TRANSPORTATION RESEARCH RECORD 764

Transportation Energy: Data, Forecasting, Policy, and Models

TRANSPORTATION RESEARCH BOARD

COMMISSION ON SOCIOTECHNICAL SYSTEMS
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C. 1980

Transportation Research Record 764
Price $9.60
Edited for TRB by Susan Singer-Bart

modes
1 highway transportation
2 public transit
3 rail transportation

subject area
17 energy and environment

Library of Congress Cataloging in Publication Data
National Research Council (U.S.). Transportation Research Board.
Transportation energy–data, forecasting, policy, and models.

(Transportation research record; 764)
Reports presented at the 59th annual meeting of the Transportation Research Board.
1. Transportation and state–Addresses, essays, lectures. 2. Energy policy–Addresses, essays, lectures. 3. Transportation–Energy consumption–Addresses, essays, lectures. I. Title. II. Series. TE7.H5 no. 764 [HE152.6] 380.5s [333.79]
81-1665 ISBN 0-309-03107-9 ISSN 0361-1981 AACR2

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Authors of the Papers in This Record

Boyce, D. E., Department of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801
Cheslow, Melvyn D., DHR Inc., 1055 Thomas Jefferson Street NW, Washington, DC 20007; formerly with Evaluation Research Corporation
Cohen, Gerald S., Planning and Research Bureau, New York State Department of Transportation, 1220 Washington Avenue, Albany, NY 12232
Dorfman, Nancy S., Center for Transportation Studies, Massachusetts Institute of Technology, Cambridge, MA 02139
Eash, R. W., Chicago Area Transportation Study, 300 West Adams Street, Chicago, IL 60606
Erlbaum, Nathan S., Planning and Research Bureau, New York State Department of Transportation, 1220 Washington Avenue, Albany, NY 12232
Ferris, M., Department of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801
Glover, Matthew F., Research and Evaluation Division, Michigan Department of State, Lansing, MI 48918
Golomb, D. Henry, Everlasting Sporting Goods Manufacturing Co., Inc., 750 East 132nd Street, Bronx, NY 10454; formerly with the University of Michigan
Harrington, Ian E., Center for Transportation Studies, Massachusetts Institute of Technology, Cambridge, MA 02139
Hartgen, David T., Planning and Research Bureau, New York State Department of Transportation, 1220 Washington Avenue, Albany, NY 12232
Hatmaker, Michael L., Arizona Department of Transportation, 206 South 17th Avenue, Phoenix, AZ 85007
Janson, B. N., Department of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801
Lee, Martin E. H., Research and Evaluation Division, Michigan Department of State, Lansing, MI 48918
Lee, William C., SRI International, 333 Ravenswood Avenue, Menlo Park, CA 94025
Lerman, Steven R., Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139
Luckey, Michael M., Merrill Lynch Economics, Inc., 165 Broadway, New York, NY 10080; formerly with the University of Michigan
Mahmassani, Hani, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139
Manski, Charles F., Department of Economics, Hebrew University, Jerusalem, Israel
Maxwell, Donald A., Department of Civil Engineering, Texas A&M University, College Station, TX 77843
Morris, Michael, North Central Texas Council of Governments, P.O. Drawer COG, Arlington, TX 76011; formerly with the State University of New York at Buffalo
Neels, J. Kevin, Rand Corporation, 1700 Main Street, Santa Monica, CA 90406
Prastacos, Poulicos P., University of Illinois at Urbana-Champaign, Urbana, IL 61801
Prins, Victor, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139
Richardson, Barbara C., Highway Safety Research Institute, University of Michigan, Ann Arbor, MI 48109
Romanos, Michael C., University of Illinois at Urbana-Champaign, Urbana, IL 61801
Sheffi, Yosef, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139
Sherman, Leonard, Transportation Consulting Division, Booz, Allen, and Hamilton, Inc., 675 Massachusetts Avenue, Cambridge, MA 02139
Suits, Daniel B., Department of Economics, Michigan State University, East Lansing, MI 48823
Talvitie, Antti, Department of Civil Engineering, State University of New York at Buffalo, Buffalo, NY 14214
Tye, William B., Charles River Associates, Inc., 200 Clarendon Street, Boston, MA 02116
Williamson, Dennis V., Texas Transportation Institute, Texas A&M University, College Station, TX 77843
Wolfe, Robert A., Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139
Zahavi, Yacov, Consultant, 7304 Broxburn Court, Bethesda, MD 20034

Assessment of Energy and Petroleum Consumption of Different Transportation Modes in the Buffalo Area

MICHAEL MORRIS AND ANTTI TALVITIE

This analysis evaluates the results of a local rail vehicle performance model. Line-haul travel calculations, operating energy consumption, and total energy consumption, especially of petroleum energy, are calculated for an example situation in Buffalo, New York. The energy impacts that result from the implementation of a carpool and express bus system are also included. The comparison of these results with energy estimates by using average values indicates that the variance in urban rail system performance is too large for generalizations at the national level. A second reason for the promotion of local energy studies is the need to develop criteria to calculate the petroleum consumption of modes that do not burn petroleum products directly. The results of this study demonstrate that a light rail system in the example city will save energy; however, due to the relatively small demand, the net energy and petroleum savings are rather small. Recent trends toward the purchase of foreign-manufactured light rail vehicles have a negative impact on energy savings.

The energy-saving capabilities of various urban transportation modes has been an intensely studied subject area throughout the 1970s. Much of the data collection and discussion has pertained to local evaluations of energy strategies. However, a substantial amount of discussion has come from the aggregation of local energy and system performance information for the purpose of evaluating conservation measures in a different or at a higher spatial unit. For example, in order for federal officials to evaluate the effectiveness of national energy policies, especially with regard to various approaches to encourage individuals to switch to more energy-efficient modes, the collection and summation of local information was undertaken. This process of collecting local information for the purpose of evaluating energy-conserving strategies is referred to in this paper as the aggregate approach.

There are three major objectives of this study:

1. To develop a local energy model to be used as one component of a much larger transportation system performance model (special consideration for including direct and indirect energy considerations is an essential requirement),
2. To assess the difference between this locally developed energy model with that of the aggregate approach (this will aid in the validation of the developed procedures as well as refine differences in the two approaches), and
3. To conduct a sensitivity analysis on the major variables that affect rail energy consumption in order to determine the effects of rail design and operating decisions on rail operating energy consumption, as well as to demonstrate the benefits generated from a locally developed, policy-sensitive modeling system.

Six modes are included in this local energy model: automobile, carpool, local bus, express bus, light rail, and heavy rail. From information that will be discussed later in this paper, several modes are set to default values due to the lack of variability in operating performance at the aggregate level. Therefore, emphasis in this study is on methods for evaluating the impact of rail modes. This results from the observation that aggregate methods ignore the variation in urban rail system data.

The following analysis addresses four areas that pertain to rail vehicle performance at the local level:

1. Line-haul travel time;
2. Operating energy consumption;
3. Total energy consumption, especially that of petroleum energy; and
4. An example application of the generated methodology in Buffalo, New York.

PROBLEM DEFINITION

This investigation into the energy dilemma of the United States is required in order to establish appropriate criteria for the evaluation of energy aspects of various transportation modes. Some controversy about the efficiency of the rail mode stems from various definitions of the energy problem.

It is generally accepted that the current energy supply is dwindling and the demand for energy is increasing. The existence of price controls on energy has meant that the demand for energy has not adjusted to supply. This gap between supply and demand is widening every year. The following statistics demonstrate that the energy problem is particularly acute for petroleum energy:

1. The United States produced 81 percent of its energy needs in 1976 (1), but
2. The United States produced only 49 percent of its petroleum-derived energy needs in that year (1).

Since a large share of petroleum is imported, emphasis on solutions that reduce petroleum consumption should be one of our major objectives.

The activity system most vulnerable to a petroleum shortfall is that of transportation. The following statements demonstrate transportation's role in the petroleum energy problem:

1. Transportation is run on 96 percent petroleum (2);
2. Transportation uses 60 percent of all petroleum in this country (3);
3. Urban passenger transportation, the largest petroleum-consuming group, uses approximately 25 percent of the petroleum in the United States (3); and
4. Less than 1 percent of the energy used in transportation is converted from coal, which is an abundant domestic energy resource (4).

All indications are that the relationship between urban passenger transportation and petroleum use will intensify if current patterns continue. This is substantiated by recent projections from analyses into the petroleum-consumption problem:

1. Vehicle miles of travel, the number of automobiles, passenger miles, and the number of automobile drivers will continue to increase at a substantial rate (5);
2. The supply of foreign oil may decrease to all importing nations and greatly affect both the amount and the price of petroleum; and

3. Current energy regulation in the United States is thought to have a far less petroleum-conserving impact than had previously been thought (6).

The above discussion indicates that the incorporation of additional criteria for evaluating modal energy consumption on the basis of Btus of petroleum seems justified. The following analyses assess the impact of a policy that promotes a shift from automobile to express bus, carpooling, or rail transit. Emphasis on the rail mode in this study is the result of seemingly inadequate methods to deal with rail modal efficiencies at the national (i.e., aggregate) level.

LITERATURE REVIEW

A review of several studies that pertain to approaches to calculate energy consumption, important variables to include in energy calculations, and the results or estimates of energy consumption under varying conditions are summarized in this paper (2,6-22).

There are three major outcomes of this review. First, most studies that analyzed energy demand in urban passenger transportation have measured energy intensity on the basis of Btus per passenger mile. This method does not take into consideration the type of energy used for transportation. The previously stated problem definition indicates that the energy type is also an important consideration. Therefore, the transportation alternatives should also be evaluated in those terms, which results in the measurement of energy intensity on the basis of Btus of petroleum per passenger mile.

The second point is that average values were frequently used to measure the net energy impact of a shift in mode choice. This approach does not take into consideration any effect that local areas have on mode choice or the energy consumption of various modes. Analyses that use average figures to measure the change in energy consumption are insensitive to the range and variance of energy consumed at the local level. This is especially true with regard to the rail mode.

To demonstrate the large variance in energy estimates by using aggregate methods [e.g., the Congressional Budget Office (CBO) report (8)], estimates of operating energy consumption are examined more closely. Operating energy includes the energy used in the propulsion of the vehicle plus the auxiliary energy (e.g., heating and air conditioning). This particular energy component has been selected for demonstration purposes because (a) it is the most important variable in the determination of total energy consumption, (b) it is the most important energy component to a transit agency, and (c) it is thought to have the smallest variance because of the engineering aspects that do not vary among local areas.

Operating energy consumption from local studies on six urban passenger modes was collected and compared with the results of the CBO report. The reason for a somewhat duplicate effort in collecting energy data was the omission of standard deviation information from the CBO report. Table 1 contains a comparison of the two information sources as well as some summary statistics on the data. The mean columns and the confidence interval columns demonstrate the similarity between the data. The standard deviation column, the coefficient of variation column, and the extreme error coefficient column all show that rail systems, especially light rail, have a large variance in operating energy consumption. Automobiles and local buses, on the other hand, each possess a similarity in operating energy values.

Some authors indicate potentially severe errors with the input data [e.g., Chomitz (14) and Rose (1)]; therefore, it is difficult to justify very little dispersion in the energy consumption of the automobile and local bus modes and generally a great deal of dispersion in the rail modes. There are two plausible reasons for this large dispersion in operating energy consumption values in the rail modes--measurement error in the input data as well as variance in the age, local geometrics, vehicle types, station spacing, and operating policies that vary greatly from city to city. However, for whatever reason, any definite conclusion that uses this information to demonstrate the ability of rail to save or lose energy must be questioned. What must be addressed is the adoption of a sound methodology for local areas to determine the feasibility of rail systems to save energy.

The potential petroleum savings of a rail system in an urban area depends on the type of system selected, the locality where the system is built, the layout and operation of the system, and the type of fuel used to generate the electricity for the particular rail operation in question. Therefore, under certain circumstances, a policy that promotes a mode shift will have beneficial results on energy consumption. Sometimes, however, it will be unsuccessful.

The third important result of this review is that most studies evaluate various modes at a constant point in time, usually early after the implementation of the system. For instance, modes such as rail transit accrue energy benefits over the long run when access modes have adjusted to increasing use of the new alternative. Other factors, such as land use changes, technological improvements, residential relocation, and travel-demand increases will also affect energy consumption in the long run. This phenomenon is much more difficult to measure than an evaluation at one point in time. The fact that large capital expenditures accrue benefits over time is not new; however, accurate methods to represent this phenomenon are difficult to come by, even in a cursory fashion.

There has been growing interest in transportation research for adopting a more comprehensive strategy for analyzing energy consumption. The consideration of a local perspective, the calculation of values over time, and the adoption of a petroleum-measuring

Table 1. Average operating energy estimates.

Mode	N	Mean Btus per Vehicle Mile ($\bar{X}$)	Mean Btus from CBO Report	Confidence Interval [$\bar{X} \pm 2(S/\sqrt{n})$]	Confidence Interval from CBO Report	SD	Coefficent of Variation (SD/$\bar{X}$)	Extreme Error Coefficient [(H - L)/L]
Automobile	9	10 400	10 800	9 500-11 300	10 400-11 000	1 170	0.11	0.19
Heavy rail, old	19	72 300	72 500	65 500-79 100	50 000-95 000	14 130	0.20	0.81
Heavy rail, new	9	87 200	90 000	72 300-102 000	70 000-110 000	19 400	0.22	1.08
Commuter rail	9	114 900	125 000	101 200-128 500	100 000-150 000	17 750	0.15	0.53
Light rail	15	79 000	75 000	65 100-92 900	50 000-100 000	25 090	0.32	1.70
Bus	11	32 100	29 500	30 200-33 900	29 900-34 000	2 760	0.09	0.33

framework represents an attempt toward a more comprehensive approach to the investigation of this problem.

STUDY METHOD AND APPLICATION RESULTS

Adoption of the CBO methodology for the previous three criticisms results in an approach that is responsive to local needs, in accord with an appropriate problem definition, and comprehensive in specification. An additional variable is included to take into consideration not only the additional trips of the new mode but also additional trips that are generated by the forfeited mode (e.g., additional trips from automobiles left at home). This method inputs local values for each variable instead of national averages. A set of default aggregate values is included in the absence of a local value. The variables are listed below.

Program Energy (Increased Energy Use Due to Changes in Demand)

1. Source of new patronage,
2. Additional trips generated by the new mode, and
3. Additional trips generated by the forfeited mode.

Modal Energy

Line-Haul Energy

1. Propulsion energy per vehicle mile,
2. Auxiliary energy per vehicle mile,
3. Construction energy per vehicle mile,
4. Vehicle manufacturing energy per vehicle mile,
5. Station and maintenance energy per vehicle mile,
6. Average number of passengers (passenger miles per vehicle mile), and
7. Percentage of petroleum in 1-5.

Access-Circuity Variables

1. Mode of access,
2. Fraction of trip devoted to access, and
3. Circuity.

The input data used for the rail mode partly come from the other portions of the transportation planning model but mostly from what is often called the work (i.e., force through distance) methodology (15, 16, 18, 22). A simplified derivation of this approach demonstrates the relationship between force and resistance as well as the resulting travel time and energy consumption. Propulsion force of a rail vehicle can be defined as follows:

$$M \leqslant \mathrm{MIN}\left\{[1584 \cdot (TD + 6.8)], [3471 \cdot K3 \cdot (Y/V)]\right\} \qquad (1)$$

where

M = propulsion force (N),
TD = weight of the rail vehicle (t),
K3 = actual tractive effort divided by the hourly power rating (this value is calculated internally by dividing the total line-haul time by the travel time incurred in acceleration and at maximum speed),
Y = the rated kilowatt output reserved for propulsion (kW), and
V = velocity (km/h).

The acceleration of the vehicle is defined as

$$AC = (M - R)/MA \qquad (2)$$

where

AC = acceleration rate (m/s^2),
R = total resistance force (e.g., flange friction or air resistance) (N), and
MA = mass (N--s^2/m).

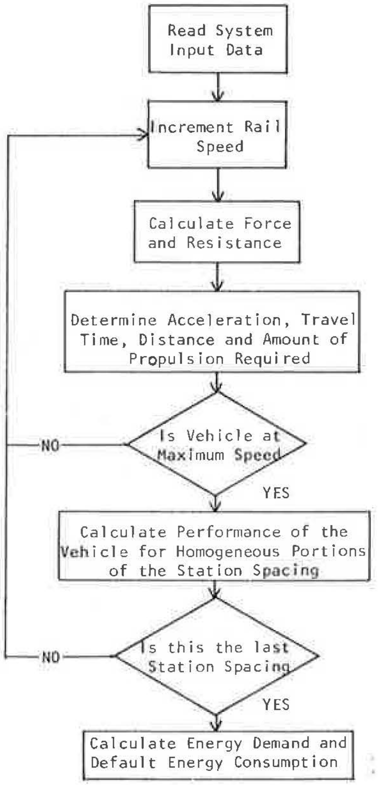
From these equations, along with the system characteristics (e.g., station spacing distance and maximum speed) one is able to determine important characteristics of rail vehicle performance. Figure 1 demonstrates this overall methodology.

Line-Haul Travel Time

Accuracy in line-haul travel time calculations are important for three interdependent reasons. First, there is a trade-off between energy consumption and travel time. Second, the travel-time savings of a particular mode determine the benefits of that alternative. Rightly or wrongly, travel-time benefits in excess of 60 percent are common in studies that justify the implementation of a rail system. Third, line-haul travel time is usually a large percentage of the total travel time and, as such, is important for forecasts of rail patronage.

A popular method used to estimate line-haul travel time assumes a linear acceleration of a vehicle from zero to maximum speed. This, however, can have very serious consequences on the travel time estimates. Since the propulsion force of a rail vehicle decreases with increasing velocity (Equation 1) and resistance increases with increasing speeds, the acceleration rate will be nonlinear (Equation 2). This results in a decreasing acceleration rate with increasing speeds. Therefore, the assumption of a linear acceleration rate results in a serious underestimate

Figure 1. Methodology for obtaining local performance information for the rail mode.



of the rail line-haul travel time. In a case study application of a light rail line in Buffalo, New York, the assumption of a linear acceleration rate underestimated the travel time by 16 percent.

Operating Energy Consumption

The method selected to calculate the line-haul travel time of rail is intertwined with the method used to calculate energy consumption. The simultaneous calculation of both of these components at the local level leads to more realistic results and adds few coding requirements.

There are two potential users of the previously defined energy and travel-time model. The first class of users is the local planners. They are interested in the line-haul travel time, operating energy consumption, and energy costs that result from the performance of a rail system. The second type of users is energy policy analysts. These users are interested not only in the operation of the system but also in all other features, components, and activities that consume energy. This user group is interested in total energy consumption.

This analysis assesses the energy implications of a rail system during a typical peak period. This decision results from energy studies that conclude that regenerative braking may be feasible during this period (22).

The energy consumption of a particular rail system is affected by three interrelated decisions. The first is the type of technology and the layout of the track. For this example analysis, a light rail vehicle (LRV) and the planned right-of-way of the Buffalo system is held constant throughout the sensitivity of the rail energy model. The second decision is the selection of a rail vehicle (i.e., which manufacturer). The third decision is the operating policies of a vehicle once purchased. These decisions are obviously not as mutually exclusive as this distinction portrays.

The following investigation addresses the impacts of different LRVs and operating policies in greater detail. Table 2 lists the major input variables that pertain to different vehicles as well as the values from three internationally known LRV manufacturers, all of which meet the specifications of the operating agency.

For this portion of the study, all vehicles are simulated by using the same operating policy as defined by the local transportation agency. The maximum speed in mixed traffic is 45 km/h and 80 km/h in the tunneled portion. The acceleration and deceleration rates are 1.22 and 1.34 m/s^2, respectively. The other operating variables and the parameters that represent the attributes of the vehicle itself are listed in Table 2. These simulations are represented by 1-1, 2-1, and 3-1. All three of these simulations vary the values of the vehicle type and hold constant the values that represent the operation of the system.

Table 3 summarizes a different situation. The 1-1 vehicle is selected and its design characteristics held constant, but the values that represent the operation are allowed to vary. Alternative 1-2 is identical to 1-1 except that the acceleration and deceleration rates are reduced by 20 percent. Alternative 1-4 is also identical to 1-1 except that the acceleration and deceleration rates are increased by 20 percent. Alternative 1-3 is also identical to 1-1; however, in this alternative the vehicle contains regenerative braking. This results in an increase in vehicle weight (variable 9), auxiliary output (variable 15), and an 80 percent recovery of braking energy (variable 6) (22). In these model simulations, it is assumed that there will be priority signalization for the rail vehicle in mixed traffic and on cross streets.

Table 4 contains a summary of these six alternatives. The energy consumption varies greatly from vehicle to vehicle. Vehicle 1-1 has a total operating-energy consumption of 8.05 kW•h/vehicle mile and vehicle 2-1 exhibits an estimate of 11.22 kW•h/vehicle mile. The travel time difference among the vehicles tested is less than 40 s for the 6.22-mile length of the system.

In this example application, the Btus of petroleum per vehicle mile are comparable to that of a city bus. The articulated light rail car has a capacity that is three times larger than that of a bus and, in this case, an average speed that is approximately twice as great. The difference in energy consumption for the three operating policies is minimal. For regenerative braking, it seems clear that the energy saved in reduced propulsion energy is lost in increased auxiliary energy. The three latter alternatives, which vary the operating variables, all contain energy costs of $0.32/vehicle mile (i.e., assuming a rate of $0.04/kW•h).

The two most important variables that affect energy consumption, from the perspective of the local planner, are categorized in the earliest decisions in the hierarchy of decisions that affect the performance of a rail vehicle. The station spacing and the vehicle type purchased are by far the most important decisions because they affect not only the energy consumption but also the overall performance of the system. Variation in the vehicle

Table 2. Input variables to energy model by vehicle type.

Input Variables		Manufacturer[a]		
No.	Definition	1-1	2-1	3-1
8	N = number of axles per car	6	6	6
9	TD = weight of car (t)	31.4	39.1	39.0
10	ACC = maximum acceleration (m/s^2)	1.22	1.22	1.22
11	K3 = tractive effort/hourly power[b]	1.744	1.826	1.805
12	DC = deceleration rate (m/s^2)	1.34	1.34	1.34
14	Y = propulsion output (kW)	247	435	335
15	YA = auxiliary output (kW)	35	35	35
19	Petroleum used in generation (%)	28	28	28

[a] In 1-1, the first number indicates the manufacturer, and the second number refers to the system options used. In this table, the same system options are used for all three vehicle types.

[b] Calibrated from energy model.

Table 3. Input variables to energy model by operating policy.

Input Variables		Operation[a]		
No.	Definition	1-2	1-3	1-4
6	K5 = percentage of regenerated braking	0.0	0.8	0.0
9	TD = weight of car (t)	31.4	32.3	31.4
10	ACC = maximum acceleration (m/s^2)	0.98	1.22	1.48
11	K3 = tractive effort/hourly power[b]	1.82	1.62	1.69
12	DC = deceleration rate (m/s^2)	1.07	1.34	1.61
15	TA = auxiliary output (kW)	35	83	35

[a] The first number indicates the manufacturer, and the second number refers to the system options used.

[b] Calibrated from energy model.

Table 4. Operating energy summary statistics.

Performance Summary	Vehicle[a]			Operation[a]		
	1-1	2-1	3-1	1-2	1-3	1-4
Travel time in one direction (min)	17.1	16.7	16.9	17.7	17.2	16.7
Energy consumption (kW·h/vehicle mile)						
Propulsion	6.48	9.68	8.46	6.42	4.09	6.51
Auxiliary	1.57	1.54	1.56	1.63	3.76	1.54
Total	8.05	11.22	10.02	8.05	7.85	8.05
Btus per vehicle mile	91 700	127 500	114 000	91 700	89 300	91 700
Btus of petroleum per vehicle mile	15 700	35 700	31 900	25 700	25 000	25 700
Energy costs ($/vehicle mile)	0.32	0.45	0.40	0.32	0.32	0.32

[a] The first number indicates the manufacturer, and the second number refers to the system options used.

Table 5. Comparison of program energy savings for Buffalo in 1985.

Mode	Estimated Yearly Passenger Demand (million passenger miles)	CBO Results (Btus/passenger mile)	Local Energy Model: Btus per Passenger Mile	Local Energy Model: Btus of Petroleum per Passenger Mile
Carpool	6578[a]	4895	4060	4060
Express bus	219[b]	3591	2743	2743
Light rail	61[c]	85	620	2448
Heavy rail[d]	61	-928	686	2343

[a] This figure is for automobile travel; a small percentage of this value is for carpool demand.

[b] This figure is for local bus travel; a small percentage of this value is for express bus demand.

[c] Estimated by the Niagara Frontier Transportation Authority.

[d] This is a crude approximation of the energy consumption of the heavy rail mode; the existing right-of-way in Buffalo could not handle a heavy rail vehicle for the entire length of the rail right-of-way.

operation has a minimal impact on energy consumption except in very rare cases (e.g., electric motors on rail vehicles are run continuously when vehicles are in nonservice operation). Lack of priority signalization for rail vehicles in mixed operation is one possible exception to the proposed notion that operating decisions have little impact on operating energy consumption; however, this question can really be categorized within the domain of station spacing.

Other energy-saving strategies seem to have little impact on light rail operations. Ideas to save energy by using a coasting phase cannot be applied in situations where spacing between stations is small. Adjustment of track profile as an energy-saving measure often conflicts with the minimization of construction costs, especially in drilling operations. Regenerative braking systems often substitute increased auxiliary energy for lower propulsion energy consumption.

Total Energy Consumption

Program energy savings take into consideration all factors that affect total energy consumption and thus determine the net energy savings from the implementation of a particular mode. Therefore, this section addresses the amount of energy saved by the implementation of a particular mode. Three important factors affect the range in program energy values for the light rail mode:

1. Weight of the vehicle,
2. Kilowatt output of the motors for propulsion, and
3. Average number of passengers per vehicle (this value is determined for an average loading over the entire workday).

Due to recent developments in the domestic manufacturing of LRVs and taking into consideration the often overestimated travel demand, a moderately patronized and relatively heavy LRV is felt to accurately portray the circumstances that are ahead for the Buffalo rail system. A saving of 2450 Btus of petroleum/passenger mile results in an annual conservation of about 1 million gal of fuel/year. This is a considerable saving; however, it is certainly not the panacea to our petroleum problem.

The program energy savings from the implementation of a carpool, express bus, light rail, or heavy rail system are listed in Table 5. This table contains the results of the local approach as well as the results that would have been obtained from using the CBO report. The CBO results indicate the energy saved in Btus per passenger mile. The local energy model contains both the Btus per passenger mile and the Btus of petroleum per passenger mile. The explicit petroleum consideration is one of the advantages of using a local energy model.

This table measures the net energy savings of the implementation of one of these previously mentioned modes. For example, the CBO states that the implementation of a light rail system will save very little energy--just 85 Btus/passenger mile. The results of the test application for Buffalo indicate that a light rail system will save 620 Btus/passenger mile and 2448 Btus of petroleum/passenger mile. These results seem to clearly indicate the usefulness of the local energy approach. The additional flexibility, without rigorous data preparation, makes the local planning effort more responsive to local concerns.

The cost of construction for the light rail system in Buffalo will approach $0.5 billion for the 6.22 operating miles. If the benefits of a rail system rest heavily on the energy (or, more specifically, petroleum) savings, then the rail mode is an expensive means to use for the reduction of our petroleum dependence.

SUMMARY

The results of this study emphasize the need to address the modal energy intensity of rail systems at the local level. Due to variability in the physical components and patronage levels, a decentralized perspective is required. This approach adds to the flexibility in evaluating locally generated, policy-sensitive alternatives. A summary of the main findings follows.

Due to the petroleum problem in the United States, the establishment of petroleum measuring criteria (with local petroleum values) aids in the evaluation of modes that do not directly use petroleum-based fuels.

Operating energy consumption of new light rail and heavy rail systems is higher than the values adopted from national averages. This is due to the increased size of these vehicles, especially foreign-manufactured articulated light rail cars.

A light rail system in Buffalo, New York, will save energy; however, it will have a small overall energy impact in the region. Station spacing and rail vehicle type greatly affect the operating energy consumption of rail vehicles at the local level. Operating policies that affect rail speed have much less impact. Regenerative braking on the vehicle tested in this example city does not produce an appreciable saving in operating energy.

Urban areas that contain electric generating plants with high percentages of petroleum as fuel sources need to address the petroleum performance of their particular system in much more detail.

The aggregation of local studies into national market segments, defined by the age of the system, vehicle manufacturer, geographic area, or size of the particular study region should aid in the evaluation of national energy-conserving strategies on local areas.

ACKNOWLEDGMENT

This research was supported by the Urban Mass Transportation Administration under contract to the State University of New York at Buffalo. We are responsible for all research, comments, and conclusions. This work does not necessarily represent the views of the Urban Mass Transportation Administration. This research is one part of a much larger modeling effort conducted for the Urban Mass Transportation Administration.

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

Long-Range Forecasts of Transportation Energy Consumption in New York State

DAVID T. HARTGEN AND NATHAN S. ERLBAUM

This paper summarizes the methods used by the New York State Department of Transportation to prepare long-range baseline forecasts of energy use in each of the subsectors of the transportation sector in New York. By use of a variety of techniques that relate energy to the economy, fuel price and supply, and vehicle efficiency, five-year forecasts to 1995 are prepared for trucks, passenger cars, aviation, rail, vessel, and transit modes. Within each group, separate forecasts are made for relevant segments (e.g., passenger rail). Results show that in 1995 total transportation energy in New York will expand by 13 percent from its 1976 level. Growth in air passengers of 108 percent, intercity rail of 10 percent, transit of 9 percent, and light truck of 59 percent will be offset by declines in passenger car fuel use of 24 percent. The latter are caused primarily by increasing vehicle efficiency. Gasoline use is projected to fall by 8 percent over the period; use of most other products will increase. The report concludes that growth will be moderate, generally even, tied to the New York economy, and highly dependent on increases in the efficiency of personal cars.

Energy conservation in the U.S. transportation sector is one of the major actions by which U.S. dependence on foreign oil and petroleum can be reduced. Numerous studies (1-5) have estimated the potential for energy conservation of transportation actions; most have concluded that concentrated efforts to improve the efficiency of private cars and trucks offer the maximum savings over the intermediate term. Partly in response, the Energy Policy and Conservation Act of 1975 mandated increases in average new-car fuel economy to 27.5 miles/gal by 1985; higher standards are being contemplated beyond 1985. Such analyses have intermittently been neglected in favor of short-term contingency planning (6,7); however, long-term conservation efforts must continue if we expect continued growth in mobility without a concomitant increase in gasoline consumption. Further, New York State law mandates that the New York State Energy Office, in cooperation with major energy suppliers, develop and submit to the New York State Energy Planning Board for approval a state energy master plan. The plan, which was approved in January 1980, included forecasts of energy requirements, energy resources, and energy policy recommendations by sector through 1995.

Over the last two years, the Planning Research Unit of the New York State Department of Transportation has conducted a number of analyses of the use and supply of transportation energy in New York. The studies have concentrated on automotive fuel use (i.e., gasoline) because this segment constitutes more than 60 percent of transportation energy. Preliminary forecasts of automotive fuel use have been made in earlier documents (5,8-10). They generally account for the increasing efficiency of passenger cars and changes in travel related to price and supply of fuel. To complete the work, recent studies have been prepared that forecast other subsectors of the transportation sector (11). The purpose of this paper is to summarize that work and recent updates to it and to describe the methods used to make baseline forecasts to 1995 for each subsector. The methods used to prepare these forecasts vary but, in general, they relate transportation energy use to projections of energy supply, real gross state product, disposable income, inflation, population, employment, and (for some items) fuel price. Projections of these background variables were provided by the New York State Energy Office. The methods are generally noncomputerized and rely on simple curve-fitting procedures and can be performed with a hand calculator. As such, they provide rapid turnaround to numerous policy questions.

ANALYSIS

Trucks

The basic procedure for estimating truck fuel use is as follows:

1. Estimate truck registrations,
2. Estimate market shares by vehicle type,
3. Estimate diesel and gasoline share of each vehicle type, and
4. Apply vehicle efficiency and use rates to calculate energy requirements.

The procedure is summarized in Table 1. Total truck registrations in New York and for the nation as a whole have been increasing rapidly in recent years. Much of this growth is due to the expansion of the light-duty truck market. Much of this growth has been the substitution of trucks for cars, for use predominantly in personal transportation. In fact, the 1977 Census of Transportation (12) notes that, in New York, light-duty trucks constituted 82.6 percent of all trucks in 1977 and that 62.7 percent of those light-duty trucks were used primarily for personal transportation.

To estimate future truck registrations, we assume that the growth rate for light-duty trucks will begin to level off by the mid-1980s as these vehicles become subject to fuel economy and emission standards and the public's concern about gasoline supply constraints and rising fuel prices. Based on a comparison of registrations from 1972 to 1976, this approach yields growth estimates for 1980, 1985, 1990, and 1995 registrations of 25.7, 59.6, 91.9, and 121.9 percent, respectively, above the 902 226 trucks registered in 1976.

The estimates of the future shares of light-, medium-, light-heavy-, and heavy-heavy-duty truck registrations were developed by extending the trends noted in the 1963, 1967, 1972, and 1977 Censuses of Transportation, Truck Inventory, and Use Survey for the shares of the different truck types. The 1977 shares for light-, medium-, light-heavy-, and heavy-heavy-duty trucks are 0.826, 0.088, 0.02, and 0.066 and the estimates for 1995 are 0.888, 0.06, 0.011, and 0.041, respectively. Similarly, the share of total truck registrations that are diesel powered are the following:

Year	Percentage
1977	4.0
1972	5.6
1967	11.3
1963	2.7

In view of the uncertainty about the growth of diesel use in the heavier of the light-duty-vehicle types, the breakdown of diesel fuel vehicles of the 1977 Truck Inventory and Use Survey (12) has been

Table 1. Truck use and energy consumption in New York State.

Item	1976			1978			1980		
	Gasoline	Diesel	Total	Gasoline	Diesel	Total	Gasoline	Diesel	Total
Vehicle registrations									
Light	730 596	207	730 803	839 716	238	839 954	960 183	269	960 452
Medium	84 579	1 132	85 711	82 489	1 104	83 593	85 042	1 137	86 179
Light-heavy	16 990	1 055	18 045	18 965	1 178	20 143	20 285	1 260	21 545
Heavy-heavy	29 258	38 409	67 667	27 435	36 015	63 450	28 439	37 339	65 778
Total			902 226			1 007 139			1 133 946
Efficiency (miles/gal)									
Light	13.11	12.25				14.6			16.0
Medium	8.30	7.75				8.5			8.8
Light-heavy	6.72	6.27				6.72			7.0
Heavy-heavy	5.83	5.45				5.83			5.9
Vehicle miles of travel per year									
Light			12 183			12 183			12 183
Medium			13 061			13 061			13 061
Light-heavy			12 542			12 542			12 542
Heavy-heavy			22 478			22 478			22 478
Travel (billion vehicle miles of travel)									
Light	8.9	0.0025	8.9	10.2	0.0029	10.2	11.7	0.0033	11.7
Medium	1.1	0.0148	1.1	1.08	0.0144	1.1	1.11	0.0149	1.12
Light-heavy	0.21	0.0132	0.22	0.23	0.0148	0.24	0.25	0.0158	0.27
Heavy-heavy	0.66	0.863	1.52	0.62	0.81	1.43	0.64	0.84	1.48
Total	10.87	0.8935	11.76	12.13	0.8421	12.97	13.7	0.8740	14.57
Energy (trillion Btus)									
Light	84.9	0.029	84.9	87.6	0.028	87.6	91.4	0.028	91.4
Medium	16.6	0.26	16.9	15.8	0.24	16.1	15.8	0.23	16.0
Light-heavy	4.0	0.29	4.3	4.4	0.30	4.7	4.5	0.31	4.8
Heavy-heavy	14.1	22.0	36.1	13.2	19.3	32.5	13.5	19.7	33.2
Total	119.6	22.579	142.2	121.0	19.868	140.9	125.2	20.268	145.4

Note: Figures for 1980-1995 are forecasts of projected use and consumption.

assumed to accurately describe the truck fleet with adjustments made to reflect 1976 data.

Vehicle Type	Diesel (%)	Gasoline (%)
Light	0.03	99.97
Medium	1.3	98.7
Light-heavy	5.9	94.1
Heavy-heavy	56.8	43.2
Weighted total	4.5	95.5

Average vehicle efficiency and use rates are also available in the 1977 Truck Inventory and Use Survey (12). Vehicle use rates have been fairly stable since 1972 and are assumed to remain so during the analysis period. Vehicle efficiency rates for light-duty vehicles are assumed to increase with respect to the light-duty-vehicle corporate average fuel efficiency (CAFE) standards to a maximum of 19.7 miles/gal (the low end of the proposed 1985 efficiency range) in 1985.

These statistics may be combined as in Table 1. Light-duty-truck fuel use is projected to increase by 59 percent by 1995, primarily due to the continued growth in the light truck market as a substitute for personal-use automobiles. Heavy-duty-truck fuel use is projected to increase by 15 percent by 1995.

Passenger Cars

To determine automotive fuel requirements and the impact of numerous background factors that concern the economy and general population growth, the department of transportation has constructed a model that relates gasoline price, fuel requirements, travel, and passenger-car vehicle efficiency (10, 13-16).

The model has been built for each of the nine metropolitan areas of New York State and the remainder of the state and has the following general form:

$$\mathrm{VMT_F} = (\mathrm{VMT_{75}})(\mathrm{POP_F}/\mathrm{POP_{75}})\ [1 + (e)(x/x_{75}) + \ldots] \qquad (1)$$

where

VMT = vehicle miles of travel,
POP = population,
x = gasoline price and availability,
e = elasticity of gasoline price with respect to x,
F = future year, and
75 = 1975 (base year).

$$\mathrm{GASOLINE_F} = \mathrm{VMT_F}/\mathrm{EFF_F} \qquad (2)$$

where EFF = average over-the-road fleet efficiency (miles/gal). The model structure assumes that increases in vehicle miles of travel will be a function of (a) increases in population and (b) changes in various background factors, including gasoline price, fuel requirements, inflation, and improvements of vehicle fleet efficiency. Calibration of the demand equations described above was accomplished through least-square regression on 48 data points for the months of 1972 through 1975. This period of time encompassed the "energy crisis" and was generally characterized by rapid increases in gasoline price and radical shifts in gasoline availability and automobile travel. Model statistics are shown in Table 2.

A baseline analysis for New York State automotive fuel was prepared for the period 1976-1995 by using this model. Background projections with respect to population, unemployment, labor-force participation, business activity, and inflationary pressure [consumer price index (CPI)] were used.

In addition, other assumptions that are made are as follows.

1. The real price of gasoline increases annually:

1985			1990			1995			Change From 1976 (%)
Gasoline	Diesel	Total	Gasoline	Diesel	Total	Gasoline	Diesel	Total	
1 261 122	357	1 261 479	1 530 355	434	1 530 789	1 777 541	504	1 778 045	143.3
88 104	1 179	89 283	102 528	1 372	103 900	118 551	1 587	120 138	40.2
21 694	1 347	23 041	22 826	1 417	24 243	23 565	1 464	25 029	38.7
28 642	37 600	66 242	31 447	41 283	72 730	35 496	46 598	82 094	21.3
		1 440 045			1 731 662			2 002 303	121.9
		19.7			20.0			20.0	
		8.8			8.8			8.8	
		7.0			7.0			7.0	
		5.9			5.9			5.9	
		12 183			12 183			12 183	
		13 061			13 061			13 061	
		12 542			12 542			12 542	
		22 478			22 478			22 478	
15.4	0.0043	15.4	18.6	0.0053	18.6	21.7	0.0061	21.71	143.9
1.15	0.0154	1.17	1.34	0.0179	1.36	1.55	0.0207	1.57	42.7
0.27	0.0169	0.29	0.29	0.0178	0.31	0.30	0.0184	0.32	45.5
0.64	0.85	1.49	0.71	0.93	1.64	0.80	1.05	1.85	21.7
17.46	0.8866	18.35	20.94	0.9710	21.91	24.35	1.0952	25.45	116.4
97.5	0.031	97.5	116.5	0.037	116.5	135.3	0.043	135.3	59.4
16.3	0.24	16.5	19.0	0.28	19.3	22.0	0.33	22.3	32.0
4.9	0.33	5.2	5.1	0.35	5.5	5.3	0.36	5.7	32.6
13.6	19.9	33.5	15.0	21.8	36.8	16.9	24.6	41.5	15.0
132.3	20.501	152.7	155.6	22.467	178.1	179.5	25.333	204.8	44.0

Year	Annual Real Growth (%)
1978-1979	15.2
1979-1980	25
1980-1981	15
1981-1982	10
1982-1983	7.5
1983-1985	5
1985-1990	3.5
1990-1995	2.1

2. Price elasticity increases (from -0.15 in 1976 to -0.53 in 1995).
3. New-car U.S. Environmental Protection Agency (EPA) efficiency will increase to 27.5 miles/gal by 1985 and be constant thereafter.
4. Vehicle miles of travel will grow at 2-3 percent annually.
5. Gasoline will be available to meet requests--but at higher prices.

Table 3 shows the results of these forecasts. Improvements in new-model-automobile efficiency to meet the federal mandate for CAFE standards will enable the New York State automobile fleet to improve its average efficiency of 79 percent by 1995. [Recent analysis (17) shows that fleet turnover in New York has already increased fleet efficiency by 3.18 percent in 1978 over 1977 and by 3.22 percent in 1979 over 1978.] This improvement in average automobile fleet efficiency will enable a 43 percent expansion of personal mobility (annual vehicle miles of travel statewide) on considerably less gasoline--a decline of 22 percent by 1995. However, a constant standard of 27.5 miles/gal from 1985 to 1995 will result in slow increases in consumption from 1991 to 1995. The real cost of gasoline in 1995, when adjusted for inflationary effects, will be 165 percent over 1976 or $1.97/gal in 1978 dollars (the real price in 1978 was $0.693/gal).

Additional tests have been made of the sensitivity of these forecasts to fleet turnover and gasoline price (17-21). These tests show that

1. Delayed progress in meeting the federal CAFE

Table 2. Passenger-car gasoline demand models.

Area	R^2	Overall F	GASPR/CPI		AVGAL		RETSL		LFPR		UNEM	
			F	e	F	e	F	e	F	e	F	e
New York City	0.7829	30.285	5.20	-0.21	10.45	0.34			40.85	1.47		
Buffalo	0.7273	22.407	5.77	-0.13	2.52	0.08	6.12	0.36				
Rochester	0.7135	26.775	1.65	-0.09	11.67	0.39						
Albany	0.8412	57.004	2.31	-0.11	9.27	0.38						
Syracuse	0.7972	38.304		-0.10[a]	13.99	0.58						
Utica-Rome	0.8460	46.186		-0.10[a]	15.74	0.83						
Binghamton	0.8183	30.776		-0.10[a]	3.95	0.31					4.80	-0.29
Poughkeepsie	0.8411	44.465		-0.10[a]	18.76	0.54						
Elmira	0.8037	34.385		-0.10[a]	8.97	0.37						
Watertown	0.8972	59.628		-0.10[a]	2.23	0.28					6.67	-0.15

Notes: e = elasticity; GASPR/CPI = deflated gasoline price; AVGAL = gasoline sold x average efficiency; RETSL = retail sales index; LFPR = labor-force participation rate; UNEM = unemployment rate.
Models also include seasonal indices.

[a] Assumed.

Table 3. Summary of baseline forecasts for automobile fuel.

Item	1976	1978	1980	1985	1990	1995	1976-1995 (%Δ)
Model inputs							
Gasoline price (cents/gal)							
Nominal	64.7	69.3	130.7	305.2	481.4	701.3	984
Real (1978 dollars)	74.5	69.3	99.8	149.5	177.5	197.0	165
Gasoline requirements (trillion Btus)[a]	567.8	563.8	552.6	470.0	427.9	453.8	-20
New York State vehicle efficiency	13.3	14.0	14.9	19.2	23.1	23.8	79
Model outputs							
Vehicle miles of travel (billions)	57.97	63.12	63.56	69.37	79.63	82.65	43
Gasoline requirements (trillion Btus)[b]	558.4	565.4	534.9	452.6	431.5	434.5	-22
Annual gasoline cost per capita							
Nominal	183.84	172.76	234.50	292.45	324.04	353.67	92
Real (1980 dollars)	117.29	110.22	149.61	186.58	206.74	225.64	

[a] Gasoline necessary to sustain 2-3 percent growth in vehicle miles of travel along with fleet turnover.

[b] Gasoline demanded at price profile and actual growth in vehicle miles of travel.

standards in 1980-1985 would result in about 1.7 percent less vehicle miles of travel and 0.52 percent more gasoline use over the 1976-1995 period and

2. Further standards (up to 35 miles/gal by 1995) could result in as much as 12 percent additional gasoline savings but would likely also increase vehicle miles of travel in the 1985-1995 period.

Aviation

Aviation fuel use consists of three parts: air passenger, air cargo, and general aviation. The first two constitute a substantial share of New York transportation energy (16.1 percent) because of the major national and international services in the New York City region.

Forecasts were made by relating current fuel use to seat miles, revenue miles per capita, and load factor, state gross product, and civilian employment. The equations are as follows.

