a household-sticker plan. The VMT reductions of such a plan are fairly uniform for households of all incomes. This uniformity arises partly from the fact that, although lower-income households are more sensitive to changes in levels of automobile availability, such households are likely to own fewer vehicles than higher-income households.

As Table 1 indicates, a household-sticker plan has the potential for inducing substantial reductions in the shadow price of fuel. Furthermore, it is indicated that the distribution of stickers that control weekend and weekday automobile use can have a significant impact on plan effectiveness. The net effects of the plan are generally to shift VMT from work trips to social-recreational trips and to shift work trips away from the drive-alone mode.

SUMMARY AND CONCLUSIONS

This research has developed a modeling system that considers the complex interactions between various travel demand components and proposed energy contingency plan options. Because the modeling system uses a number of Monte Carlo simulation techniques that require minimal amounts of data, it can readily be adapted to the consideration of alternative geographic areas and to test a wide variety of possible policy options. In the current study, the model was applied on the national level in an effort to forecast the likely travel-related impacts induced by various energy contingency plans.

The results of the model applications indicate that a relatively wide range of impacts relating to fuel consumption, income effects, and other factors can be achieved with alternative contingency plans. Of the limited number of plans considered in this study, the household-sticker and four-day-work-week measures produce the largest reductions in the demand for gasoline. In terms of the income impacts of these two plans, the sticker measure provides for an equitable distribution among income groups whereas the shortened work week disproportionately affects higher-income brackets. However, it must be recognized that the evaluation of contingency measures should not be based entirely on the impacts addressed in this study, since the implementability, costs, and enforceability of a measure are also critical factors in the selection of an appropriate plan.

ACKNOWLEDGMENT

The research reported in this paper was sponsored by the U.S. Department of Energy. The views expressed in this paper are solely our own.

REFERENCES

1. Travel Estimation Procedures for Quick Response to Urban Policy Issues. NCHRP, Rept. 186, 1978.
2. Analytic Procedure for Estimating Changes in Travel Demand and Fuel Consumption. U.S. Department of Energy, Rept. DOE/PE/8629-1, Oct. 1979.
3. Case City Applications of Analysis Methodologies. U.S. Department of Energy, Rept. DOE/PE/8628-1, Vol. III, Oct. 1979.
4. Carpool Incentives: Analysis of Transportation and Energy Impacts. Federal Energy Administration, Rept. FEA/D/76-391, June 1976.
5. T. Domencich and D. McFadden. Urban Travel Demand. North Holland Publishing Co., Amsterdam, 1975.
6. F.S. Koppelman. Travel Prediction with Models of Individual Choice Behavior. Massachusetts Institute of Technology, Cambridge, Ph.D. dissertation, 1975.
7. F.A. Reid. Minimizing Error in Aggregate Predictions from Disaggregate Models. TRB, Transportation Research Record 673, 1978, pp. 59-65.
8. Nationwide Personal Transportation Study: 1969-1970. U.S. Bureau of the Census, April 1972.
9. Nationwide Personal Tranportation Study: 1977-1978. U.S. Bureau of the Census, Oct. 1980.
10. Statistical Abstract of the United States. U.S. Bureau of the Census, 1979.
11. 1979 Motor Vehicle Facts and Figures. Motor Vehicle Manufacturers Assn. of the United States, Detroit, 1979.
12. F.L. Mannering. The Use of Density Function and Monte Carlo Simulation Techniques in the Evaluation of Policy Impacts on Travel Demand. Massachusetts Institute of Technology, Cambridge, Project Rept., June 1980.
13. M. Ben-Akiva and T. Atherton. Transferability and Updating of Disaggregate Travel Demand Models. Presented at 55th Annual Meeting, TRB, 1976.
14. M. Ben-Akiva and T. Atherton. Methodology for Short-Range Travel Demand Predictions. Journal of Transport Economics and Policy, Sept. 1977.
15. Concepts for an Energy Conservation Contingency Plan: Compressed Work Week. Jack Faucett Associates, Inc., Chevy Chase, MD, Jan. 1979.

Publication of this paper sponsored by Committee on Energy Conservation and Transportation Demand.

Direct Energy Consumption for Personal Travel in the Chicago Metropolitan Area

D.E. BOYCE, B.N. JANSON, AND R.W. EASH

A set of calculations of direct energy consumption for the Chicago region is prepared. The methodology for developing the energy accounts is illustrated by using two examples for a transit and an automobile trip. Direct operating energy statistics for personal travel are shown in both tabular and mapped forms. Both absolute energy consumption and rates of energy consumption by areal unit are listed. Tables showing how energy consumption varies with trip origin and destination are discussed, and maps that show the energy consumption contours for travel to the Chicago central business district are presented.