Air Carrier: Passenger Transportation

The model is given by the following equation (22):

$$BTU_f = (1.08)(BTU/SM)\,[(RPM/capita)/load\ factor]\,(P_f)\,(SGP_f/SGP_{75}) \quad (3)$$

where

BTU_f = Btus in future year f,
1.08 = pivot factor to adjust projected demand to observed demand,
BTU/SM = Btus/seat miles = 4050 (1975 national data),
RPM/capita = revenue passenger miles per capita = 1052.6 (projected from national data) (23),
P_f = population in year f,
load factor = 55.9 percent (1975 national data), and
SGP_f/SGP_{75} = index that relates future travel to the ratio of future business activity (measured by the future real state gross product) to the 1975 business activity (measured by the 1975 state gross product) (SGP_{75} = $114.989 billion).

Air Cargo

The model is given by the following equation (24,25):

$$BTU_f = BTU_{75}\,(0.846)\,SGP_f/SGP_{75} \quad (4)$$

where BTU_{75} = 48.55 in 1975 trillion Btus and 0.846 = pivot factor to adjust projected demand to observed demand.

General Aviation

The model is given by (24)

$$BTU_f = BTU_{75}(SGP_f/SGP_{75})\,(\text{no. civilian employees}_f/\text{no. civilian employees}_{75}) \quad (5)$$

where

BTU_{75} = 1.15 trillion Btus in 1975,
no. civilian $employees_f$ = number of civilian employees in future year f, and
no. civilian $employees_{75}$ = number of civilian employees in 1975 = 6 938 000 (26).

These forecasts are summarized in Table 4. Air carrier travel is expected to increase by 122 percent overall; air cargo by 47 percent overall, and general aviation by 140 percent overall. Projections of air travel are expected to result in a significant increase in energy requirements for passenger travel (108 percent) and cargo (55 percent) by 1995. General aviation is expected to increase rapidly (136 percent) by 1995; however, its share of aviation energy will continue to remain small.

Intercity Rail

Intercity rail traffic consists of passenger and freight. The energy-use forecasts of rail passenger travel in New York State come from earlier research (27). Forecasts were made for rail passenger travel in the New York City-Buffalo corridor for the years 1975-1980. These forecasts accounted for the train, track, and service improvements planned by the National Railroad Passenger Corporation (Amtrak) over the next several years. By using common conversion factors, energy use is converted into equivalent gallons of gasoline and equivalent gallons of diesel fuel. Discussions with rail division staff at the New York State Department of Transportation indicate that 1995 rail passenger volumes will be about triple those of 1976--an increase from 980 000 to approximately 3 million passengers--and current train consists will be replaced by more efficient Amfleet equipment or the equivalent. Based on these assumptions, the energy used for rail passenger travel in New York State can be expected to increase 11 percent by 1995 (see table below).

Year	Energy Use (trillion Btus)
1976	0.475
1978	0.525
1980	0.425
1985	0.450
1990	0.488
1995	0.525

Data on rail freight movements within New York State come from a 1 percent waybill sample of shipments that originated and terminated in New York State. The data are in ton miles of travel and are related to real state gross product. By using an average efficiency of 670 Btus/ton mile (28), the energy use of freight movement can be computed.

By using the time-series data, a forecast procedure for predicting ton miles for future years was developed. The central hypothesis was that ton miles (TMT) for any year are related to the real gross state product (RGSP) for that year. The model developed is

$$\text{TMT}\,(\times 10^9) = \{15.24 + 0.085\,[\text{RGSP}\,(\times 10^9)]\} \quad R^2 = 0.82 \tag{6}$$

By using the methodology outlined above, a set of yearly forecasts of ton miles and energy used for rail freight movements in New York State was developed (Table 5). However, due to the continued rationalization of the Northeast rail system (mostly abandonment) and the potentials of meaningful deregulation, a continued decline in rail freight in the Northeast is anticipated until a more rational commodity base is developed, probably in the mid-1980s. In view of this, rail freight energy is expected to remain constant until 1985, at which point rail freight energy is expected to grow with real gross state product, as noted in the model above. Rail freight used approximately 1.6 percent of the energy consumed in the transportation sector in 1976. The energy used in freight movements by rail is estimated to increase by 27 percent during the next 20 years. Given the goal of energy conservation, total transportation energy should not grow as rapidly as rail freight energy, so its share should increase in the future.

Vessels

Demand for bunker fuel depends on two main factors:

1. Demand for vessel transportation services and
2. Effectiveness with which the fuel is applied to the transportation task.

Over the last 10 years, sales of fuel for marine purposes (residual, distillate, and gasoline) in New York State have declined precipitously, more than 50 percent (29,30). During this time, other modes, particularly pipeline, have captured a larger share of freight movement from vessels, primarily due to cheaper transportation costs, because light petroleum products can be moved through pipelines more efficiently than by means of vessels. Petroleum products constituted 70 percent of vessel freight tonnage in 1976 and 68 percent in 1977. Also, refueling of vessels in the port of New York is occurring on the New Jersey side as well as the New York side. The combination of energy conservation and import restrictions will have an adverse impact on the future demand for vessel transportation services.

The demand for petroleum products carried by vessels makes it difficult to establish a realistic elasticity of demand for bunker fuel (a fuel used primarily to transport fuel). This is because (a) the price of bunker fuel is largely dependent on general petroleum prices and (b) the demand for bunker fuel is that required to move other petroleum products. To avoid such problems, the real gross state product was chosen because the demand for other-than-petroleum products shipped is believed to vary closely with business activity. The model used to forecast the demand for other-than-petroleum products is as follows (29):

$$\text{TONS} = [0.835\,(10^{-3}) * \text{RGSP} - 20.737\,(10^6)] \quad R^2 = 0.5 \tag{7}$$

We assume that other-than-petroleum products continue to constitute a larger share of freight tonnage by vessels, or conversely, petroleum products either shift to other modes or experience 2 percent less demand a year to 1980 and 0.4 percent less demand to 1995. Estimates for total state tonnage thus result.

Table 4. Forecasts of aviation fuel use.

Item	1976	1978	1980	1985	1990	1995	Change From 1976 (%)
Real gross state product ($ billions)	128	135	136	150	167	199	55
Population (millions)	18.08	18.09	18.195	18.497	18.927	19.362	7
Employment (millions)	6.771	7.255	7.188	7.551	7.771	8.514	26
Load factor (%)	56	61.5	61.5	59.0	59.0	59.0	5
Revenue miles per capita	688	1042	1140	1200	1200	1200	74
Travel							
Air carrier passenger miles (billions)	16.5	20.2	22.4	26.3	30.1	36.6	122
Air cargo (million tons)	537	536	540	594	665	789	47
General aviation (million plane miles)	38	43	45	55	68	91	140
Fuel requirements (trillion Btus)							
Air carrier	130.3	143.6	159.2	195.2	223.3	271.3	108
Air cargo	41.7	44.0	44.3	48.7	54.5	64.7	55
General aviation	1.1	1.2	1.3	1.6	2.0	2.0	136

Table 5. Forecasts of intercity rail freight energy.

Item	1976	1978	1980	1985	1990	1995	Change From 1976 (%)
Real state gross product ($ billions)	128	135	136	150	167	199	55
Ton miles (billions)	25.26	23.76	23.69	27.97	29.48	32.15	27
Fuel use (trillion Btus)	16.9	15.9	15.9	18.7	19.8	21.5	27

Table 6. Vessel fuel use.

Item	1976	1978	1980	1985	1990	1995	Change From 1976 (%)
Real state gross product ($ billions)	128	135	136	150	167	199	55
Tons (millions)	255.7	271	245	261	283	330	29
Fuel use (trillion Btus)	63.5	50.2	48.7	53.6	58.5	63.5	0

Table 7. Transit energy use.

Item	Btu (trillions)						Change From 1976 (%)
	1976	1978	1980	1985	1990	1995	
Commuter rail	3.7	3.3	3.3	3.4	3.5	3.6	-2.7
Subway	5.5	5.0	5.4	5.7	6.0	6.3	14.5
New York City buses	5.8	5.7	5.7	6.0	6.3	6.6	13.8
Upstate buses	1.2	1.24	1.26	1.29	1.32	1.36	13.3
School buses	4.8	4.9	4.4	4.6	4.7	4.8	0
Intercity buses	0.52	0.57	0.57	0.60	0.63	0.66	26.9

Table 8. Transit travel distances.

Item	Vehicle Miles of Travel (millions)						Change From 1976 (%)
	1976	1978	1980	1985	1990	1995	
Commuter rail	62.6	61.6	61.6	63.2	64.8	66.4	6.1
Subway	275.8	248.0	259.9	273.1	287.1	301.7	9.4
New York City buses	152.7	150.6	150.6	158.3	166.4	174.8	14.5
Upstate buses	36.3	37.2	38.0	38.9	39.9	40.9	12.7
School buses	281.9	284.6	260.3	266.9	273.6	280.5	-0.5
Intercity buses	22.3	24.5	24.7	26.0	27.3	28.7	28.7

When the relationship between tonnage and Btus of bunker fuel consumed is known, it is then a straightforward task to estimate the total Btus of energy consumed. But in New York, the sale of bunker fuel is not related to the consumption for transport of tonnage due to the availability of fuel in the port of New York but sold in New Jersey. Also, a large portion of tonnage is shipped to New York by foreign vessels that can provide their own supply of bunker fuel. Therefore, to the extent to which these factors occur, any forecasts would be meaningless with respect to New York State's consumption. To resolve this dilemma, we assume that current sales will continue to decline to 1980 and then increase slightly to 1995. Results are summarized in Table 6.

Transit

Transit energy consists of several major parts: subway, public bus, and commuter rail systems; school buses; and intercity buses. Transit energy consumes a significantly higher share of New York's transportation energy than that of the United States, primarily because of the extensive bus and subway systems in New York City. In 1976, this energy accounted for 2.0 percent of New York's total, compared with 0.5 percent nationwide. In addition to urban transit systems, school buses constitute a major transit energy user.

Transit vehicle miles of travel (VMT) have been declining in the state; slight increases upstate have been offset by declines in the New York City area. However, Governor Carey is committed to holding down fares through 1981. As the impact of the Mideast oil situation continues to be felt in the state, mass transit becomes an increasingly attractive alternative. The New York State Department of Transportation forecasts a 1.0 percent rise in bus and rapid transit VMT for New York City area bus and rapid transit and a 0.3 percent rise in commuter rail VMT and upstate bus VMT. We assume an annual 1.0 percent increase in VMT and energy use in New York City area bus and rapid transit through 1995 and an annual 0.5 percent increase in VMT and energy use of commuter rail and upstate bus.

School bus VMT has remained constant over the past few years. The population in New York State is expected to rise; however, the general tendency toward smaller families means that the school-age population may rise at a slower rate than the overall population. It is safe to assume a 0.5 percent annual rate of growth for school bus VMT in New York State.

Over the past 10 years, intercity bus VMT in New York State has declined gradually, although some of the smaller companies have expanded their operations. The Surface Transportation Assistance Act of 1978 authorizes expenditures for intercity bus service, but it is currently unclear whether the money will actually be appropriated. If federal money is put into intercity bus service, a significant expansion of intercity bus VMT could be expected. Given the uncertainty concerning funding, an annual growth rate of 1.0 percent in intercity bus VMT is reasonable.

The above assumptions lead to a straightforward extrapolation of 1976 energy requirements, as shown in Tables 7 and 8.

Although transit service and use have been declining until recently, the availability of federal, state, and local transit operating assistance is expected to reverse this trend and cause a 0.8 percent growth in transit energy by 1995. School bus energy is primarily a function of the school-age population, which is projected to increase very slightly in the same period.

SUMMARY AND POLICY IMPLICATIONS

The above statistics and forecasts are combined in Tables 9-11 and Figures 1 and 2. In 1976, the

Table 9. Baseline fuel projections.

Item	BTUs (trillions)	Change from 1976 (%) 1978	1980	1985	1990	1995
Passenger cars						
Private	567.7	-0.4	-5.8	-20.3	-24	-23.5
Taxi	22.0	-1.9	4.3	42.1	23.0	16.5
Government	23.6	-1.3	-2.6	-17.2	-24.6	-20.1
Trucks using gasoline						
Light	84.9	3.2	7.7	14.8	37.2	59.4
Medium	16.6	-4.6	-5.0	-1.8	14.5	32.5
Light-heavy	4.0	10.0	12.5	22.5	27.5	32.5
Heavy-heavy	14.1	-6.4	-4.3	-3.5	6.4	19.9
Trucks using diesel fuel						
Light	0.029	-5.1	-2.1	6.9	27.5	48.3
Medium	0.29	-9.6	-10.0	-6.9	7.7	26.9
Light-heavy	0.29	3.4	6.9	13.8	20.6	24.1
Heavy-heavy	22.0	-12.3	-10.5	-9.5	-0.9	11.8
Transit						
Upstate bus, diesel	1.2	3.3	5.0	7.5	10.0	13.3
Downstate bus, diesel	5.8	-1.7	-1.7	3.4	8.6	13.8
Commuter rail, electric	2.1	-7.7	-6.0	-3.6	-1.2	1.2
Commuter rail, diesel	1.6	-17.5	-16.2	-14.6	-12.3	-10.0
Subway, electric	5.5	-9.1	-1.8	3.6	9.1	14.5
School bus, gasoline	4.8	2.1	-8.3	-4.2	-2.1	0.0
Intercity bus, diesel	0.52	9.6	9.6	15.4	21.2	26.9
Rail						
Intercity, passenger, diesel	0.5	10.5	-10.5	-5.3	2.6	10.5
Freight, diesel	16.9	-5.9	-6.2	10.7	16.7	27.3
Aviation						
Air carrier, jet	130.3	10.2	22.2	49.8	71.4	108.2
General aviation	1.1	14.0	19.8	46.5	81.4	141.9
Cargo, jet	41.7	5.5	6.2	16.8	30.7	55.2
Motorcycle or moped, gasoline	1.8	2.8	20.3	46.9	73.4	100.0
Vessel	63.5	-20.9	-23.3	-15.6	-7.9	0.0
Other highway, diesel	8.4	108.9	100.6	180.2	236.0	280.4
Other nonhighway and losses, gasoline	27.8	4.2	8.5	19.0	30.0	40.0
Other, liquefied propane gas	1.4	8.0	17.0	38.0	58.0	79.0

Table 10. Summary of fuel use.

Fuel	BTUs (trillions) 1976	1978	1980	1985	1990	1995	Change From 1976 (%)
Gasoline	774.8	775.3	752.1	685.6	685.8	716.3	-7.6
Diesel	63.7	69.2	68.6	79.2	88.1	97.7	53.4
Liquefied propane gas	1.4	1.5	1.6	1.9	2.2	2.5	78.6
Jet fuel	172.0	187.6	203.5	244.0	277.8	336.0	95.3
Aviation gasoline	1.1	1.2	1.3	1.6	2.0	2.6	136.4
Residual[a]	49.8	37.9	36.5	40.7	44.9	49.1	-1.4
Electricity[b]	7.6	6.8	7.4	7.7	8.0	8.4	10.5
Total	1070.4	1079.5	1071.0	1060.7	1108.8	1212.6	13.3

[a] Does not include military.

[b] Includes only electricity for propulsion.

transportation sector of New York's energy consumption was 26.4 percent of the state total. It is thus the largest energy-using sector. Figure 1 summarizes the sources and uses of this energy. Most (72.3 percent) is gasoline used to power cars and trucks, but a significant share (16.1 percent) is jet fuel and vessel bunker fuel (4.7 percent). Cars use about 57.3 percent of New York's transportation energy, and light trucks contribute an additional 7.9 percent. Heavy trucks use 5.3 percent, and air 16.2 percent. Other modes (transit, vessels, and rail) use smaller amounts.

Tables 9 and 10 show a detailed breakdown of 1976 and projected energy use. The baseline travel distances for 1976 are given below.

Mode	1976
Passenger car (billion vehicle miles of travel)	
Private	58.0
Taxi	1.7
Government	2.5
Truck (billion vehicle miles of travel)	
Light, gasoline	8.9
Medium, gasoline	1.1
Light-heavy, gasoline	0.2
Heavy-heavy, gasoline	0.7
Light, diesel	0.0025
Medium, diesel	0.02
Light-heavy, diesel	0.01
Heavy-heavy, diesel	0.9
Transit (billion vehicle miles of travel)	
Upstate bus	0.03
Downstate bus	0.16
Commuter rail	0.06
Subway	0.28
School bus	0.20
Intercity bus	0.022
Rail	
Intercity (billion passengers)	0.001

Mode	1976
Freight (billion ton miles)	0.02
Aviation	
Air carrier (billion passenger miles)	16.50
General (billion plane miles)	0.04
Cargo (thousand tons)	537
Motorcycle, moped, and snowmobile (billion vehicle miles of travel)	0.6
Vessel (million tons)	0.26

Table 11. Baseline travel projections.

	Change from 1976 (%)				
Mode	1978	1980	1985	1990	1995
Passenger car					
Private	8.9	9.6	19.7	37.4	42.6
Taxi	1.6	3.1	33.0	71.6	117.6
Government	4.0	8.0	20.0	32.0	44.0
Truck					
Light, gasoline	14.6	31.5	73.0	109.0	143.8
Medium, gasoline	-1.8	0.9	4.5	21.8	40.9
Light-heavy, gasoline	9.5	19.0	28.6	38.1	42.9
Heavy-heavy, gasoline	-6.1	-3.2	-2.4	7.6	21.2
Light, diesel	16.0	32.0	72.0	112.0	144.0
Medium, diesel	-2.7	0.7	4.1	20.9	39.9
Light-heavy, diesel	12.1	19.7	28.0	34.8	39.4
Heavy-heavy, diesel	-6.1	-2.7	-1.5	7.8	21.7
Transit					
Upstate bus	2.5	4.7	7.2	9.9	12.7
Downstate bus	-1.4	-1.4	3.7	9.0	14.5
Commuter rail	-1.6	-1.6	1.0	3.5	6.1
Subway	-10.1	-5.8	-1.0	4.1	9.4
School bus	1.0	-7.7	-5.3	-2.9	-0.5
Intercity bus	9.9	10.8	16.6	22.4	28.7
Rail					
Intercity passengers		50.0	100.0	150.0	200.0
Freight	-5.9	-6.2	10.7	16.7	27.3
Aviation					
Air carrier	22.3	35.6	59.6	82.6	121.7
General	5.4	6.3	16.8	30.7	55.1
Cargo	-0.2	0.6	10.6	23.8	46.9
Motorcycle, moped, and snowmobile	1.4	19.1	43.9	68.7	93.5
Vessel	6.0	-4.2	2.1	10.7	29.1

Figure 1. New York State transportation energy.

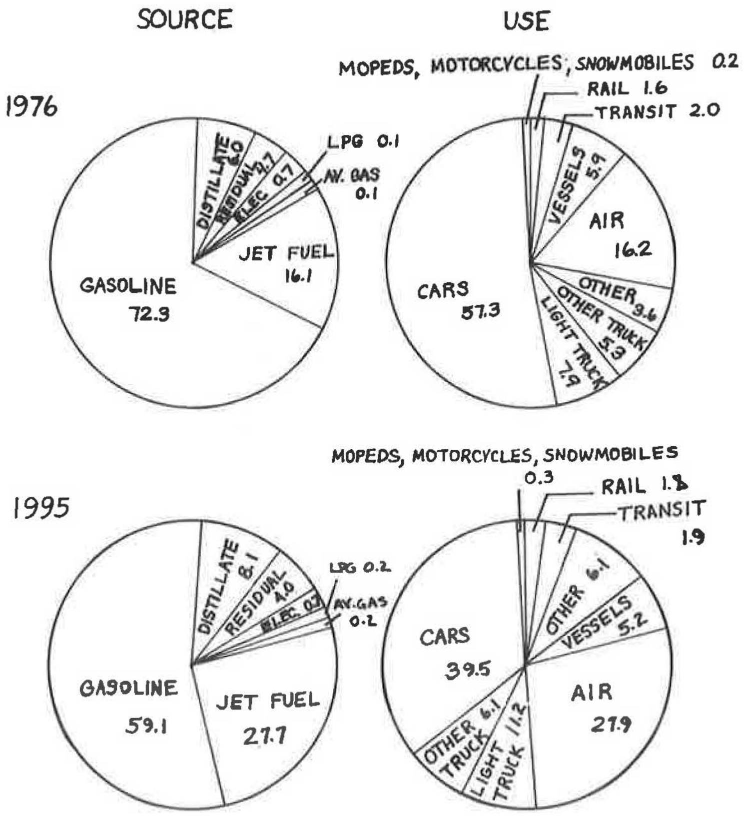

Figure 2. Projected growth in New York State transportation energy consumption 1976-1995.

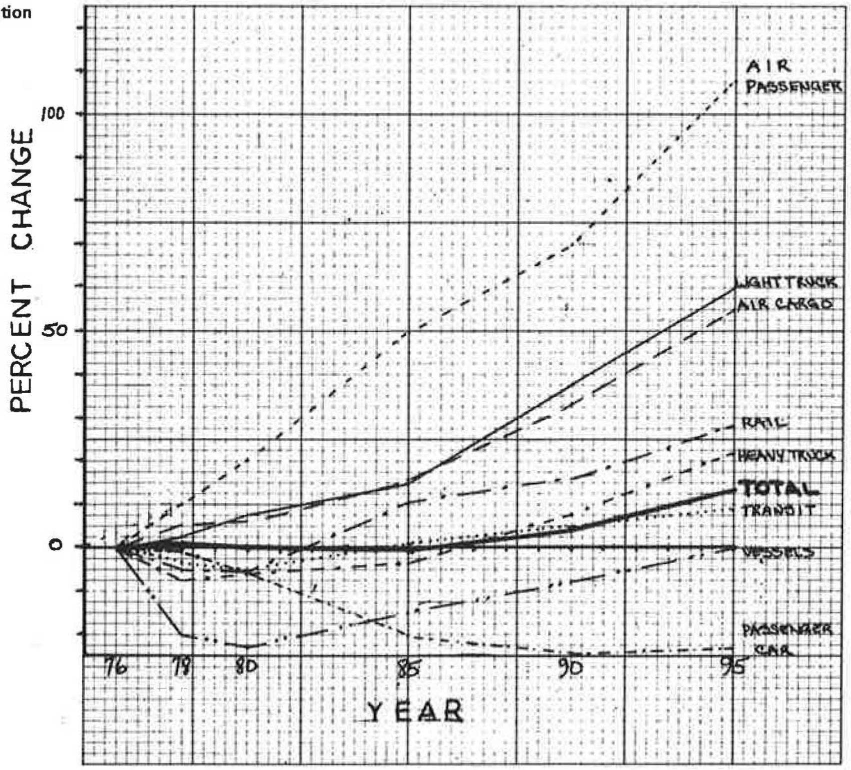

Table 11 shows current and projected travel. Overall, transportation energy requirements are expected to increase 13 percent by 1995. Future transportation energy requirements grow slowly because of projected improvements in fuel economy for cars and light trucks through 1985; beyond that time, continued improvements in efficiency will be needed to maintain a lower growth rate.

Major shifts in the percentage distribution are apparent in the projections. Aviation will grow most rapidly and almost double its share of energy use, and passenger cars will decline in share.

Numerous policy implications can be drawn from these analyses. Most clear is the major positive impact that increases in the fuel economy of automobiles and light trucks will have on transportation energy use in the next 20 years. Without such improvements, transportation energy use might be expected to skyrocket. The importance of maintaining the current path toward increased fuel economy for cars and trucks cannot be overestimated. If possible, improvements beyond 1985 should also be mandated.

The fastest growing subsector, air traffic, warrants special attention. Air passenger travel was, until recently, primarily a function of the economy, but fare deregulation and service changes as a result of the Airline Deregulation Act of 1978 are likely to bring a surge of nonbusiness travelers. The tight energy situation of 1979 has also accelerated traffic in air passenger systems. To the extent that such traffic can be accommodated on existing equipment (i.e., by increasing load factors), it represents direct savings via diversion from automobiles.

The analysis further shows that, to a large extent, trends in the New York State and U.S. economy will significantly influence transportation fuel use. One negative aspect--continuing dependence on foreign oil--is likely to increase vessel fuel use requirements as well. The sense of the analysis is that transportation energy growth in New York over the next 20 years will be moderate and measured, dependent primarily on personal vehicle fleet turnover and growth in the state economy.

ACKNOWLEDGMENT

The period January to December 1979 was one of rapid change in energy price and supply in the United States. The forecasts contained herein have been updated from the original estimates by using the most available data as of February 1980. Passenger car forecasts have been adjusted to account for more recent (1980) rapid price increases. The New York State energy master plan reflects some of these changes and also reflects other changes that occurred since this paper was prepared. However, due to the numerous attempts to keep estimates current, the forecast contained here and updated as of February 1980 may vary from those contained in the master plan (which was published at an earlier date). We would like to thank Diane E. Davis and Linda Unangst for the preparation of the manuscript of this paper. We also appreciate the support of the New York State Energy Office in funding this and other studies of transportation energy undertaken by the Planning Research Unit. Most importantly, the work of Gerald S. Cohen, Peter Koeppel, Alfred J. Neveu, Michael A. Kocis, Daniel K. Boyle, and Joanna M. Brunso formed the original basis for this work. We wish to acknowledge the special assistance provided by Michael A. Kocis, Peter Koeppel, Don Baker, and Gordon Peters in updating the forecasts. We wish to emphasize that the views, facts, and opinions expressed in this paper are ours and should not necessarily be attributed to the New York State Department of Transportation or the New York State Energy Office.

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

Use of Disaggregate Data to Evaluate Gasoline Conservation Policies: Smaller Cars and Carpooling

MARTIN E. H. LEE AND MATTHEW F. GLOVER

A microdata base of vehicle ownership and use characteristics was built from 7581 interviews of Michigan applicants for renewal of driver's licenses taken throughout the state in 1976. Analyses of gasoline efficiency in occupant kilometers per liter suggested that the greatest potential for conservation policy was to be found in commuter carpooling and a shift to smaller cars. Six scenarios for carpooling and smaller cars were defined in sufficient detail to exclude types of trips or classes of vehicle users for which these policies would present significant difficulties. The scenarios were run against the 1976

data to calculate the gasoline savings and improvements in occupant kilometers per liter obtainable in the best case. Smaller reductions in liters were found than would be predicted from gross estimates, but considerable consistency was found in the pattern of hypothetical responses of different subgroups of drivers distinguished by income or the urbanization of their home area, despite large differences in gasoline consumption. It is suggested that suburban drivers could provide 25 percent more gasoline savings than the statewide per capita average under the most optimistic scenarios analyzed. It is also suggested that the microdata techniques be calibrated to externally measured behavioral data on travel and conservation choices.

During 1979, the President and the U.S. Congress made numerous attempts to agree on national policies to conserve gasoline. Emergency rationing legislation was enacted, but the guidelines for standby rationing were made the subject of a plan to be submitted later by the President to the Congress for approval. Even less progress was made toward development of an ongoing plan for reducing oil use. In the political debates, many assertions have been made about the need to maintain certain types of travel, notably commuting. Given that almost all automobile uses are defended by some interest group or region, interest is increasing in improving efficiency rather than in reducing kilometers traveled.

An exploration of candidate policies for improving efficiency is even more difficult than an exploration of methods for inhibiting travel because it requires detailed information on vehicle fleet mix and fuel performance, kilometers traveled, and passenger load. Moreover, it is highly desirable to know variations in the relationships between these factors among different population subgroups and among different regions: Differential impacts of policies may result from these variations.

This paper describes the development of a microdata base on vehicle ownership and use throughout Michigan. We use it to identify some of the characteristics of inefficient travel and to develop a rationale for two policies (use of smaller cars and commuter carpooling) that the data suggest are appropriate responses to inefficiency. We then use the microdata to calculate the best-case changes in gasoline consumption and efficiency of use that would result from the full or partial implementation of these policies. These analyses use highly detailed personal trip data to limit hypothetical adherence to these policies to favorable conditions.

Various levels of travel data aggregation have been used in previous efforts to compare these and other conservation policies. For example, Lutin (1) used 1970 census data on work trips aggregated at the county level and applied hypothetical load factors and fuel-efficiency factors to estimate energy savings from carpooling and smaller cars (as well as some modal shift considerations). Erlbaum (2) used household survey data on annual driving distance by vehicle class and the age and sex of the owner; observed trends in vehicle kilometers and hypothetical fleet mixes were applied to the owner age and sex groupings to estimate future demand for gasoline. In a later paper, Erlbaum and others (3) forecast more detailed impacts of conservation scenarios by manipulating average trip rates, lengths, and occupancy; vehicle efficiency; and household automobile ownership from daily data in the same survey. Inputs to the models were aggregated over different combinations of location, trip purpose, and automobile ownership level. This study differs from these approaches in that it individually queries the characteristics of each trip reported by a large number of respondents on a designated day, applies conservation factors if conditions are met, and then aggregates the results by population sector.

DESCRIPTION OF THE SURVEY AND DATA BASE

The Michigan Driving Experience Survey (MDES), a microdata base on vehicle ownership and use, was built from 7581 personal interviews of applicants for renewal of driver's licenses conducted throughout Michigan during 1976. It used a controlled selection procedure for random selection of sites within two dimensions--level of urbanization and gasoline sales per capita (the latter is the only indicator available of gross personal travel activity). Because of the scarcity of rural trip-making data, rural areas were deliberately oversampled. All data are capable of being weighted to compensate both for sampling rates and for variations due to the day of week of the interview and the level of nonresponse. Overall response was very high--85 percent of those asked to participate. The number of usable interview forms (7581) represents 72 percent of the number of interviews predicted from the work load of the 30 local driver license bureaus selected for the survey. The difference between the two percentages primarily represents some continuity gaps inevitable in the conduct of a decentralized survey that operated over an entire year.

Within the 30 sites, a random number system, beyond the control of the employees, was used to select seven or eight interviewees per office per week from among all applicants for renewal of driver's licenses. Because the system used a meaningless sequence number that becomes a transaction identifier in an audit trail, it was possible to verify later that none of the (unannounced) eligible drivers had been missed. Follow-up procedures, which were more time consuming than an interview done at the time the driver was in the local bureau, helped keep administrative response very high. Overall, this provided a representative sampling of the Michigan driver population; however, drivers under the age of 19 are not represented because they are not old enough to renew a driver's license.

Interviews were conducted by the managers of the local license bureaus, who generally have excellent public contact skills and who received training in the interview procedures in a seminar and on site. The emphasis of the survey was on the careful reconstruction of a recent trip day (usually the previous day) and on the complete set of vehicles to which the respondent had access.

The survey was designed to yield a series of measures of the amount and type of driving undertaken, aggregated over the entire trip day. Thus, the total time and distance driven by each respondent are expressed in terms of the travel under different trip regimes, purposes, light conditions, road types, vehicles used, and passenger load. The vehicles owned and used are identified at the level of make, model, and year, and this information is available for each trip made during the day.

The survey data have been integrated with the individual accident and traffic conviction records from the files of the sponsoring agency (individual identity has been deleted). Cross-reference capability has been established with selected socioeconomic characteristics of the traffic zones (used by state transportaton modelers) in which the respondents resided. Certain socioeconomic characteristics are also available by zip code of residence. In addition, the interview itself provides basic biographical information on the respondent and her or his household.

Considerable effort has been made to build two verified summary files:

1. In a driver file, all time and distance information has been aggregated over the trip day for

all trip attributes, including algorithm-assigned travel by purpose in multipurpose trips.

2. In a second file, each trip is treated as a separate case, and driver descriptors are repeated.

The files were built primarily with OSIRIS.IV software for use with both the OSIRIS and the MIDAS software packages on the University of Michigan computing system.

SOME CONSIDERATIONS FOR THE ANALYSIS OF GASOLINE USE

Because MDES is a carefully drawn sample of the entire Michigan driver population (19 years and over), the total amount of gasoline consumed by different sectors of the population may be calculated. One problem is in the definition of the size of the active driving population, since some drivers retain a license essentially for identification or to permit only very limited travel, such as to assist a spouse on a vacation trip. (This sampling problem may be disregarded for analysis of policies, such as rationing, that use driver licensing in the allocation of gasoline.) In order to realistically represent those who would be targets for improving efficiency, we decided to consider those respondents who reported that they drive 322 km/year or less as inactive. This led us to reduce the estimated number of drivers for 1976 by 2.4 percent. From the result (6 150 000), gasoline consumption based on vehicle size, and a trip rate based only on trips in automobiles, vans, and pickups, we calculated the overall 1976 gasoline consumption for the state to be 17.20 billion L. Taxation data yields a sales figure of 18.57 billion L, and most of the difference is explained by the exclusion of gasoline-burning large trucks and buses from the analysis. Sales to out-of-state vehicles and inaccurate constants for fleet kilometers per liter would also affect this estimate. Nevertheless, we wish to compare the relative effect of conservation policies on this total.

EXPLORATORY ANALYSIS OF EFFICIENT VERSUS INEFFICIENT DRIVING

On the grounds that in 1979 it is easier to promote fuel-efficient driving than to encourage people to drive less, we examined the personal and travel characteristics of those above and below the median of a measure of efficiency. That measure was defined as

$$\mathrm{OKPL}_i = \sum_j (\mathrm{PT}_{ij} * \mathrm{KT}_{ij} * \mathrm{KPL}_{ij}) \Big/ \sum_j \mathrm{KT}_{ij} \qquad (1)$$

where

OKPL_i = occupant kilometers per liter for the ith respondent,

PT_{ij} = number of occupants (including driver) for the ith respondent on his or her jth trip,

KT_{ij} = kilometers driven for the ith respondent on his or her jth trip, and

KPL_{ij} = fuel efficiency (in kilometers per liter) of vehicle used for the ith respondent for his or her jth trip.

This measure was applied only to the driving of automobiles, vans, and pickups in the driver file and, by definition, assigns the value zero to those who did not drive on their designated trip day.

The median value of OKPL for the use of these vehicles was found to be 8.06. We compared the distributions of respondents above and below the median across age; sex; marital status; number of drivers, nondriving adults, preschool children, and school children in the household; employment; occupational class; level of education; income group; length of time at current address; type of residence; and population density of residence location.

By examining the percentage of respondents above and below the median OKPL within each stratum on these 14 variables (e.g., all those age 25 to 34 or all males), we found few distributions that differed substantially from a 50-50 split. Only 2 of the 75 population subgroups analyzed showed more than 60 percent above. Those subgroups that showed a distribution greater than 52.5-47.5 percent in either direction are listed below. Note that these analyses treat each variable stratum (i.e., subgroup) independently.

Subgroup	Characteristics
Low efficiency	
More than 60 percent below	Widowed, living alone
55-60 percent below	Over 45 years old, no other drivers in household, middle-status occupation, 8-11 grades of education
52.5-55 percent below	Male, no children in household, employed full time, household income over $25 000, divorced or separated, same address for 6-11 months
High efficiency	
More than 60 percent above	Two preschool children in household, unemployed or houseperson, postgraduate education
55-60 percent above	Under 35 years old, one or more nondrivers in household, one preschool child or one to three school-aged children in household, student, very high-status occupation, household income under $5000, less than seven grades of education, same address one or two years
52.5-55 percent above	Female, four or five drivers in household, employed part time, live in small rural community, same address less than six months or more than 20 years

The lack of a clear relationship with income, sex, and age contrasts with large differences in kilometers driven across these variables. Altogether we infer a weak pattern of gasoline inefficiency among lower-middle status, older drivers, who typically live alone or in childless households; but the small concentrations of low-efficiency drivers hardly identify them as the major target groups for efforts to reduce gasoline consumption.

In the area of travel characteristics, we examined the number of kilometers driven for various purposes to determine whether certain purposes were relatively less efficient than others and, therefore, logical targets for conservation efforts. In the table below, all respondents who reported driving on their assigned day were divided into two groups: those whose OKPL (averaged over the day's driving) was below the median of 8.06 and those whose OKPL was above. As the table (based on 1976 travel figures) shows, the more-efficient drivers of automobiles, vans, and pickups average a much higher number of kilometers per day in all purpose categories, except for commuting to work or school and travel on the job; and, although the more-efficient drivers also do more driving to and from school, the difference is much smaller.

Trip Purpose	Low-Efficiency (below median OKPL) (km/day)	High-Efficiency (above median OKPL) (km/day)
Commute to and from work	19.5	11.3
On the job	10.1	3.5
Commute to and from school	1.6	2.4
Personal business	2.6	5.1
Shopping	4.7	8.9
Social purposes	5.5	13.2
Recreation	2.6	12.1
Interchange modes	0.05	1.0
Other	4.5	11.6

It is to be expected that it would be difficult to substantially change vehicle kilometers per liter or occupancy for driving on the job, but commutes to work (and also school) are trip purposes that seem to hold promise for decreased consumption by increased efficiency. Because most commuting (unlike other purposes) has regular trip ends and regular times, there is a logical case for carpooling within the existing vehicle fleet. This analysis confirms a finding of the 1969-1970 Nationwide Personal Transportation Survey (4) that nonwork travel is relatively efficient and contrasts with the political appeal of "save our journeys to work".

The analysis also suggests that if efficiency is to be increased in a high proportion of nonwork travel (which represents about 70 percent of all driving according to MDES) it will require a change in vehicle, more than passenger, load. It would seem prudent, therefore, to promote a consumer shift to the purchase and use of smaller cars.

Commuter carpooling and smaller cars were thus selected for further analysis. Both are subject to a variety of constraints. For example, only people who can afford to replace automobiles can shift to smaller cars, and carpooling is only possible when a sufficient number of people have similar working hours.

These constraints can only be explored with detailed travel data. We have built a number of reasonable constraints into a series of scenarios for smaller cars and commuter carpooling and applied the scenarios retroactively to 1976 automobile, van, and pickup travel in Michigan. From this, we measured the maximum possible benefits in the form of changes in liters consumed per driver and in OKPL. These scenarios are arbitrary. The consequences of many sets of assumptions, other than those described below, could be compared by means of this technique.

SCENARIOS FOR COMMUTER CARPOOLING AND SMALLER CARS

We have attempted to describe for both of these policies one likely situation in which limited shifts toward carpooling or smaller cars occur and one maximum scenario in which all eligible travel is shifted into the most-efficient configuration. Eligibility is defined as a series of prohibitions on the improvement of efficiency because of unfavorable conditions; these represent the reasonable constraints and apply equally to the likely and the maximum scenarios.

Carpooling

Our reasoning in limiting additional commuter carpooling to three occupants is based largely on the observation that the logistics of ridesharing are reasonably manageable at this level, especially in a situation in which many more motorists are pressed to participate than currently do so voluntarily. It is reasonable to assume that current pooling behavior represents the exploitation of the most-attractive opportunities by the most-willing motorists [we note that in a 1978 survey of state employees in Albany, New York, about 25-30 percent of commuter carpools had occupancies greater than three (5)]. We postulate the likely scenario of adding one passenger, aware that for most commuters this means giving up solo driving and that the addition of a second passenger may well be less traumatic than the addition of the first. No adjustment was made for additional travel distance to pick up or drop off passengers:

1. Scenario 1--likely pool--any trip by a vehicle carrying less than two passengers (excluding driver) adds one passenger and
2. Scenario 2--maximum pool--any trip by a vehicle carrying less than two passengers (excluding driver) increases its passenger load to two (excluding driver).

Rules and prohibitions of scenarios 1 and 2 are as follows:

1. Trips of less than 10 min in duration are ineligible;
2. Trips to work that commence outside the time period 6:00-9:00 a.m. are ineligible;
3. Trips from work that commence outside the time period 3:00-7:00 p.m. are ineligible;
4. Trips made by persons from households that have more drivers than automobiles are subject to a penalty of 30 percent of the reduction in gasoline use for each additional day that the car is left at home;
5. For trips that involve chauffeuring someone to work and a return home without serving any other purpose, additional savings accrue due to the reductions in distance traveled and increase in available seats;
6. Trips for respondents in small villages and remote areas are ineligible; and
7. Rules 1-3, 5, and 6 do not apply to trips to and from school.

On the prohibitions, our 10-min minimum is close (with startup and shutdown time) to the poor-potential market segment derived in the analyses by Brunso and others (5). The constraints on time periods allow commuter carpooling during most normal working hours. As noted by Atherton and others (6), people who join pools leave their cars at home part of the time and, if other drivers are available to use them, gasoline savings due to ridesharing may be reduced. We calculated the proportion of the time a car would be left at home under both scenarios and arbitrarily applied a reduction of 30 percent for that proportion of the savings. Chauffeured commutes (trips in which someone is driven to work) may yield extra savings under ridesharing. In MDES, we were able to identify chauffeured work commutes specifically and to test that the driver returned home without serving any other purpose. In these cases, one-half of the gasoline was counted as saved, in addition to a reduction of the other half, dependent on the scenario. The elimination of small villages and remote areas for work commuting was perhaps the most crude prohibition; a more detailed approach would be to use the MDES data to investigate the prevalence of existing commuter ridesharing in different types of residential locations and to derive a more precise rule. Finally, all of these rules and prohibitions were applied to work commuting, but only number 4 (car left at home) was applied to school commuting. Chauffeured trips were ignored for school commutes, because most of these trips carry nondrivers as passengers, and the remaining prohibitions were ignored on the grounds that school commuting has higher passenger loads now and that the flexibility and social relationships that facilitate pooling seem more likely in school than at work.

Smaller Cars

A shift to the next-smallest vehicle size makes intuitive sense as the likely behavior of the market under fuel cost pressures. However, uncertainty of gasoline supply is likely to bring about more abrupt and unpredictable market shifts than incremental increases in fuel cost or taxes. For example, vehicle range may sometimes outweigh even kilometers per liter in purchase decisions if fuel is only available at certain hours or on certain days. Nevertheless, this scenario presumes incentives to shift to vehicles of higher kilometers per liter, and the maximum is therefore based on the subcompact. The kilometer per liter figures below are based on 1972 model-year cars because this was the median year in the data.

1. Scenario 3--likely size shift--all eligible trips are shifted to the next-smallest vehicle size.

Old Model	Old Kilometers per Liter	New Model	New Kilometers per Liter
Luxury	4.2	Intermediate	5.9
Van or pickup	4.7	Intermediate	5.9
Full size	5.1	Intermediate	5.9
Intermediate	5.9	Compact	6.8
Compact	6.8	Subcompact	9.3

2. Scenario 4--maximum shift to smaller automobiles--all eligible trips are shifted to subcompacts, regardless of vehicle size previously used.

Rules and prohibitions of scenarios 3 and 4 are as follows:

1. Trips in subcompacts remain unchanged,
2. Trips by households that have income less than or equal to $10 000 are ineligible, and
3. Trips that have three passengers or more (excluding driver) are ineligible.

We postulate in the prohibitions that trips currently in subcompacts are not shifted to a more-fuel-efficient subcompact. Trips by drivers from low-income households are excluded on the grounds that a size shift requires capital investment or tax incentives that are unattractive to these groups; also, they drive, on the average, about one-half to two-thirds of the statewide average driving distance. Finally, travel with an occupancy of four or more is excluded; for about 6.8 percent of all trips, this represents perhaps the most resilient demand for large cars.

Combined Scenarios

Because the carpool and size-shift policies involve independent factors, they can be simply combined to estimate joint effects.

1. Scenario 5--combined likely--combination of scenarios 1 and 3 and
2. Scenario 6--combined maximum--combination of scenarios 2 and 4.

We want to reemphasize that these scenarios are only six of a very large number of possible combinations of definitions and prohibitions: Our intention is to use the microdata to apply reasonable limitations to these two policies and to measure what, at best, they could possibly achieve.

ANALYSIS OF THE SCENARIOS

The effects of the six scenarios on gasoline consumption and efficiency of use were calculated from the MDES trip file. The scenarios were translated into sets of complex filters on trip attributes and driver characteristics in order to isolate trips that are eligible for fuel savings.

Gasoline consumed exists in the file as a variable calculated for each trip; for eligible trips, this was recalculated according to the reductions attainable by increasing passenger load or kilometers per liter. Thus, in the case of carpooling, the gasoline consumption for each eligible trip was reduced by 50 percent if a solo driver took on one passenger, by 33.3 percent if a two-person pool took on a third occupant, and so forth. The assumption was that such reductions reflected the reductions in vehicle kilometers traveled that would result from some vehicles being left unused. In the case of the use of smaller cars, the constants for kilometer per liter were simply changed according to the scenario.

The 1976 gasoline consumption figures were obtained by the formula:

$$\overline{\mathrm{LD}}\mathrm{cp} = \left[\overline{\mathrm{LT}}\mathrm{cp} * \mathrm{T_p} \middle/ \sum_p \left(\overline{\mathrm{LT}}_{\mathrm{cp}} * \mathrm{T_p}\right)\right] * (\mathrm{SG}/\mathrm{N_p}) \qquad (2)$$

where

$\overline{\mathrm{LD}}_{\mathrm{cp}}$ = mean liters of gasoline consumed per driver in 1976 under the cth scenario by the pth subgroup of the driving population,
$\overline{\mathrm{LT}}_{\mathrm{cp}}$ = mean liters of gasoline per trip under the cth scenario by the pth subgroup of the driving population,
$\mathrm{T_p}$ = number of trips by the pth subgroup in 1976,
SG = statewide total gasoline consumption in 1976 (L), and
$\mathrm{N_p}$ = estimated number of Michigan drivers in the pth subgroup (extrapolated from sample).

The recalculated gasoline consumption figures for each trip under the various scenarios were used in the computation of the efficiency index:

$$\overline{\mathrm{OKPL}}_{\mathrm{cp}} = \sum_t (\mathrm{OT}_{\mathrm{pt}} * \mathrm{KT}^2_{\mathrm{pt}}/\mathrm{LT}_{\mathrm{cpt}}) \Big/ \sum_t \mathrm{KT}_{\mathrm{pt}} \qquad (3)$$

where

$\overline{\mathrm{OKPL}}_{\mathrm{cp}}$ = mean occupant kilometers per liter under the cth scenario for the pth subgroup of the driving population,

OT_{pt} = number of occupants in the tth trip by the pth subgroup,

KT_{pt} = kilometers driven on the tth trip by the pth subgroup, and

LT_{cpt} = liters consumed under the cth scenario by the pth subgroup of the driving population.

All of these calculations were weighted for sampling- and response-rate factors. In the case of the use of smaller cars, the constants for kilometer per liter were simply changed according to the scenario.

RESULTS

We have compared the six scenarios with the measured consumption levels and efficiency of driving in Michigan in 1976. Because the kilometer per liter averages for vehicle size classes were held constant at the 1976 fleet estimates given above, it would be possible to project further reductions in gasoline consumption from the scenarios by applying recent factors for improvement of kilometers per liters.

The statewide gasoline consumption for 1976 that would have occurred under each scenario is given in the list below.

Scenario 0--1976 baseline; gasoline consumption = 17.2 billion L/year.

Scenario 1--Commuter pool: add one passenger; gasoline consumption = 15.9 billion L/year.

Scenario 2--Commuter pool: driver and two passengers; gasoline consumption = 15.5 billion L/year.

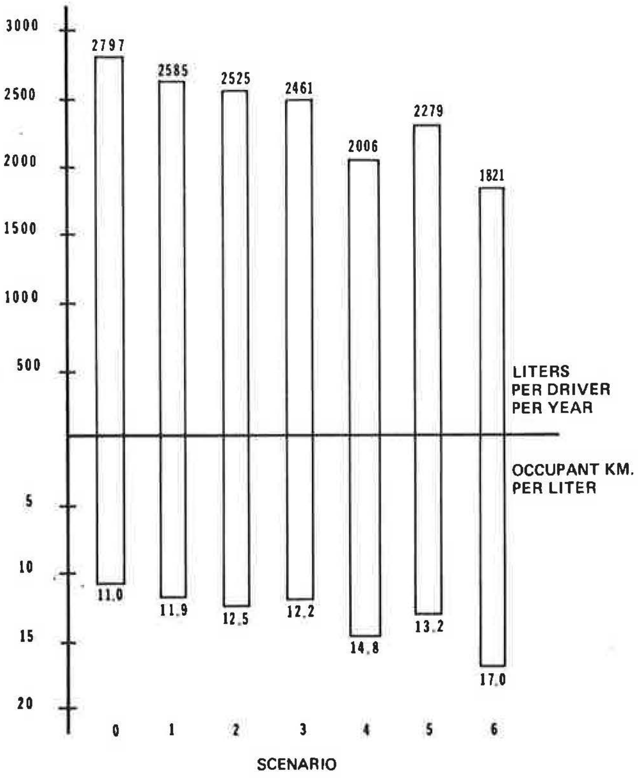
Scenario 3--Shift to next-smallest car; gasoline consumption = 15.1 billion L/year.

Scenario 4--Shift all vehicles to subcompacts; gasoline consumption = 12.3 billion L/year.

Scenario 5--Combine scenarios 1 and 3 (likely); gasoline consumption = 14.0 billion L/year.

Scenario 6--Combine scenarios 2 and 4 (maximum); gasoline consumption = 11.2 billion L/year.

Figure 1. Gasoline consumption and efficiency by scenario.



The reductions in total gasoline consumed are of the order of 8-10 percent for carpooling and 12-28 percent for smaller cars. The combined effect of the maximum scenarios would be a reduction of about 35 percent, or about 6.0 billion L. It is important to note that these reductions are less than would be estimated by a simple manipulation of kilometers per liter, vehicle kilometers traveled, and market penetration of different automobile sizes. This is primarily because small cars are being driven higher average distances than large cars, as was reported in an earlier MDES paper on gasoline rationing (7).

We believe that the moderate difference in overall gasoline savings between the scenarios to add one passenger (7.6 percent reduction) and that raising all eligible commuting trips to at least three occupants (9.7 percent reduction) is largely a measure of the tendency for current passenger loads to increase with trip length.

Figure 1 summarizes average annual liters consumed per driver and efficiency measured in occupant kilometers per liter for 1976 and the six scenarios. The pattern of reduced consumption and increased efficiency is relatively consistent across the income groups shown in Table 1 and the regional groupings of drivers shown in Table 2. This pattern prevails, except where explicitly prevented by the prohibitions in the scenario (e.g., no smaller cars for low-income respondents), despite large differences in the consumption levels of all these groupings of drivers. This parallels an important conclusion from other MDES analyses: There is considerable consistency in the proportional allocation of kilometers driven to types and purposes of travel by different population and regional subgroups, regardless of the major differences in the average number of kilometers driven.

In 1976 there was a monotonic (large) increase in consumption and decrease in efficiency with increasing income. This is despite the fact that the highest-income group looks slightly more fuel efficient if passenger load is disregarded [see Lee (7)]. When the scenarios are applied, in contrast to the very substantial differences in liters saved, there is only a slightly higher payoff in terms of percentage changes in gasoline consumption and efficiency as income increases. Low-income people, by definition, are unable to gain the financial rewards of smaller cars; hence the maximum smaller car and combined scenarios show that the \$5000-\$10 000 income group uses more gasoline than does the next-highest income group.

There are very substantial differences in gasoline use between drivers who reside in areas that have different levels of urbanization in Michigan. Table 2 shows the very heavy dependence of the suburbs (urban fringe) and the remote parts of the state on gasoline. Efficiency is lowest in the suburbs and the outskirts of urban areas. We should point out that these are groups of zip codes that vary largely by the density of housing; as a result, the central-city category includes the areas of affluent urban areas and medium cities, such as Ann Arbor, and the city-outskirts category includes some of the poorer neighborhoods in Detroit. Therefore, assumptions about economic factors are risky. Table 2 shows very low average consumption for the outskirts, and yet their potential improvement in OKPL through carpooling is the highest in percentage

Table 1. Annual gasoline consumption per driver and occupant kilometers per liter by income group.

		Income Group					
Scenario	Item	<$5000 (N = 516 000)	$5 000-10 000 (N = 1 089 000)	$10 000-15 000 (N = 1 536 000)	$15 000-25 000 (N = 1 952 000)	>$25 000 (N = 1 058 000)	All (N = 6 150 000)
0	Annual liters per driver	1647	1984	2582	3062	4013	2797
	OKPL	12.4	11.9	11.3	10.8	10.4	11.0
1	Annual liters per driver	1552	1843	2370	2828	3676	2585
	OKPL	13.0	12.7	12.1	11.7	11.3	11.9
2	Annual liters per driver	1548	1817	2317	2767	3592	2525
	OKPL	13.1	13.3	12.7	12.3	12.0	12.5
3	Annual liters per driver	1647	1984	2211	2620	3399	2461
	OKPL	12.4	11.9	12.8	12.4	11.9	12.2
4	Annual liters per driver	1647	1984	1736	2006	2559	2006
	OKPL	12.4	11.9	15.9	15.6	15.3	14.8
5	Annual liters per driver	1552	1843	2044	2423	3131	2279
	OKPL	13.0	12.7	13.9	13.3	13.0	13.2
6	Annual liters per driver	1548	1817	1579	1813	2302	1821
	OKPL	13.1	13.3	18.2	17.9	17.8	17.0

Notes: N = estimated number of Michigan drivers in category.
1 L = 0.264 gal; 1 km/L = 2.352 miles/gal.
Table is based on 1976 fleet kilometers per liter figures.

Table 2. Annual gasoline consumption per driver and OKPL by residential density.

		Type of Residential Area						
Scenario	Item	Central Cities (N = 1 015 000)	City Outskirts (N = 934 000)	Urban Fringe (N = 2 511 000)	Rural Towns (N = 988 000)	Small Villages (N = 507 000)	Remote Areas (N = 195 000)	All (N = 6 150 000)
0	Annual liters per driver	2339	1999	3210	2790	2986	3187	2797
	OKPL	11.2	10.2	10.7	11.7	11.6	12.7	11.0
1	Annual liters per driver	2131	1779	2953	2567	2964	3146	2585
	OKPL	12.2	11.4	11.6	12.7	11.7	13.2	11.9
2	Annual liters per driver	2071	1726	2881	2510	2960	3078	2525
	OKPL	12.9	12.3	12.3	13.3	11.7	13.3	12.5
3	Annual liters per driver	2040	1772	2801	2487	2665	2911	2461
	OKPL	12.5	11.3	11.9	12.8	12.7	13.6	12.2
4	Annual liters per driver	1700	1457	2218	2075	2218	2563	2006
	OKPL	14.6	13.6	14.8	15.2	15.4	15.9	14.8
5	Annual liters per driver	1862	1582	2582	2290	2638	2843	2279
	OKPL	13.6	12.8	13.1	14.0	12.8	14.2	13.2
6	Annual liters per driver	1522	1276	1999	1874	2173	2449	1821
	OKPL	17.1	16.6	17.3	17.6	15.6	16.5	17.0

Notes: 1 L = 0.264 gal; 1 km/L = 2.352 miles/gal.
Table is based on 1976 fleet kilometers per liter figures.

terms. The city outskirts are also the only area in which the maximum carpool scenario has more effect in total gasoline consumption than the likely smaller-car scenario. Recall that carpooling was declared impossible (except for to and from school) for those in the small villages and remote areas. Of the four categories to which the pooling scenarios were applied, the city outskirts achieved better gasoline savings and improved efficiency than did the others. The best improvement in efficiency from smaller cars is achieved by rural towns, followed by the suburbs. The greatest percentage improvement in liters used under all of these scenarios, however, is consistently found in the suburbs.

Together these policies have the potential to bring suburban and rural consumption down to current urban levels. Because more than 40 percent of Michigan's drivers live in the urban fringe, their having the highest per capita consumption and the largest potential reduction under these scenarios amounts to enormous savings in the best case--as much as 3.0 billion L of gasoline on 1976 standards. For comparison, their share of the maximum benefits shown in Table 1 if it were proportionate to population would be about 2.5 billion L annually. We also note that, under the maximum combined scenario, OKPL becomes more homogeneous throughout the state than it was in 1976, which could be considered a desirable change in addition to overall improvements in average efficiency of gasoline use.

CONCLUSION

The analysis of logically reasonable conservation scenarios by using microdata suggests that the differing levels of consumption between income and regional subgroups provides a scale against which similar percentage reductions could be predicted if commuter carpooling and shift to smaller cars were promoted to reasonable limits. From a policy standpoint, it would be useful to take the present consumption levels of those who use less gasoline (lower-income groups and urban dwellers) as a goal for the rest of the state, especially the suburbs. However, apart from unwelcome precedents, the most remotely located drivers could be allowed extra gasoline supplies with little impact on state consumption because of their small number.

In promoting fuel efficiency rather than efforts to reduce personal travel through traffic restraint or taxation, it must not be assumed that this is necessarily a more equitable approach for lower-income groups just because we found them to be more fuel efficient now. The mechanisms for promoting these policies (tax incentives and pool subsidies) may be out of reach, and lower-income groups may be trapped (especially with older cars) at efficiency levels that will become more burdensome as gasoline goes up in price.

A further development of this policy-analysis technique would be to introduce independently measured factors into the scenario definitions, such as the personal characteristics of those revealed by marketing studies to be willing to buy a smaller car or certain trip attributes that are associated with successful carpools of different sizes. The MDES data base has been constructed to facilitate this. In our view, the collection of sample data of this kind should become a routine matter in the monitoring of energy use and the planning of energy-conservation policy.

ACKNOWLEDGMENT

The Michigan Driving Experience Survey was initiated by Lee at the request of the Michigan Department of State while he was on the staff of the University of Michigan Highway Safety Research Institute (HSRI). HSRI assisted in the early stages of the survey under joint sponsorship from the department and the Michigan Office of Highway Safety Planning, which later provided funds under the U.S. Department of Transportation's 402 program. We gratefully acknowledge the review of this paper and suggestions of Richard H. Shackson of Carnegie-Mellon Institute of Research. The views presented in this paper are ours and do not necessarily reflect those of the Michigan Secretary of State, the Michigan Office of Highway Safety Planning, or the U.S. Department of Transportation.

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

Abridgment

How Much Fuel Does Vanpooling Really Save?

DONALD A. MAXWELL AND DENNIS V. WILLIAMSON

Opinions vary as to how much fuel is actually saved by vanpools. Estimates range from an optimistic 49 210 L/year (13 000 gal) to a conservative estimate of 5700 L/year (1500 gal). A reliable estimate is required by policy planners so that preferential treatment for vanpools with regard to fuel allocation can be justified. During the fall of 1978, drivers of 211 vans provided the information necessary to compute values for average trip length by van and automobile and vehicle occupancy rates for the van and automobile. Late in the following spring, 211 van passengers responded to a questionnaire designed to obtain estimates for van and automobile fuel-efficiency rates and the use of vehicles formerly used for commuting. Fuel savings were determined by substituting the values into a modified version of a model developed for the U.S. Department of Energy. The results indicate that the most probable saving per van is 17 400 L/year (4600 gal). This is based on 11.2 occupants/van, a previous vehicle occupancy of 1.47, an 86.6-km (53.8-mile) commute distance, vehicles left at home being driven 9.8 km/day (6.1 miles/day), 4.25 km/L (10 miles/gal) for the van, and 6.8 km/L (15.9 miles/gal) for the previous vehicle. If the vanpoolers formerly drove by themselves in gas guzzlers that were disposed of immediately, the optimistic savings estimate is 30 280 L/year (8000 gal). If they drove the average fleet, carpooled some, and gave their previous cars to teenagers, a more pessimistic estimate of savings is 5700 L/year (1500 gal).

In Texas, vanpooling is a highly visible, and somewhat controversial, energy-conservation measure under the State Energy Conservation Plan (SECP). Because of their energy-saving potential, vanpools were given some preferential treatment during the gasoline shortage in the summer of 1979 and will be given higher priority during future emergency situations. In order to justify this position, fuel-allocation officials and conservation planners need reliable estimates of the fuel demand and the fuel savings created by the vanpool fleet. This study grew out of a need to establish a reliable estimate to replace current rules of thumb.

Almost everyone agrees that vanpools save gasoline, but opinions vary as to exactly how much. The Texas vanpool program has previously used 18 900 L (5000 gal) per van annually to make savings estimates. Most Texas vanpool programs (1) claim savings between 18 900 and 30 300 L (5000 and 8000 gal). The original SECP, which used guidelines developed by the Stanford Research Institute (SRI) (2) for the Federal Energy Administration (3), used a conservative figure of 5700 L (1500 gal) per van annually. The enthusiastic support given to the

30 300 L figure by various employer programs makes the 18 900 L figure appear too conservative and the 5700 L one look ridiculous.

The SRI methodology used to develop the original SECP estimates was the study's starting point. An extensive vanpool driver and rider survey produced a Texas data base to replace the national averages used in the original effort. These values were then substituted into a modified form of the SRI methodology.

The results show that an average van saves 17 400 L/year (4600 gal). The 1109 vans in operation at the end of 1979 save 73 700 L/day or 1 597 000 L/month. These vans are located at 76 sites and provide 987 000 passenger-km (613 300 passenger miles) of service per day--more than any single metropolitan transit system in the state.

MODEL DEVELOPMENT

Some of the standard techniques for estimating vanpool fuel savings are based on the following idea:

$$\text{Fuel saving} = \text{fuel used by automobiles before vanpooling} - \text{fuel used by automobiles left at home} - \text{fuel used by vans} \qquad (1)$$

The assumption is that any fuel used to run after-hours errands is offset by a gain from the elimination of lunch-time travel. This concept also assumes that the number of vanpoolers diverted from transit is very small. The maximum potential saving can be realized if employees originally commuted alone in gas guzzlers and sold their second car immediately. More realistically, broken-up carpools and extra use of the vehicle left at home often dilute this potential substantially.

The original SRI model required two modifications to adapt it to the Texas situation and to expedite data collection. First, the number of cars replaced by a van should be expressed as a ratio of the vanpool occupancy rate divided by the automobile (used prior to vanpooling) occupancy rate. This accounts for the fact that some programs use 15-passenger vans and some use 12-passenger vans and that some programs attempt to fill every seat but others do not. Second, vanpool fuel consumption is computed directly by dividing the van trip length by the vehicle's fuel efficiency instead of indirectly from an adjusted average automobile trip length.

The equation used to calculate daily fuel savings for each Texas vanpool program is

$$GS(VP) = V\,[(VPOR/AOR)\,(F - H) - (L/VKPL)] \qquad (2)$$

where

GS(VP) = daily gasoline savings,
V = number of vanpools in each program,
VPOR = vanpool occupancy ratio,
AOR = automobile occupancy ratio,
F = liters per day consumed by the average commuter automobile,
H = liters per day consumed by the average automobile left at home,
L = van roundtrip commute distance (km/day), and
VKPL = van fuel efficiency (km/L).

Savings for a specific program can be calculated by substituting appropriate regional values into this equation. If none of the regional values are appropriate, the statewide averages should be used. The statewide savings is the sum of all program savings.

DATA COLLECTION

In November and December 1978, a questionnaire was sent to all 23 vanpool managers in the state for distribution to their drivers; 14 responded and gave data for 211 vans out of 325 (65 percent). Where a program responded, all vans were included; at least one program responded from every geographic area. Survey results are given in Table 1.

The statewide average vanpool roundtrip length is 86.2 km (53.6 miles). The trips are shortest in the Houston area and longest in the rural areas. The fuel efficiency of vans averages 4.25 km/L (10 miles/gal). The relatively high prior automobile occupancy rate for the vanpools (1.47 as compared to 1.25 for the average Texas work trip) indicates that many vanpoolers are former carpoolers.

Statewide, van occupancy averages 11.2 persons/van; however, this is somewhat misleading. Included in this average are both 12- and 15-passenger vans. All San Antonio and rural area vans held 15 passengers. The remainder were 12-passenger vans. Taken separately, the average occupancy for 12-passenger vans is 10.2 persons and for 15-passenger vans, 13.4 persons. Both operate at approximately 90 percent capacity with two empty seats, counting the driver as a passenger.

Preliminary energy savings, computed by using national averages for automobile kilometers per liter and fuel used by the vehicle left at home, tended to support the 18 900 L/year figure. Later, it became apparent that an accurate determination of fuel savings hinged on the accuracy of the estimate for the actual amount of gasoline saved by not commuting in the vehicle left at home. Some vanpool program managers thought that the estimates for the fuel efficiency for this vehicle were too high and that its use was greatly exaggerated. The effect of this error would be to underestimate actual fuel saving.

In order to put this issue to rest, another survey was conducted in May and June of 1979. A second questionnaire was distributed to a Houston and a Dallas vanpool program. At the time of the survey, Aramco Services operated a 22-van, 227-person program in Houston; 178 passengers (78 percent) responded. In Dallas, Texas Instruments had a 16-van program that served 178 passengers; 157 passengers (89 percent) responded. Survey results appear below.

1. Automobile fuel efficiency = 6.76 km/L (15.90 miles/gal),
2. Automobile roundtrip length = 86.50 km (53.75 miles),
3. Distance driven by vehicle left at home = 9.80 km (6.09 miles), and
4. Automobile occupancy ratio = 1.40.

Prevanpool Commute Vehicle	Aramco and Texas Instruments (%)	State Average (%)
Large vehicle	39.9	40.7
Mid-sized vehicle	39.6	39.3
Compact vehicle	15.8	14.6
Subcompact vehicle	4.6	5.4

The number of liters per day consumed by a commuting automobile (F) is calculated by dividing the number of kilometers the automobile is driven by its fuel efficiency. By dividing the average automobile commute distance (86.5 km) by the average automobile fuel efficiency (6.76 km/L), the F-value is found to be 12.8 L/day. Because the average commuter roundtrip by automobile and by van is almost the same, F can be calculated from the

Table 1. Results of statewide vanpool survey.

Item	Texas Average	Houston	Dallas	San Antonio	Rural
Vehicle characteristics					
Vanpool roundtrip distance (km)	86.2	79.0	94.0	90.7	106.2
Vanpool occupancy ratio[a]	11.2	10.3	11.3	13.4	13.4
Van fuel efficiency (km/L)	4.25	4.21	4.25	4.12	4.51
Automobile occupancy ratio	1.47	1.35	1.72	1.76	1.67
Prevanpool commute mode (%)					
Carpool with one other	18.6	17.7	13.2	23.3	20.0
Carpool with two others	15.4	9.9	8.0	15.2	35.5
Carpool with three others	15.8	12.7	40.4	28.0	8.6
Drive alone	48.2	56.7	38.4	32.0	35.9
Bus	1.9	3.0	0.0	1.0	0.0

Note: 1 km = 0.62 mile; 1 km/L = 2.35 miles/gal.
[a] 10.3 for 12-passenger vans; 13.4 for 15-passenger vans.

Table 2. Comparison of assumptions and gasoline savings for various cases.

Item	Maximum Potential	Realistic	SECP	Survey Results
Vanpool occupancy ratio	12.0	11.0	9.0	11.21
Automobile occupancy ratio	1.0	1.4	1.4	1.46
Number of automobiles replaced by one van	12.0	8.0	6.4	7.7
Automobile commute distance (km)	72.4	72.4	25.9	86.6
Automobile kilometers per liter	4.25	4.25	5.19	6.76
Consumption by average commuter automobile (L/day)	17.0	17.0	5.0	12.8
Consumption by average automobile left at home (L/day)	0.0	0.0	0.46	1.44
Van roundtrip commute distance (km/day)	72.4	72.4	25.9	85.8
Van fuel efficiency (km/L)	4.25	4.25	0.06	4.25
Gasoline savings				
Liters per day	187.4	119.2	20.6	67.3
Liters per year	48 713.0	30 999.0	5340.9	17 487.5

Note: 1 km = 0.622 mile; 1 L = 0.264 gal; and 1 km/L = 2.352 mile/gal.

average van distance for a region rather than by using the statewide average value of 12.8 L if a more consistent estimate is desired.

Responses indicate that the vehicle left at home is driven, on the average, 9.8 km/day. Dividing this distance by the automobile's fuel efficiency (6.76 km/L) yields a value of 1.44 L for the liters per day consumed by a vehicle replaced by a vanpool (H). These vehicles, which are driven much more than was anticipated, represent a significant loss in potential savings.

RESULTS

The wide range of published estimates for yearly fuel savings from vanpooling is caused primarily by differing assumptions about how people commute before they joined a vanpool. To illustrate this, gasoline savings for the average 12-passenger van were determined for each of the following situations: (a) maximum possible potential, (b) more-realistic case advocated by Texas vanpoolers, (c) case stated in the Texas energy conservation plan by using the SRI methodology, and (d) savings by using the survey results. The modified SRI equation was used for all calculations except that of the state's energy conservation plan. Table 2 summarizes the assumptions made for each variable and the resulting daily and annual gasoline savings (3,5). The potential and realistic assumptions were made by using Murrell (5).

The primary differences between the assumptions made from the survey and those used by the others are the automobile and van roundtrip distances, the automobile fuel efficiency, and the amount of savings attributed to the vehicles left at home. The survey reveals that automobile and van roundtrip distances are slightly higher than the estimate for either the maximum potential or realistic cases and more than three times the estimate used in the SECP. The automobile fuel efficiency was also significantly higher than previous estimates. Another major difference lies in the liters per day used by the vehicles left at home. The maximum potential and realistic cases ignore this value altogether, and the value used in the SECP is low by slightly more than a factor of three.

CONCLUSIONS AND RECOMMENDATIONS

Vanpools save a significant amount of fuel. In Texas the 17 400 L/year per van saving is enough to justify preferential treatment in fuel allocation. Steps are being taken to ensure that vanpoolers will be able to get to work during the next period of severe shortage. This has become as important to the vanpoolers as the concept of money saved that was the primary consideration during the program's first stages. Employers see this as a technique for expanding their labor market in the face of increasing costs and shortages.

The potential savings are not as high as some of the more enthusiastic vanpoolers would like to see. This is because of the increasing fuel efficiency (6.0 km/L in 1973 to 6.8 km/L in 1979) (5) of the vehicles replaced by the vans and because the vehicle replaced is used during the day for other purposes. When these vehicles are disposed of, it is hoped that they will not be replaced. However, if the prior mode included a significant percentage of transit ridership (very rare in Texas), the savings are overstated.

Finally, there is an admitted bias toward Houston vanpools since the majority of Texas vanpools are located in Houston. By actual count, 72 percent of the vanpools are in Houston, 11 percent in Dallas, 11 percent in San Antonio, and 6 percent in rural Texas. When the goal of 1500 vans is reached by the end of 1980, the growth of vanpooling in San Antonio and Dallas-Fort Worth will eliminate, or at least reduce, this bias.

ACKNOWLEDGMENT

We thank the many vanpool program coordinators who helped to gather the data for this report; Kathi Townsend of Aramco Services Co. and Emerson Miller of Texas Instruments deserve special thanks for their efforts. The Texas vanpool program is a part of the State Energy Conservation Plan and is financially supported by the U.S. Department of Energy. Opinions are ours and do not necessarily reflect the official view of any of the above organizations.

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

Evaluating the Costs and Benefits of Plans to Reduce Gasoline Queues

NANCY S. DORFMAN AND IAN E. HARRINGTON

The costs in terms of service station queuing of contingency plans designed to reduce gasoline demand during a shortfall in petroleum supply are analyzed. Queues are recognized as a response to market disequilibrium that will grow until the cost per gallon of queuing fills the gap between the equilibrium price and the price charged at the pump. The cost of queuing can thus be inferred from this price differential; the reduction in total queuing costs represents the benefits produced by the contingency plan. Benefits and costs of a contingency plan are measured relative to the alternative of rationing by queuing. The value of these benefits is measured for three such plans and compared with rough estimates of the costs of achieving them. Costs include the losses in consumer surplus caused by a plan and the expenses of implementing a plan. An economic model of the retail gasoline market is presented graphically to describe the theory that underlies the analysis. An important inference that can be drawn from the analysis is that, when more-efficient policies are precluded, restrictions on consumption may be designed that will yield benefits in excess of costs. The three plans analyzed in this paper are an employer-based plan to encourage more energy-efficient commuting travel, a sticker plan to require each household to give up use of all of its cars on a selected day of the week, and a ban on weekend use of off-road recreational vehicles, private boats, and aircraft. Estimates are based on data from secondary sources and a set of assumptions that include a 7 percent shortfall in the supply of gasoline in 1981. Benefits from all three plans are found to exceed their costs.

In the winter of 1973-1974 and again in the spring of 1979 the United States experienced shortages of gasoline. Not only did the supply of gasoline fall below consumers' demand, but also the price was not permitted to rise sufficiently to clear the market. The result was an excess of demand at the prices being charged at the pump. When prices fail to rise to the equilibrium level, some other mechanism perforce takes over to determine how limited supplies are allocated among competing users.

In the absence of any other type of rationing (for example, government-issued coupons), the tendency is for queues to form at gasoline stations. Under perfect market conditions (perfect information and absence of discrimination or product differentiation), queues will grow to be equal in length at all gasoline stations in a given market, and we would expect their length to be sufficient to cause the cost of queuing per gallon of gasoline to consumers to make up the difference between the dollar price at the pump and the price consumers would be willing to pay for the marginal gallons purchased. The cost of queuing will thus equilibrate the market when price is controlled. The queues' length will be determined by the excess of demand over supply.

Queuing is a real resource cost, in contrast to dollar payments, which represent transfers of purchasing power. They are what economists call a dead-weight burden. No one benefits from the use of resources employed in queuing nor can their cost be recovered through taxation. It is, therefore, a good idea to reduce or eliminate queues even at some cost to society at large. This paper concerns one method for doing so.

It is necessary at the outset to distinguish between queues that consumers join in order to stake a claim to a share of a product when there is not enough to go around at the current price and queues due to congestion caused by bottlenecks in distribution. The former phenomenon concerns us here. The latter can be eliminated by removing the bottlenecks (e.g., increasing the number of gasoline station pumps and attendants, having stations remain open longer, or instituting minimum purchase requirements); the former cannot. Speeding up the distribution system will merely cause the number of cars in line to grow to restore queuing time to its former level when queues serve as a price to bring demand and supply into equilibrium. It will also force stations to close sooner.

Barring an increase in the supply of gasoline, there are three ways to eliminate queues caused by a gasoline shortage:

1. Let the price rise to clear the market, via either market forces or a tax increase;
2. Substitute some other form of rationing that assures consumers a given amount of gasoline without queuing; and
3. Reduce demand for gasoline to the point where consumers are satisfied to purchase no more than the available supply at the price that is charged at the pump.

We report here on a study undertaken for the U.S. Department of Energy (DOE) to investigate measures to reduce demand. Under terms of the Energy Policy and Conservation Act of 1975, DOE was required to present to Congress standby plans for dealing with an emergency petroleum shortage. That act, as well as its successor, explicitly excluded the use of pricing and taxing measures by the federal government, and rationing is permitted only when the shortage is expected to reach 20 percent of normal. The Energy Emergency Conservation Act of 1979 calls for contingency plans to be imposed on a state-by-state basis only when states do not adequately implement their own plans in an emergency. Once again, taxing and pricing measures are not permitted to be imposed on states by the federal government. Thus, in spite of the fact that taxing, and possibly rationing, policies can be designed to eliminate queues at gasoline stations more efficiently (and therefore at a lower social cost) than can the alternatives, the focus of this paper is on contingency measures to reduce demand.

A major conclusion of the study is, however, that, although a reduction in demand is not the most-efficient or equitable means of eliminating queues and restoring an orderly market, in the event that other means are precluded, measures can be designed that will achieve total benefits in terms of reducing queues that exceed their costs to society.

ANALYSIS OF THE PROBLEM

Figure 1 illustrates the effect of a reduction in demand for gasoline on the total cost of queuing. Gallons of gasoline supplied per year are measured horizontally and price per gallon in terms of dollars or the dollar equivalent in queuing cost is measured vertically. The curve DD represents the normal demand for gasoline as a function of dollar price. The total supply of gasoline per year (q') will be completely inelastic above the dollar pump price. The equilibrium price is evidently at p'. If the pump price is controlled at p (below the equilibrium), queues will form to raise the total price, including the cost of queuing per gallon, to the average consumer, to the point where consumers are satisfied with purchases of q' gallons when the dollar price is controlled at p. The number of minutes of queuing time per gallon will depend on the demand for gasoline as a function of dollar price and on the marginal cost per minute of queuing to consumers. Since the latter will vary among consumers, the demand for gasoline as a function of its dollar price will not necessarily be identical with demand as a function of average queuing cost. It will, however, represent an adequate approximation. We assume in the analysis that follows, therefore, that demand can be measured interchangeably as a function of dollar price or of the dollar cost of queuing per gallon from the point of view of the average consumer.

The queuing cost would be exacted on all q' gallons of gasoline under perfect market conditions. Due to discrimination in favor of old customers or other market imperfections, however, some customers may obtain gasoline with little or no queuing. They will therefore consume more gasoline than they would at the higher price and less will be available for others. The result will be higher queuing costs for those who must queue. The cost of queuing averaged over all q' gallons of gasoline will be p' - p, which leads to a total queuing cost of q' (p' - p).

Approximately 1.7 billion gal of gasoline are currently sold at retail outlets each week. If the difference between the equilibrium price and the controlled price were $1.00, queuing would cost consumers in the neighborhood of $1.7 billion/week, or $90 billion/year. A $1.00 differential between the controlled price and the equilibrium price is not an outlandish possibility. By using a liberal estimate for demand elasticity of -0.15, a 10 percent reduction in supply starting from a $1.00/gal price in equilibrium before the shortfall would call for a $1.00 price increase in order to equilibrate the market if demand remained unchanged.

On the other hand, recent experience shows that a shortage may cause demand to shift. When prices or queues start to rise, fear that gasoline may be less available or higher priced in the future may shift the demand curve upward temporarily. Some consumers hoard gasoline against future contingencies. They increase the amount of gasoline stored in tanks by filling their tanks when they have less excess capacity than normal. Once the supply stabilizes, however, so that there is no reason to anticipate gasoline will be harder to find or more expensive in the future, tank storage returns to normal and demand is temporarily reduced below normal.

A more permanent downward shift in demand occurs, however, because gasoline stations voluntarily close on Sundays and often during other normal operating hours. There can be little question that the possibility of being unable to obtain supplies on out-of-town weekend trips significantly reduced demand during the summer of 1979. This, in turn, reduced queues so that the total cost of queuing was less than what it would have been had demand remained at its normal level.

We are concerned here with measures specifically designed to reduce demand. By a reduction in gasoline demand we mean a downward shift in the demand curve, which implies a reduction in the price that consumers are willing to pay for any total quantity. For any amount of gasoline, a reduction in demand will cause the price that will clear the market to be lower than before.

There is no costless way to reduce demand for gasoline. (This is not meant to imply that there is no costless way to reduce queues. Tax shifting can eliminate queues at no real cost to the economy as a whole.) Either alternatives to gasoline consumption must be made more attractive or gasoline consumption made less so. The first will generally impose a cost on the provider or promoter of substitutes in the form, for example, of increased subsidies to transit, paratransit, or ridesharing programs. The second will exact a loss in consumer or producer surplus from both individuals and businesses (the latter account for 16 percent of retail gasoline sales) by reducing the utility of some or all

Figure 1. Effect of demand reduction on total cost of queuing.

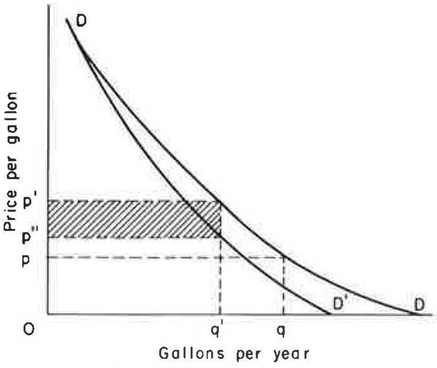
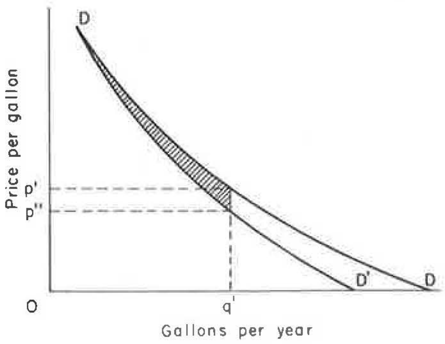


Figure 2. Effect of demand reduction on total gasoline consumption.



consumption and by causing consumers to substitute lower-valued uses for some that they are obliged to forgo. Total consumption will remain the same, given the inelastic supply. A measure, for example, that reduces the time, place, or manner in which consumers can obtain or use gasoline lowers the marginal utility of any given quantity of gasoline to consumers and, in turn, the price that they are willing to pay for it, whether in cash or in queuing.

If demand reduction is to be used as a means to reduce queuing costs, the minimum criterion for accepting a measure will have to be that the benefits (in the form of queuing costs saved) exceed the costs of reducing demand. This criterion is not, as it happens, difficult to meet. Figure 2 provides a clue as to why. DD' represents the new demand for gasoline after imposition of the contingency plan.

If the reduction in demand is achieved by restricting the use or sale of gasoline in such a way that people are willing to pay only a lesser price per gallon for any total quantity than before, consumers will suffer a loss in surplus on each gallon of consumption unless the price falls. If price remains at p', the loss in surplus on each incremental gallon will amount to the vertical difference between DD and DD' at the point on the graph that corresponds to that increment. For example, the loss in consumer surplus on the qth gallon would be equal to p' - p". The loss in surplus on all q' gallons together would amount to the shaded area in Figure 2.

If, on the other hand, the price paid falls by more than the reduction in demand for any gallon, there will be a net gain in consumer surplus on that gallon. In order to ensure that the cost per gallon of queuing falls by more than the reduction in demand on all q' units, all that is necessary is that demand be reduced in such a way that DD' is steeper, as well as lower, than DD. In that case, the fall in queuing cost on each gallon of q' (as illustrated by p' - p") will exceed the fall in value of consumption on that gallon for all units except the marginal one. The steeper DD' is in relation to DD, the lower will be the cost of reducing queues relative to the benefits. This steepening is achieved by designing the demand-restraint measure in such a way that it will eliminate uses of gasoline that consumers value least (i.e., the marginal uses) rather than those whose utility is relatively high to consumers.

There is no excuse, therefore, for designing measures to be any more onerous than is necessary to achieve a given reduction in demand at the margin. To deprive consumers of uses of gasoline that are especially valuable to them serves no purpose that cannot be achieved in a less-costly manner.

MEASURING IMPACTS

The main direct and intended benefits of a plan to restrict demand consist of the reduction in total queuing time it achieves. In order to assess these benefits it is necessary to have a good approximation of the demand for gasoline as a function of queuing cost and to be able to estimate the impact a given plan will have on that demand function. A subsequent section of this report describes the method used for approximating the impacts on queuing costs of three different contingency plans along with the results of analysis in each case. Although in interpreting the results allowance must be made for wide margins of error, the results represent, we feel, useful approximations.

The costs of a measure are likely to be more speculative. If the plan consists of reducing gasoline demand by making substitutes for gasoline consumption more attractive (e.g., improvement of transit or paratransit services), the costs will generally be susceptible to measurement according to straightforward accounting procedures. If, on the other hand, demand is reduced through restrictive measures, an estimate of the cost in terms of consumer surplus lost will necessarily demand a high degree of improvisation.

Three other considerations deserve attention when any measure is evaluated. Specifically, a measure may have more or less significant secondary impacts on specific industrial or geographical sectors. It may have some impact, favorable or otherwise, on aggregate variables such as gross national product, employment, and the price level. And, finally, whatever its overall benefit/cost ratio, the distribution of its costs and benefits among different income or other groups may be more or less acceptable.

METHOD FOR ESTIMATING EFFECTS OF PLAN ON QUEUING COST

As illustrated in Figure 2, we want to estimate for each of three contingency plans the amount by which the shift in demand from DD to DD' lowers the price from p' to p", with the quantity of gasoline stationary at q'. Briefly, the three plans include

1. An employer plan that requires that employers adopt measures to facilitate and promote energy-efficient work travel by their employees,
2. An automobile sticker plan that requires car owners to forgo use of their vehicles on a selected day of the week for the duration of the emergency, and
3. A ban on weekend use of off-road vehicles, private boats, and aircraft.

The Base Case

Since any such plan will be directed at some specific use of gasoline by category of traveler, day of week, purpose of trip, or type of vehicle, it is necessary, first, to project to the year in question the normal distribution of gasoline consumption according to the relevant travel categories and, second, the distribution after the shortage. We based our normal projections to 1981 on the McNutt and Dulla model of automobiles and light trucks (1), the growth rates indicated by 1974-1977 Highway Statistics data for heavy trucks and buses (2-5), and the personal travel characteristics indicating mode and purpose of trips on the 1970 Nationwide Personal Transportation Study (6).

In addition, we made the assumption that the 1981 price of gasoline, under normal conditions in 1977 dollars, would remain at about the 1978 level of \$0.70/gal.

A fall in the supply of gasoline will cause its price to rise, either in dollars or in queuing costs, which will lead to a change in travel patterns. This effect must be estimated for the assumed level of shortfall before the net impact of the contingency plan can be assessed. Estimates of the price increase and the resulting distribution of consumption of gasoline by mode and trip purpose describe what we refer to as the base case, or the situation on which the contingency plan is assumed to be imposed.

For the analysis, we assumed that the total supply of gasoline available at retail outlets will fall 7 percent below the projected 1981 normal level and become completely inelastic beyond that level. The price increase caused by the shortage occurs, under our assumptions, in the form of gasoline station queues, rather than a dollar increase, which implies that the pump price is effectively controlled at the preshortfall level. Current gasoline price controls in the United States cannot actually prevent retail prices from rising because they permit increased import prices to be passed on to consumers. At best, they delay the impact on retail prices.

As noted earlier, we assume that the amount of time each consumer is willing to spend waiting in queues is equal to the price per gallon he or she would be willing to pay over and above the pump price for the marginal gallon. We also assume that the queues will lengthen until the queuing cost per gallon paid by the average customer is equal to p' - p. Thus

$$p + w = p' \qquad (1)$$

where w is the cost of queuing per gallon of gasoline to the average customer.

To estimate p', we have assumed a total highway gasoline demand elasticity (e) with respect to either queuing or dollar price of -0.15. This is in line with a number of empirical estimates of price elasticities, although in the short run it may be, if anything, on the high side. The further assumption that elasticity is constant over the relevant range of prices is not as well substantiated.

By substituting the assumptions that e = -0.15, q'/q = 0.93, and p = \$0.70 in Equation 2,

$$p' = [(q'/q)^{1/e}]p \qquad (2)$$

we get p' = \$1.14. This would imply a queuing cost per gallon of \$1.14 - \$0.70 = \$0.44.

The assumption that the demand function used to estimate the price change remains unchanged in the face of the shortfall is tenuous, for reasons discussed previously. The assumption that dollar price would remain at the preshortfall level is also questionable on the basis of recent experience, but it does not seriously affect the analysis so long as the contingency plan does not reduce demand sufficiently that the equilibrium price falls below the pump price.

In order to estimate the redistribution of gasoline consumption among travel modes and trip purposes that results from the increase of queuing price, partial price elasticities of demand (e_{mi}) were estimated for combinations of mode m and purpose i. Price elasticities were estimated for fuel consumption by automobile, light truck, heavy truck, and bus from a review of available price elasticity literature. These elasticity estimates were then adjusted for different trip purposes based on the relative reduction in different trip frequencies during the 1973-1974 supply shortfall (7). The resulting distribution of gasoline consumption by mode and trip purpose was then estimated by using Equation 3, with p'/p = 1.57 and q_{mi} from the base case:

$$q'_{mi} = (p'/p)^{e_{mi}} q_{mi} \qquad (3)$$

Effect of Contingency Plans on Queuing Price

From the base-case distribution of gasoline consumption by travel category, we estimated the likely reduction in gasoline consumption that the plan would cause in each category. These estimates were arrived at differently for each plan, depending on sources of data and the specific types of assumptions required. Considerable uncertainty necessarily surrounds them. Among other things, the degree of compliance with the law is hard to predict in each instance.

The total reduction in gasoline consumption targeted by a contingency plan is measured by the horizontal distance from C to B in Figure 3. Such plans do not reduce total consumption, which remains at q'; they merely reduce the price that consumers are willing to pay for q' gallons by forcing them to substitute uses that they would not have undertaken when the price was p' for some uses that were worth at least p' to them. This causes a shift to the left in the demand curve (DD).

Under some kinds of plans the new demand curve will be parallel to the old one below p', as illustrated by DD". The so-called employer plan, for example, would change the slope of the demand curve above p' but not below p', because it does not reduce the value of uses of gasoline that might replace those given up as the price falls. The effect of such a plan is to reduce queuing price by p' - p" in Figure 3.

If we call the distance from C to B (which is equal to the distance from G to H), Δq', the reduction in queuing price (Δp') can be estimated by making the appropriate substitutions in Equation 4:

$$\Delta p' = p' - p'' = p' - \left\{[(q' + \Delta q)/q']^{1/e}\right\}p' \qquad (4)$$

This is equivalent to the effect of increasing the supply of gasoline by Δq'. The total reduction in queuing costs on all q' gallons of gasoline will be q' (Δp').

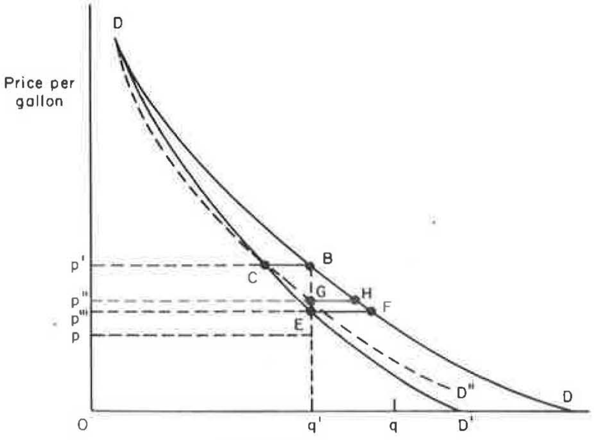
Other plans will not only shift the demand curve to the left but also lower e, which causes the new demand curve to be steeper than DD below p', as illustrated by DD' in all of the figures. This will occur when a plan not only causes consumers to forgo gasoline uses that they had undertaken at price p' but also restricts incremental uses that they would have undertaken when the price fell. The off-road plan and sticker plan have this effect on gasoline demand.

In order to estimate the new partial elasticity (e') for any category, we have assumed that increases in consumption in that category due to a price decrease are restricted in the same proportion as the reduction in consumption at price p'. The new total elasticity is thus derived from Equation 5:

$$e' = \sum_{m}\sum_{i} e_{mi}(q'_{mi} - \Delta q'_{mi}) / \sum_{m}\sum_{i} q'_{mi} \qquad (5)$$

The effect of such a plan on the equilibrium price will exceed the effect of an increase in gasoline supply of Δq'. This follows from

Figure 3. Effect of demand reduction on changes in price with alternative elasticities.



substitution of e' for the larger e in Equation 4. The greater effect can also be seen from Figure 3, where the shift in demand from DD to DD' causes the equilibrium price to fall from p' to p'", below p". The fall in price is equivalent to the effect of an increase in gasoline supply that amounts to EF rather than GH. This quantity, which we refer to as Δq", can be estimated from Equation 6:

$$\Delta q'' = [(p'''/p')^{e'} - 1]\, q' \qquad (6)$$

The resulting fuel consumption for each travel category q''_{mi} is thus estimated as a function of the relative price change and previous consumption, as shown in Equation 7:

$$q''_{mi} = (p'''/p')^{e'_{mi}} (q'_{mi} + \Delta q'_{mi}) \qquad (7)$$

ESTIMATED IMPACTS OF THREE CONTINGENCY PLANS

Three possible contingency plans, an employer-based plan, a vehicle-use sticker plan, and an off-road travel-restriction plan, have been analyzed under the procedures described above. As of this writing, DOE has taken no position with respect to any of these plans.

To recapitulate the major assumptions that underlie the analysis:

1. Implementation is carried out in conjunction with a 7 percent shortfall from normal gasoline supplies in 1981 and supply becomes perfectly inelastic beyond that point;
2. Fuel allocations to retail service stations, airports, and marinas are reduced in proportion to the 7 percent shortfall;
3. Prices charged at the pump remain fixed at the assumed preshortfall level of $0.70/gal in 1977 dollars;
4. The price elasticity of demand for highway gasoline consumption is -0.15 and is constant over all quantities within the range considered;
5. The public is informed regarding the length of queues at different gasoline stations and responds in a rational manner;
6. Annual vehicle miles of travel and fuel efficiency for buses and heavy trucks will maintain the growth rates they exhibited in the 1974-1977 period;
7. Personal travel in preshortfall 1981 will have the proportional characteristics identified in 1972; and
8. Shortfall travel reductions for different purposes or modes will be proportional to those exhibited in the 1973-1974 supply shortfall.

Employer-Based Plan

This plan would require private-firm work sites of 100 or more employees and government work sites of 50 or more employees to implement at least a minimum number of measures to encourage shifts of mode for work travel from the single-occupant automobile to more energy-efficient modes. The measures may be selected by employers from a list that includes carpool matching programs, vanpools, transit subsidies, parking management strategies, transit prepaid-pass distribution, alternative work-hour programs, fleet-use restrictions, paratransit service programs, and a work-at-home plan.

The shortfall itself will, of course, induce an increase in carpooling. It may also make employees more responsive to employer efforts. On the other hand, employers will be more inclined to undertake such efforts in the event of a shortfall even without a plan; thus the effect of the plan will be minimized.

If the programs implemented under this plan achieve employer and employee responses similar to those of the more-successful employer experiments to date, we estimate that the demand for gasoline would be reduced by about 20 000 bbl/day (about 0.3 percent of retail sales at sevice stations). However, if employee responses actually improve enough to achieve a goal of 50 percent use of modes other than single-occupant automobile and the shortfall pressures produce greater employer response, the demand for gasoline may be reduced by about 50 000 bbl/day (about 0.8 percent of retail station sales). The latter case would lead to about a 6 percent reduction in the shortfall equilibrium price of gasoline.

The potential effect of the employer-based plan is rather limited, due in part to its limited scope, since it only affects the commuting trip and covers only work sites of sufficient size to implement effective programs. In addition, it does not place any restrictions on travel; it merely requires work sites to take steps to encourage voluntary modal shifts in commuter travel.

Sticker Plan

The vehicle sticker plan would require members of a household to display stickers on all of their automobiles to indicate a single day of the week on which none of them can be driven for the duration of the emergency. We assume that households in which all workers have access to work via modes other than single-occupant automobile during a shortfall would opt for a weekday sticker day. Also, since most trips other than work trips and recreational trips of two or more days are transferable to other days of the week, only a portion of the normal travel demand for any household's sticker day will be cut.

It was necessary to make plausible assumptions regarding levels of trip transferability, public compliance, and the granting of exceptions and exemptions. By using these assumptions, analysis indicates that the sticker plan would reduce the demand for gasoline by about 310 000 bbl/day (about 5 percent of retail gasoline sales) and lower the shortfall equilibrium price of gasoline by about 28 percent. This is the only one of the three plans that would have a significant impact. A side effect of the plan is to increase personal recreational and commercial travel and cause commuter automobile travel to fall below its expected shortfall level.

The plan would also overwhelm the capacity of many transit systems to carry passengers.

Although the potential effects of a vehicle-use sticker plan thus appear to be fairly large, it involves serious inequities. It would impose a severe burden on those households that do not have access to alternative work-trip modes but not force persons who customarily travel to work by other modes to make any sacrifices.

Off-Road Plan

The plan for emergency restrictions on boats, aircraft, and off-road vehicles would prohibit all personal, business, or executive flying of private planes, recreational powerboat trips, and off-road recreational travel on motorbikes, snowmobiles, four-wheel-drive vehicles, and dune buggies on weekends. Only portions of the off-road trips by these modes would be eliminated, since significant amounts of their use occurs on weekdays and some of their weekend use can be transferred to weekdays. Enforcement problems would be serious.

It was necessary to make plausible assumptions regarding the portion of use on weekdays, weekend-use transferability, and public compliance with the plan's restrictions for each type of off-road-vehicle use. We estimated that the plan would reduce the demand for gasoline by about 100 000 bbl/day (about 1.6 percent of retail gasoline sales) and lower the shortfall price of gasoline by about 11 percent. The plan would result in a net reduction in total recreational travel, although other forms of such travel would increase. Commuting and commercial travel would rise to compensate for the fall as the queuing price fell. The plan has serious distributional problems, impinging as it does chiefly on a small segment of the public. Industries that serve and supply recreational vehicle owners would also suffer serious losses. The inequity would be moderated if the plan were imposed in conjunction with the automobile sticker plan.

COSTS AND BENEFITS

The benefits of each of the three plans described above were measured in terms of the dollar value to all consumers combined of the reduction in queuing time that resulted. The percentage reductions in the queuing price that were estimated were converted to dollar reductions by multiplying by $1.14 (the equilibrium price after the shortfall). In the case of the employer plan, benefits would come to between $0.02 and $0.07/gal; for the sticker plan they would be in the neighborhood of $0.30/gal, and for the off-road plan between $0.10 and $0.15/gal.

The costs of reducing demand are of two sorts--implementation costs to government, employers, or other institutions responsible for financing measures and the loss in consumer (producer) surplus exacted from gasoline users.

In a program such as the employer-based plan described above, which depends on voluntary response by automobile users to an enhancement of the attractiveness of more energy-efficient modes, the cost will be borne entirely by those responsible for financing its implementation. The specific measure described here was estimated to cost employers about $0.5 billion if it were implemented for a full year. Under the assumptions described above, the reduction in queuing cost that would result was estimated to range from $0.02 to $0.07/gal. On the more than 90 billion gal sold at retail in a year, these savings would range from about $2 to $6 billion. If the estimates are anywhere near to being correct, the plan would be worthwhile on cost-benefit grounds in an emergency energy shortfall that was expected to last for several months. Note, however, that this plan would compensate for only a very small reduction in gasoline supply.

The other two plans take their toll mainly in the form of consumer surplus lost to gasoline users. This loss is the sum of the amounts over and above the price that consumers would be willing to pay, if necessary, for each of the q' gallons of gasoline purchased before the plan goes into effect. The loss is extremely difficult to estimate.

Based on the analysis, the loss is almost certain to be less than the benefits since neither plan will be likely to require most consumers to give up their more highly prized uses of gasoline. One way of thinking of the surplus from gasoline consumption that will be lost is the loss in value of fixed investment in vehicles due to their being unusable one or two days per week. We have developed some crude approximations to this value for each plan on the basis of estimates of the value of capital invested in vehicles or craft whose availability would have to be forgone in order to comply with the measures. These estimates fail to take account of the surplus that will be lost on these investments.

For the sticker plan we estimated that the average fixed cost of owning a car is about $1000/year in 1977 dollars. To give up one-seventh of its availability would mean a loss of $140/year if the value of the day's use given up every week (net of variable costs) were equal to the average cost per day of car ownership. This would come to less than $3/week. We can argue that, since a vehicle owner would give up the day of the week that is of least value to him, $140 would overstate the loss. But, on the other hand, it must be remembered that loss of a car on the least-valued day of the week will rarely mean giving up the least-valued one-seventh of its availability. Moreover, the $140 estimate does not allow for the consumer surplus on car ownership that will be lost but only for the cost of investment. Nevertheless, if $140/car is taken as the average cost of the sticker plan to owners, the total cost would come to about $14 billion if the plan were in effect for as long as a year. The sticker plan was estimated to reduce queuing costs by over $0.30/gal for a total of more than $28 billion in savings in the course of a year's gasoline purchases. Once again, on the basis of our approximations, the plan passes the cost/benefit test.

By use of a similar approach we estimated the cost to owners of off-road vehicles and craft that would result from the weekend ban on their use. This came to a total of about $2 billion at a minimum in lost use of investments. It compares with estimated savings in queuing costs as a result of the plan of about $11 billion in a year.

CONCLUSIONS

Although measures to reduce demand are neither the most efficient nor the most equitable way to reduce gasoline queues, they can serve a useful purpose when better alternatives are precluded for political or other reasons. By directing gasoline use restrictions at the uses of gasoline that are of only marginal value to consumers, the benefits in terms of reduced queuing costs can be made to exceed the costs of the plan, whether they take the form of losses in consumer surplus or implementation and administrative burdens. Crude estimates of the costs and benefits of such plans can be developed. In the case of three measures evaluated here, the estimated benefits would appear to exceed the cost.

ACKNOWLEDGMENT

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

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

Queuing and Search Delays Due to Gasoline Station Closings: Simple Equilibrium Framework

HANI MAHMASSANI AND YOSEF SHEFFI

This paper presents a simple framework for modeling the delays involved in searching for an open gasoline station and queuing at the station in urban areas. It includes an elastic response of the demand for gasoline and solves simultaneously for the number of users per unit of time and the search and queuing delays. The search-time model is based on simple geometric probability considerations, open gasoline stations are modeled as M/G/1 queues, and the demand curve is assumed to be a simple two-parameter curve. The model is concerned only with aggregate averages and not with detailed distribution of the delays. The solution is demonstrated, in a numerical example, as a function of the percentage of open gasoline stations and a demand sensitivity parameter. The example is focused on relative changes (in the output parameters) only, because the model is not calibrated to a particular urban area.

This paper describes a simple equilibrium framework for modeling the delays involved in searching for gasoline and queuing in gasoline stations, including an elastic response of the demand for gasoline. The analysis is macroscopic in scope and aggregate in nature. We deal with the aggregate number of users and average delay only, over a ubiquitous urban area characterized by a random distribution of gasoline stations and a random distribution of trip origins. Furthermore, we deal with relative delays only, since the model is not calibrated to a specific urban area.

The searching time and queuing delay involved in the process of obtaining gasoline can probably be found with a detailed network simulation. With the use of a disaggregate-choice model, the analyst can also determine the number of users in the system at equilibrium. Such methodology can provide microscopic analysis of a variety of policy options. However, it would involve a large data collection effort and a considerable computer budget.

The model presented in this paper is much simpler. Given the area size, the number of gasoline stations, and the percentage of stations that are open, it computes the average delay incurred by a motorist in finding an open station. Also, given the number of users per open station and the stations' average service rate, the model computes the average queuing delay. Lastly, given the search time and queuing delay, a simple demand curve is used to determine the number of users (customers) in the system. Naturally, the queuing delay grows as the number of users grows, and the number of users decreases as the queuing (and search time) grow. Thus, the queuing delay and the number of users in the system have to be solved for simultaneously, and their solution is referred to as the equilibrium queuing delay and the equilibrium number of users.

By use of this model one can investigate the effect of the percentage of open stations on the delays and number of users as well as the effect of other parameters, such as the service variability and the shape of the demand function for gasoline.

The strength of our approach lies in its simplicity. All the calculations can be performed with the aid of a programmable pocket calculator, and most of the major factors of the problem are included in the analysis.

THE TIME SPENT IN SEARCH

Consider an urban area of size A that has n_o gasoline stations located at random throughout the area. Assume that users (gasoline seekers) act independently of each other. Each user starts from a random point in the area and travels to the nearest gasoline station. If the station is closed, he or she keeps searching until the nearest open gasoline station is found. In this section we derive an expression for the mean time spent in the search (i.e., from the origin until an open station is found).

We start by developing an expression for the mean distance that a user has to travel in order to visit m stations, assuming an area of size A and a total number of stations n_o ($m < n_o$). From geometric probability considerations (1), the distance between a randomly selected point and the closest of a set of n_o points (D_{n_o}) is

$$D_{n_o} \cong \theta\sqrt{2\pi A/n_o} \qquad (1)$$

where Θ is a network structure coefficient. For right-angle distance, $\theta \simeq 1/4$; for airline distance, $\theta \simeq 1/5$ (2). Equation 1 holds only for $n_o \rightarrow \infty$; however, it is accurate to within 1 percent for all values of n_o (3) for areas that are approximately circular or square.

Thus Equation 1 is the distance traveled to the first gasoline station. If this station is closed, the customer travels to the next gasoline station that is the closest out of a set of n_o-1 remaining possibilities. (A cluster of gasoline stations at a particular location is considered as one gasoline station for the purpose of this discussion. Therefore, n_o is more exactly the number of clusters of gasoline stations.) Thus, the expected distance to the next stations (D_{n_o-1}) is

$$D_{n_o-1} \cong \theta\sqrt{2\pi A/n_o - 1} \tag{2a}$$

In general, after i stations have been visited, the distance to the closest one [out of the remaining (n-i) stations] is

$$D_{n_o-i} \cong \theta\sqrt{2\pi A/n_o - i} \tag{2b}$$

Thus, the total distance traveled in order to visit m stations in an area of size A with network struture coefficient Θ and n_o stations [$D_m = D_m(n_o, A, \Theta)$] is given by

$$D_m(n_o, A, \theta) \cong \theta\sqrt{2\pi A} \sum_{i=0}^{m-1} (1/\sqrt{n_o - i}) \tag{3}$$

Note that the argument used to derive Equations 2 and 3 is not entirely correct because the locations of the second and successive stations visited are not independent of the first station visited. However, as argued by Daganzo and others (3) this causes two errors that tend to cancel each other and the total error introduced by Equation 3 is less than 5 percent.

We now derive the probability mass function of the number of stations visited (n) if only n_p out of the total of n_o stations are open. Assuming that stations operate independently and that the weak law of large numbers applies, the probability of finding a given station open is $P = n_p/n_o$. This is also the probability that the first station visited is open. The conditional probability of finding the second station open given that the first one is closed, Pr(2nd open|1st closed), is given by

$$\text{Pr(2nd open|1st closed)} = n_p/n_o - 1 \tag{4a}$$

Note that Pr(2nd open|1st closed) $\neq$ Pr(1st closed) since the number of open stations is finite and as the search proceeds the probability of finding an open station increases. Thus,

$$\begin{aligned}&\text{Pr[ith open|1st through (i-1)th closed]}\\ &\quad = n_p/n_o - i + 1 \qquad \text{for } i \leqslant n_o - n_p + 1\end{aligned} \tag{4b}$$

For $i = n_o - n_p + 1$, the above probability is 1. This corresponds to a case where ($n_o - n_p$) stations have been visited (and found closed). The remaining n_p stations are open, in accordance with our initial assumption, and thus the next one visited would be open (number $n_o - n_p + 1$ in the search process) and the search terminates. In other words, $1 < n < (n_o - n_p + 1)$ where n is the number of stations visited.

The probability of visiting n stations (P_n) equals the probability of finding the first (n - 1) stations closed and the nth one open. From Equation 4b and our independence assumption, the probability mass function of n is given by

$$\begin{aligned}P_1 &= \text{Pr[1st open]} = n_p/n_o\\ P_2 &= \text{Pr[2nd open|1st closed]} \times \text{Pr[1st closed]}\\ &= (n_p/n_o - 1)\,[1 - (n_p/n_o)]\\ P_3 &= \text{Pr[3rd open|2nd and 1st closed]} \times \text{Pr[2nd closed|1st closed]}\\ &\quad \times \text{Pr[1st closed]} = (n_p/n_o - 2) \times [1 - (n_p/n_o - 1)]\\ &\quad \times [1 - (n_p/n_o)]\end{aligned} \tag{5a}$$

$$P_n = (n_p/n_o - n+1) \times \prod_{i=1}^{n-1} [1 - (n_p \div n_o - i+1)] \qquad \text{for } 1 < n \leqslant n_o - n_p + 1 \tag{5b}$$

$$P_n = 0 \qquad \text{for } n > n_o - n_p + 1 \tag{5c}$$

From the probability mass function of n (given by Equations 5a-5c), the mean number of stations visited (n) is given by

$$\bar{n} = \sum_{n=1}^{n_o-n_p+1} n \times P_n \tag{6}$$

We can now derive the mean distance traveled until the first open station is found, by substituting the distance traveled in order to visit n stations (from Equation 3) for n in Equation 6. The mean distance traveled in search for gasoline [$d(n_o, n_p, A, \Theta)$] is

$$d(n_o, n_p, A, \theta) = \theta\sqrt{2\pi A} \sum_{n=1}^{n_o-n_p+1} P_n \times \sum_{i=0}^{n-1} 1/\sqrt{n_o - i} \tag{7}$$

When the probability mass function of n is substituted from Equation 5, the distance becomes

$$d(n_o, n_p, A, \theta) = \theta\sqrt{2\pi A}\left((n_p/n_o^2) + \sum_{n=2}^{n_o-n_p+1}\left\{(n_p/n_o - n+1)\prod_{j=1}^{n-1}\left[1 - (n_p/n_o - j+1)\right] \times \sum_{i=0}^{n-1} (1/\sqrt{n_o - 1})\right\}\right) \tag{8}$$

The average driving time to find gasoline (t_d) is derived by dividing the average distance by the average network speed (V) [i.e., $t_d = t_d(n_o, n_p, A, \Theta, V) = d(n_o, n_p, A, \Theta)/V$].

In order to demonstrate the effect of the number of open stations on the search time, the percentage increase in search time versus the percentage of open stations is depicted in Figure 1. In this figure, as well as in all of the following numerical examples, we use an area of A = 259 km² (100 miles²), a right-angle (dense-grid) network structure (i.e., $\Theta = 1/4$), a total number of gasoline stations of $n_o = 150$, and an average network speed of V = 48 km/h (30 miles/h).

The percentage increase in the average search time is given by $100 \times [t_d(n_o, n_p) - t_d(n_o, n_o)]/t_d(n_o, n_o)$, where the arguments A, Θ, and V were omitted from the notation of $t_d(. . .)$ since their values are fixed at the above-mentioned levels. Note that these notations are used only for clarity of presentation. The expanded expression for the percentage increase in delay is $100 \times [t_d(n_o, n_p, A, \Theta, V) - t_d(n_o, n_o, A, \Theta, V)] \div t_d(n_o, n_o, A, \Theta, V)$. As Figure 1 illustrates, the model predicts that, when 50 percent of the gasoline stations are open, the search time is approximately twice its value when all stations are open. When the number of open gasoline stations decreases, the search time increases sharply.

A more interesting result is depicted in Figure 2, where the percentage increase in delay is plotted again (the curve labeled "no information"). However this time the delay can be compared to a situation

Figure 1. Percentage increase in the average search time as a function of the percentage of open stations.

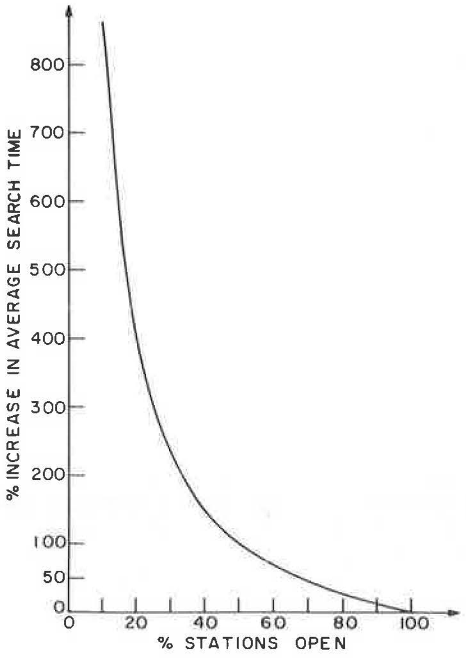
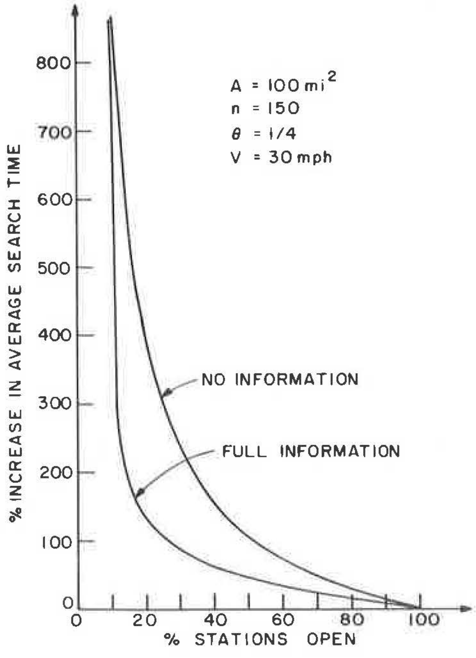


Figure 2. Impact of full information about station closings on the search time.



where the motorists have complete information regarding which stations are pumping gasoline and which are closed. To model the complete-information case one can assume $n_o = n_p$ (since motorists would not visit closed stations). In other words, the percentage increase in delay is given by 100 x $[t_d(n_o,n_p) - t_d(n_o,n_o)] \div t_d(n_o,n_o)$. [Note that from Equation 1, $t_d(n_p,n_p) = 1/V\sqrt{2\pi A/n_p}$.] This curve is labeled "full information" in Figure 2.

The full-information situation may correspond to a continuous broadcast of the location of open gasoline stations. As seen from the figure, the value of the information increases rapidly as the percentage of open stations decreases. Thus, for example, when 50 percent of the stations are open, the information on the locations of open gasoline stations can eliminate more than half of the time (and gasoline) wasted in searching for an open station.

THE TIME SPENT IN QUEUE

So far we have ignored any interaction among users and the familiar effect of queues at the station. However, before we adopt a familiar queuing model in order to model the time spent in queue, we have to clarify the meaning of the term gasoline station as used in this paper.

The definition of a station bears on the accuracy of the assumption that stations are distributed randomly, since stations tend to be clustered at intersections. Thus, for our purposes, a station may represent a cluster of stations (i.e., stations at all corners of a given intersection may be represented as one station cluster or simply as one station).

A more difficult problem is the definition of the service rate of gasoline stations. In this case the proper unit of service may be the single pump (or island) rather than a station or a station cluster. In other words, the distribution of pumps per station (or station cluster) should be accounted for in the computation of the service rate. The problem is compounded by the fact that the distribution of open pumps may be different from the distribution of pumps. In the absence of accurate data, such sophistication of the model seems hardly worthwhile, and thus we use the average service rate (μ) to represent the service rate per station (cluster).

Thus we model a gasoline station as an M/G/1 queuing process, where M is the arrival process, G is the general distribution of service time, and 1 is the number of servers for the queue. In other words, a queue with Poisson arrivals, a general distribution of service time, and one server. The basic result from queuing theory (4) that we use is that the average time spent in the queue, for an M/G/1 queuing system (t_q) is given by the Pollaczek-Khintchine mean value formula:

$$t_q = (\rho/\mu + \lambda\sigma^2)/2(1 - \rho) \tag{9}$$

where $\rho = \lambda/\mu$ is the utilization factor and σ_s^2 is the variance of the service time distribution.

In Equation 9, the arrival and service rates (λ and μ, respectively) are measured in customers per time unit (e.g., customers per hour), and the model assumes that customer arrivals follow a Poisson process with mean λ and that the service time per customer is distributed with mean $1/\mu$ and variance σ_s^2.

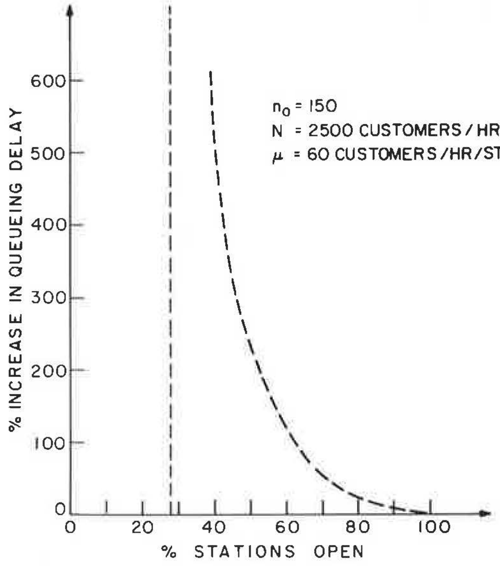
As mentioned in the beginning of this section, the mean service time is taken as the average per station (cluster) across the study area and assumed to be applicable to all stations in the area.

The average arrival rate is given by the rate of customers looking for gasoline divided by the number of open gasoline stations. If we let N denote the total areawide number of customers per time unit, the average (across stations) arrival rate is given by

$$\lambda = N/n_p \tag{10}$$

where n_p is the number of open gasoline stations.

Figure 3. Percentage increase in the average queuing delay as a function of the percentage of open stations.



When λ is substituted by Equation 10 in Equation 9, the queuing delay as a function of the above-mentioned parameters becomes

$$t_q = t_q(N, N_p, \mu, \sigma_s^2) = (N/n_p) \times \left\{(\mu^{-2} + \sigma_s^2)/2[1 - (N/n_p \cdot \mu)]\right\} \tag{11}$$

Figure 3 depicts the percentage increase in the queuing delay with n_p stations open compared with the queuing delay with n_o stations open {i.e., $[t_q(\cdot n_p \cdot\cdot) - (t_q(\cdot n_o \cdot\cdot)]/t_q(\cdot n_o \cdot\cdot)$ for given values of N, μ, and σ_s^2}. In order to conform to our earlier notation, the abscissa in Figure 3 is given in terms of the percentage of open stations (i.e., 100 n_p/n_o) for $n_o = 150$. The other values for which the graph is drawn are N = 2500 customers/h and μ = (60 customers/h)/station. Note that the variance in service time has no effect on the percentage increase of delay even though the delay itself would increase substantially with increasing variance in service time.

As is evident from Figure 3, the relative delay increases rapidly as the percentage of open stations decreases. Note that for N = 2500 customers/h and μ = (60 customers/h)/station, the delay approaches infinity as the percentage of open stations decreases to 28 percent (since with $n_o = 150$, this implies an arrival rate that equals the service rate). In general, the queuing delay would approach infinity as $n_p \rightarrow N/\mu$.

Thus, Equation 11 expresses the queuing delay as a function of the number of open stations, the service time distribution parameters, and the total number of customers searching for gasoline per hour.

THE DEMAND FUNCTION

The demand function that we describe in this section relates the number of customers in the system (per time unit) to the queuing and search time. It assumes that, as the delays increase, more users would be discouraged and abandon the system. In accordance with the level of analysis of the preceding sections, we have assumed a demand function of the type

$$N = N_o \left\{[t_d(n_o) + t_q(n_o)]/[t_d(n_p) + t_q(n_p)]\right\}^{\alpha} \tag{12}$$

where $t_d(n_o)$, $t_q(n_o)$ are the search and queuing times, respectively, that correspond to n_o gasoline stations open; $t_d(n_p)$, $t_q(n_p)$ are the search and ueuing delay that correspond to n_p (out of n_o) open stations; α is a positive parameter that reflects user sensitivity to search and queuing times; and N_o is the number of users when all the stations are open.

Note that N_o might reflect a demand effect that is not modeled in our work (i.e., the known or expected closings). Since there are times, such as late nights or Sundays, when almost no gasoline station is open, the volume of customers that would have normally (i.e., without gasoline shortage) been serviced during these hours is added to the number of users during business hours. In fact, the basic number of customers (N_o) is probably a function of the expected (or advertised) number of open stations and thus one might interpret Equation 12 as including this effect [through $t_d(n_p)$ and $t_q(n_p)$]. However, without data the use of a more complicated functional form for the demand does not seen warranted, and thus Equation 12 may be interpreted both ways.

The parameter α captures the sensitivity of customers to queuing and search time. This parameter can be estimated by use of standard econometric techniques. However, note that, in a rapidly changing environment, this parameter may be unstable since it reflects the users' belief that gasoline might be more (or less) available at some other time. Due to the high degree of uncertainty associated with α, in this paper we perform a parametric study of the effects of this parameter.

Note also that we assumed α to be independent of $t_q(\cdot)$ and $t_d(\cdot)$, although one may argue that, as the search time increases, customers might accept longer queues. Incorporation of such an effect would lead, again, to a more complicated demand function, which we tried to avoid.

In specifying the demand function we hypothesized that the searching and queuing time have equal effect on the number of users. Naturally one can specify a model with different weights on $t_d(\cdot)$ and $t_q(\cdot)$ and test for this assumption when the model is estimated econometrically.

Figure 4 illustrates the demand function that depicts N/N_o versus $[t_d(n_p) + t_q(n_p)]$, for α = 0.2, 0.5, and 0.8, assuming that $[t_d(n_o) + t_q(n_o)] = 1$ (for normalization purposes).

Given the area parameters (A, n_o, Θ, and V), the service parameters (μ, σ_s^2), and the demand parameters (N_o, α), we can now solve for the number of users (N) and queuing and searching time (t_d, t_q) as a function of the number of open stations (n_p). This solution specifies an equilibrium situation.

EQUILIBRIUM CONDITIONS

The equilibrium solution (N^*, t_d^*, t_q^*) has to satisfy the following system of equations (see Equations 8, 11, and 12). (We use asterisks to denote the value of these variables at the equilibrium solution.)

$$t_d^* = (\theta/V)\sqrt{2\pi A}\left((n_p/n_o^2) + \sum_{n=2}^{n_o-n_p+1}\left\{[n_p/(n_o-n+1)]\prod_{j=1}^{n-1}\left[1 - [n_p \div (n_o - j+1)]\right] \times \sum_{i=0}^{n-1} 1/\sqrt{n_o - i}\right\}\right) \tag{13a}$$

$$t_q^* = (N^*/n_p)\left\{(\mu^{-2} + \sigma_s^2)/2[1 - (N^*/n_p \cdot \mu)]\right\} \tag{13b}$$

$$N^* = N_o\left\{[t_d(n_o) + t_q(n_o)]/(t_d^* + t_q^*)\right\}^{\alpha} \qquad (13c)$$

Given the area parameters (A, n_o, Θ, and V) and n_p, Equation 13a can be computed independently of the remaining two equations (since the search time is independent of the queuing delay and the number of users). Given t_d^*, one can substitute Equation 13b in 13c to get the fixed-point problem:

$$N^* = C_1\left(t_d^* + C_2\left\{N^*/[1 - (N^*/n_p \cdot \mu)]\right\}\right)^{-\alpha} \qquad (14)$$

where the constants C_1 and C_2 are given by the demand function parameters and the service time distribution parameters, respectively; i.e.,

$$C_1 = N_o[t_d(n_o) + t_q(n_o)]^{\alpha}$$

and

$$C_2 = (\mu^{-2} + \sigma_s)/2n_p$$

Many numerical methods can be used to solve for N* in Equation 14. (We used a bisecting method.) Once N* is know, t_q^* can be determined from Equation 13b.

Figure 4. Relative number of users as a function of the normalized sum of search and queuing time.

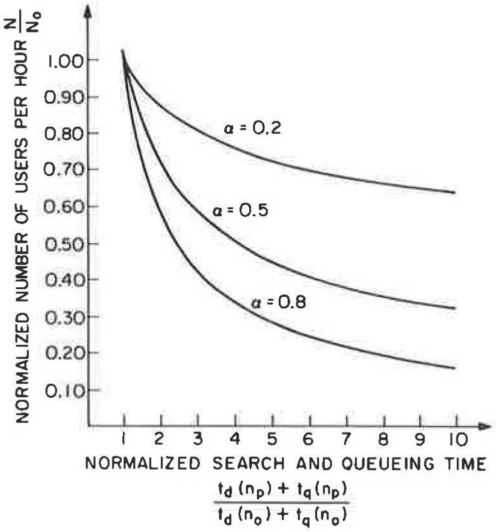
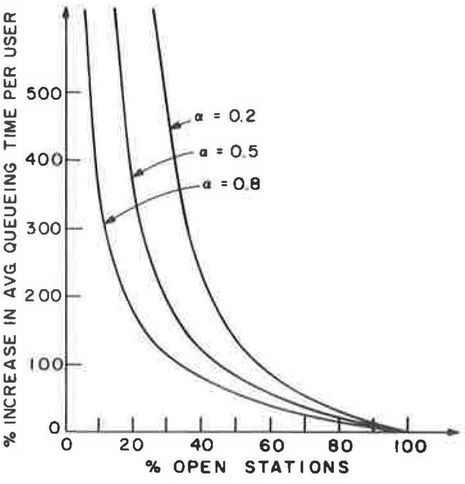


Figure 5. Percentage increase in queuing time per user—equilibrium result.



In the remainder of this section we show the characteristics of the equilibrium solution as a function of the percentage of open stations, in the context of a simple numerical example.

The parameters of our example are as follows:

1. Area size, A = 259 km² (100 miles²) with rectangular grid structure of the road network (Θ = 1/4);
2. Total number of stations in the study area, n_o = 150;
3. Average speed over the network, V = 48 km/h (30 mph);
4. Average station service rate, μ = 60 vehicles/h; and
5. The number of users with all the stations open, N_o = 2500 customers/h.

The model is solved for three values of α: 0.2, 0.5, and 0.8.

Figure 5 depicts the percentage increase in average queuing time, $100 \times [t_q^*(n_p) - t_q(n_o)]/t_q(n_o)$, as a function of the percentage of open gasoline stations ($100\ n_p/n_o$) and the demand parameter (α). Note that this figure depicts the average waiting time per user (i.e., per waiting customer). The general shape of all the curves shown in Figure 5 is similar to the queuing delay curves shown in Figure 3. However, due to the demand effect, these curves are all asymptotic to the ordinate rather than to N/μ, since N is a decreasing function of n_p as well.

Note that for a given number (or percentage) of open gasoline stations, the delay per user decreases with increasing α. This, of course, is due to the demand effect; as α increases, more users are discouraged by the long search time and queuing time, and the queues decrease.

Figure 6 shows the combined effect of the increased delay and the reduction in the number of users. It depicts the percentage increase in total queuing time; i.e., $100[N^* \cdot t_q^*(n_p) - N_o \cdot t_q(n_o)] \div N_o \cdot t_q(n_o)$, versus the percentage of open stations and the demand parameters. In this case, two opposite effects influence the shape of the total queuing delay. The queuing time per customer, $t_q(\cdot)$, is an increasing function of n_p and the number of customers in the system is a decreasing function of n_p. Thus, their product depends on the input parameters and, in our particular example, on the demand parameter (α).

The effect of the demand parameter is more pronounced in Figure 6 than in Figure 5 since both N and $t_q(\cdot)$ decrease with increasing α. As seen

Figure 6. Percentage change in aggregate queuing time—equilibrium result.

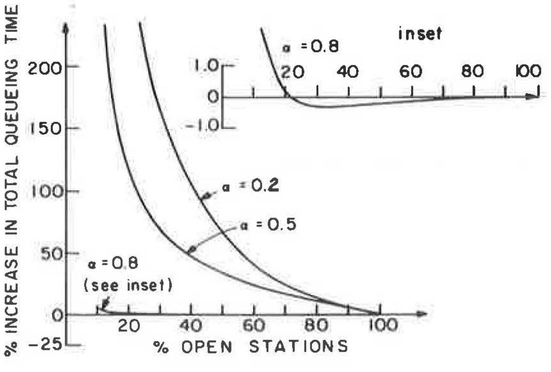


Figure 7. Percentage increase in total search time—equilibrium result.

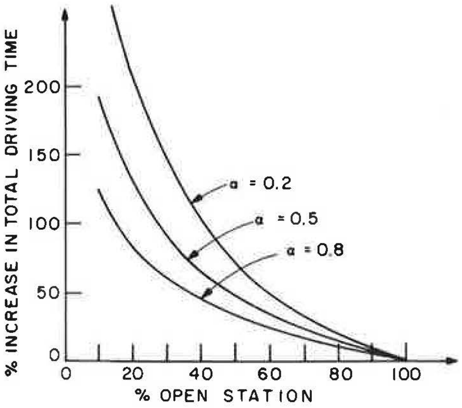
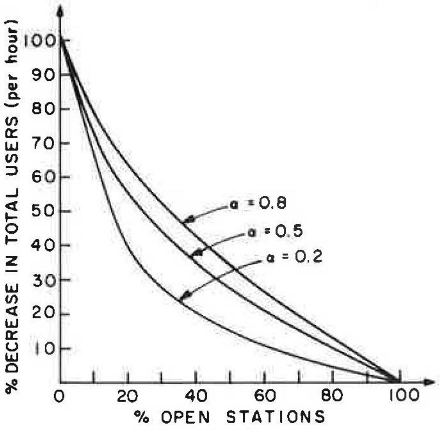


Figure 8. Percentage decrease in the number of users per hour—equilibrium result.



in Figure 6, the curve is almost zero for 10 percent $\leq$ 100 n_p/n_o $\leq$ 100 percent for $\alpha = 0.8$. With such value of α, the relative decrease in the number of customers who search and queue for gasoline approximately offsets the relative increase of the queuing time per customer. However, note that, since the number of open stations becomes very small, the total delay would increase, regardless of α.

The percentage increase in average driving time per customer in searching for gasoline, for this example, is shown in Figure 7. Note that the search time (t_d^*) is not affected by the number of customers in the system and, therefore, Figure 7 applies to our example as the equilibrium solution for t_d.

However, the total search time (for all users in the system) is a function of the percentage of open stations and the demand parameter. As expected, the total search time decreases with increasing percentage of open stations and with increasing α.

The effect of the percentage of open stations on the equilibrium number of users is shown in Figure 8. This figure depicts the percentage decrease in the total number of customers per hour in the system, $100(N_o - N^*)/N_o$, as a function of $100n_p/n_o$ and α. The number of users in the system decreases with decreasing percentage of open stations and with increasing α. Note that these curves are not asymptotic to the ordinate since as $n_p \rightarrow 0$, so does N^* and the percentage decreases as the number of customers approaches 100 percent (i.e., there are no customers in the system).

CONCLUSION

This paper presented a simple model for assessing the delays associated with the search for an open gasoline station and the wait in line at the station and estimates the number of customers in the system.

The model consists of three equations. The first one is the search-time model. Based on geometric probability considerations and the assumption of a random distribution of gasoline stations, this equation relates the area parameters and the number of open stations to the time spent in search for an open station. The area (input) parameters include the area size, the total number of gasoline stations, the network structure parameter, and the average network speed.

The second equation is based on viewing each gasoline station as an M/G/1 queuing system. The equation relates the time spent in the queue to the mean and variance of the service time and to the rate of customer arrival. The arrival rate is, in turn, determined by the ratio of the number (per time unit) of customers in the system to the number of open gasoline stations.

The third equation, the demand function, relates the number of users in the system to the time spent in search and in queue (relative to those times when all the stations are open) and the number of customers in the unconstrained case (where all stations are open).

These three equations have to be solved simultaneously to get the driving time, queuing time, and the number of customers (per time unit) at equilibrium. We demonstrated numerically the solution of these equations for given values of the input parameters (A, N_o, θ, V, μ, and σ_s^2) for the the whole range of n_p (the number of open gasoline stations) and for several values of α, the demand function parameter.

The effect of N_o on the equilibrium solution would be opposite in direction to the effect of α. An increase in α (with everything else remaining constant) means an equilibrium solution that has fewer users in the system and, therefore, lower queuing times. As can be seen from Equation 13c, a decrease in N_o would have a similar effect on the equilibrium solution.

The parameters θ, V, and A affect the equilibrium solution through the search-time equation. As can be seen from Equation 13a, as long as $\theta\sqrt{A}/V$ remains constant, the solution is not affected. If $\theta\sqrt{A}/V$ increases (either θ or A increase, or V decreases) the driving time would increase (holding everything else constant). The effect of increasing search time would diminish the queuing effect (since the area parameters under consideration appear in both the numerator and the denominator of the demand function). However, as can be seen from Equations 13b and 13c , the number of users in the system would somewhat decrease and the queuing time would decrease accordingly.

The effect of increasing the service rate is to reduce the queuing time and therefore to increase the number of customers in the system. A similar effect would be generated by an increase in the variance of the service time. Note, however, that the effect of both of these parameters on the demand is somewhat limited since (as with the area parameters) they affect both the numerator and the denominator of the demand function.

In Figure 2 we showed the effect of full information about station closings in the system on the driving time in search for an open station. This result still applies in an equilibrium framework. However, one can expect long queues and more users than in the no-information situation because a reduction in the search time would generate an increase in customer volume and longer queues.

Once calibrated, the model presented in this paper may be used to obtain first-cut estimates of the effects of relief policies. One such policy directed at reducing the search time is the above-mentioned information dissemination. Another policy, directed at reducing the queuing time, can be a variance-reduction policy, used in the summer of 1979 by many station attendants (i.e., $7 worth of gasoline to every car, or variants of this policy). Such a policy would decrease the queuing time; however, as with all other variables, this reduction is absorbed to some extent by the equilibrium effect (the reduced queuing time encourages more customers to look for gasoline, which causes an increased queuing time). A minimum purchase policy can be modeled by decreasing N_0, which should be interpreted as the number of gasoline trips rather than the number of customers. A maximum purchase policy can be modeled by increasing N_0, which of course would cause increased queues. In appplying our model to the evaluation of an odd-even plan, one might naively assume that N_0, the number of potential gasoline trips per hour, should be halved and therefore (after allowing for the equilibrium effect) queuing time should decrease somewhat. However, under an odd-even plan, individuals' determination to obtain gasoline is drastically increased; or, in terms of our model, α decreases substantially. In other words, under an odd-even plan (which is usually coupled with weekend closing as well), customers are relatively inelastic with respect to queuing delays, and stay in the system, which causes even larger delays.

The model presented in this paper should not, of course, be used for detailed analysis and policy assessment. It is intended more as a framework for thought about the problem and general assessment of the search and queuing delays involved in obtaining gasoline in a situation similar to that of the summer of 1979.

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

Demand for Travel and the Gasoline Crisis

WILLIAM C. LEE

This paper uses traffic count data to estimate and analyze the demand for gasoline and different kinds of work and leisure travel in California from 1970 to 1975. Empirical results of the ordinary least-squares regressions show the price elasticity of gasoline and travel to be quite inelastic—between -0.05 and -0.50. The income elasticities range between 0.5 and 1.5. Furthermore, the results suggest that leisure-oriented travel is less price- and income-sensitive than work-oriented travel. Results also indicate that travel and gasoline are affected by seasonal variations. In addition to the conventional demand analysis, the study investigates the gasoline crisis in California in 1974. During the gasoline crisis, the existence of queuing at service stations suggested that disequilibrium existed in the gasoline market. Due to the difficulty in purchasing gasoline, the true price of gasoline exceeded the actual price paid at the pump. Results show that the true price of gasoline rose from a precrisis price of $0.31/gal to more than $1.00/gal in some instances during the height of the crisis in March 1974. Furthermore, the value that would have been transferred from consumers of gasoline to suppliers was approximately $355 million. This amount, which averages about $27/licensed California driver, could be thought of as a measure of the gross welfare loss of gasoline rationing.

Recent developments in the worldwide energy situation have caused economists to become interested in the demand for both gasoline and automobile travel. In general, studies in this area have estimated the price and income elasticities of demand for gasoline and have come to reasonably consistent conclusions. However, these studies generally are subject to two main shortcomings:

1. By focusing on gasoline demand they are unable to distinguish between different types of automobile travel and

2. They have failed to analyze the period from December 1973 to April 1974 (henceforth referred to as the gasoline crisis), a period when the gasoline market was in disequilibrium.

This paper presents an analysis that overcomes these shortcomings by direct assessment of the demand for automobile travel by the use of monthly traffic counts on the California state highway system. These traffic counts have been disaggregated into urban, rural, weekday, and weekend trips. Furthermore, by employing traffic count locations of different characters near the San Francisco area, the study investigates the demand for recreation (I-80) and commercial and commuter travel (I-580). By using ordinary least-squares regression techniques on the monthly time series data from January 1970 to December 1975, along with seasonal monthly dummy variables, the price and income elasticities of each category of travel with respect to the price of gasoline are determined. In addition, monthly gasoline-crisis dummy variables are used to calculate what shall be called the waiting price for gasoline (due to nonprice rationing) for each month of the gasoline crisis. Once the waiting price of gasoline is calculated, the effects of the disequilibrium situation are investigated empirically by calculating the welfare loss caused by the gasoline crisis. Finally, as a

Table 1. List of variables.

Variable Name	Notation for Econometric Specification	Variable Name	Notation for Econometric Specification
Monthly average daily traffic[a]	TT	California real personal income[d]	RINC
Total monthly weekend traffic[a]	TWE	California population	POP
Monthly average weekday traffic[a]	TWD	December 1973 gasoline crisis dummy	DEC73
Urban monthly average daily traffic[a]	URT	January 1974 gasoline crisis dummy	JAN74
Urban total monthly weekend traffic[a]	URWE	February 1974 gasoline crisis dummy	FEB74
Urban monthly average weekday traffic[a]	URWD	March 1974 gasoline crisis dummy	MAR74
Rural monthly average daily traffic[a]	RUT	April 1974 gasoline crisis dummy	APR74
Rural total monthly weekend traffic[a]	RUWE	February seasonal dummy	DFEB
Rural monthly average weekday traffic[a]	RUWD	March seasonal dummy	DMAR
I-80 monthly average daily traffic[a]	SFT	April seasonal dummy	DAPR
I-80 total monthly weekend traffic[a]	SFWE	May seasonal dummy	DMAY
I-80 monthly average weekday traffic[a]	SFWD	June seasonal dummy	DJUN
I-580 monthly average daily traffic[a]	DUBT	July seasonal dummy	DJUL
I-580 total monthly weekend traffic[a]	DUBWE	August seasonal dummy	DAUG
I-580 monthly average weekday traffic[a]	DUBWD	September seasonal dummy	DSEP
Adjusted average daily gallons of gasoline[b]	GAL	October seasonal dummy	DOCT
California retail price for regular gasoline, real terms[c]	RPG	November seasonal dummy	DNOV
		December seasonal dummy	DDEC

[a] Data taken from the California Department of Transportation.
[b] Data taken from the California State Board of Equalization.
[c] Data taken from the Oil and Gas Journal.
[d] Data taken from the California Department of Finance.

byproduct of this research, the price and income elasticities of the demand for gasoline are determined.

SPECIFICATION OF THE AGGREGATE DEMAND FOR TRAVEL

The aggregate demand for gasoline and for each kind of travel is a function of the real price of gasoline, total real personal income, population, and seasonal variables:

$$Q = g(\mathrm{RPG}, \mathrm{RINC}, \mathrm{POP}, \mathrm{S}) \tag{1}$$

Table 1 identifies the variables. The expected a priori partial derivatives are as follows:

$$\partial Q/\partial \mathrm{RPG} < 0,\ \partial Q/\partial \mathrm{RINC},\ \partial Q/\partial \mathrm{POP} > 0 \tag{1a}$$

For empirical testing, Equation 1 must be specified explicitly. To achieve this, both the linear and logarithmic forms for the demand function were chosen. The linear explicit form of the equation becomes

$$A = A + \beta_1 \mathrm{RPG} + \beta_2 \mathrm{RINC} + \beta_3 \mathrm{POP} + \beta_4 \mathrm{S} \tag{2}$$

and the logarithmic form becomes

$$Q = \mathrm{ARPG}^{\beta_1}\, \mathrm{RINC}^{\beta_2}\, \mathrm{POP}^{\beta_3}\, \mathrm{S}^{\beta_4} \tag{3}$$

Once the demand equation is specified, the gasoline crisis can be integrated into the analysis.

Gasoline Crisis

During the gasoline crisis of late 1973 and early 1974, automobile travel and gasoline consumption were both reduced substantially. Furthermore, the gasoline market was in a state of disequilibrium. As a result of this disequilibrium, queuing occurred in service stations. Queuing causes the true price of gasoline (P_T) to exceed the pump price (RPG) by a waiting premium (P_W) when the model is specified in the linear form (i.e., P_T = RPG + P_W). When specified logarithmically, P_T = RPG x P_ω where P_ω is a unitless rationing parameter. If P_T is decomposed and substituted in Equations 2 and 3,

$$Q = A + \beta_1(\mathrm{RPG} + P_W) + \beta_2 \mathrm{RINC} + \beta_3 \mathrm{POP} + \beta_4 \mathrm{S} \tag{4}$$

$$Q = A(\mathrm{RPG} \times P_\omega)^{\beta_1}\, \mathrm{RINC}^{\beta_2}\, \mathrm{POP}^{\beta_3}\, \mathrm{S}^{\beta_4} \tag{5}$$

Estimation Procedure

A single-equation ordinary least-squares (OLS) estimation procedure was applied to Equations 4 and 5:

$$Q = \beta_0 + \beta_1\left(\mathrm{RPG} + \sum_{i=1}^{5} D_i P_{Wi}\right) + \beta_2 \mathrm{RINC} + \beta_3 \mathrm{POP} + \sum_{i=1}^{11} \beta_{3+i} D_{mi} + \mu \tag{6}$$

$$Q = \beta_0 \left(\mathrm{RPG} \prod_{i=1}^{11} P_{\omega i}^{D_i}\right)^{\beta_1} \mathrm{RINC}^{\beta_2}\, \mathrm{POP}^{\beta_3}\, e^{\prod_{i=1}^{11} \beta_{3+i} D_{mi}}\, \mu \tag{7}$$

for each dependent variable.

In both specifications, the error term (μ) is assumed to be normally distributed with zero mean and constant variance. In accordance with the theoretical structure presented by Equation 5, it is expected that

$$\beta_1 < 0 \text{ and } \beta_2,\ \beta_3 > 0$$

for each dependent variable.

The estimate of the time and true prices of gasoline (P_W and P_T) during the months when nonprice rationing was effective comes directly from the estimate of Equations 6 and 7. When Equation 6 is multiplied by β_1 the equation becomes

$$Q = \beta_0 + \beta_1 \mathrm{RPG} + \beta_1 \sum_{i=1}^{5} D_i P_{Wi} + \beta_2 \mathrm{RINC} + \ldots + \mu \tag{8a}$$

$$Q = \beta_0 + \beta_1 \mathrm{RPG} + \sum_{i=1}^{5} \gamma_i D_i + \beta_2 \mathrm{RINC} + \ldots + \mu \tag{8b}$$

The coefficient on each gasoline crisis month (D_i) is $\beta_1 P_{Wi}$ or γ_i. To solve for the time price in each month (P_{Wi}) the estimated value of γ_i is divided by the estimate of the coefficient of the price of gasoline (β_1). The resulting value is an estimate of P_{Wi} because γ_i/β_1 equals P_{Wi}. The sum of P_{Wi} and the actual pump price of gasoline (RPG) equals the true price of gasoline (P_{Ti}) during each month of the gasoline crisis. The solution for $P_{\omega i}$ in the logarithmic specification is similar, except that $P_{\omega i}$ is a multiplicative constant.

It would also be expected that the calculated

Table 2. Linear estimation results excluding seasonal effects.

Independent Variables	Dependent Variables Constant	RPG	RINC	POP	DEC73	JAN74	FEB74	MAR74	APR74	R^2	F	Durbin-Watson Statistic (d)
GAL	-25 193.1	-18 552.8	277.283	1 567.94	-1 801.5	-1 629.67	-2 313.14	-2 524.14	162.7	0.9188	30.96	1.97
t-value	3.378	5.342	6.293	2.923	-2.836	-2.573	-3.604	3.879	0.248			
TT	-1 211 080	-370 235	4578.84	65 660.1	-20 744.1	-20 841.2	-51 063.3	-87 070.6	-6 221.33	0.9693	86.46	1.37
t-value	-7.51	-4.93	4.80	5.66	-1.51	-1.52	-3.68	-6.19	-0.44			
TWE	-2 064 710	-588 820	6527.38	125 584	-75 404	-146 590	-230 998	-282 479	-16 269.3	0.9394	42.393	1.53
t-value	-4.11	-2.51	2.19	3.47	1.76	-3.43	-5.34	-6.43	-0.369			
TWD	-1 282 570	-400 565	5104.91	66 807.4	-13 961	140.31	-25 289	-65 403	-5 455.98	0.9655	76.61	1.599
t-value	-7.61	-5.10	5.12	5.51	0.972	0.0098	-1.74	-4.44	-0.369			
URT	-847 807	-193 364	2749.13	41 229.3	-7 474.25	-8 124.20	-26 664.9	-34 185.8	-8 451.3	0.9807	138.909	1.73
t-value	-14.64	-7.17	8.03	9.90	-1.51	-1.65	-5.35	-6.76	-1.66			
URWE	-1 591 920	-288 960	2348.8	88 966.1	-21 990.3	-32 869.3	-81 322.2	-101 796	-9 807.49	0.9389	42.0751	1.50
t-value	-7.28	-2.84	1.82	5.66	-1.18	-1.77	-4.32	-5.34	-0.51			
URWD	-808 547	-212 917	3379.02	39 927.8	-6 065.91	-4 800.04	-21 066.5	-27 501.0	-9 870.30	0.9722	95.81	1.6547
t-value	-12.382	-6.519	8.15	7.91	-1.01	-0.806	-3.48	-4.49	-1.60			
RUT	-363 300	-176 900	1830	24 430	-13 270	-12 720	-24 400	-52 880	2 230	0.9438	45.93	1.52
t-value	-2.84	-2.96	2.42	2.65	-1.22	-1.17	-2.21	-4.73	0.20			
RUWE	-472.800	-299 900	4179	36 620	-53 410	-113 700	-149 700	-180 700	-6 462	0.8822	20.50	1.5
t-value	-1.10	-1.50	1.65	1.19	-1.46	-3.12	-4.05	-4.83	-0.17			
RUWD	-414 000	-187 600	1726	26 880	-7 895	4 940	-4 223	-37 900	4 414	0.9393	42.32	1.91
t-value	-3.16	-3.08	2.23	2.85	0.71	0.44	-0.37	-0.332	0.38			
SFT	-108 786	-11 165.9	570.303	5 755.32	-1 281.55	1 023.62	-4 072.55	-13 143	-3 662.13	0.9222	32.4265	1.398
t-value	-3.44	-0.787	2.79	2.44	-0.443	0.354	-1.39	-4.46	-1.23			
SFWE	-10 339.3	-31 858.9	1344.57	1 552.00	-11 828.8	-18 888.2	-41 696.3	-43 068.7	-13 621.0	0.8099	18.31	1.61
t-value	-0.109	-0.746	2.197	3.73	-1.359	-2.178	-4.75	-4.87	-1.52			
SFWD	-150 232	-9 260.44	529.51	7 747.05	571.6	5 210.71	2 637.68	-9 786.98	-2 402.79	0.9055	26.22	1.81
t-value	-4.22	-0.579	2.30	2.93	0.17	1.60	0.802	-2.95	-0.719			
DUBT	-200 811	-66 921.5	849.858	9 672.98	-2 220.57	-2 660.9	-5 104.78	-8 102.91	-952.087	0.9564	60.0958	1.6578
t-value	-9.17	-6.81	6.01	5.94	-1.10	-1.33	-2.52	-3.97	-0.464			
DUBWE	-323 520	-150 704	1446.74	16 755.8	-9 391.86	-3 374.79	-18 470.0	-21 611.6	-3 758.40	0.8974	23.9731	1.7933
t-value	-4.70	-4.89	3.26	3.28	-1.49	-0.538	-2.91	-3.38	-0.584			
DUBWD	-216 432	-63 549.3	900.453	10 191.0	-1 230.43	-3 050.40	-3 452.70	-7 021.77	-581.241	0.9445	46.56	1.728
t-value	-8.47	-5.53	5.46	5.36	-0.525	-1.31	-1.46	-2.95	-0.242			

Table 3. Price and income elasticities of demand for gallons and trips.

Dependent Variable	Price		Income	
	Linear	Logarithmic	Linear	Logarithmic
Gallons	-0.216	-0.211	0.876	0.890
Total trips	-0.236	-0.264	0.792	0.820
Weekend trips	-0.174	-0.203	0.525	0.540
Weekday trips	-0.263	-0.292	0.910	0.960
Urban trips	-0.305	-0.361	1.179	1.271
Urban weekend trips	-0.221	-0.268	0.489	0.568
Urban weekday trips	-0.340	-0.399	1.460	1.560
Rural trips	-0.189	-0.205	0.531	0.552
Rural weekend trips	-0.145	-0.164	0.546	0.546
Rural weekday trips	-0.209	-0.220	0.523	0.556
I-80 trips	-0.056	-0.092	0.760	0.750
I-80 weekend trips	-0.069	-0.098	0.773	0.712
I-80 weekday trips	-0.050	-0.090	0.753	0.773
I-580 trips	-0.381	-0.438	1.288	1.330
I-580 weekend trips	-0.428	-0.462	1.092	1.140
I-580 weekday trips	-0.363	-0.432	1.367	1.420

waiting prices of gasoline would correspond to the severity of the nonprice rationing. In other words, when rationing was most prevalent, the greatest amount of excess demand existed and, therefore, the waiting price was highest. When rationing was insignificant, excess demand was minimal and P_{Ti} would approach RPG. Given these a priori notions, it is expected that $P_W(P_\omega)$ for March 1974 weeks would be the highest, whereas $P_W(P_\omega)$ for April 1974 weekends would be lowest, and $P_W(P_\omega)$ for December, January, and February would fall between the two.

In addition to the hypothesis that the purchase of gasoline was more difficult on weekends than on weekdays, other hypotheses can be tested. Because the general uncertainty of purchasing gasoline increases the farther drivers are from familiar surroundings, they would be expected to remain close to home during the crisis. If this is indeed the case, other things being equal, the waiting price of gasoline in rural areas would be higher than the waiting price in urban areas. Vacation (or recreation) travel would also be expected to be affected more adversely by the gasoline crisis than would commercial and commuter traffic. For this reason, the waiting price of gasoline along I-80 should exceed the waiting price along I-580.

ANALYSIS OF RESULTS

Table 2 presents the results of the linear estimating equations for the demand for gasoline and the different classifications of trips for 1970-1975. All of the signs on the regressors are consistent with the theoretical implications discussed earlier. Besides having the expected signs, nearly all the parameters are significant at the 5 percent level. The coefficients of determination (R^2) are all significant and explain at least 80 percent of the variation of each of the dependent variables. The linear specification of the models is discussed first.

Table 2 shows that the change in the dependent variable with respect to a change in the real price of gasoline was negative in all cases. These coefficients are converted into price elasticities calculated at the means and are reported along with the income elasticities in Table 3. Also reported here are the logarithmic elasticities. These results imply that both gasoline and all kinds of travel are price inelastic with respect to the price of gasoline in the short run.

Considerable information is contained in the pattern of the price and income elasticity coefficients of the different classes of travel (Table 3). First of all, the price elasticity of weekend travel (TWE) is less (in absolute value) than that of weekday travel (TWD) for all aggregate categories. For example, the elasticity (linear) of weekend trips with respect to the price of gasoline is -0.174, whereas the elasticity of weekday trips is -0.263. Furthermore, results show that, for both weekdays and weekends, rural travel is less responsive to changes in gasoline prices than is urban travel. The elasticity of urban total trips (URT) with respect to the price of gasoline is -0.305, whereas that of rural total trips (RUT) is only -0.209. Finally, the isolated points as measured by I-80 and I-580, respectively, show that travel on the vacation-oriented route is much less responsive to price (SFT = -0.056) than is travel on the commercial and commuter route (DUBT = -0.381).

Taken together, these results show that leisure-oriented trips (weekend, rural, and I-80) are less responsive to price than are their work-oriented counterparts (weekday, urban, and I-580). This can be explained because of the lack of substitute modes for driving when taking a leisure-oriented trip. Once the decision is made to take a leisure trip in California, few good substitutes exist for driving. However, in the case of work trips, substitutes such as alternative modes (rapid transit) or carpooling can be found. Furthermore, because leisure trips are probably more time-intensive than work trips, it would be expected that they exhibit a small money price-responsiveness.

As to the income effects, it can be seen from Table 3 that the income effects are positive in all cases, which is also consistent with theoretical expectations. The income effects are similarly converted into elasticities and are also shown in Table 3. In most classes of travel, the weekend income elasticity is less than the weekday income elasticity. For example, the income elasticity of total weekend trips (TWE) is 0.525, whereas the income elasticity of weekday trips is 0.910. Furthermore, rural travel tends to be less sensitive to income than urban travel (e.g., the income elasticity of RUT equals 0.531, whereas the income elasticity of URT equals 1.179). Finally, vacation travel (SF) is less sensitive to income than is commercial and commuter travel (e.g., the income elasticity of SFT equals 0.760; for DUBT it is 1.788). This implies that leisure trips are less sensitive to income than are work trips. One explanation for this is the inverse relationship between income and income elasticity. In other words, as income increases, luxury goods exhibit more of the properties of necessities; hence, as income increases, the income elasticity associated with leisure (luxury) travel would decrease. Assume that high-income groups take a higher percentage of leisure-oriented trips than do lower-income groups. That is, higher-income groups are more likely to travel through rural vacation areas on weekends than are lower-income groups. Under these assumptions, these types of travel would be expected to exhibit smaller income elasticities than the work-oriented counterparts. These findings are summarized below:

1. Leisure trips (rural, weekend, or vacation): Price elasticities are lower (more inelastic) since there are few good substitutes; income elasticities are lower because of a larger percentage of high-income groups.
2. Work trips (urban, weekday, and commercial or commuter): Price elasticities are higher (less inelastic) as a result of model substitution and carpools; income elasticities are higher because of the proportion of lower-income groups.

The logarithmic results conform favorably to the linear specification of the models. The significance of the monthly dummies also conforms well with those in the linear specification, as do the R^2 and F statistics.

Because the Durbin-Watson statistics gave some evidence of autocorrelation in both linear and logarithmic specifications, the Cochrane-Orcutt iterative technique was used to correct for this on all of the equations. Because the effect of running this technique on the signs, magnitudes, and t-values of all the coefficients was negligible, it appears that autocorrelation had little effect on the results. Furthermore, the correlation between the residuals of the dependent variables did not warrant any sort of seemingly unrelated regression procedure.

The remaining variables in the models are gasoline crisis parameters. By using the coefficients on the gasoline crisis months, the waiting price of gasoline is determined for each dependent variable. Next, the true price of gasoline is calculated. Finally, some measurement of the total value lost due to nonprice rationing is determined.

The coefficient for each gasoline crisis month (γ_i) represents the change in the dependent variable due to nonprice rationing being in effect. For example, Table 2 shows that there were 282 479 fewer weekend trips (TWE) made in March 1974 than would have been made had gasoline been available with a zero waiting cost.

Next, the actual time price of gasoline is calculated for each month by

$$P_{Wi} = \gamma_i/\beta_1$$

because $P_{Wi}\beta_1 = \gamma_i$, where γ_i is the coefficient on each gasoline-crisis dummy variable and β_1 is the coefficient of RPG. Thus, on the average, on the basis of their actual behavior, individuals would have been explicitly willing to pay $\$P_{Wi}$ more per gallon of gasoline at the pump rather than implicitly pay by waiting. Table 4 shows the calculated waiting prices for each month of the gasoline crisis for each classification of travel. This waiting price was highest during the height of the gasoline crisis--February-March 1974.

The true price of gasoline was calculated by summing the pump price and the waiting price each month for the different models and is presented in Table 5. This table reports the actual price, including waiting, that was, on the average, being paid for a gallon of gasoline. For example, during the acute period of the crisis (March 1974), if the reduction in total trips is considered, consumers of

Table 4. Time prices of gasoline.

	Linear Specification ($/gal)				
Dependent Variable	DEC73	JAN74	FEB74	MAR74	APR74
Gallons	0.097	0.088	0.125	0.134	
Total trips	0.056	0.056	0.138	0.235	0.168
Weekend trips	0.128	0.249	0.392	0.478	0.028
Weekday trips	0.035		0.063	0.163	0.014
Urban trips	0.039	0.042	0.138	0.177	0.044
Urban weekend trips	0.076	0.114	0.281	0.352	0.034
Urban weekday trips	0.029	0.023	0.099	0.129	0.046
Rural trips	0.075	0.071	0.138	0.299	
Rural weekend trips	0.178	0.379	0.499	0.603	0.022
Rural weekday trips	0.042		0.023	0.202	
I-80 trips	0.115		0.365	1.180	0.328
I-80 weekend trips	0.371	0.593	1.310	1.352	0.428
I-80 weekday trips	0.062			1.060	0.259
I-580 trips	0.033	0.040	0.076	0.121	0.014
I-580 weekend trips	0.062	0.022	0.123	0.143	0.025
I-580 weekday trips	0.019	0.048	0.054	0.111	0.010

Table 5. True prices of gasoline.

Dependent Variable	Linear Specification ($/gal)				
	DEC73	JAN74	FEB74	MAR74	APR74
California pump price, real	0.313	0.324	0.326	0.357	0.367
Gallons	0.410	0.412	0.415	0.491	
Total trips	0.369	0.380	0.464	0.592	0.535
Weekend trips	0.441	0.523	0.718	0.835	0.395
Weekday trips	0.348		0.389	0.520	0.381
Urban trips	0.352	0.366	0.464	0.534	0.411
Urban weekend trips	0.389	0.438	0.607	0.709	0.401
Urban weekday trips	0.342	0.347	0.425	0.486	0.413
Rural trips	0.388	0.395	0.464	0.656	
Rural weekend trips	0.491	0.703	0.825	0.960	0.389
Rural weekday trips	0.355		0.349	0.559	
San Francisco area pump price, real	0.315	0.329	0.331	0.358	0.368
I-80 trips	0.430		0.696	1.538	0.696
I-80 weekend trips	0.686	0.922	1.641	1.710	0.786
I-80 weekday trips	0.377			1.418	0.627
I-580 trips	0.348	0.369	0.407	0.479	0.372
I-580 weekend trips	0.377	0.351	0.454	0.501	0.393
I-580 weekday trips	0.334	0.377	0.385	0.469	0.378

gasoline were, on the average, paying $0.84/gal on the weekends and $0.52/gal on the weekdays. However, the true price of gasoline converged to the pump price the following month (April 1974) as nonprice rationing subsided.

So far, all indications point to the conclusion that driving was drastically reduced during the gasoline crisis for all categories of travel. However, the reduction was by no means uniform. Certain kinds of travel were more adversely affected than others, as can be seen when the waiting and true prices of gasoline are examined. First of all, Table 5 shows that the waiting price of gasoline on the weekends exceeded that on the weekdays for all categories of travel in nearly every month of the gasoline crisis. Furthermore, during the rationing period those routes classified by the California Department of Transportation as urban were much less adversely affected than were those classified as rural. Although the waiting price of gasoline was nearly $0.18/gal for URT, it rose to nearly $0.30/gal for RUT in March 1974. This difference was accentuated on the weekends. In other words, these results imply that travel was much more costly in rural areas than in urban areas during the gasoline crisis. The waiting price of gasoline in the rural areas was practically twice the price that it was in urban areas during this period.

It appears that the bulk of driving during the gasoline crisis shifted toward urban areas. As long as the population distribution between urban and rural remained constant during this period, individuals were driving closer to home. It is concluded that, during the gasoline crisis, drivers traveled, on the average, shorter distances.

Additional credence for this conclusion can be found in the results for the two locations. Along the recreational rural route, the waiting price of gasoline exceeded $1.00/gal during March 1974. This is in marked contrast to the commercial and commuter location where the waiting price of gasoline rose only about $0.14/gal at best. This result conforms to the earlier reasoning that leisure travel is more time-intensive and is undertaken by people from high-income groups (with high opportunity costs). Therefore, as the waiting price of travel increased during the gasoline crisis, it would be expected that leisure travel would be more adversely affected than work travel.

The measurement of the welfare loss due to nonprice rationing can be decomposed into two parts. One part represents the amount consumers of gasoline would have been willing to transfer to suppliers of gasoline rather than implicitly forgo gasoline to avoid queuing and inconvenience. This would be represented by the rectangle P_W times GAL. The other component of the loss is the loss in consumers' surplus from having to pay a higher price for less gasoline. This is represented by $(P_W/2)$ (ΔGAL). The total value thus lost due to rationing during the gasoline crisis in California from December 1973 through April 1974 was $355 million. At the 1974 figure of approximately 13 million licensed California drivers, this averages about $27/driver. Assuming that California represents approximately one-tenth of the licensed drivers in the nation and that the nonprice rationing affected drivers across the nation in a similar way, the value lost because of nonprice rationing could be placed in the order of magnitude of $3 billion nationally.

CONCLUSIONS

Statistical analyses of the empirical assessment are highly encouraging and conform well to theoretical expectations. The coefficients for price, real income, population, seasonal variation, and the gasoline crisis take on the hypothesized sign and are generally statistically significant at conventional levels.

In addition to the conventional demand analysis, this study investigated the gasoline crisis directly. Results of the analysis indicate that, on the basis of the waiting price paid for gasoline, leisure travel was much dearer than commercial travel during the gasoline crisis. Furthermore, driving during the crisis was confined to shorter distances. Finally, by using the results of the waiting-price calculations, measurements of the cost of the nonprice rationing of gasoline determined that it averaged about $27/driver.

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

Simple Analytical Model for Understanding Gasoline Station Lines

VICTOR PRINS, ROBERT A. WOLFE, AND STEVEN R. LERMAN

Recent gasoline shortages have necessitated a better understanding of queues at gasoline stations and how to minimize their lengths. This paper is an attempt to model the gasoline-line phenomenon and to predict the effects of various policies on factors such as mean waiting time, quantity of gasoline purchased, hours that stations are open, and mean frequency of visits to stations. This is achieved through the use of a Cobb-Douglass demand equation and, simultaneously, an equation that represents "topping-off" behavior. No comprehensive data were available to estimate the model; therefore, the model was calibrated judgmentally. Policy tests should be seen in this light. Preliminary indications are that the use of odd-even gasoline rationing minimizes aggregate wait time as well as wait time per visit more than do minimum or maximum purchase plans. This paper represents more of a framework of analysis than econometrically acceptable results. The model, although simple, is elegant and produces logical results.

During June 1979, Americans again experienced the frustration of waiting in line to buy gasoline for their automobiles. Even the trend toward smaller, more fuel-efficient automobiles (which was accelerated by the first oil crisis) was not enough to prevent the occurrence of another gasoline crunch. Politicians were caught by surprise, and governments hastily developed policies to alleviate the inconveniences suffered by their irate citizens. Much to the relief of the governments, they found that whatever policy they adopted, it worked. Gasoline lines soon began to disappear as mysteriously as they had appeared.

Since accurate data on available supplies during that period are hard to find, it is difficult to determine whether gasoline lines disappeared due to government action or simply due to an improvement in supply. Since the problem may occur again, research efforts should be directed toward a better understanding of how and why gasoline lines form and toward developing models that could predict the effect of various policies on the gasoline-line situation should another (possibly more prolonged) supply shortage occur.

There is at least one serious obstacle to building a good model of the formation of gasoline lines--the lack of available data on which to calibrate a model. However, in real life, most decisions are based on the incomplete data on hand, and the situation is therefore not unique.

This paper is a modest attempt to use existing knowledge, of both a theoretical and a practical nature, to set up a model that would facilitate a better understanding of the complex phenomenon of gasoline lines. It is a beginning and not an end; however, there is some elegance in its simplicity.

The approach followed in this paper is to build what Manheim (1) terms a "judgmentally estimated model". By combining microeconomic theory with professional judgment on the selection of important variables, much can be learned from the process as well as inferred from the results even without an available full data set.

The procedure followed in this paper was to formulate a simple set of equations that reflect gasoline purchase behavior and to judgmentally estimate the model. The estimation was done by first using parameters, such as estimated elasticities, that are available from prior studies. Next, the conditions that existed immediately after the worst of the crisis was over were used as a point for which the model had to be valid. From this, inferences could be drawn with regard to the relationships between parameters. An extensive sensitivity analysis was then done on both unknown and known parameters. The final selection of parameters was based on the model's ability to reproduce known conditions as well as the plausibility of its general behavior.

The paper is concluded with a discussion of the model results for various policies used during the previous energy shortage: (a) an odd-even plan, (b) a maximum purchase plan, and (c) a minimum purchase plan. A pricing policy is also treated.

BACKGROUND

Although generally transient in nature, severe queues for gasoline are perhaps the most publicly visible manifestation of what has been loosely termed the energy crisis. Given the dependence of the U.S. transportation system on the private automobile, gasoline shortages typically create enormous economic and social disruptions. At a minimum, these disruptions result in high economic costs (see paper by Dorfman and Harrington in this Record); at the worst, violent crimes are associated with gasoline lines.

In order to understand the formation of gasoline lines at the qualitative level, one must first recognize that the queues for gasoline serve a significant (albeit inefficient) function. In the recent shortages, the queues for gasoline have provided the basic short-run mechanism through which gasoline has been rationed.

In the short run, the supply of gasoline to service stations is, for practical purposes, fixed by federal allocation formulas and oil company delivery schedules. Maximum pump prices are regulated by using formulas that reflect estimated production and acquisition costs, not the demand for gasoline. If under these conditions the available supply of gasoline suddenly is curtailed to a level less than the equilibrium volume at the regulated price, some nonprice mechanism for clearing the market will operate. In the absence of any governmental action (e.g., relaxation of price regulation, restriction of operating hours, or rationing), the most typical mechanism is for queues to build up. Essentially, people pay more for gasoline through a time (rather than monetary) cost that is high enough to clear the aggregate, short-run market for gasoline.

Given this perspective, a number of questions are relevant to policy:

1. What is the social cost of allowing queues to serve as the basic market-clearing mechanism?
2. Are alternative mechanisms available for clearing the market that are more cost effective?
3. What is the effect of alternative mechanisms for clearing the market on various segments of the population?

Dorfman and Harrington estimated that the cost of using queues to clear the gasoline market in an urban area is significant. The obvious solution of allowing prices to perform their usual market-clearing function has been widely rejected by the political process, particularly as a response to the very short-run shortage problems manifested in long gasoline lines.

Other strategies have been oriented toward reducing the number of visits to stations per liter of gasoline purchased. These plans all involve some form of minimum purchase or limited access to stations (e.g., odd-even plans). In an analysis of the effect of such strategies, one must explicitly recognize that lines can be reduced only by imposing some cost (monetary or other) that reduces the demand for gasoline to equal the current, fixed supply. Such costs can include reduced access to stations (the effect of odd-even plans).

The above discussion suggests that, in modeling the demand and market clearing of the gasoline market, one must incorporate measures of nonpecuniary cost into the demand function. Thus, the traditional notion of a demand function for gasoline must be extended to include wait time and availability. Nonpecuniary costs always influence demand, but in most typical situations they can be ignored since they are small and relatively uniform for the entire population. Only when gasoline queues are significant factors in clearing the market should these variables be explicitly modeled.

MODEL STRUCTURE

Before proceeding with a detailed description of the model, some assumptions of the analysis should be stated. First, market forces will be assumed to clear the market for gasoline. In the case where the dollar price of gasoline is artificially restricted to a price below the equilibrium market price, the consumer will have to pay the additional price in some other form, such as waiting time in line. Second, the model is aggregate in the sense that expected values of variables are used rather than disaggregate individual observations. This does not imply that all consumers are expected to have the same values for the different variables, since individual consumers might have values that vary around the expected values. Third, the model is applicable to an urban area in which gasoline stations are distributed proportionally to population. The actual size of the area under consideration is not important.

On the model's supply side, the allocation of gasoline to the area under consideration is assumed to be fixed--the amount is determined by forces outside the area, such as government allocation rules. This amount is then divided among the gasoline stations in the area. Because the supply of gasoline is limited, all gasoline will be consumed and each consumer (defined here as an automobile owner) is expected to obtain a fraction of the gasoline. Mathematically, this can be stated as follows:

$$Q = mq = Pu \qquad (1)$$

where

Q = allocation of gasoline per day to the area under consideration (L),
P = automobile population in area,
m = number of gasoline stations in area,
u = use rate per vehicle per day (L), and
q = average allocation per station in the area (L).

From Equation 1 follows

$$u = (m/P) \times q \qquad (2)$$

The above equation implicitly assumes that owners of gasoline stations ration their monthly supplies to a daily schedule.

The demand side is more complex and the following demand function is proposed:

$$u = \beta_0 \times C^{\beta_1} \times \mu^{\beta_2} \times n^{\beta_3} \times t^{\beta_4} \qquad (3)$$

where

C = cost per liter of gasoline ($),
μ = mean waiting time in line per visit (min),
n = expected number of visits to gasoline stations per day, and
t = average number of hours per day that gasoline stations are open in the area.

β_0, β_1, β_2, β_3, and β_4 are coefficients. Equation 3 assumes that various factors influence the demand for gasoline.

Cost of gasoline enters the demand function as expected. As price is increased, demand will decrease, and β_1 can therefore be expected to be less than zero.

It is postulated that waiting time in line to purchase gasoline will also influence the demand for the gasoline. An increase in waiting time can be expected to cause a decrease in demand if everything else is kept constant. It is further postulated that not only is waiting time important but also the number of times a consumer has to wait in line. Again, one would expect demand to drop with an increase in the number of trips, if everything else is kept constant. Therefore, β_2 and β_3 are expected to be less than zero.

The last variable used in the demand function is t, the number of hours per day that each gasoline station is open. This measure is an indication of schedule flexibility available to the consumer. If gasoline stations should open only on weekdays between 8:00 a.m. and 12:00 p.m., for example, this would severely limit the customer's flexibility in buying gasoline and, therefore, will also restrict his or her ability to make trips. The variable also serves to reflect risk aversion by drivers, so it can be expected that, as station hours become shorter, people will tend to conserve the fuel that they have due to the uncertainty of availability reflected in the short station hours. As station hours decrease, consumption will decrease (given that everything else stays constant), and β_4 can therefore be expected to be greater than zero.

In order to link the station hours to the shortage of gasoline, we postulated that stations only stay open every day until that day's allocation is sold. During that period, the service station is also constantly busy and people wait in line to be served. This means t is equal to the product of the vehicles that visit a station per day and the average service time per vehicle. Mathematically,

$$t = (P \times n/m) \times (1/\lambda) \qquad (4)$$

where λ = service rate in vehicles per hour.

In the demand equation there is some interaction involved between the left-hand side (u) and the right-hand side that is not immediately apparent:

$$n = u/x \qquad (5)$$

where x = number of liters of gasoline purchased per visit.

The measure x is set by each consumer according to his or her taste and his or her perception of the gasoline shortage. It is postulated that x is influenced by the total time spent waiting in line per time period and the hours that gasoline stations are open. Mathematically, this relationship is presented as follows:

$$x = \alpha_0 + \alpha_1 \times t + \alpha_2 \times (\mu \times n) \quad (6)$$

where α_0, α_1, and α_2 are parameters.

The functional form of this equation was assumed, for simplicity, to be linear. Obviously, any other functional form might also be appropriate. The linear form, with positive parameters α_0, α_1, and α_2 implies a decrease in purchase size (x) with a decrease in station opening time and an increase in purchasing size with an increase in waiting time. This is in accordance with what is expected to happen in the real world. As gasoline supplies get more and more uncertain (t gets smaller), the motorist is expected to "top off" more regularly, hence the smaller x. However, for each visit the consumer makes to the gasoline station, there is a wait time. To minimize the wait time, the consumer can be expected to buy more gasoline per visit, hence an increase in x. There is also, therefore, a trade-off between these variables. This trade-off, as well as the fact that lines can be avoided altogether by not driving, is represented in the demand function. By solving the system of equations, the unknown variables t, x, n, and μ can be solved for as functions of q, P, m, λ, and the parameters.

MODEL ESTIMATION, BEHAVIOR, AND SENSITIVITY ANALYSIS

Since no data were available to econometrically estimate the α's and β's, the model parameters could not be estimated by conventional techniques, and a method of judgmental estimation was adopted. In such situations, a combination of previously reported conclusions, a priori expectations, and intuition are combined. This procedure, although far from ideal, can provide useful insights into the process under study. It should be further noted that frequently data are not available when real-world policy decisions need to be made and, by using judgment to estimate a model, some structure may be imposed on an otherwise unstructured decision-making process.

Returning to Equation 3, one is able to treat the coefficients β_1 through β_4 as elasticities of consumption with respect to their respective variables. Initially, signs and expected ranges can be assumed for their values as follows.

1. There is a considerable literature that attempts to estimate the elasticity of gasoline consumption with respect to price. Available estimates range from 0 to -0.9 with the figure of -0.15 most often cited in the literature [Charles River Associates (2)].
2. As stated earlier, β_2 and β_3 are expected to be negative, and it is now further assumed that they are set such that the elasticity with respect to mean waiting time and with respect to number of trips made are greater in absolute value than the elasticity with respect to price. This assumption is based largely on inferences from various mode-choice studies [e.g., Lisco, Lave, and McGillivray (3-5)].
3. It was also felt that consumers are more sensitive to mean waiting time than to number of trips. Hence the β_2 and β_3 coefficients were assumed to be in the range of -0.15 to -0.20, with β_3 closer to the more negative extreme of the range than β_2.
4. Finally, the elasticity of consumption with respect to hours that a station is opened was assumed to be relatively low and would be in the area of +0.10.

In order to set β_0, a point on the demand curve was selected that was assumed to simulate the non-gasoline-crisis situation. This value is denoted by an asterisk. Hence mean waiting time (μ*) was set to 6 min, x* to 30 L/visit, u* to 7.5 L/vehicle per day, (P/m)* to 1000 vehicles/station, C* to $0.26/L, and λ to 20 vehicles/h. This leads to a value for t* of 12.5 h/day and a β_0 of 3.19.

Similarly, in Equation 6 one can interpret α_0 as approximately the average amount of gasoline a consumer would typically purchase if there were no crisis, and this could range from 19 to 38 L/visit. The remaining coefficients, α_1 and α_2, can both be expected to be positive. Remember that for the base-case (existing) conditions the number of hours the station is open (t*) is large and the expected waiting time in line (μ*) is small. A decrease in station hours would therefore be expected to lead to a decrease in refill level (x), mostly due to the uncertainty and schedule inflexibility that accompany reduced station hours. This requires a positive α_1.

However, as station hours decrease, waiting time increases and one would expect the amount purchased to increase, since the consumer would rather make fewer visits to the gasoline station to prevent waiting. This requires a positive α_2.

It is difficult to predict exactly what the values of α_1 and α_2 should be and, as a starting point, values were obtained subjectively. This was done by (a) constructing typical cases for the independent variables, (b) hypothesizing the likely response in x, and (c) fitting α_1 and α_2 to those hypothesized responses. Note that subsequent sensitivity analysis on the values of the α's indicated the model to be very insensitive to the chosen values.

In order to arrive at final values for exogenous variables and the coefficients, each coefficient was varied iteratively, and the effects on the model were observed. Coefficients were selected such that a priori decisions regarding model behavior were not violated. (Given the exploratory nature of this model, the actual predicted values are not as important as the qualitative behavior of the model as a whole.) The final selection of coefficient values is shown in the list below.

β_0 = 3.19,
β_1 = -0.15,
β_2 = -0.18,
β_3 = -0.20,
β_4 = +0.07,
α_0 = 19.00,
α_1 = 0.95, and
α_2 = 22.80.

When they are set as in this list, the model behaves as follows: As allocations per station (q) decrease from the base-case values of 7600 L/day,

1. The amount of gasoline purchased (x) initially drops, as the number of hours that stations are opened decreases; when supply (q) is low, there is some topping off and consequently x will be small but, as q becomes even smaller, people will want to buy more per visit in order to minimize the number of visits in all as the waiting time for each visit becomes excessive;
2. The hours that stations are open (t) also decreases;

Figure 1. Wait time and purchase size as allocation varies for the do-nothing scenario.

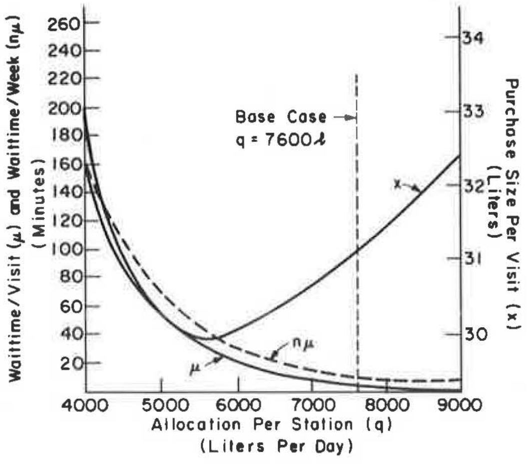
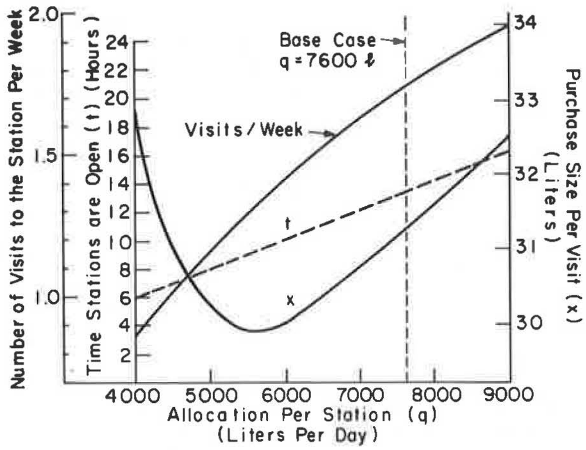


Figure 2. Purchase size, station hours, and visits per week as allocation varies for the do-nothing scenario.



3. Mean waiting time (μ) increases; and
4. The number of visits (n) decreases.

Also, as cost increases,

1. μ and x decrease and
2. t increases slightly.

POLICY ANALYSIS

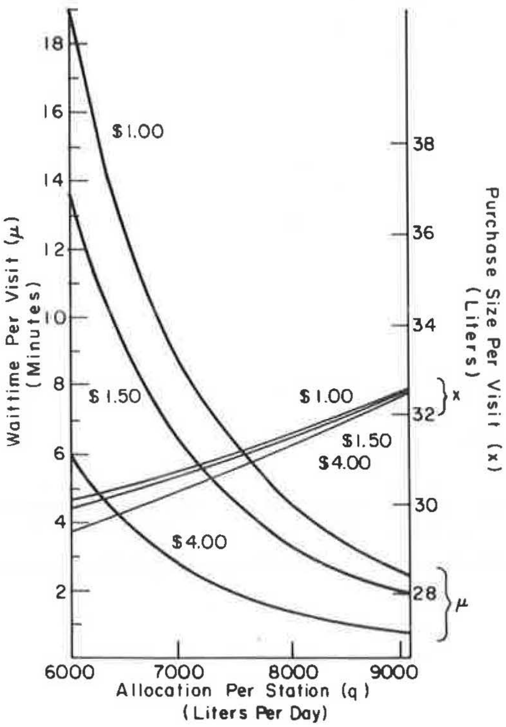
The model was designed so that it could be used to test the relative effects of various gasoline-supply policies, some of which were in effect during the gasoline crisis of spring 1979. Specifically, the tests include

1. The raising of the price of gasoline,
2. Minimum and maximum purchase plans, and
3. Odd-even rationing.

Other types of rationing (for example, coupon rationing) could not be tested due to their complexity.

First, it is necessary to analyze what happens as the allocation per station (q) varies, particularly when no policy is in effect. Essentially, this is what happened during the recent crisis, before government intervention and, therefore, this can be termed the do-nothing scenario.

Figure 3. Wait time per visit and purchase size as a function of station allocation for different prices per gallon.



Figures 1 and 2 depict what occurs as q decreases. As stated earlier, allocations of about 7600 L/station per day are assumed to be the base-case or noncrisis situation.

In Figure 1, as q decreases, mean waiting time per visit and total waiting time both begin to rise. At the same time, the amount of gasoline purchased drops, and in Figure 2 the number of visits and hours that a station is open both fall. Here, less gasoline is being purchased, less is being used, and waiting time increases. This seems to indicate that the topping-off phenomenon is simulated in this model.

As supplies of gasoline become much lower, waiting time begins to increase drastically; hence, for every visit, consumers will want to buy as much gasoline as they can. Because less gasoline is being sold, the hours that a station is open continue to be less than in the base case. Conversely, as allocations per station increase over the base case, mean waiting time falls, more gasoline is used, and more is purchased per visit.

Increasing Price of Gasoline

One would expect that, as the price of gasoline increases, waiting time (μ) and the amount of gasoline purchased per visit (x) would decrease. This is indeed the case, as shown in Figure 3. If one examines the base-case situation where 7600 L are allocated per station, μ drops quickly as price increases. Gasoline purchases per visit do fall but not dramatically. Not shown in Figure 3 for this example is that the number of visits per week and hours that stations are open both increase but not enough to have a significant impact on the results.

Also shown in Figure 3 is the impact of both changing price and allocation per station. As allocations decrease, the differences between the variables at different prices appear to diverge. In

Figure 4. Wait time per visit and purchase size as a function of allocation and maximum and minimum purchase policies.

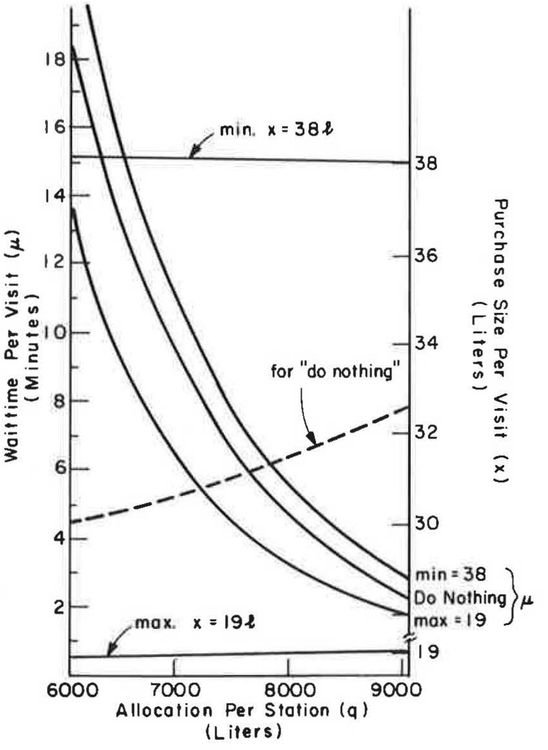
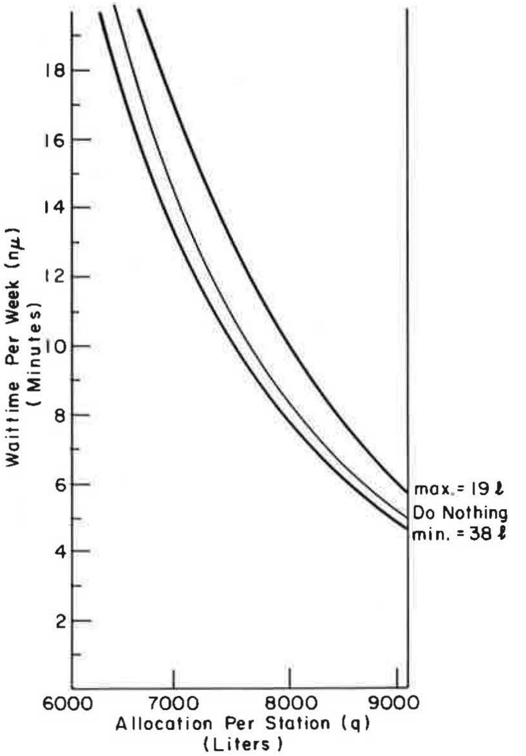


Figure 5. Wait time per week as allocation varies for maximum and minimum purchase policies.



other words, as price increases and allocations decrease, μ and x become increasingly small. This is not entirely intuitively obvious, but, as allocations fall, less gasoline is used, so this

Figure 6. Visits per week as allocation varies for maximum and minimum purchase policies.

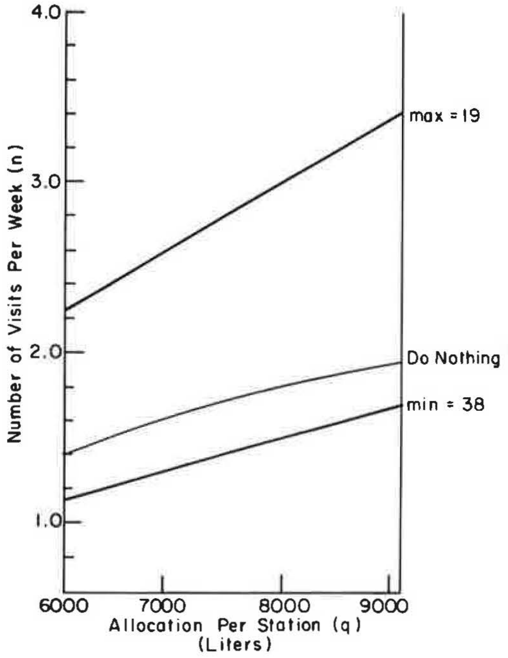
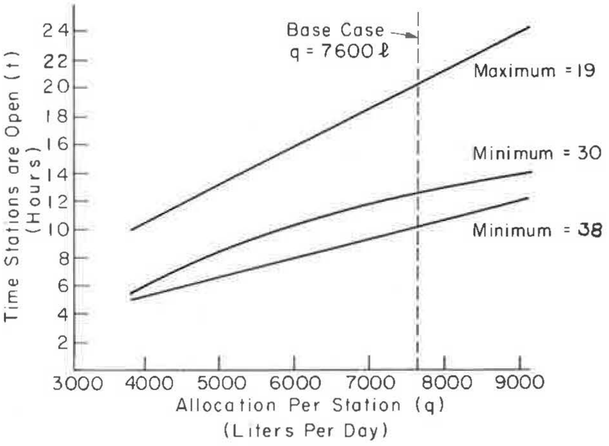


Figure 7. Time stations are open as q varies for maximum and minimum purchase policies.



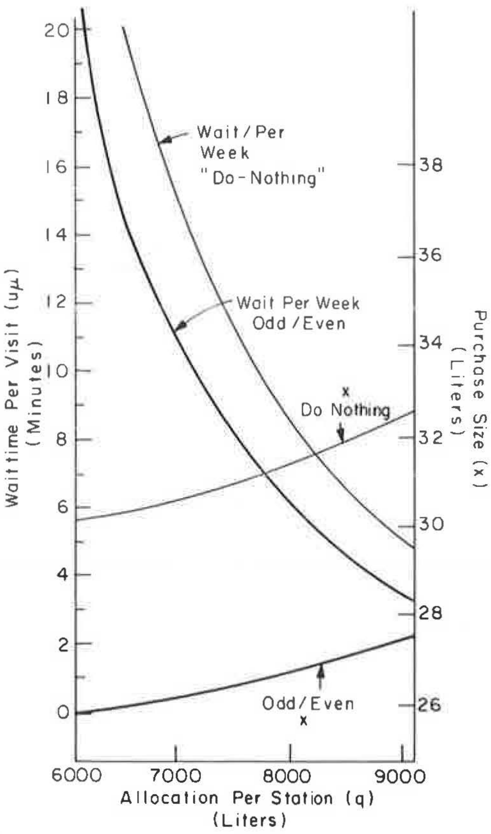
fact combined with smaller purchases per visit and increasing price cause μ to fall more than it would otherwise.

Minimum and Maximum Purchase Policies

During the recent gasoline crisis, numerous retailers and several governments instituted one form or another of maximum or minimum purchase plans in hopes that gasoline lines would become shorter. Such policies can be simulated by this model and compared with the do-nothing policy results. Figures 4-7 describe various aspects of this simulation for a maximum purchase plan of 19 L and minimum purchase plans of 30 and 38 L.

Figure 4, which graphs the effects of this policy, is presented for later comparison with similar graphs for other policies. It shows that, at a given q, the least waiting time per visit is when a maximum plan of 19 L is in effect. This is

Figure 8. Wait time per week and purchase as allocation varies for the odd-even plan.



immediately counterintuitive, because one would expect that lines would be long because consumers would return frequently for more gasoline. On the contrary, one would expect the minimum purchase plan of 38 L to be the best.

By comparing total waiting time and number of visits per week (Figures 5 and 6), the issue becomes more clear. Although there is little difference in the total waiting times for a given q, the maximum plan is worse than the minimum plans or the do-nothing approach. Although not graphed, this observation is more pronounced at extremely low allocations of gasoline.

The final piece of evidence that places this issue in perspective is the hours per day that stations are open (Figure 7). It seems that waiting time per visit can be so low for the maximum purchase plan because drivers must make more visits per period than for other options.

Of the three policies presented, the minimum purchase plan of 38 L seems to be most appropriate because it limits total waiting time and the hours stations must be open to a reasonable level under all allocation levels.

Odd-Even Rationing

Odd-even rationing is a method by which consumers may be barred from purchasing gasoline on a given day depending on a digit of their vehicle's license plate. Essentially, this means that, for any given consumer, stations are perceived to be open only half the total hours per day. This decrease in t (as perceived by each individual) induces smaller purchases per individual but also reduces queues at the station needed to reduce demand to the available supply. Given the parameters chosen for the model, the net effect is a reduction of total wait time per week.

The results of the model for different allocation levels are presented in Figure 8.

Comparison of Policies

Even though this model was estimated judgmentally, some guarded statements can be made with regard to the relative merits of the various policies tested.

It is clear that the higher the price of gasoline, the shorter gasoline lines will be, but there is evidence from European experiences and from activity during the American gasoline crises that indicate that, in the short run, higher gasoline prices may not curtail consumption as much as was previously believed. In other words, the population does not necessarily have a constant elasticity of consumption with respect to price, as is assumed by this model. Therefore, the results of the price simulations must be examined with this thought in mind.

If a policymaker were forced to choose among maximum or minimum purchase plans or odd-even rationing, the results of these simulations imply that odd-even rationing yields lower total waiting time. Given the political infeasibility of enormous short-run price changes and all else considered, the odd-even plan seems to be relatively better than the others tested with this model.

FUTURE DIRECTIONS

The model developed in this paper is a first attempt to represent the formation of gasoline lines as a result of the supply-demand interaction. Given the paucity of existing data, the first priority in improving the model is the collection of information on traveler behavior both before and during serious, short-run gasoline shortages. Such data, in the form of vehicle logs or traveler diaries, have been collected in the past under normal circumstances. Other information, such as measurements of q in the model, is easily collected. The key to obtaining such data during periods of shortage is to prepare for the data collection in anticipation of a future shortage and to implement the plan immediately on occurrence of a shortage. Such data would provide the basis for rigorous estimation of the demand function and the equation for x and would provide some greater assurance regarding the appropriateness of the chosen functional forms.

A second area for potential extension of the model is disaggregation of the population. Different socioeconomic groups will be affected quite differently by various policies. The current model provides no insight into the incidence of the impacts. By either estimating different demand functions for different socioeconomic groups or incorporating socioeconomic variables (particularly income) into the demand equations, the relevant impacts could easily be forecast for different segments of the population.

A third potential area for further work is the incorporation of dynamic effects into the model. In a situation that occurs as quickly as the formation of a gasoline line, people adjust dynamically to a rapidly changing environment. It is quite possible that some of the lines are the result of drivers' increasing the amount of gasoline they carry in their tanks to levels greater than normal, thereby, in the short run, reducing dealers' inventories. Such effects would obviously be transitory, since each individual's shortage capacity is limited. It would be useful to be able to predict such responses over time and to better understand how they influence the length of queues.

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

Review of Analytical Models of Gasoline Demand During an Energy Emergency

WILLIAM B. TYE

This paper provides a framework for evaluating various proposals for reducing the costs of queueing for gasoline during energy shortages. Two types of proposals have been offered to address the problem: queue-management techniques, such as minimum or maximum purchase requirements, and demand-managment techniques, such as improved transit service or bans on weekend sales of gasoline. The paper starts with the presumption that three bodies of literature are relevant to the problem: (a) literature on wartime hoarding and speculative demand, (b) literature on congestion pricing, and (c) literature on inventory managment and transport cost trade-offs. Which of these bodies of literature is the dominant determinant of public behavior during gasoline shortages to a large degree determines the success of any proposed policy recommendation. For example, if the congestion cost imposed by waiting in line is necessary to equilibrate the total supply and demand for gasoline, queue-management techniques will be self-defeating, because reduced congestion costs only encourage more demand and reestablishment of the equilibrium. If speculative demand is a large factor in explaining shortages, controls on purchase size could reduce total demand, free up inventories in tanks for consumption, and reduce the length of queues. If the inventory cost-transport cost model prevails, lengthy queues will discourage speculative demand and lead to recommendations for demand management such as carpooling incentives and improved transit service. Without an adequate time-series data base to monitor the public's behavior during a crisis, a definitive policy recommendation is not possible and the debate will not be resolved. Based on the present state of knowledge, a combination of minimum purchase requirement and demand suppression (especially of the "carrot" variety through improved transit service and carpooling) is recommended. Even-odd plans do not have a sufficiently plausible conceptual rationale to make it likely that they will improve queueing costs materially.

The paper first identifies behavioral principles that are relevant to the issue. It concludes with suggestions for future research.

BEHAVIORAL PRINCIPLES RELEVANT TO EXPLAINING CONSUMER BEHAVIOR DURING AN ENERGY EMERGENCY

Literature on the economics of demand provides three precedents for understanding how automobile drivers will respond to gasoline shortages. Before this literature is reviewed, however, note that the gasoline queueing that we are examining is a relatively temporary phenomenon. Lines result from the domestic price controls that prevent suppliers from taking advantage of the shortage to raise prices. However, the price at the pump is a weighted average price from various suppliers, designed to spread the effects of price controls evenly over suppliers and consumers. However, the consequence is that gasoline lines are a signal to the Organization of Petroleum Exporting Countries (OPEC) that prices are too low. Experience has shown that world oil prices and domestic pump prices rise after a relatively short lag, and eventually prices are raised to eliminate the queues. Any proposals to eliminate queues must recognize, therefore, that the cost will be large but temporary under current regulatory mechanisms.

The first body of literature relevant to the issue is that on wartime hoarding and speculation. Keynes identified speculative demand as a major element of instability in a market economy (1). The current price of a commodity and the history of price changes create destabilizing expectations of further price changes. Where there is great uncertainty regarding the future terms on which a commodity is available, this speculative demand leads to boom and bust cycles.

However, in the case of gasoline demand, there is a limit to the magnitude of speculative demand caused by the size of a gasoline tank. Speculative demand can be affected by "topping off," but a limit is imposed by the size of the tank and the increase in waiting time per gallon caused by more frequent fill-ups. Once such demand is satisfied, there may be a tendency for lines and expectations to stabilize, which will lead to tank inventory reductions and actual decreases in lines. Any theory of demand must, therefore, distinguish between gasoline demand for consumption and demand for hoarding and between purchase decisions and consumption decisions.

The second body of relevant literature is that on congestion pricing (2,3). An external economy is imposed by congestion, which arises from the fact that each individual who joins a queue does not take into account the fact that service for that individual imposes costs on other users. Depending on the circumstances, an extra individual who joins a congested facility may impose additional waiting time on other users that is many times more than his or her own waiting time. This additional waiting time is a social cost, or deadweight loss, not offset by benefits to any users. Therefore, any proposals to discourage use of congested facilities must account for the benefits of reduced congestion on other users as well as the affected individuals.

The third parallel is the traditional trade-off among inventory stock, purchase size, and transportation cost, which is well known in the literature of economics and logistics. As the threshold transportation cost of adding to inventory rises, there is a strong motivation to increase order size and reduce the number of orders, thereby reducing transportation costs per unit. In the case of gasoline, increases in waiting time per visit (a threshold cost of buying not dependent on purchase size) would encourage the purchase of more gallons per visit (if gasoline were expected to be available on comparable terms in the future) in order to minimize waiting time per gallon.

EVALUATION OF POLICY PRESCRIPTIONS IN LIGHT OF THE PRINCIPLES

Sensible public policy for dealing with queues should be designed to minimize waiting time per gallon by the least costly means available, because this is a cost imposed by price controls in the presence of a shortage. Other things being equal during a shortage, anything that maximizes purchase size per visit will reduce waiting time per gallon. Since waiting time per visit does not depend on size, a minimum purchase plan would ordinarily achieve the intended objective; it would reduce or eliminate speculative demand and spread the fixed waiting time per visit over more gallons for each visit. For an analytical demonstration of this common-sense conclusion see Daskin and others (4), who demonstrate by the use of queueing theory that very small changes in average purchase size can have very large effects on average waiting times in their model. This conclusion is in part dependent on their assumption that demand is completely inelastic with respect to average waiting times. The paper by Daskin and others is an interesting application because mean waiting time is represented as a U-shaped function of mean purchase size that does not incorporate speculative demand. Very large purchase sizes cause increased waiting time because service time is a function of purchase size in their model.

There are several caveats. First, the policy objective may be to spread available supplies more evenly among the consumers, which calls for a maximum purchase policy despite the fact that it increases wait time per gallon. Second, if, as implied by the Dorfman and Harrington paper in this Record, waiting time per gallon is endogenous and will return to whatever level is required to equilibrate supply and demand, it will be impossible to reduce waiting time per gallon in this manner.

If one does not accept the view of Dorfman and Harrington, the public's response to shortages and the most appro- priate strategy for dealing with the congestion costs depend greatly on which of the two behavioral principles--speculative demand or inventory theory--holds the greatest power over consumers.

For example, if speculative demand is extremely powerful and if the magnitude of the speculative demand is large relative to available supplies, a strong case can be made for any policy that increases purchase size per visit, such as a minimum purchase requirement. If the magnitude of the hoarding is relatively small, on the other hand, the case can be made that hoarding will soon reverse itself when lines stabilize.

If consumers respond to rational inventory theory, individual behavior will be consistent to some degree with the public interest. Consumers will act to minimize wait time per gallon and will actually reduce inventories in the face of lines. The issue then becomes whether the entire system will equilibrate to a lower level of wait time per gallon.

In any event, such socially responsible behavior would point toward the value of overall demand-management techniques rather than techniques designed to influence average purchase size. Such demand-management techniques would be justified on the grounds of the second principle, that of externality. Further, the appropriate test of demand management is whether the net costs of providing a transportation alternative or the costs imposed as a result of inconveniencing some gasoline users are less than the benefit of shorter lines derived by other motorists.

The three principles point to considerable confusion over the effects of the even-odd rationing plan. Motorists may be able to adjust inventories to compensate for the policy; therefore, even-odd works only if it reduces consumption or speculative demand. Consumption will be affected only for multiple-day trips or for drivers who consume more than half a tank daily, which is not likely to be a significant volume. It will reduce speculative demand for vehicles that do not qualify on a given day but will probably increase it for those that do qualify because the motorist knows that gasoline must last two days. The net effect is unclear.

REVIEW OF SELECTED LITERATURE ON MODELS OF GASOLINE DEMAND DURING AN EMERGENCY

The literature on these issues reflects our ignorance of appropriate methodology and policy recommendations. The discrepancies appear to be centered around these controversies:

1. Whether public policy should encourage increased or decreased purchase size per visit during a shortage through maximum or minimum limits;
2. Whether shortages naturally increase or decrease average purchase size with no regulatory intervention;
3. Whether demand management or queue management is the most-appropriate strategy, which in turn depends on whether the waiting time per gallon depends only on the aggregate supply and demand for gasoline and therefore is a constant regardless of queue-management techniques;
4. Whether even-odd plans can affect the demand for gasoline and queues and, if so, how; and
5. Whether speculation can materially affect automobile tank inventories and average purchase size (topping off).

The policymaker can find support from experts in the transportation planning literature for both sides of each issue. Until the experts can agree, or at least until they can agree on why they do not reach the same conclusions, research is likely to have limited impact on policy.

Turning first to the issue of the effect of shortages on average purchase size--a key behavioral relationship--the paper by Prins and others in this Record specifically addresses the issue. As such, it is a useful start in understanding this critical behavioral relationship. The paper makes a very useful distinction between x, a variable that measures average purchase size per visit, and u, a measure of gallons per day consumed. There are three possible relationships between x and μ, the mean waiting time per visit. The paper by Prins and others hypothesizes a U-shaped relationship of average purchase size as a function of shortages, which implies that small shortages encourage topping off and reduced gallons per visit but that large shortages encourage increased gallons per visit in order to minimize waiting time per gallon as lines lengthen (see Figure 1 in Prins and others). [Daskin and others (4) show that the same result can come entirely from supply-side dynamics of queueing, as noted above. Their model, in fact, assumes that demand is independent of waiting time.] Alternatively, the relationship may show declining purchase size with increased waiting time, which shows increased hoarding as lines lengthen. This relationship cannot continue, because the increasing waiting cost per gallon must ultimately eliminate speculative demand.

The relationship may, however, show increased purchase size with increased waiting time for all levels of shortage. This result would be consistent with the dominance of the inventory model, where increased waiting time encourages less-frequent fill-ups and larger purchases per visit.

Since the hoarding model and the inventory model give exactly opposite results, future research must identify which influence prevails and under what conditions. If different and inconsistent behavioral relationships exist, the reasons should be identified.

Demand models of the variety proposed by Prins and others should incorporate the following:

1. Make the demand function for gallons depend on waiting time per gallon and make the purchase size per visit function dependent on waiting time per visit,
2. Distinguish explicitly between demand for current use and speculative demand, and
3. Place a limit on average purchase size that depends on tank capacity.

The paper by Prins and others endorses the even-odd plan on the grounds that motorists "perceive twice as much gasoline supply as they would otherwise." However, their model implies that "consumers will purchase less gasoline more frequently," but total waiting time will be reduced. The basis for this conclusion is difficult to understand, because a reduction in average purchase size would normally make things worse and, in any event, it is not clear why their model would predict such a response.

The answer apparently lies in the dual effect of the reduced station openings. The availability of gasoline is reduced because a consumer can purchase gasoline with only half the convenience. There are two effects assumed: demand for gasoline is reduced because of decreased gasoline availability, but average purchase size declines because of greater incentives for topping off. [The paper by Daskin and others (4) concludes just the opposite, that "the odd-even plan has the important advantage of preventing drivers from topping off their tanks every day."] The paper by Prins and others assumes that the first effect is dominant, so that the queue-reducing effects of demand suppression more than offset the queue-increasing effects of topping off. The paper illustrates the problems of merely trying to minimize wait time per gallon, since the cost of the shortage is shifted from wait time to decreased availability of open stations. In any event, there is no certainty that the demand reduction will more than offset the effect of increased topping off. The paper by Mahmassani and Sheffi in this Record, in fact, predicts just the opposite from that of Prins and others, namely that the even-odd plan will worsen queues. Their conclusion, however, does not follow from the model itself. In future research, the authors might consider changing the modeling assumptions that (a) motorists drive until they find an open station, (b) openings are random, and (c) the equilibration mechanism works through opening and closing of stations. Drivers often only change their routes in search of gasoline, stations often sell out in the early part of the day, and wait time per gallon (as the equilibrating variable) is more easily integrated into existing demand functions.

The paper by Dorfman and Harrington in this Record, on the other hand, implies that there would be no effect from the policy, since lines would form to equilibrate supply and demand. The Dorfman and Harrington paper presents an extremely interesting format for evaluating alternative policies to reduce waiting time. The paper's focus on demand entirely makes an interesting comparison with the paper by Daskin and others (4). The latter is entirely supply oriented, and demand is assumed to be completely inelastic with respect to waiting time. The result is extreme sensitivity of average waiting time to average purchase size. In Dorfman and Harrington, waiting time per gallon depends on demand elasticity and is not dependent on average purchase size.

As the analysis of Mahmassani and Sheffi shows, anything that increases demand elasticity is likely to improve the situation (since inelastic demand is what causes small supply shortfalls to cause larger lines). The Dorfman and Harrington approach is to accomplish this objective by suppressing demand, either through the stick (banning off-road use of gasoline and uses on certain days of the week) or the carrot (improved carpooling opportunities). Evaluation of this policy depends on whether the model is supply-oriented or demand-oriented. Dorfman and Harrington see potential benefits. Daskin and others (4) argue that Sunday closings would almost double waiting time because demand is not substantially affected and more cars would be competing for the gasoline during the rest of the week. The essence of the Dorfman and Harrington approach is to try to eliminate the least-valuable uses of gasoline, that is, those that would have been squeezed out if the price mechanism had been allowed to operate.

Although elimination of demand for these marginal uses will be the most cost-effective means of reducing demand (i.e., it attempts to approximate the market mechanism), in actual practice many other second-best techniques will probably also prove to be cost effective. Any diverted gasoline demand generates benefits of reduced waiting not only for the individual motorist but also reduces waiting time for other users (after consideration of the equilibration effect on demand that results from lower waiting times). This external economy creates a situation in which many reasonable public policies to reduce the demand for gasoline (a shift to the left in the demand curve) will be cost effective. The benefit of reduced congestion that results from an individual's decision to not join a line is much greater than the value of the forgone gasoline, which implies a much stronger endorsement for demand reduction than that suggested by the paper.

To be sure that some extremely valuable uses of gasoline are not prohibited, voluntary policies that involve the carrot would ordinarily be preferred over those that involve the stick. The latter could prohibit uses that have extremely high value. Stick policies have the disadvantage that they run the risk of serious departures from the welfare optimum in a competitive economy, namely that gasoline might have substantially different incremental value in differing uses. As Dorfman and Harrington point out, the proper comparison is the consumer surplus lost on the prohibited use or the cost of supplying the alternative service with the value of the reduction in waiting time. The loss of consumer surplus would ordinarily have to be quite large to offset the large social benefit of reduced waiting time in the system. No doubt a cost/benefit analysis would justify significant net benefits for a wide variety of demand-suppression techniques, especially when lines become quite lengthy.

The paper by Lee in this Record follows up the Dorfman and Harrington work to assign actual waiting time costs for gasoline by means of a time series and cross-section analysis. However, a major point of difference between the two approaches emerges. The Dorfman and Harrington paper illustrates the fact that, whatever its faults, queueing at least equates the total congestion cost for gasoline everywhere in the system. In other words, reallocation of gasoline from one place to a more desired place and improvement of the public welfare is not possible. (If consumers have different values of time, available supply could be efficiently reallocated, however.) The Lee paper, however, hypothesizes significantly different total prices (money and waiting) for different uses and different markets. Moreover, the Lee analysis concludes that the greatest value for gasoline is for use on rural and recreational facilities. The rationale for evaluating various restrictions in the Dorfman and Harrington paper would imply that public welfare could be improved (if one accepts Lee's results) by diverting gasoline use from commercial-commuting facilities to recreational-rural facilities. The author hypothesizes that substitutes are more readily available on urban-commercial facilities than they are for rural and recreational travel.

This recommendation, of course, is exactly contrary to a common policy prescription designed to suppress discretionary travel, namely station closing on weekends to discourage recreational travel. Since the recommendation that follows from Lee's results is also inconsistent with common sense and the empirical evidence, we must ask how the paper's methodology would lead to such a bizarre conclusion. In reviewing the methodology of the paper, we find the following steps:

1. Demand is disaggregated by type of facility, and single-equation least squares is employed for each market segment. Total price is composed of money price and waiting or congestion price. The average waiting price per gallon was about $0.134/gal in March 1974.
2. Demand elasticities for rural and leisure travel were found to be less elastic than those for commercial-commuting travel, a finding that is exactly opposite from a priori expectations and the fact that demand dropped most precipitously on these types of facilities during shortages, both in Lee's data and for the country as a whole.
3. The apparent inconsistency was reconciled in Lee's paper by imputing a much higher "shadow price" for gasoline for use on rural and leisure travel--the precipitous drop in travel was assumed to be caused by the fact that the implicit price of travel on these facilities rose much higher than that for urban-commercial-commuting travel; thus the effects of much lower elasticity for rural-leisure travel were offset and the greatest loss in traffic was caused on such facilities.

Before such results are accepted, however, policymakers should consider carefully the contrary evidence. The price of gasoline, including the congestion cost of waiting, should tend to equalize if motorists have reasonably good information, since gasoline purchased on a commuter facility can often be consumed on a rural facility. Any estimation of substantially different prices for different trip purposes should not be done endogenously (inferred from demand effects) but should be done exogenously (by measuring the actual waiting times on different types of facilities). Endogenous imputation of prices is especially tenuous when it is done by using single-equation methods that do not consider the demand on facilities as part of a simultaneous system and when the resulting imputed total prices fly in the face of the facts, namely that waiting times (and therefore the true prices of gasoline) were actually less, in many circumstances, on rural and recreational facilities. Uncertainty of supply apparently caused motorists to take shorter trips and further increased the demand and gasoline lines in urban areas. In short, evidence of significantly different total costs of gasoline for trip purposes should come from actual measurement of queueing in different locations and should not be imputed from differing demand elasticities that are inconsistent with a priori expectations. Put another way, Lee has incorporated a shift variable in his demand equation to account for the periods of shortage and has imputed the differences in shifts across markets to differences in total price. This is an unconventional way of measuring price differences in demand studies.

Comparisons of the waiting time for such lines with the literature on gasoline demand elasticities and values of time would provide interesting checks on estimates of the value of public policy alternatives to reduce lines. For example, if the average purchase were 10 gal, a $0.14/gal imputed waiting cost would generate an average value of time of $2.80/h for a half-hour wait. Research on queueing might therefore provide interesting insights into the demand elasticity for gasoline and for the value of time. Both the Dorfman and Harrington and Lee papers impute a value of time from waiting time and demand elasticity rather than from price and time elasticities in a demand model, the usual methodology.

RECOMMENDATIONS FOR FUTURE RESEARCH

These issues will not be solved by further speculation by researchers; what is needed is a conceptual framework and a data set that tracks consumer response to these effects. Ideally, the data collection should be a time series (perhaps a panel that uses the diary method) that would monitor buying habits before, during, and after an energy crisis. The types of data that it would be useful to collect are as follows:

For gasoline purchase decisions:

1. Average gallons per purchase;
2. Tank inventories and capacity;
3. Queueing time per visit and queueing time per gallon;
4. Time of day, date, and place of purchase;
5. Value of time for different market segments; and
6. Socioeconomic data on motorists.

For driving and travel decisions:

1. Trip purposes,
2. Origin and destination,
3. Trip lengths,
4. Local and intercity vehicle miles of travel,
5. Mode shifts and carpooling,
6. Trip generation, and
7. Demand elasticity by type of travel.

For gasoline availability:

1. Supplies for area and location of station,

2. Station opening and purchase policy,
3. Waiting time for stations with different locations and gasoline prices,
4. Station pricing policies, and
5. Sales data on average purchaser and self-service.

For public policy and station policies:

1. Minimum-maximum purchase,
2. Regular customers only,
3. Even-odd or other rationing,
4. Incentives for carpooling,
5. Improved transit service or other alternative service, and
6. Forced station closing (e.g., on weekends).

These data would be used to calibrate models of gasoline consumption and purchase behavior to address the research differences outlined above. These models would be used for evaluation of the costs and benefits of alternative queue-management and demand-management techniques. Particularly interesting would be evaluation of various contingency plans for changing transit service and increasing automobile occupancy. As indicated in these research papers, the costs of queueing could amount to billions of dollars nationwide. The value of such research, therefore, should be considered in light of these immense costs.

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

Direct Energy Accounts for Urban Transportation Planning

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

Methods for computing accounts of direct energy consumption by urban person travel are described. These accounts are compiled by mode, trip purpose, time of day, and origin-destination pair and are designed to be compatible with the existing transportation planning software and data sets. For automobile trips, a program is used to trace equilibrium assignment paths and calculate zone-to-zone fuel consumption based on link speeds and distances. A similar program for public transit modes calculates zone-to-zone energy consumption based on modal vehicle kilometers per person trip along each minimum impedance path. The final accounts are separate matrices of zone-to-zone energy flows for both public and private modes that can be summarized in tables or displayed graphically. Results from a case study of the Chicago metropolitan area are briefly presented.

A number of plans have been proposed to reduce the energy consumed by urban transportation. These include both contingency plans for short-term shortages of petroleum (1) and long-term plans that require major capital investment and reorganization of land use (2,3). Yet these plans remain controversial because their evaluation has been limited. Often the analyses rely on misleading or inconclusive statistics of modal energy use, or results from one metropolitan area are assumed to be correct for another, quite different, urban region.

Energy planning for urban transportation remains largely separate from the institutionalized urban transportation planning process that has evolved over the last two decades. Therefore, an accepted methodology for conducting urban transportation energy analyses compatible with this planning process does not exist. There are no state-of-the-art procedures from which the analyst may produce an energy evaluation of regional transportation plans or corridor modal alternatives. Evaluation of transportation investments is greatly hampered by the lack of detailed procedures for energy analyses that use the transportation models and data sets available to a metropolitan planning organization.

The objective of the project discussed in this paper is to contribute to the needs cited above by (a) designing procedures for computing urban transportation energy accounts, (b) developing computer programs for these procedures that are compatible with the urban transportation planning models and data sets, and (c) completing a trial application of these procedures in a case study. This paper is primarily concerned with the first two of these objectives; however, a summary of results from a case study of the Chicago metropolitan area is also presented.

OVERVIEW OF THE ENERGY ACCOUNTING PROCEDURES

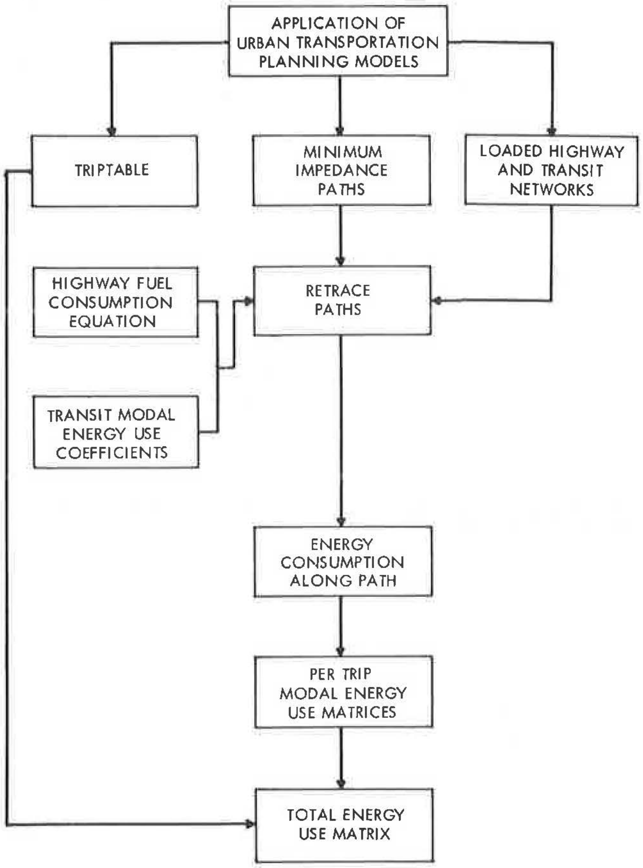
A general flowchart of the energy accounting procedures is shown in Figure 1. Three data files are required as inputs:

1. A loaded network that contains a description of the highway or public transportation network plus the estimated traffic or patronage,
2. A zone-to-zone trip table, and
3. A path or tree file that contains the minimum impedance routes between zones.

These files would usually be required or produced in any application of the urban transportation planning sequence.

Energy consumption is computed for origin-destination pairs by tracing the paths that result from using trip assignment models. First, the minimum impedance routes between zones in the highway and transit networks are read from the tree files. Fuel consumption for each highway path is calculated directly during the tracing procedure by using fuel-consumption coefficients for travel time and distance. For public transit modes, the path-tracing

Figure 1. General procedure for calculating energy-use matrices.



procedure calculates matrices of zone-to-zone modal vehicle kilometers per person trip. Energy consumption per person trip is then calculated by using values of modal energy consumption per vehicle kilometer. If the transit system includes electrically powered heavy rail, then a matrix separate from diesel-powered rail can be retained. The resulting files are matrices of modal energy consumption for the study area where each i-to-j cell in a matrix contains the modal energy per person trip between two zones. Energy consumption for all trips is calculated by multiplying these energy-per-trip matrices by the highway or transit trip table.

The structure of the energy accounts is shown below.

1. Mode
   a. Private automobile
      i. Driver
      ii. Passenger
      iii. Automobile-only trip
      iv. Transit access
   b. Public transportation
      i. Bus
         (a) Rail access
         (b) Local
         (c) Express
      ii. Rail rapid transit
      iii. Commuter rail
         (a) Electric
         (b) Diesel
2. Trip purpose
   a. Home-to-work
   b. Work-to-home
   c. Nonwork
3. Time of day
   a. 24-h weekday
   b. Morning and evening peak period
   c. Off-peak period
4. Origin and destination
   a. Analysis zones
   b. Districts
   c. Radial corridors
   d. Circumferential rings

These categories reflect the objectives of the study, the availability and disaggregation of data, and the types of transportation provided in the study region. In our study of the Chicago metropolitan area, separate accounts are computed for automobiles (including taxis) and public transit modes. For transit trips that use more than one mode (including access by automobile), energy consumption for each leg of the trip is allocated to the proper modal account. The accounts can also be compiled by trip purpose and time of day by using only the relevant portion of the highway and transit trip tables. The energy accounting procedures discussed in this paper deal only with direct energy consumption (i.e., the fuel or electricity consumed for vehicle propulsion and appurtenances). Methods for computing the indirect energy required for construction and maintenance of transportation vehicles and infrastructure are part of the accounting procedures developed for this study but are not discussed in this paper.

CONSTRUCTION OF THE ACCOUNTS

The basic approach to constructing these accounts is to use urban transportation trip-assignment models to compute person kilometers and vehicle kilometers of travel by the categories shown above. Detailed rates of energy consumption per vehicle kilometer by vehicle type (automobile, bus, or rail) are applied to convert vehicle kilometers of travel into units of energy consumed. Link speeds that result from equilibrium assignment are also used to compute automobile fuel consumption.

Highway Assignment

The highway trip table for the Chicago standard consolidated area (SCA) was developed from the 1970 census urban transportation planning package (4) data file of home-to-work trips, a home-interview survey conducted by the Chicago Area Transportation Study (CATS) in 1970, and a 1970 CATS commercial vehicle survey. The census file is a 15 percent sample of work trips, and the CATS home interview is a 1 percent sample of all trips. The combined trip table is factored from 1970 to 1975 by using changes in land use during this period. The trip table assigned to the network is the 2-h morning peak-period matrix of automobile, taxi, and commercial truck trips. However, the energy accounts for person travel that are calculated from the assignment do not include the energy consumed by truck trips.

The coded highway network for the Chicago SCA includes approximately 40 000 links and 15 000 nodes. A highway trip table is assigned to this network by using an equilibrium assignment algorithm (5) that was adapted for use with the Federal Highway Administration (FHWA) PLANPAC transportation planning software (6). Equilibrium assignment allocates trips to alternative paths such that, for each pair of zones, all used paths have equal travel cost and no unused path has a lower travel cost. These are known as Wardrop's equilibrium conditions (7). Each iteration of the algorithm converges toward equilibrium by combining the current all-or-nothing assignment with the previous combined assignment. Because the Chicago highway network is very large, only five iterations of the algorithm are performed. However, unlike the FHWA iterative assignment, each iteration of equilibrium assignment is guaranteed to improve the solution.

Highway Path Averaging

The procedure used to calculate fuel consumption for automobile trips is to first calculate the amount of fuel consumed by an average car on each link of the highway network. Then, as each zone-to-zone path is retraced, fuel consumption for each link along the path is summed. Because equilibrium assignment improves the estimation of zone-to-zone travel times and distances, it provides a sounder basis for the calculation of automobile fuel consumption than does the use of one all-or-nothing assignment. On a congested highway network, on which trips use several alternative paths, travel distance and fuel consumption are likely to be different for each path used. For this reason, the following procedure is used to calculate average zone-to-zone travel distance or fuel consumption that corresponds to an equilibrium assignment.

By using standard notation for equilibrium assignment, λ_n equals the fraction of the nth all-or-nothing assignment that is combined with $(1-\lambda_n)$ of the previous combined assignment. Each all-or-nothing assignment has a matrix of minimum path distances (m_{ij}). Once the value of λ_n is determined, it can be used to determine the average distance from zone i to zone j for the current nth solution $(d_{ij,n})$:

$$d_{ij,n} = (1 - \lambda_n)\, d_{ij,n-1} + (\lambda_n)\, m_{ij,n} \tag{1}$$

Or, more generally

$$\begin{aligned} d_{ij,n} = {} & (\lambda_n)\, m_{ij,n} + (1 - \lambda_n)(\lambda_{n-1})\, m_{ij,n-1} + \ldots \\ & + (1 - \lambda_n)(1 - \lambda_{n-1})(1 - \lambda_{n-2}) \ldots (1 - \lambda_1)\, m_{ij,0} \end{aligned} \tag{2}$$

The average travel distance from zone i to zone j is a weighted average of the travel distances along the minimum cost paths from i to j, where the λ's form the appropriate weights. Average zone-to-zone fuel consumption is computed in the same manner. In contrast, the travel times that are used to compute fuel consumption are those that result from the final set of combined link loadings.

Highway Path Tracing

Since PLANPAC does not compute zone-to-zone travel time, distance, or fuel consumption in the manner prescribed above, a separate program must be used to read and trace the paths from each all-or-nothing assignment. For this purpose, a program called CHPSUM is used to trace FHWA highway paths in an efficient manner. CHPSUM reads link records from the historical record network file and stores the distance and travel time for each link. It also computes the amount of fuel consumed by the average car for each link based on link type, distance, and speed. Then CHPSUM sums travel time, distance, and fuel consumption while each zone-to-zone path is traced in the reverse direction.

Note that travel time, distance, and fuel consumption for each link are stored only once prior to the tracing of all trees. Also, each link only needs to be traced a single time for all paths from a single origin because of the branching structure of a minimum-path tree. Otherwise, the tracing procedure would repeat itself over common segments of paths from the origin zone to the intersection node where these paths diverge. Avoidance of redundant calculations in the tracing procedure greatly reduces computer time needed to process trees for a large network, particularly since this is necessary for each set of assignment paths.

Each execution of CHPSUM produces matrices of zone-to-zone travel times, distances, and fuel consumption. Figure 2 displays the sequence of these calculations. These matrices correspond to distinct all-or-nothing assignments and must be averaged together in the manner described above. These weighted matrices are next multiplied by the original trip table and aggregated into district-to-district flows. Aggregation of the zonal calculations at this stage avoids the gross assumptions of calculations that begin with district averages of trip distance and speed.

Fuel Consumption as a Function of Speed

CHPSUM was originally designed to sum travel time and distance over each path by link type. However, travel time per unit distance (i.e., the inverse of speed) has been found by General Motors Research Laboratories (GMRL) (8) to be the single-most-significant variable that affects fuel consumption of a given vehicle in urban traffic. In a subsequent study by Chang and others (9), data were collected by GMRL employees who drove 1975-model-year vehicles with fully warmed engines on arterial streets in the Detroit metropolitan area. Travel time, distance, and fuel consumption were recorded each time the vehicle came to a full stop. The following linear equation was calibrated for each vehicle type for which data were collected:

$$R = k_0 + k_1\,(1/S) \tag{3}$$

where

R = fuel consumption rate (L/km),
S = speed (km/h),
k_0 = liters per kilometer, and
k_1 = liters per hour.

The resulting fuel-consumption equations are shown in Figure 3 for a subcompact, compact, and standard-size automobile. The dashed lines are shown for speeds between 24 and 56 km/h (15 and 35 mph) because the majority of GMRL's data observations fell within this range. GMRL did not perform separate tests for freeway driving. However, the Urban Transportation Planning System (UTPS) Characteristics of Urban Transportation Systems (10) contains fuel consumption coefficients for arterial and freeway driving for the three basic vehicle types listed above. Freeway driving is characterized by higher and relatively constant speeds over longer distances. The plots of these coefficients are also shown in Figure 3.

Although the manual states that these coefficients represent 1973-model-year vehicles, there is no clear explanation for the difference between the UTPS and GMRL values for arterial streets. It is difficult to evaluate contradictory data without additional information. We assume that the GMRL coefficients are more reliable since they resulted from well-documented experimental procedures. The UTPS values for freeway driving are similar to those reported by Claffey (11), despite the fact that Claffey used much older vehicles. In this study, the GMRL arterial coefficients are used for all links that have assignment speeds less than 40 km/h (25 mph) regardless of the designated link type, and the GMRL coefficient for 24 km/h (15 mph) is used for all links that have speeds less than 24 km/h. The UTPS freeway coefficients are used for

Figure 2. Direct energy calculations for automobile trips.

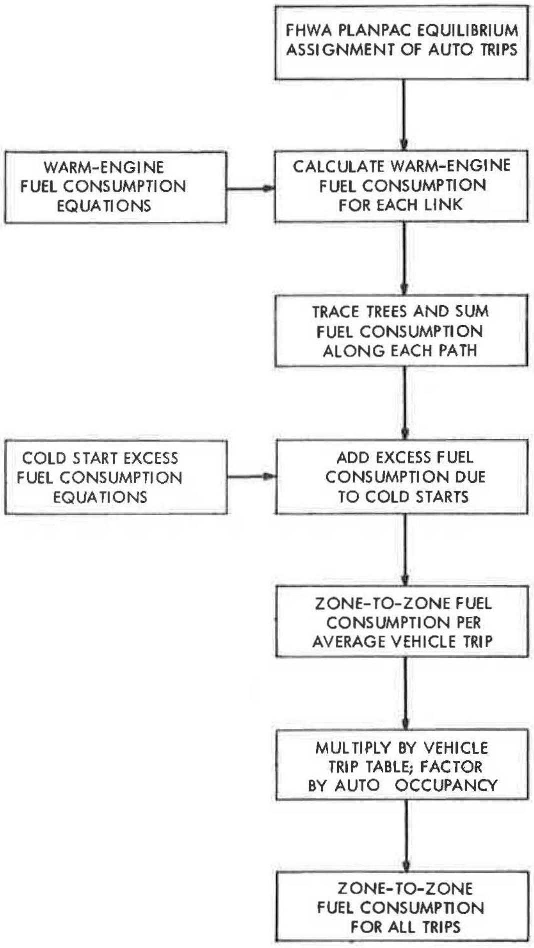
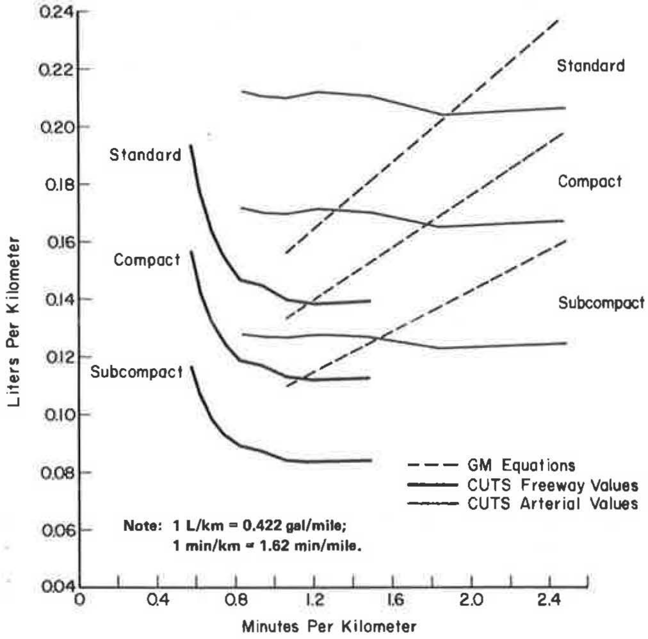
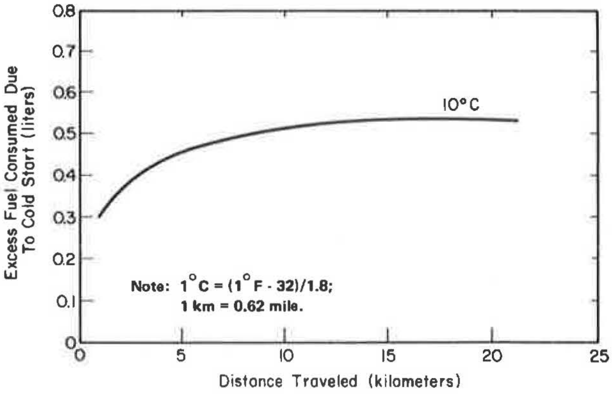


Figure 3. Warm-engine fuel-consumption coefficients for automobiles.



Note: 1 L/km = 0.422 gal/mile; 1 min/km = 1.62 min/mile.

Figure 4. Cold-start fuel-consumption coefficients for automobiles.



Note: $1^\circ C = (1^\circ F - 32)/1.8$; 1 km = 0.62 mile.

all links that have speeds in excess of 64 km/h (40 mph). The link type is used to select the fuel-consumption rate for all links that have speeds between 40 and 64 km/h, and the rate for arterial links that have speeds greater than 56 km/h (35 mph) is assumed equal to the GMRL rate for 56 km/h. Although the UTPS values are for the 1973 model year, a two-year difference from the GMRL cars is assumed to be negligible.

When multiplied by the distance of a link, Equation 3 becomes

$$F_a = k_0 D_a + k_1 T_a \tag{4}$$

where

F_a = fuel consumed on link a (L),
D_a = distance of link a (km), and
T_a = travel time on link a (min).

Values for the coefficients k_0 and k_1 are input to CHPSUM for each 8-km/h (5-mph) speed range from 0 to 160 km/h (0 to 100 mph). Thus, Equation 4, approximated by linear segments, is used to estimate the amount of fuel consumed per vehicle on each link, given link distance and travel time from the assignment. One may question whether travel times from the assignment are proper to use with coefficients based on data collected at actual driving speeds. Although equilibrium assignment may distribute traffic among links in a manner that approximates actual counts, an extensive validation between assignment times and survey times has not yet been completed by CATS.

Fuel Consumption Due to Cold Starts

A cold engine consumes fuel less efficiently than a warm engine. Because Equation 3 assumes a fully warmed engine, additional fuel consumption must be accounted for during the initial portion of each trip. Chang and others (9) estimated the curve shown in Figure 4 from tests performed by using a 1975 standard-size automobile at 10°C (50°F) ambient air temperature. Since cold-start curves for smaller cars were not available, this study uses 80 percent of the standard car values for compact cars and 60 percent of the standard car values for subcompact cars. These are the percentage differences between the UTPS arterial values in Figure 3. These curves represent fuel consumption in excess of that predicted by Equation 4 as a cumulative function over distance that ceases to increase beyond roughly 16 km (10 miles) of driving. Thus, Equation 4 is still applied to all links along the path.

Fuel-Consumption Coefficients for the Average Car

Numerous assumptions are necessary to derive fuel-consumption coefficients that represent the proper mix of vehicles by age and type for a specific year and region. First, although there are hundreds of different car models, this study assumes that an aggregation of cars according to three basic sizes is sufficient for estimation of average fuel-consumption coefficients for the Chicago region's vehicle fleet. The UTPS manual estimates the national mix of automobiles in 1973 to be 12 percent subcompact, 30 percent compact, and 58 percent standard-size vehicles (10). Although the vehicle fleet for a region may differ from that of the nation, specific data on vehicle mix for a particular region are very difficult to obtain. Thus, coefficients for the average car are derived in this study by combining the warm-engine and cold-start curves according to these percentages. Because these composite coefficients represent a 1973 (or 1975) vehicle, the calculations that result must be adjusted for the mix of vehicle ages in the operating fleet. Murrell and others (12) estimate that the average fuel efficiency of new cars sold nationally in 1975 was 36.7 km/L (15.6 miles/gal), but only 32.2 km/L (13.7 miles/gal) for the nationally operating fleet. Thus, actual fuel consumption in 1975 might be as much as 15 percent greater than estimates that assume the same model year for all cars in the study region. Clearly, the estimation of fuel-consumption coefficients for the average car in a given year requires a great deal of refinement that is only possible with more complete data.

Transit Assignment

The transit trip table for the Chicago SCA was developed from the same data files in substantially the same manner as was the highway trip table. One trip table that contained all users of transit in the 2-h morning peak period was assigned to the transit network. CATS codes all transit service for the Chicago region as one network that includes walk and automobile access links. CATS uses the UTPS ULOAD all-or-nothing transit assignment (13), which assigns trips to minimum impedance paths that include access and egress.

Transit Path Tracing

Details of the direct energy calculations for automobile trips have been discussed above. The procedures used to calculate direct energy consumption for transit trips maintain this same approach, except that transit energy consumption is assumed to be directly proportional to vehicle kilometers of travel. However, calculation of vehicle kilometers of travel per person trip between two zones is not a simple task because trips may use several different modes that have constantly changing vehicle occupancies.

ULOAD does not report zone-to-zone vehicle kilometers of travel per person trip; therefore, a path-tracing program called CTPSUM, which follows the same tracing logic as CHPSUM, was designed and used to perform these calculations. Whereas CHPSUM first calculates the average fuel consumption per vehicle trip on each link, CTPSUM calculates vehicle kilometers per person trip for each transit link. This is done by multiplying each link length by the frequency of vehicles and dividing by passenger volume. The number of vehicles per train and the length and time of day of the assignment period are taken into account when the number of vehicles that serve each link over the assignment period is computed. CTPSUM then proceeds to retrace the transit paths while summing both travel distance and vehicle kilometers per person trip by mode along each path. Since only one all-or-nothing assignment is performed, the tracing program is executed only a single time and no averaging is needed for alternative paths.

Calculation of Direct Energy from Vehicle Kilometers per Person Trip

Since a very limited number of access links are coded into a transit network, the access portions of transit trips require additional calculations. For this purpose, two separate transit trip tables are prepared: (a) transit-only trips and (b) transit trips that use automobile access to rail rapid transit or commuter rail. The transit-only trip table includes all trips that either walk to transit (rail or bus) or use access bus to a rail transit mode. The automobile-access trip table includes both automobile-driver and automobile-passenger trips. These access-mode trip tables are calculated from district access-mode factors computed from the CATS 1970 home interview survey. A matrix of zone-to-zone automobile-access distances is produced by taking the average distance by car to the closest rail rapid transit or commuter rail station. Whether to use distance to the rapid transit or to the commuter rail station is determined by the first rail mode of each assignment path. These automobile-access distances are converted into a matrix of zone-to-zone automobile vehicle kilometers per person trip by using zonal ratios of automobile-driver to automobile-passenger trips. In contrast, a matrix of zone-to-zone access-bus vehicle kilometers per person trip is output directly by CTPSUM.

A list of the transit matrices discussed thus far helps to explain the final calculations shown schematically in Figure 5:

1. Transit-only trips,
2. Transit trips that use automobile access to a rail mode,
3. Automobile-access vehicle kilometers per person trip,
4. Access-bus vehicle kilometers per person trip,
5. Bus (excluding access) vehicle kilometers per person trip,
6. Rail rapid transit vehicle kilometers per person trip, and
7. Commuter rail vehicle kilometers per person trip.

Matrix 1 times matrix 4 equals zone-to-zone vehicle kilometers of access-bus travel. (This is not the matrix algebra form of matrix multiplication but just a simple cell-by-cell multiplication.) Paths that use walk links to rail transit or do not use rail transit at all register as zeros in matrix 4 and thus do not contribute to access-bus kilometers. Matrix 2 times matrix 3 equals zone-to-zone vehicle kilometers of automobile travel for all transit trips that use automobile access to a rail mode. Finally, both the transit-only and the automobile-access trip tables (matrices 1 and 2) are multiplied by matrices 5, 6, and 7 to yield total vehicle kilometers of travel by each nonaccess mode.

To calculate direct energy consumption, the five matrices just described must be multiplied by coefficients of direct energy per vehicle kilometer for each mode. Average coefficients such as these tend to vary widely between cities because of age and operating differences (14,15). Based on operating

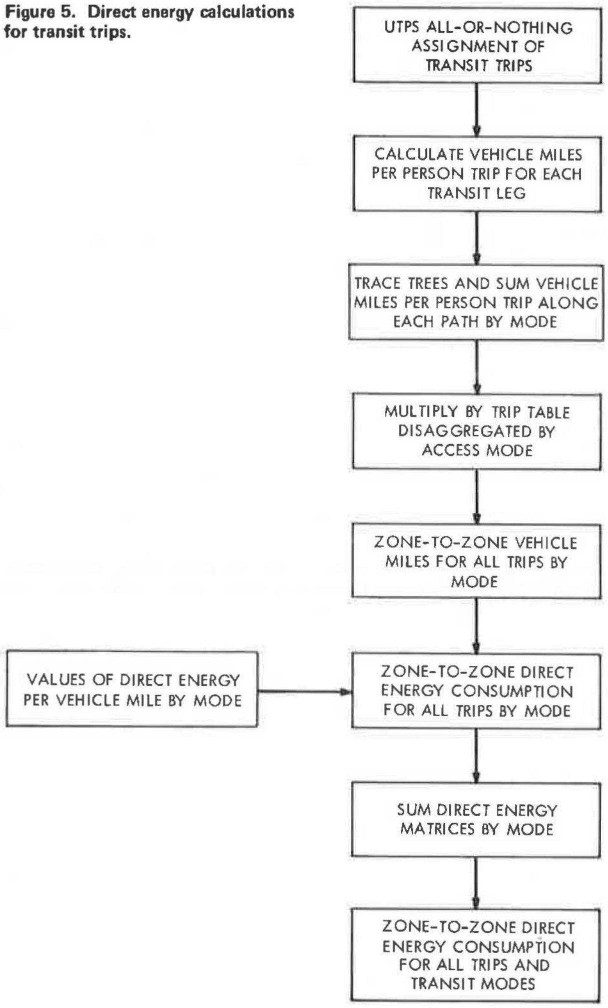


Figure 5. Direct energy calculations for transit trips.

Table 1. Summary of direct energy accounts for Chicago SCA morning peak period.

Statistic	Private Travel	Public Travel
Direct energy (MJ)	177 300 000	9 910 000
Person trips	2 965 369	511 751
Person kilometers	33 967 381	7 754 486
Average trip length (km)	11.45	15.15
Megajoules per person trip	59.79	19.36
Megajoules per person kilometer	5.22	1.28
Person air kilometers	28 401 301	7 138 409
Average trip length (air-km)	9.58	13.95
Megajoules per person air-kilometer	6.24	1.39
Petroleum energy (MJ)	177 300 000	6 250 000
Electrical energy (MJ)	0	3 660 000

Note: 1 MJ = 947.8 Btu; 1 km = 0.621 mile.

data for the Chicago region, the estimates of direct energy per revenue vehicle kilometer used in this study are as follows:

Urban bus = 27.54 MJ/km (42 000 Btu/mile)
Rail rapid transit = 37.37 MJ/km (57 000 Btu/mile)
Commuter rail (diesel) = 68.18 MJ/km (115 000 Btu/mile)
Commuter rail (electric) = 86.54 MJ/km (132 000 Btu/mile)

For automobile access, this study assumes the 40-km/h (25-mph) fuel-consumption rate estimated by GMRL for arterial roads and the UTPS vehicle-mix percentages discussed earlier. The final matrices of zone-to-zone modal energy consumption for all trips can now be aggregated into district-to-district flows. These matrices (before or after aggregation) can also be added together to equal energy consumed by complete origin to destination trips. This last result is directly comparable to the matrix of direct energy consumption for automobile trips.

DIRECT ENERGY ACCOUNTS FOR THE CHICAGO SCA

The Chicago SCA covers the eight-county northeastern Illinois-northwestern Indiana metropolitan area. This region is divided into approximately 1800 zones that range from 0.65 km^2 (0.25 $mile^2$) in downtown Chicago to 23.3 km^2 (9 $miles^2$) in rural portions of outlying counties. Although all calculations are carried out at the zonal level, the results are aggregated into 64 larger districts to facilitate their presentation. These districts result from the intersecting areas of circumferential rings and radial corridors that extend from the Chicago central business district (CBD).

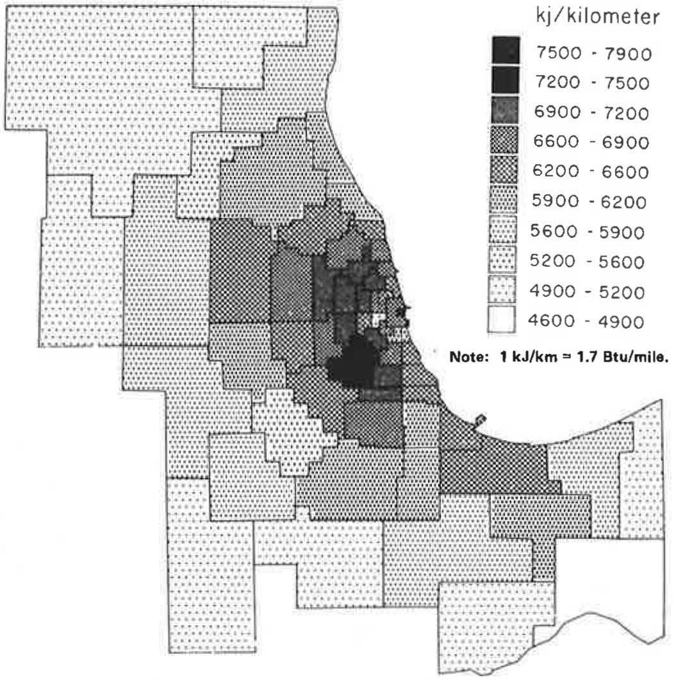
Table 1 presents a summary of the energy accounts for the entire region. Note that direct energy consumption for private travel is 18 times larger than that for public travel but that the number of person trips by automobile is only 6 times as large. Thus, an average automobile trip consumes 3 times the energy of an average public transit trip, including access by automobile or bus. This difference occurs despite the fact that the average automobile trip is 30 percent shorter than the average public transit trip. By comparing actual kilometers traveled to air kilometers (straight-line distances), these figures also show that the public transit trips are not longer because of circuity. The circuity of automobile trips is actually greater. This nonintuitive result occurs for the Chicago SCA because transit trips are heavily focused on the CBD, which is serviced by radial rail transit that permits direct trips. More than 55 percent of the total person kilometers traveled by public transit modes in this region are by rail rapid transit or commuter rail. One other observation to be made from Table 1 is that electrical energy, which can be produced from nonpetroleum resources, equals 37 percent of the public travel energy but only 2 percent of the public plus private energy.

These regional totals are obtained by aggregating results that were performed at the zonal level. The aggregation of these results into districts are shown as maps in Figures 6 and 7. The limited length of this paper does not allow a full display of maps, but the two shown here reveal an expected observation: Direct energy per person air kilometer increases toward the CBD for automobile trips because of greater traffic congestion. On the other hand, direct energy per person air kilometer decreases toward the CBD for public travel because of higher patronage and less use of automobile access. Note that these maps are for all public or private trips that originate from each origin and not just trips that have CBD destinations. That these maps are almost negatives of each other suggests that shifting more CBD-oriented trips with suburban origins to public modes represents a possible energy-reduction strategy for the Chicago region.

ACKNOWLEDGMENT

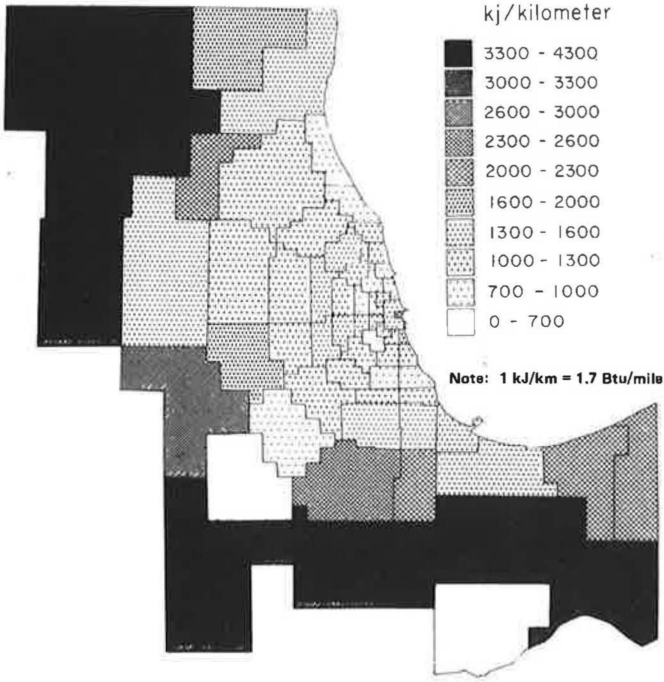
The research for this paper was supported by a contract with the Urban Mass Transportation Administra-

Figure 6. Peak-period private transportation by origin district (kJ/person air-km).



Note: 1 kJ/km = 1.7 Btu/mile.

Figure 7. Peak-period public transportation by origin district (kJ/person air-km).



Note: 1 kJ/km = 1.7 Btu/mile.

tion. We would like to thank the technical monitor, Richard Cohen, for his advice and encouragement and also the staff of the Chicago Area Transportation Study for their cooperation in the development and implementation of this research.

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

Transportation Energy Effects on Urban Growth: Results of Simulations

MICHAEL C. ROMANOS, POULICOS P. PRASTACOS, AND MICHAEL L. HATMAKER

This paper evaluates the impact on urban growth and spatial structure of policies aimed at conserving energy in the transportation sector through a series of simulations that employ an optimization urban development model. In the model, transportation energy becomes an integral part of the land use component and thus trip making and land use allocation are determined simultaneously. After a brief presentation of the model, which is characterized by a highly nonlinear objective function, the solution method used is discussed at length. A major feature of the solution is the use of the out-of-kilter algorithm, which is accomplished by representing zonal activities by nodes and the number of acres of each activity by the flows in the arc. The paper reports extensively on the results of simulations performed under various assumptions. These tests reveal that, under transportation energy minimization objectives, central zones are considerably more attractive than outlying zones to both households and business. They also show the availability of transit service as a major determinant of the direction of urban growth. In addition, they reveal that, although energy minimization would produce considerable fuel savings, it would also cause an increase in mean trip lengths and mean trip cost over those generated by a cost-minimization model.

The recent shortage of fuel in California and the nationwide spiraling price of gasoline indicate the beginning of a new era for urban transportation, an era in which energy is one of the most critical and limited resources. Different ways to cope with the limited supply of energy include the use of higher-efficiency automobiles, the shift from the automobile to public transportation, and a restructuring of our cities to encourage the development of new urban centers in a more energy-conserving manner. Because the first two measures can result only in marginal reductions of total energy consumption and changes in the existing urban structure are difficult to implement in the short run, the need for policies to govern the future allocation of land uses (with the objective of increased transport energy efficiency) becomes pressing.

The impact of these policies could be evaluated by using existing models of urban development, properly modified to include energy consumption among their variables. In their current form, these models do not consider energy efficiency when allocating activities to zones. In the Lowry model, for example (the best-known model of this kind), population and service employment are forecast and, together with exogenously supplied basic employment, are allocated to zones through the use of a gravity model and based on zonal accessibility. After the allocation is completed, the trips generated are estimated and distributed among the possible destinations and modes. Total energy consumption could then be computed, given the average energy consumption per rider of each mode (1).

Models of this type, when used to evaluate the impact of alternative energy policies, are characterized by the insensitivity of the allocation process to the energy consumption of the transportation component. This insensitivity arises from the recursive structure of the models, which does not allow consideration of energy efficiency when activities are allocated to zones. Both trip matrix and energy consumption are estimated after the allocation is completed, and no iterative procedure is included that would permit the modification of the results obtained in the allocation process on the basis of transport energy concerns.

MODEL OF ENERGY-EFFICIENT LAND ALLOCATION

In an earlier paper we developed a land use model that attempted to overcome the above shortcomings (2). In that paper, transportation energy becomes an integral part of the land use component, and thus trip making and land use allocation are determined simultaneously. The model is concerned with the minimization of total transportation energy consumption and specifically with the interaction among land uses, the existing transportation network, and the trip distribution and modal choice components of trip making.

To minimize transportation energy, the model does not dispense with realistic urban location and travel behavior. The current urban structure as well as the existing zoning restrictions are taken into account, individual travel behavior is simulated by introducing an entropy-maximizing model, and travelers are assumed to select their trip ends and their mode on the basis of the travel costs involved and some realistic parameters that explain their behavioral characteristics. In this paper we report on the solution procedures and the results of extensive testing.

THE DEVELOPED MODEL

In mathematical terms, the full model is

$$\text{Min } Z = \sum_i \sum_j \sum_k e_{ij}^k T_{ij}^k \tag{1}$$

$$\text{subject to } \sum_i X_i^r = X^r \quad \text{for all } r \tag{2}$$

$$\sum_r X_i^r \leq L_i \quad \text{for all } i \tag{3}$$

$$X_i^r \leq C_i^r \quad \text{for all } i \text{ and } r \tag{4}$$

$$X_i^r \geq 0 \quad \text{for all } i \text{ and } r \tag{5}$$

where

Z = total operational energy consumed by the transportation system,
e_{ij}^k = energy consumption per person trip from zone i to zone j by mode k,
T_{ij}^k = volume of person trips by mode k from zone i to zone j,
X_i^r = number of acres of activity r to be allocated in zone i,
L_i = number of acres of vacant land in zone i, and
C_i^r = exogenously specified upper limit on the number of acres of activity r to be allocated in zone i.

The objective function (Equation 1) requires minimization of the total energy consumed by the trip makers, subject to constraints that assume that (a) all the new land must be allocated (constraint

2), (b) the land allocated in each zone should not be greater than the land available for development in that zone (constraint 3), and (c) the land to be allocated in each zone should not exceed a certain amount for some activities. The solution variables are the X_i^r's.

In order to relate the number of trips to the land use configuration, a trip-distribution and modal-shift model derived through entropy maximization is introduced. The volume of trips between any two zonal pairs is written as

$$T_{ij}^k = A_iB_jO_iD_j \exp(-\beta\tilde{c}_{ij}) \exp(-\lambda c_{ij}^k)/\sum_k \exp(-\lambda c_{ij}^k) \qquad (6)$$

where A_i and B_j are the Lagrangian multipliers that ensure that the trip conservation constraints for both origins and destinations are met and are equal to

$$A_i = [\sum_j B_jD_j \exp(-\beta c_{ij})]^{-1} \qquad (7)$$

$$B_j = [\sum_i A_iO_i \exp(-\beta c_{ij})]^{-1} \qquad (8)$$

where

O_i = number of trips with origin in zone i,
D_j = number of trips with destination in zone j,
β = behavioral constant of trip distribution that determines the willingness of trip makers to select other than the nearest destination,
$\tilde{c}_{ij}$ = composite cost between i and j that indicates the relative costs of traveling (4),
λ = behavioral constant of modal choice that determines the willingness of trip makers to use other than the least-cost mode, and
c_{ij}^k = generalized travel cost between zones i and j by mode k.

The total number of trips generated in a zone is obtained by multiplying the rate of trip generation per acre of each activity by the number of zones of the activity to be allocated. In order to account for the existing land uses, the number of trips generated by the existing activities is added on. That is

$$O_i = \sum_r OR^r (X_i^r + E_i^r) \quad \text{for all i} \qquad (9)$$

$$D_j = \sum_r DN^r (X_j^r + E_j^r) \quad \text{for all j} \qquad (10)$$

where

E_i^r = existing amount of land (in acres) in zone i currently developed in land use activity r,
OR^r = trip production rate per acre of type r land use, and
DN^r = trip attraction rate per acre of type r land use.

By using Equations 6, 9, and 10, the objective function of the optimization model is then written as follows:

$$\begin{aligned} \text{Min } Z = \sum_i \sum_j \sum_k e_{ij}^k \Big\{ A_iB_j \Big[\sum_r OR^r (X_i^r + E_i^r)\Big] \\ \Big[\sum_r DN^r (X_j^r + E_j^r)\Big] \exp(-\beta\tilde{c}_{ij}) \\ \Big[\exp(-\lambda c_{ij}^k)/\sum_k \exp(-\lambda c_{ij}^k)\Big]\Big\} \end{aligned} \qquad (11)$$

In its final form, therefore, the model is composed of the objective function (Equation 11) subject to constraints 2-5. The nonlinearity of the objective function and the similarity of the model to the network flow problems necessitate the use of special solution techniques.

Solution Method

The developed model is composed of a highly nonlinear objective function and a set of linear constraints. Since algorithms of nonlinear problems require excessive computer time and often do not converge, it was decided to use a heuristic technique for the solution of the land use-energy model. The procedure employed is based on the TOPAZ model solution technique [Brotchie and others (5)], which consists of solving successive transportation problems until convergence is reached. The objective of these problems is the original objective function reduced to a linear form by substituting for enough variables subject to constraints 2 and 3. In our model, the addition of the zoning constraint (Equation 4) does not permit the use of the transportation algorithm for solving the reduced linear model. For this reason, the out-of-kilter algorithm is used instead by properly converting the problem to resemble that of the flow of capacitated networks, as explained below.

The solution algorithm shown in Figure 1 includes the following steps:

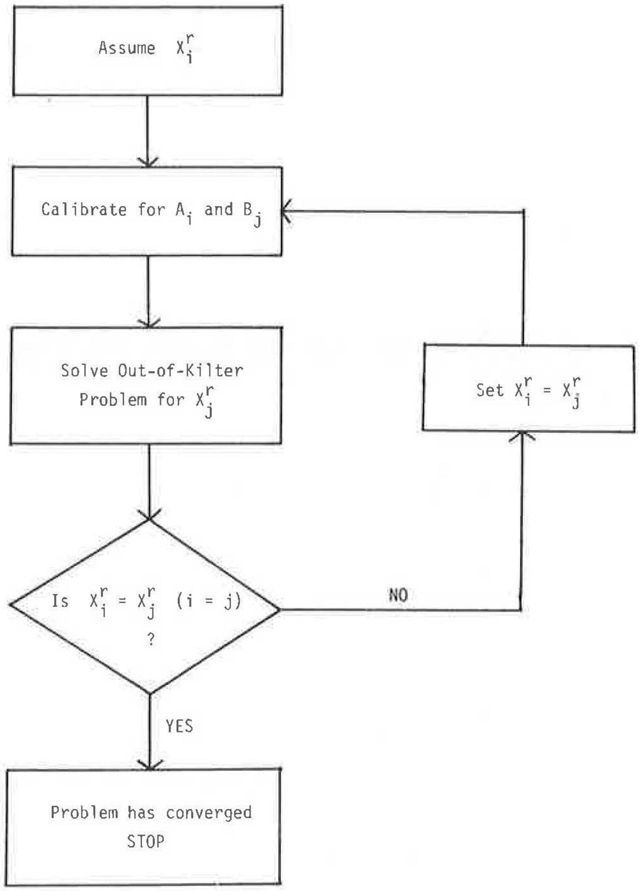
1. Assume values of X_i^r's; the assumed values must satisfy constraints 2-5;
2. Substitute for the values of X_i^r in A_i and B_j and calibrate the model given by Equations 6-8 through iteration; in calibrating for A_i and B_j, the variables X_j^r take the values of the assumed x_i^r's for i equal to j;
3. Substitute for the values of X_i^r, A_i, and B_j in the objective function; the result is a linear function in which the X_j^r's are the set of unknown variables; the out-of-kilter algorithm is used to solve the model given by Equations 11 and 2-5; and
4. Compare the assumed values of X_i^r with the values of X_j^r obtained in step 3 for i = j; if all of them are equal or almost equal, then the problem has converged and the iteration terminates. If not, go back to step 2 and substitute for X_i^r the values of X_j^r obtained in step 3 (i-j).

The iterative procedure described above continues until convergence is reached or until the maximum permitted number of iterations is exhausted. Although no formal proof exists on the convergence of this algorithm, we were able to reach convergence within six iterations in all the tests we performed. In most of these tests, convergence was accomplished within three iterations only.

Although the reduced linear model could be solved by the regular simplex method, special network algorithms were selected because of their efficiency in solving problems of network structure. Network problems are concerned with determining the flows between any two points in a network in such a way that the total cost is minimized. The collections of points are called nodes and they are connected through arcs that have cost and often capacity characteristics; the former represent the cost incurred by moving a unit of flow through the arc. If there are no capacity constraints, then the resultant problem is called the transportation problem and special algorithms exist that can solve problems that involve even hundreds of thousands of arcs (6).

The land use-energy model presented above resembles the network problem. Each activity and each zone can be represented as nodes connected by arcs, where the number of acres of a type of activity located in a zone is the flow on the arc. If there are no constraints on the amount of any activity to be allocated in any zone, the problem can be solved readily by applying the transportation algorithm.

Figure 1. Solution by using out-of-kilter algorithm.



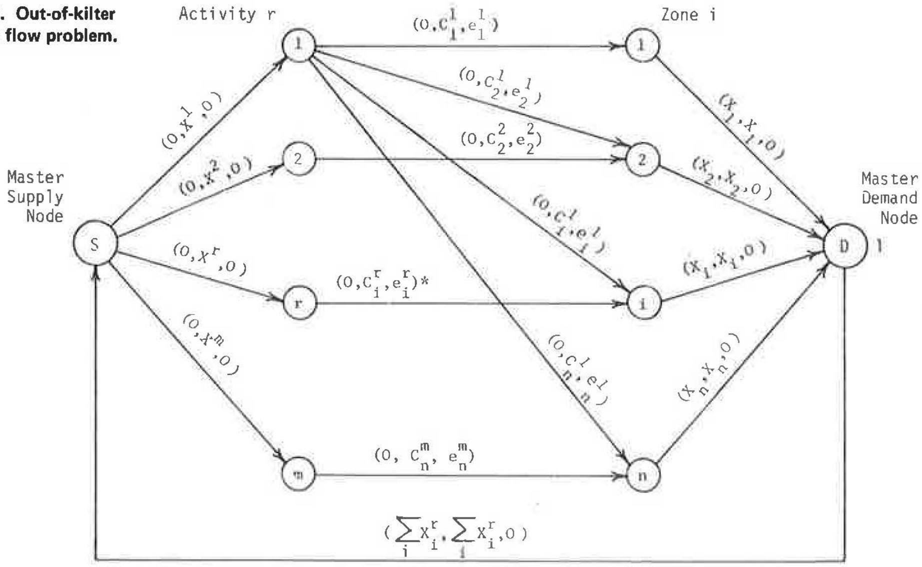
The use of a transportation problem algorithm, however, strains the realism of the resulting land use allocation. With this algorithm, the only constraints are the row (or supply constraints) and the column (or demand constraints). The supply constraints require that all of the acres of the different types of activity be allocated across the zones. The demand constraints require that all available land in each zone is filled, either by allocation of some of the land use activities or by allocation of vacant land. A realistic solution requires that an upper limit be placed on the amount of certain activities that is allowed in a particular zone. For example, zoning ordinances will limit some land uses in different zones--a constraint that may be violated by a simple transportation algorithm allocation.

In order to prevent such unrealistic solutions, a zoning constraint (constraint 4) has been added in the model and an alternative network algorithm has been adopted. The out-of-kilter algorithm (7,8) allows a solution of network flow problems that have upper and lower bounds on the flows through the arcs. Reformulation of the transportation algorithm requires creating an artificial master supply node (with arcs to each of the supply activities), an artificial master demand node (with arcs that come from each demand node), and an arc that connects the master supply and demand nodes. Figure 2 shows the graphical representation of the land use-energy model in its network form. The complexity of the problem is increased slightly, but very large problems may still be solved rapidly and efficiently.

Testing of the Model

Sioux Falls, South Dakota, was selected as the test site because of the availability of data and because of its manageable size. The area of consideration, which has a population of approximately 100 000 over 24 zones, offers enough complexity to be realistic

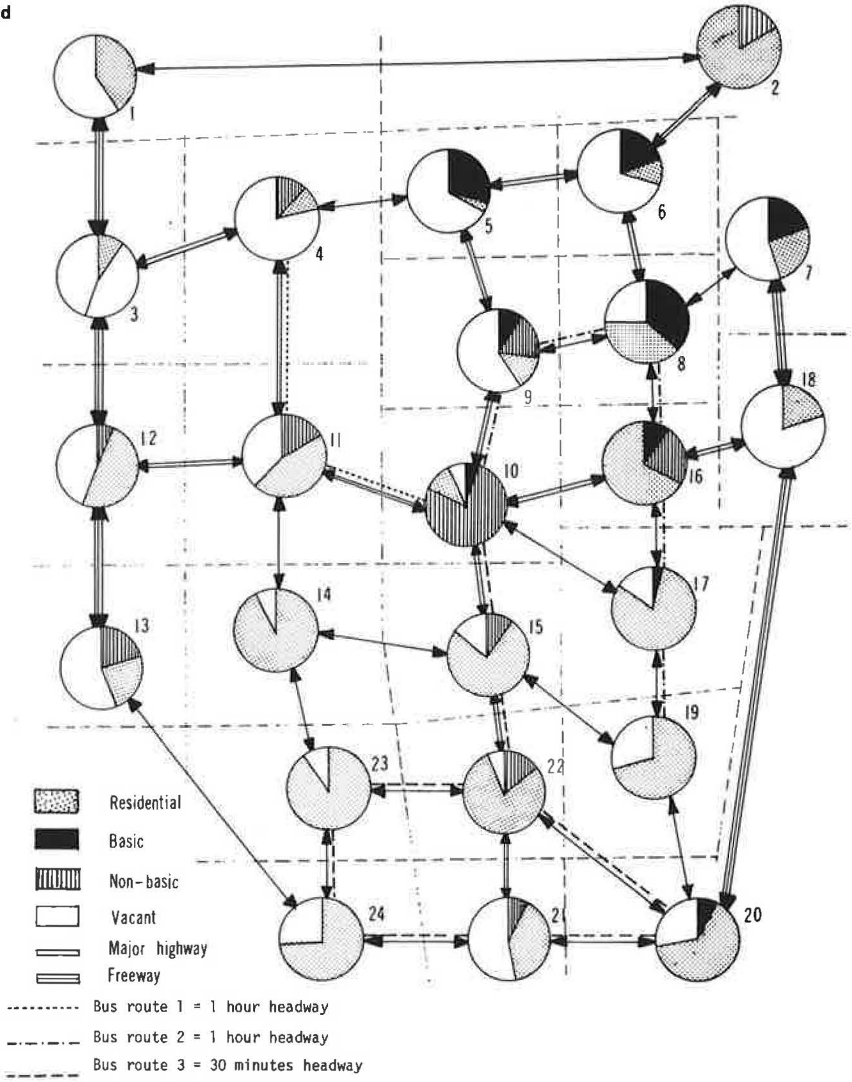
Figure 2. Out-of-kilter network flow problem.



Quantities within the parenthesis represent:
(Minimum Allowable Flow, Maximum Allowable Flow, Cost Per Unit Flow).

Absence of a subscript or superscript indicates summation over that dimension.

Figure 3. Existing land uses.



without being too unwieldy for convenient experimentation.

Although the Sioux Falls case was adopted for this experiment, it was determined that the analysis would be simplified if elements of a "toy city" were developed from the base of the actual city. For example, if the locations of existing land uses can be made more concentrated than the actual land use pattern indicates, the results of the model will be more exaggerated and interpretable. A sensitivity analysis will thus produce more distinguishable results than if a less organized, dispersed land use pattern is used for the base.

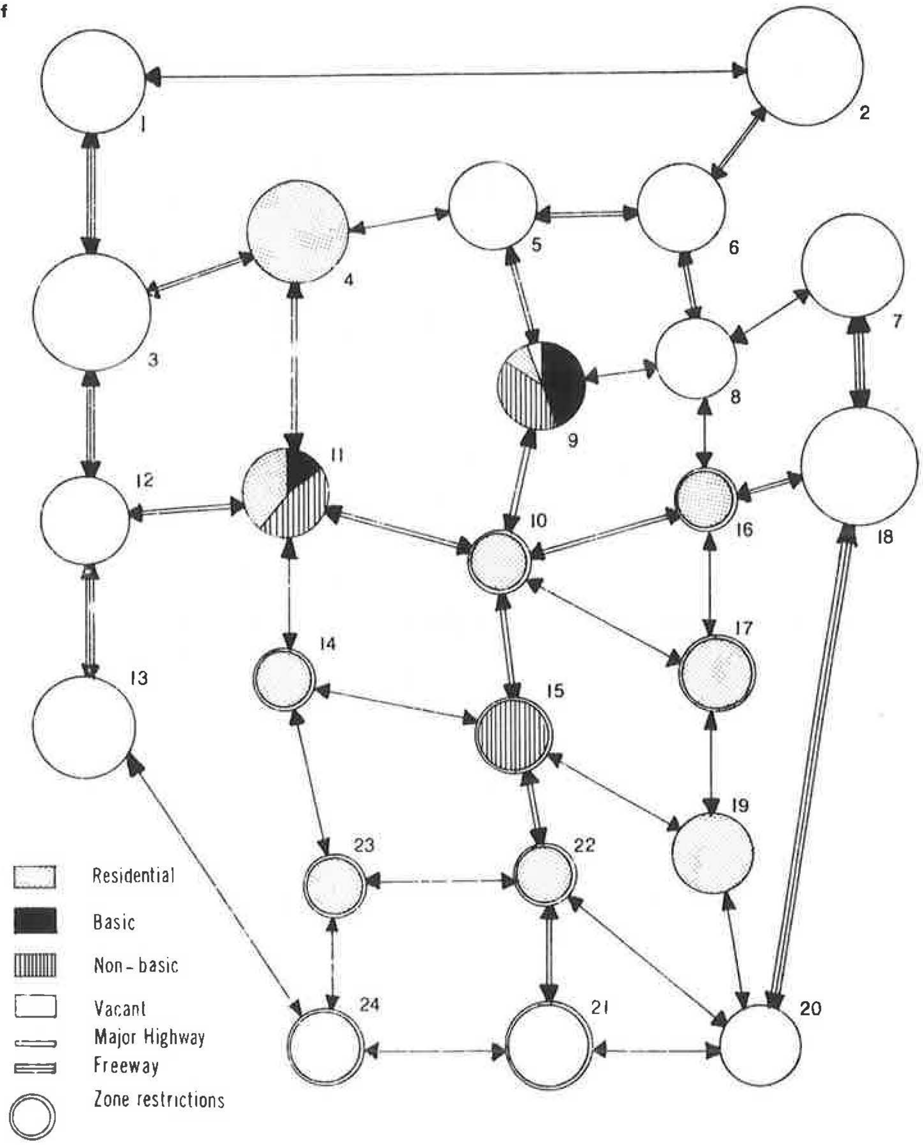
Existing Land Use and Transportation System

A simplified network used by LeBlanc (9) was adopted. It connects the 24 centroids with 37 two-way links. The population and economic activity in the city were taken from census and county business patterns sources. Maps and census tract data were used to allocate the existing activity among the 24 zones. The observed origins and destinations of trips for the zones were maintained. However, after this somewhat aggregate information was used for a framework, the treatment of the data at a more disaggregated level departed from the actual situation. The acres of land use activity of each type were placed in zones so that the basic characteristics of the land use pattern were maintained. But the pattern that was created was intended to be more concentrated and exaggerated than what may be observed in reality. The initial design was intended to produce an obvious central business district (CBD), industrial area, commercial areas, residential areas, and undeveloped open space. The design was adjusted so that the acreage of various types of land use in a zone would produce the observed number of trip ends when the trip generation rates were applied.

The configuration of the city is illustrated in Figure 3, which also displays the allocation of land use activities. The CBD centers around zone 10. Commercial uses are distributed along the highway routes. The industrial area is concentrated in the northeast in zones 5-9. A college and related high-density housing are developed in zones 14, 15, and 21-24. Other high-density housing is located near the central part of the urban area. The major park is in zone 13, and most of the vacant land is in the outlying zones.

A very simple transit system was added to the transportation network. Three routes were coded, as shown in Figure 3. Two of the routes are operated in the base year with a one-hour frequency. The third route, which extends through the higher-density college district, runs with a half-hour frequency of service.

Figure 4. Minimization of energy consumption, $\beta = 0.2$, $\lambda = 0.2$.



*Circle size indicates area of vacant land in each zone.

Zoning Limitations

In addition to specification of the existing situation, the development that may reasonably take place in the future must be considered. For the experiments described, a very limited amount of intervention in the form of zoning was included in the model constraints. The primary zoning limitations invoked were a limit to the amount of residential development that could occur in the industrial areas and limitations on industrial activities in some residential zones.

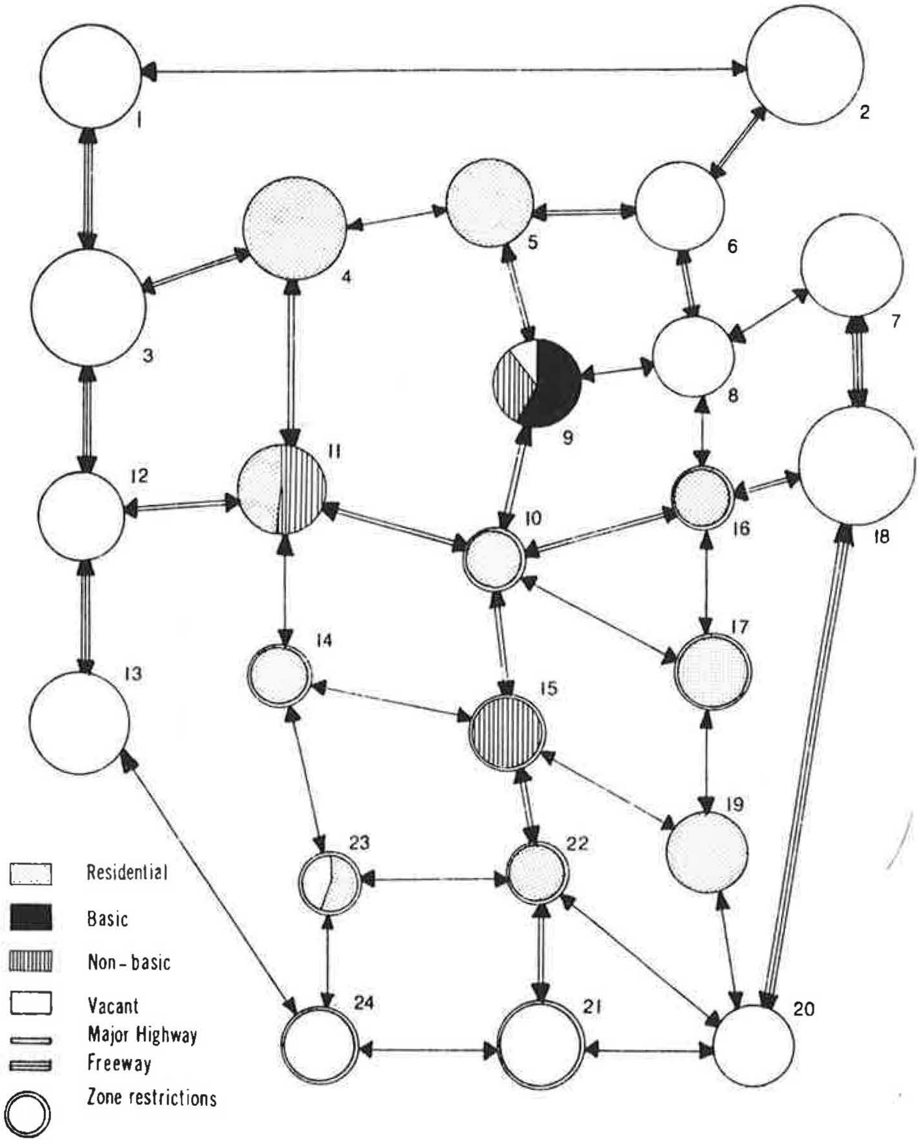
Travel Demand Parameters

The experimental problem involves minimization of transportation energy consumption where the available modes are private automobile and bus mass transit. Data are not available for Sioux Falls on which destination or modal choice models may be calibrated for this choice set. In the absence of calibrated models, a series of experimental optimizations was run in which the parameters and modal cost variables were systematically varied as a sensitivity analysis. The experiments and sensitivity analyses conducted produced a series of results, only a sample of which is reported here. The tests performed were of two types:

1. Division of the optimization time frame into subintervals with increments of growth optimized over the shorter time periods and
2. Change in the objective function to require minimization of travel costs rather than transportation energy.

In the first set of tests, the analysis consisted of varying the parameters and variables in three nested loops. For given values of the destination choice parameter (β) and the modal choice parameter (λ), the value of time for users of the three modes was increased in steps. Then λ was increased successively. Finally β was increased in steps. This analysis was intended to trace the effect on energy-efficient land use allocation of trip makers' sensitivity to modal and interzonal

Figure 5. Minimization of energy consumption, $\beta = 0.2$, $\lambda = 0.8$.



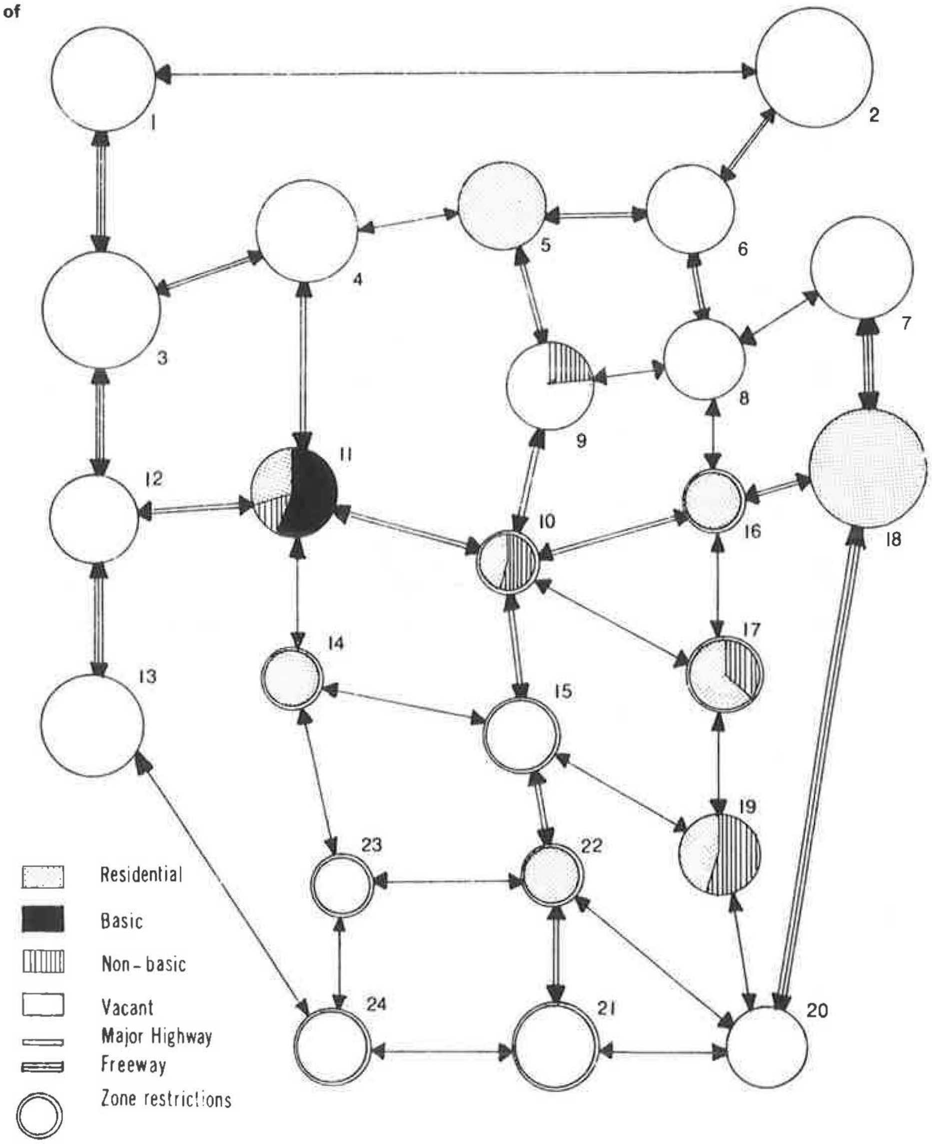
travel costs. Therefore, the influences of interest with regard to the optimal location of new land use activities are (a) the existing land use pattern, (b) the willingness to travel to other than the minimum-cost destination, and (c) the willingness to travel by other than the minimum-cost mode.

The values of the parameters were not found to have a great effect on the locations of manufacturing, construction, and public utilities. Almost all of the tests allocated these activities to zones 11 and 9; however, at higher values of β (where transportation costs become more important), some of the activity was allocated to zone 8. Service and office activity was generally allocated to zones 9 and 11, although at higher levels of λ zone 17 replaced zone 11. With few exceptions, regional shopping center land use was placed in zone 15, and local shopping was located in zone 11 (Figures 4-6 show three land use types).

The variation in parameter value also had little effect on higher-density housing location. High-density housing was generally located in zone 17. Medium-density housing was generally divided between zones 10 and 17. However, at high values of λ, zone 16 replaced zone 10. The location of low-density housing was affected more by the willingness to use other than least-cost choices. In all the tests, zones 11, 14, 17, and 19 were filled to capacity with allocations of low-density residential land use. This, however, did not happen with the rest of the zones. For example, at low values of λ, which indicate that transit is an acceptable choice, zone 4 usually received an allocation and zone 5, which has no transit, was usually developed less intensely for small values of λ. However, as λ increased, the low-density residential land use was shifted to zones such as 18 (Figures 4-6).

To gain a broader view of the results of the sensitivity analysis, it is necessary to look at these changes from a more aggregate level. Although distance and modal cost differentials remained unimportant in the choice functions, the major impact of development was west and northwest of the CBD. However, as modal cost differentials made transit less attractive, the northwest direction disappeared in favor of the eastern area, especially around the interchange of the freeway and the east-west highway in zone 18. A higher sensitivity to distance also pushed development to the northeast, around the industrial corridor of zones 7-9. Interestingly, at very high values of β and

Figure 6. Minimization of energy consumption, $\beta = 0.2$, $\lambda = 2.0$.



low values of λ, almost all new land use was forced into the northeast. All land use except low-density residential was placed in zone 6 in one run. Low-density residential was placed in zones 5, 7, and 15-17.

In this set of analyses, several points become evident. As would be expected, the close-to-center zones are filled to capacity before outlying zones become attractive. The most distant zones are completely neglected. The direction of growth depends on trip makers' willingness to travel farther than the nearest satisfactory destination, their acceptance of mass transit as a feasible modal alternative, and the availability of transit service. In these tests, however, the level of service for transit was held constant, even after growth allocations were made. These allocations, on the other hand, should have an effect on the demand for transit services and should ultimately result in better service to satisfy that demand, thus altering mass transit costs. An even more obvious effect of the allocations is the congestion that might result on some of the links. Some of the zones and corridors received massive new growth, which should cause link travel costs to increase. These and other observations will be considered in greater detail later in this paper.

The runs summarized above held the values of time for users of each mode constant. Some tests were also made in which the relative values of time were allowed to vary. To simplify the analysis, the value of β was held constant at a value of 0.2 so that the trip-interchange matrix could have a substantial degree of diffusion.

Two land use types--regional shopping center and high-density housing--were allocated to zone 15 by every run. This zone is served by the mass transit route that has twice-hourly frequency.

Mass transit was found to be an important element in the land use patterns that developed in this series of runs. At low values of λ or low values of time, the only zones that received allocations were those served by transit. The only exception was zone 9, which received varying amounts of industrial land use and park land.

In all runs, zone 11 is quite important as the location of many of the nonindustrial land uses, including housing. The sensitivity to the cost of travel and value of time is most easily seen in zones 4, 5, and 18. As trip makers become less willing to use transit or place more value on time, zone 4 loses new development. Zone 5 is the first

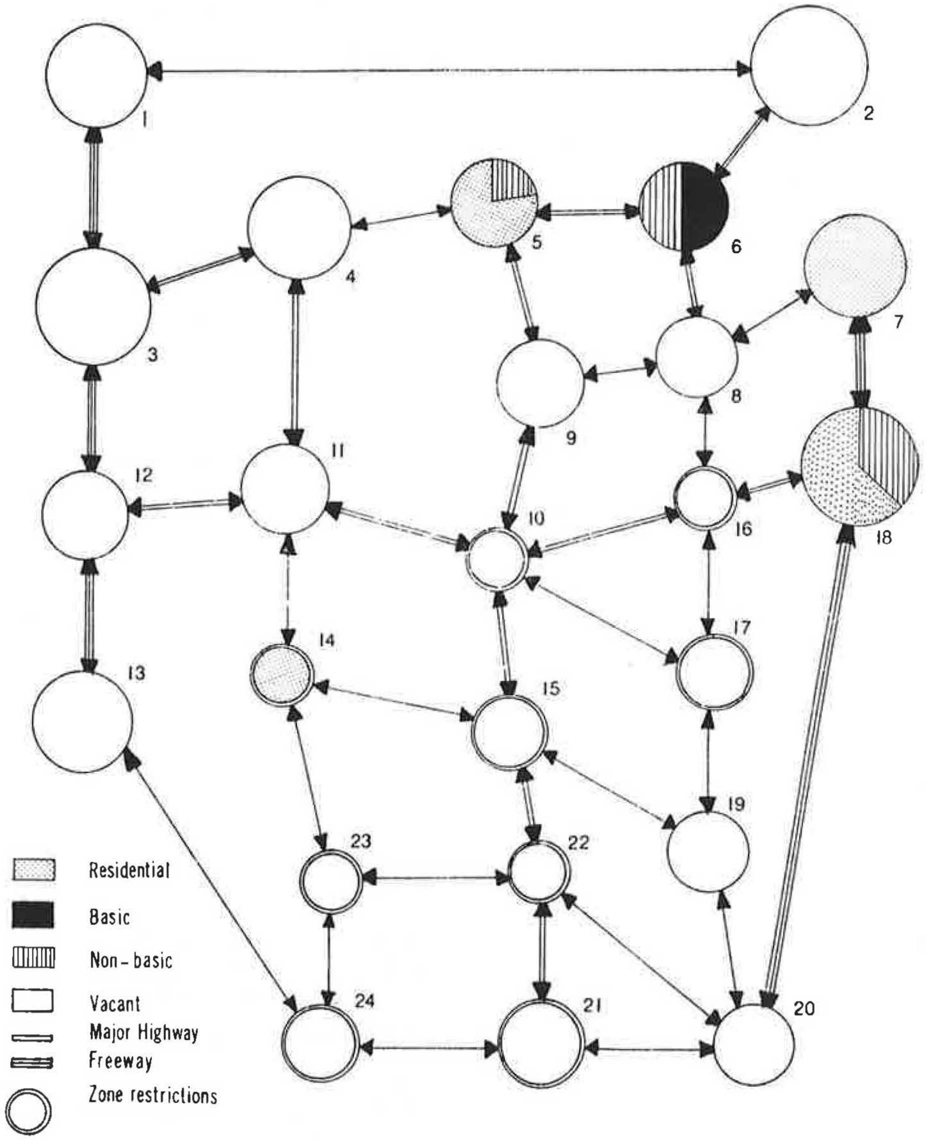


Figure 7. Minimization of transportation cost, $\beta = 0.2$, $\lambda = 0.2$.

nontransit zone to receive an allocation of low-density residential land use. Finally, as transit becomes unacceptable, zone 18 is developed.

The Cost-Minimization Solution

The preceding optimizations were based on a minimization of transportation energy consumption. The results were compact patterns for the new development. As may be seen in Figure 3, the test city has not historically developed in an energy-efficient manner, since the outlying zones that have existing development received little or no development in the allocations. Since the results have shown that the development of transportation energy efficiency would be a deviation from past trends, it was decided to produce the transportation cost-efficient allocation discussed above, for comparison. The resulting allocations were significantly different from those previously observed (Figure 7). Most importantly, the zones that had transit service were left out of every optimal land use pattern.

The allocations based on transportation costs can be divided into two groups based on the values of λ. One grouping of results occurred for low values of λ where the land uses, except some low-density housing, were allocated to zone 7. Larger values of λ, on the other hand, shifted all the land uses except low-density housing from zone 7 to zone 18 (Figures 4-6).

The cost-minimization solutions are quite different from the transportation energy minimization solutions. There are at least two possible interpretations for this distinction. On the one hand, it could be interpreted that the differences in transportation system characteristics are such that the energy-efficient links are not correspondingly cost efficient. On the other hand, the difference could be the result of energy consumption and transportation cost data that are inconsistent with each other.

A comparison of the results of the most characteristic test cases discussed so far was attempted in the graphs of Figures 8-10. The three curves of the graphs represent base-year conditions and conditions under energy cost minimization and transportation cost minimization. Although variations in these graphs are associated with trip cost changes and the values of λ, it is obvious that energy minimization as a transportation policy objective would produce considerable fiscal savings

Figure 8. Average energy consumption, $\beta = 0.2$.

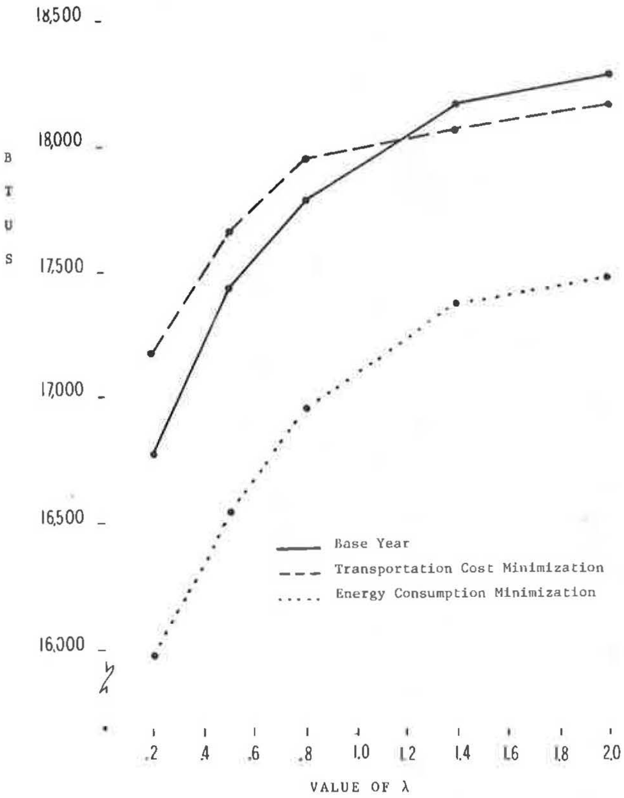


Figure 9. Mean trip length, $\beta = 0.2$.

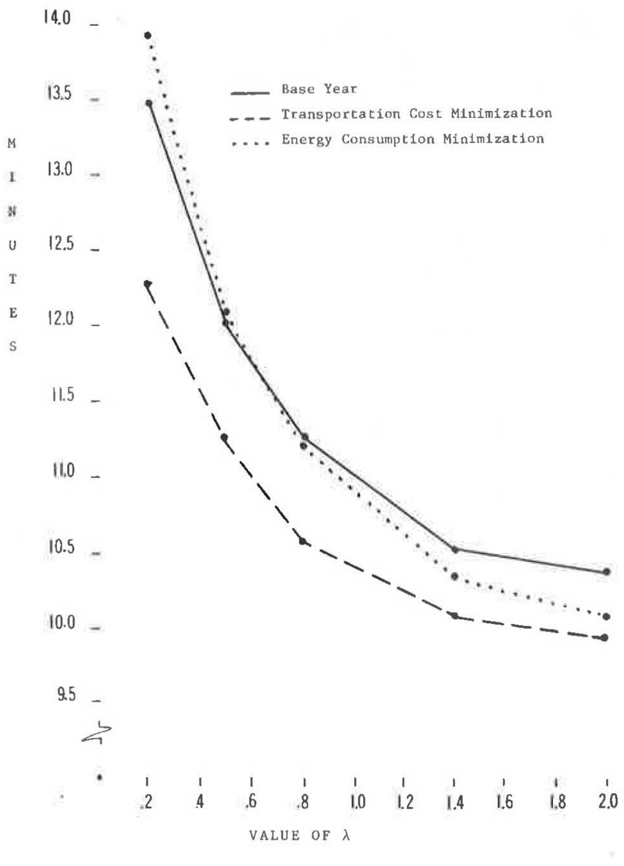
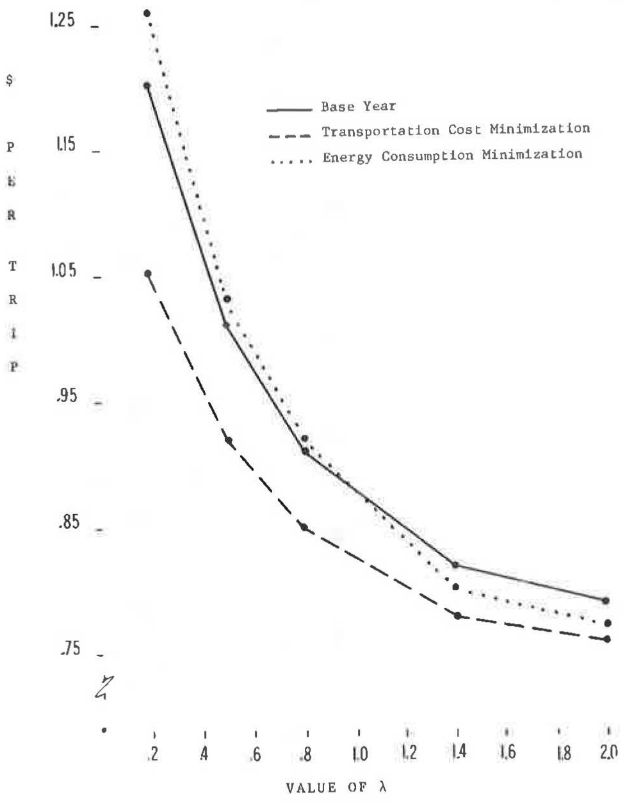


Figure 10. Mean trip cost, $\beta = 0.2$.



(Figure 8) but would also ensure an increase in mean trip lengths and mean trip cost over those generated by a cost-minimization model.

DISCUSSION AND EXTENSIONS

The land use allocations summarized in the previous section were obviously a diversion from the development patterns that had previously occurred in the city. The model incorporated elements to simulate observed travel behavior in the choice of destinations and modes but was biased in the direction of generating a transportation energy-efficient city while still allowing suboptimal travel choices. Its biased output, therefore, could reveal points that should be considered in the policy implications of the allocations and in the incorporation of further refinements in the model. This is especially true with respect to the availability of mass transit and the determination of the model's planning horizon.

The series of tests of the optimization model was performed with a very basic form of the model. Even though the complexity was increased significantly to overcome some of the shortcomings of simpler models such as TOPAZ, there are several elements that could be improved in future experimentation. A simplifying assumption used in the optimization model was that the network was capable of satisfying increased demand for travel with no decrease in travel times due to congestion. It should be possible to introduce network congestion into the optimization process and produce a land use allocation in which the resulting network assignment is in equilibrium. Variations of gradient-descent methods have been used in the creation of user equilibrium traffic assignments with fixed demands (10,11). Evans (12) summarizes the problem and different approaches to achieving equilibrium with elastic demands by combining trip distribution and assignment. The treatment of congestion has been carried a step further in allowing network characteristics to affect the development of zones in a Lowry model (13). Bowman and others (14) and Peskin and Schofer (15) have included network congestion in Lowry-type land use models.

Congestion would affect the optimal land use in two ways in this optimization model. Generally, in a land use model (including the Lowry-type energy and land use models) the destination choices are determined by travel costs on the network. Congestion reduces speeds, increases the travel times, and changes the relative attractiveness of alternative destination zones. In this transportation energy-optimizing model, the costs of transportation time determine destination choice, but energy efficiency determines optimal location of trip-generating land uses. Congestion decreases speeds, increases travel time, and may also affect fuel consumption by automobiles. In general, automobiles are more energy efficient at lower speeds, unless a significant amount of starts and stops are made. If reduced speeds due to congestion do reduce fuel efficiency, then an objective of energy minimization in an automobile-oriented city should be to produce results similar to those of a cost-minimization objective. However, in the event that the two objectives are not synonymous, an interesting problem is presented that deserves further study: The question is whether transportation energy or some other variable should be the variable to be considered in the objective function. How can transportation energy efficiency or some other objective of urban design be modeled and congestion incorporated when travel decisions are based on a different variable?

Problems of multiple objectives in another sense are dealt with by Bammi and Bammi (16), as was mentioned earlier. Their formulation deals explicitly with goals whose achievement cannot be compared without devising a common measurement system for evaluating trade-offs. Transportation energy-efficient design should also be evaluated in comparison with other urban design objectives. Unfortunately, the economies of scale or advantages of dispersion that might be beneficial for energy conservation might be detrimental to achievement of other design objectives. Goals such as preservation of open space or reduction of air pollution or other policy objectives might contrast with the needs of energy conservation.

Despite these shortcomings, the land use allocation model described in this paper accomplished several objectives. An optimizing procedure was offered as an alternative to the more common practice of using Lowry-type models in studying energy-efficient urban development. The unrealistic solutions given by early optimization models were overcome by adopting a model based on the TOPAZ concept. In addition, some of the limitations of this approach were also dealt with, primarily in the addition of development of upper- and lower-bound constraints. Furthermore, many of the problems that will confront future attempts to extend this model were discovered and examined. Some of them appear to be easily solvable; others may be impossible. However, the fact that not all of them can be readily overcome in an optimization approach should not undermine interest in the optimization solution. Note that practically all of these problems are also present in simulation models, and most of them have not been dealt with in applications of Lowry models. The most important point introduced in this paper is that energy optimization can be incorporated directly in the objective function of an urban design problem, and that its use is highly desirable if transportation energy minimization is a development objective.

ACKNOWLEDGMENT

The research on which this paper is based was supported by the U.S. Department of Energy through the Energy and Environmental Systems Division of Argonne National Laboratory.

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

Effect of Urban Development Patterns on Transportation Energy Use

MELVYN D. CHESLOW AND J. KEVIN NEELS

Many who have observed the large fraction of energy used in urban passenger transportation have suggested that this consumption could be reduced by encouraging higher densities and more compact settlements in urban areas. A study was carried out to investigate travel patterns and energy use in urban areas as determined by various descriptors of urban form. A statistical analysis of travel data from eight metropolitan areas found that energy use by urban passenger transportation is lower with some development patterns than with others. Some new neighborhoods would therefore be more energy efficient in their travel impacts than others. However, the transportation energy impacts of an extensive redevelopment (or growth) of an entire urban area would depend on the residential relocations that might occur with such drastic changes in overall housing availability. These were not examined. To calculate the energy use of various travel patterns, a simple direct approach developed at the General Motors Research Laboratories was used. This approach found that fuel consumption could be expressed as a linear function of a trip's travel time and travel distance, independent of complexities such as acceleration and deceleration rates or idle times.

Concern is now growing about the potential limits to the availability of petroleum fuel and the potential risks of our great dependence on the automobile for transportation. Even though many researchers are investigating alternative automobile fuels and energy sources that are not based on petroleum, others are concerned with additional courses of action. Increasing the efficiency of petroleum-based engines and vehicles is a major area of research that has been stimulated partly by federal legislation. In this area, making vehicles smaller, switching to lighter materials, and changing engine design are all receiving great attention.

Another approach to dealing with the potential fuel problem is to reduce our use of automobiles. Public transit, carpooling, and paratransit services are being considered as means of attracting drivers from their cars. In all of these cases, however, there is controversy over the extent to which energy use can actually be reduced (1). Part of the controversy is over the success levels attainable simply by promotion of the alternative modes. Some argue that automobile-restraint measures are necessary to get drivers out of their cars and that parking restraints, gasoline taxes, or road pricing must be used to coerce drivers to change modes. There is the additional question of whether the public transportation modes would actually save more energy than will the legislatively required efficient automobiles of the 1980s.

Other observers have suggested that the interrelated historical development of automobiles and cities during the last 50 years has led to a natural dependence on automobiles in low-density areas (2). This development has made public transportation noncompetitive in most urban areas for the majority of travelers who can afford their own automobiles. To reduce energy use, these observers suggest that we must change the structure of the cities to higher densities so that the resultant congestion would deter automobile use, and the higher densities would promote transit use as well as allow more walking. The remainder of this paper discusses this proposal to change urban form; the effectiveness of the approach is analyzed and various means for bringing it about are assessed.

Several analytical and simulation studies have been made of the relationship between urban form, transportation, and energy use. To understand their results, we must be clear about the possible ways in which urban form affects energy use. The next two sections set this background. First, the influence of travel patterns on energy use is discussed. This is followed by an analysis of the relationships between these travel characteristics and measures of urban form. The integration of these two pieces then provides the structure for the subsequent discussion.

ENERGY AND URBAN TRAVEL

The energy consumed by a single automobile trip depends on both travel time and travel distance. Research by Evans and others at the General Motors Research Laboratories has shown a simple linear relationship for a given vehicle for trip speeds less than about 35 mph (3-6):

$$F = a D + b T + c \qquad (1)$$

where a, b, and c are measured constants and

F = gallons per trip,
D = trip distance (miles), and
T = trip time (min).

The constant c represents the fuel required during cold starts compared to the use of an already warm engine and varies somewhat with ambient temperature.

Evans and others found that this relationship was a remarkably accurate representation of fuel use and that detailed trip characteristics such as acceleration and deceleration and idle times were not needed for the fuel estimate (4).

Based on the General Motors group's examination of 1973-1975 model cars, estimates of a, b, and c can be made for the fleet average. Also, Equation 1 can be written in terms of the distance and speed. The average fuel use per automobile then becomes

$$F = (0.039 + 0.078/v) D + 0.115 \qquad (2)$$

where v = average speed (mph), or

$$F = 0.039D\,[1 + (20/v)] + 0.115 \qquad (2a)$$

Equation 2a shows that the variation in trip speed has a very important effect on fuel use and that simply relating fuel to distance traveled is insufficient. With a 25-mph average speed and a 6-mile average trip distance, efficiency in cities from Equation 2a is 11 miles/gal, lower than the national average of 14 miles/gal. The latter figure, of course, includes intercity highway travel.

By adding up all the automobile trips in an urban area, the results of Evans and others can be used to estimate total fuel use. If it can be assumed that their results can be used with system averages, then total fuel will be a function of trip frequency, average trip length, and average trip speed (5).

If a trip frequency that represents total person trips rather than automobile trips is used, the modal share for transit and the automobile load factor also affect fuel use. An equation that includes all of these factors can be derived for the systemwide fuel use:

$$F_t = 0.039\,ND\,[1 + (20/v)]\,(1/L)\,(1 - t - w) + 0.115\,(N/L)\,(1 - t - w) + Ntf \qquad (3)$$

where

f_t = systemwide fuel use per year;
N = number of person trips per year;
L = automobile load factor, normally 1.2 persons/car;
t = fraction of trips by transit;
f = transit fuel use per passenger trip; and
w = fraction of trips by walking.

Most transportation studies in the United States do not determine the walking share (w) for travel, although a few have included it for trips to work. Hence, we will find later that the potential advantages of some urban forms to reduce energy use by making walking convenient cannot be estimated.

The fuel use per bus transit traveler is a value that is difficult to estimate because it depends greatly on the way the bus service is operated: the load factors, the handling of deadheading, and vehicle size. There has been a great amount of disagreement about what this value is in various cities and, more importantly, what it could be (1). Rail transit also has been controversial because of issues such as the energy use of access modes and the energy requirements for construction (1).

Another variable exists in Equation 3--automobile engineering characteristics. Chang and others found that the parameters a and b in Equation 1 are strongly related to engine size and vehicle weight (6). Hence, future changes in automobile design will change the parameter values used in Equation 3. With a mandated new-car efficiency of 27.5 miles/gal in 1985, the fleet average will be at that level by the 1990s; thus, the 14 miles/gal average of the mid-1970s will almost be doubled. This improvement in fuel efficiency will take place in the next 20 years without consideration of any changes in land use. Hence, any evaluation of policies to change either urban form or travel patterns should use the mandated improvement level as a base.

TRAVEL AND URBAN FORM

Most of the variables in Equation 3 are related to urban form and have values that can be changed by modifying the spatial relationship of urban activities. Exactly how urban structure affects the various travel characteristics has not been fully worked out, but a number of previous studies suggest that a strong relationship exists between urban land use arrangements and such travel characteristics as average vehicular trip length, trip duration, trip frequency, mode choice, and overall vehicle miles of travel.

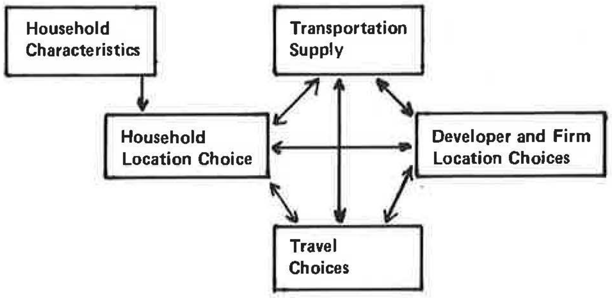
The relationships between urban development patterns and travel behavior can be considered by using the structure shown in Figure 1. One set of relationships in Figure 1 links development characteristics to transportation system characteristics, such as highway infrastructure and the availability of public transportation services. A second set links the characteristics of the households that choose to locate in a neighborhood to land use and transportation system characteristics, and the third set links neighborhood automobile ownership and travel to land use, transportation, and household characteristics.

The relationship between development patterns and transportation system characteristics is undoubtedly very complex. Public decisions to expand the transportation infrastructure influence decisions by developers and firms concerning the location and characteristics of housing, shopping, and industrial developments. The travel generated by these developments in turn influences new decisions on transportation infrastructure. These relationships are the outcome of a series of interrelated decisions made over a period of years.

A second set of relationships illustrated in Figure 1 shows the interaction between developer and transportation supply decisions on the one hand and neighborhood household characteristics and location choices on the other. Households make decisions about location based in large part on the land use and transportation characteristics of the neighborhoods available to them in a metropolitan area. Large households may tend to locate in low-density neighborhoods of single-family homes, for example, and plan on considerable automobile travel, and households that, for economic or other reasons, prefer not to rely on the private automobile may locate in neighborhoods that possess good public transportation. These decisions about household location in turn influence decisions about new land use developments and generate demand for transportation system changes, so that, as with the first set of relationships discussed above, questions of cause and effect become quite complex.

The third set of relationships shown in Figure 1 describes automobile ownership and travel behavior that result from the interaction of decisions made by households, firms, and public bodies and is the focus of most the analyses discussed in this paper. In effect, the analyses assume that public authorities have the power to alter land use and transportation system characteristics for different types of urban residents. It is emphasized, however, that

Figure 1. Structure of relationships between land use characteristics and household travel.



when policymakers actually set out to influence travel patterns through land use changes, they must consider the more complex interactions denoted at the top of Figure 1. Their problem is to take account of the second-round effects that always are present in private markets. Such matters as the prices of land, housing, and transportation will trigger population and other changes that may make it difficult to sustain any desired development pattern. These market influences on household locational choices and urban development patterns must be ignored here, but they may well be critical to any practical implementation of policies intended to influence travel behavior and energy use through alterations in the form of urban physical development.

A review of studies of transportation and land use interactions indicates that the aspect of urban form that most influences travel behavior is the separation between activities. Zahavi has found empirically, for several U.S. and foreign cities, that a measure of the separation between jobs and residences is highly related to the average trip length (7). This measure has been found by McLynn to be a function of the average distances to the urban center of jobs and residences as well as the two variances of these distances (8). Bellomo and others found by comparing data from Detroit for 1953 and 1965 that increases in the distance between residences and jobs increased the length of the work trip (9). They found a similar, but weaker, relationship for social trips and the distances between residences and social opportunities. Simulation studies that used traffic and land use models have also shown that trip lengths become longer as jobs and residences are separated (10).

All of these studies have provided support for the impression that trip lengths vary with the separation among activities. They also suggest that, for most U.S. cities, the average distance of the population or employment to the central business district (CBD) is often a good surrogate for the measure of activity separation.

Trip lengths also increase with metropolitan population, probably because the job-residence separation increases with urban size in the United States (9,11). Virtually all the metropolitan areas that have very long trip lengths are large urban centers where the population has decentralized more extensively than have job opportunities. Whether urban population size and the average separation of households from urban activities exert independent influences on travel lengths or whether population size merely serves as a surrogate for such distancing remains unclear at this point. What is clear is that average household distance from the downtown core and from other central points rises sharply with metropolitan population size. Urban size is probably important primarily as an indirect measure of origin-destination separation in explaining average trip lengths.

The average length of trips generated by residents in a specific neighborhood within an urban area is also related to activity separation (9,11). In this case, the average distance from the neighborhood to jobs or shopping opportunities is the relevant measure. It is not yet clear whether this neighborhood measure of activity separation is more or less important than the metropolitan average measure in explaining neighborhood patterns of trip lengths.

Trip length is also dependent on trip speed which, in turn, depends on the traffic volumes and capacities of the road segments being traversed. (Admittedly, this relationship between speeds and traffic volumes is somewhat circular and should be considered in an equilibrium analysis of supply and demand.) Both the capacities and flows will be related to the general intensity of surrounding land uses. Highway capacity will be easier to provide in outlying or low-density areas where land prices are lower and competing land uses are fewer. The density of traffic may be lower in these outlying areas where activities are farther apart and traffic flows are distributed more randomly.

The relationship between speed and land use measures has not been fully investigated, but the average trip speed is probably highly related, for most trips, to the local speeds at the trip ends. These latter factors appear to depend on the neighborhood density and the location of the trip ends (11). One locational measure that has been found significant is the distance to the CBD. Although this same measure has already been identified as having an important effect on trip length, in that case it was as a surrogate for separation between activities, whereas with speed it may be an indicator of traffic density.

The urban form measures that have now been described cover three different levels of geographic detail. At the highest level of aggregation, metropolitan population has been found to be important. This variable requires no knowledge about the inner structure of the urban area. The separation between activities, at the second level of aggregation, involves more detail about the urban structure and requires knowledge about the relative locations of many residential and industrial structures. The third measure is the neighborhood density--the population or employment density in a census tract or within walking distance. This last measure, like the first, requires no information about the complex interrelationships of activities, except at the geographic level of the individual household or firm and its immediate surroundings.

These three types of measures of urban form appear to be necessary and sufficient to describe the differences in metropolitan structure that affect vehicular travel patterns and, consequently, transportation energy use. The travel variables identified in Equation 3 have all been found to depend on these same measures of urban form (11,12). Although there has been little analysis of walking trips, the amount of land use mixing in a neighborhood (i.e., the close proximity of residences, jobs, and shopping) will likely promote the choice of this mode. The simple measures of employment or population density alone will not be highly related to walking. In fact, it has been found that the areas where walking has the highest fraction of commute trips are not the dense centers of large cities but medium-sized industrial or college towns (11,13).

The discussion now proceeds to analyze how the measures of urban form influence various travel characteristics. Since data are not available on walking trips or land use mixing, these characteristics will not be considered further, but this omission should not lead the reader to forget their potential importance as a means of reducing energy use.

MODEL OF THE EFFECTS OF URBAN FORM ON URBAN TRAVEL

The discussion in this section is based on analyses carried out by Cheslow and others that related land use measures and travel characteristics (11). The relationships should be viewed as preliminary due to the use of the distance-to-CBD measure as a surrogate for other, more complex, activity-separation measures.

The study by Cheslow and others examined actual travel characteristics derived from home interview surveys in eight standard metropolitan statistical areas (SMSAs). These cities, which are listed in Table 1, range in size from Los Angeles to Fresno and Youngstown. No cities that have rail transit were included in the sample. This study complements the simulation analyses carried out by others. It has more realism than simulation because actual trips are analyzed, but it is limited in the range of urban structures that can be examined to those that now exist.

The data set consisted of a pooled sample of neighborhoods drawn from the home interview surveys that were conducted between 1966 and 1971. Cross-sectional regression analysis was conducted at the level of the neighborhood, which was defined to consist of from two to four local traffic zones. The basic sample contained 234 neighborhoods drawn from the eight metropolitan areas. For each neighborhood, the individual responses to the home interview surveys were aggregated to form neighborhood means.

The several transportation characteristics that were examined are listed in Table 2 together with their mean values and standard deviations. These characteristics include all the variables in Equation 3 except transit fuel efficiency and the fraction of walking trips. The variables that describe urban structure included only neighborhood density and distance to the CBD. No employment-density values were available. Areawide characteristics, including urban population, urban density, and percentage of employment in the CBD, were also examined, but the small number of cities in the sample did not permit identification of the correct metropolitan-scale variable. These aggregate variables were highly correlated with each other in the data set.

To overcome this difficulty, dummy variables were used--one for each city. The analysis could then determine the relative importance of the metropolitan dummies and the local variables. For some travel characteristics (such as trip frequency), the dummies were not important, but for others (such as trip length), they dominated the other explanatory variables.

Household characteristics were also considered apart from the land use variables to determine the separate effects of changing densities and locations and those of changing the types of households. The land use and household characteristics are shown in Table 3.

The first aspect of urban travel characteristics to be dealt with concerns the characteristics of the urban transportation system. Equations were estimated by treating transit availability and automobile trip speed as if they were determined by the pattern of urban development. These results are shown in the following table.

Explanatory Variable	Coefficient	t-Statistic
Neighborhood transit availability		
Neighborhood density	0.000 246	7.78
Distance to the CBD	-0.155	-6.07
Metropolitan dummy variable	Varies	
Corrected R^2	0.60	
Automobile driver trip speed		
Neighborhood density	-0.029	-3.12
Distance to CBD	0.062	5.32
Metropolitan dummy variable	Varies	
Corrected R^2	0.81	

It is clear that these relationships are not supply functions in the usual sense of the term. Transit availability is the result of a long series of decisions made by public authorities over many decades. There is no reason to believe that the transit availability equation would adequately describe the type of transit service that would be provided in a newly built-up area. Problems also arise in determining the direction of causation between speed and the development pattern. Do low densities result in high automobile speeds, or does high speed

Table 1. Characteristics of the metropolitan areas.

	Urban Area			
City	Population	Density (people/ mile^2)	Percentage of SMSA Employment in CBD	Density Gradient[a]
Dayton	685 942	3062	8.3	0.14
Denver	1 047 311	3574	9.3	0.14
Fresno	262 908	3328	6.5	0.09
Los Angeles	8 351 266	5313	4.0	0.08
Omaha	491 776	3257	13.7	0.22
Pittsburgh	1 846 042	3097	8.9	0.10
Washington	2 481 489	5013	11.8	0.13
Youngstown	395 540	3066	7.5	0.15

Note: All values are for 1970.

[a] Absolute value of the slope parameter of a negative exponential density function fitted to 1970 census tract data.

Table 2. Transportation variables used in the analysis.

Variable	Definition	Unit of Measurement	Mean Value in Sample	SD
Automobile				
Ownership	Average number of automobiles per family in neighborhood	Unit	1.22	0.42
Occupancy, journey-to-work	Average persons per automobile	Unit	1.20	0.16
Average trip duration	Average duration of automobile driver trips (vehicle time only, not door-to-door time)	Minutes	18.1	7.3
Average trip length	Average distance for automobile driver trips	Miles	7.4	4.7
Vehicle miles of travel	Average daily automobile driver vehicle miles traveled per family	Miles		
Transit				
Availability	Proportion of neighborhood within 0.25 mile of a transit line	Percent	59	36
Proportion of vehicle trips	Transit trips ÷ all vehicle trips	Decimal	0.048	0.085
Speed	Total automobile driver miles of travel by residents of neighborhood over total in-vehicle automobile driver minutes of travel	Miles per minute	0.41	
Vehicle trips per family	Average daily trip frequency per family (automobile driver or passenger and transit)	Unit	5.31	2.29

Note: Trips here refers to home-based trips internal to the study area.

Table 3. Land use and family characteristics used in the neighborhood analysis.

Variable	Mean Value in Sample	SD
Land use measure		
Distance from CBD (miles)	7.15	5.43
Neighborhood density[a] (persons/mile^2)	8026	7270
Urbanized area density (persons/mile^2)	3972	969
Urbanized area population (000 000s)	2.87	3.19
Employment in CBD (%)	5.30	1.96
Urbanized area density gradient (1/miles)	0.13	0.03
Household characteristic		
Family income ($)	9546	4485
Average family size (persons/household)	3.23	
Proportion of neighborhood that is black	0.148	0.295

[a] Equals persons per square mile of net area, where net area equals gross area minus recreational land minus the area of any bodies of water in the neighborhood. This measure does not exclude land devoted to industrial or commercial uses.

Table 4. Log-linear variables for automobile driver trip length.

Variable	All Purposes		Work	
	Coefficient	t-Value	Coefficient	t-Value
Income	0.058	1.83	0.081	2.85
Neighborhood density	-0.024	-1.40	-0.049	-2.77
Average automobile driver speed	0.92	6.87	0.96	6.04
Distance to CBD	0.19	4.43	0.41	5.85
Metropolitan dummy variable	Varies		Varies	
Corrected R^2	0.92		0.91	

Table 5. Log-linear variables for home-based vehicle trips per household.

Variable	Coefficient	t-Value
Transit availability	0.051	1.38
Average automobile driver trip time	-0.121	-2.18
Household size	0.507	5.62
Average automobile ownership	0.584	9.11
Neighborhood density	-0.145	-4.03
Corrected R^2	0.68	

Note: Vehicle trips include trips made by automobile driver, automobile passenger, and transit passenger modes.

encourage a sprawling form of development in which residences and activities are far apart? In many cities bus lines follow the routes of the old streetcar lines, which at the time of their inception exerted a powerful influence on development.

Despite these difficulties of interpretation, it is probable that in some sense transportation supply functions do exist. Transit agencies do not make their decisions about construction and operations in a completely arbitrary manner. Transit service will attract more riders and generate more revenue in some situations than in others, and operators take this into account in making route extensions. Similarly, because automobile speed is partly determined by the level of road use and the resulting congestion, development characteristics probably exert some influence on this variable. Even public decisions about street widening and highway construction are influenced by congestion levels, the cost of land, and the amount of disruption that would be caused, all of which are partly dependent on land uses. These considerations suggest that, even though it is invalid to use these equations for making detailed predictions in a given metropolitan area, they may capture the average responsiveness in the past of urban areas to different development characteristics.

The main reason for including these equations in the current study was to clarify the role of land use characteristics in determining travel behavior. The observed relationship between neighborhood development traits and travel may be largely due to the intermediate association with transport supply. The direct effects of land use characteristics after supply variables are controlled may, in fact, be quite small.

Automobile ownership has been shown in many other studies to be an important factor in household travel decisions. Ownership rates in this analysis were estimated as a function of neighborhood development, household, and transportation system characteristics. Log-linear results are shown in the table below (note that "proximity to major center" is a dummy variable that has a value of 1 if the neighborhood is within 1 mile of the CBD or a major retail center).

Explanatory Variable	Coefficient	t-Statistic
Proximity to major center	-0.063	-1.48
Neighborhood density	-0.084	-2.88
Income	0.334	7.12
Average household size	0.524	7.42
Percentage black	-0.051	-5.55
Transit availability	-0.40	-1.28
Corrected R^2	0.69	

The set of travel choices was then assumed to be structured as follows. First, residents of a neighborhood choose an average trip length. This corresponds to the definition of an activity field within which people conduct most of their daily business. If a wide diversity of activities is located close to the neighborhood, this field may be relatively small. If average speeds are high, so that the time per unit of distance is small, the field will be correspondingly larger. Finally, certain types of households may have preferences for a larger- or smaller-than-average field. Trip duration, or travel time, is computed as the ratio of trip distance and trip speed. Vehicle trip frequency is then expressed as a function of travel time; household, neighborhood development, and transportation system characteristics; and automobile ownership. Mode choice is computed as a function of the same variables. These results are shown in Tables 4-7.

This formulation of the set of travel choices allows for the possibility of numerous indirect influences on household travel behavior. In principle, several of the travel choices (such as those regarding trip length and mode choice) would best be modeled as made simultaneously. However, as a first step in unraveling the way these relationships enter into travel choices, a simultaneous formulation was ignored.

Perhaps the best summary measure of differences in urban travel patterns is the total automobile miles traveled by households under different conditions. Traditionally, this measure has been called vehicle miles traveled (VMT), even though the sole vehicle involved is the automobile.

In this analysis, automobile VMT was derived indirectly from the other variables for which direct measurements are reported. In principle, automobile VMT is influenced by the number of vehicle trips, the transit share of such trips, average trip length, and the average ridership per automobile trip, or

$$\begin{aligned}\text{Vehicle miles traveled} = \ & (\text{number of vehicle trips}) \\ & \times (1 - \text{transit share}) \times (\text{average trip length}) \\ & \div \text{average automobile occupancy} \qquad (4)\end{aligned}$$

In practice, trip frequency and average trip

Table 6. Mass transit use—all trips.

	Transit Proportion of All Vehicle Trips					
	1 (linear)		2 (linear)		3 (linear)	
Explanatory Variable	Coefficient	t-Value	Coefficient	t-Value	Coefficient	t-Value
Neighborhood density	0.001 36	1.6	0.002 12	2.5	0.0275	2.6
Distance to CBD	-0.005	2.0	-0.004 03	2.8	-0.066	2.9
Average automobile speed			-0.044	0.4	-2.71	1.4
Automobile ownership per family	-0.051	3.1	-0.029	1.9	-0.519	2.2
Proportion of population black	0.056	2.9	0.066	3.5	0.952	4.0
Average family income			0.000 075	0.05	-0.040	1.7
Transit coverage	0.002	0.3	0.025	1.3	0.426	1.6
Urban area population (000 000s)	0.061	3.3				
Metropolitan dummy variables[a]			0.054-0.152	0.83-2.6	-2.74-0.43	2.9-0.5
Corrected R^2	0.45		0.49		0.73	

[a] Fresno represents the bottom of the ranges and the Dayton the top.

Table 7. Mass transit and carpool use for work trips.

	Transit Proportion of Work Trips				Automobile Occupancy for Journey to Work	
	1		2			
Variable	Coefficient	t-Value	Coefficient	t-Value	Coefficient	t-Value
Neighborhood density	0.002 94	3.0	0.001 94	1.9	0.002 58	1.6
Distance to CBD	0.005	3.1	0.005 65	3.3		
Employment concentration at urban center (proportion of jobs in CBD)					1.40	3.7
Automobile ownership per family	-0.052	2.6	-0.038	2.1	-0.080	2.7
Proportion of population that is black	0.058	2.4	0.058	2.6	0.136	3.4
Transit coverage	0.008	0.9	0.021	0.9		
Urban area population (000 000s)	0.069	4.1				
Average automobile speed			-0.112	0.8		
Metropolitan dummy variables[a]			0.11-0.23	1.5-3.2		
Corrected R^2	0.47		0.49		0.30	

[a] Youngstown represents the bottom of the range and Dayton the top.

Table 8. Impacts on automobile vehicle miles of travel of a variation of 1 SD in density and distance to CBD.

Variable	Mean Value	SD	Path of Influence	Direction and Size of Effect on VMT[a] (%)
Density	8026 persons/mile^2	7270	Direct effect on vehicle trip frequency	-13
			Indirect effect on vehicle trips via automobile ownership	- 4
			Indirect effect on vehicle trips via average automobile speed	<0.5
			Direct effect on average trip length	-3
			Indirect effect on trip length via average automobile speed	-3
			All direct and indirect effects on transit share of trips	-1
Distance to CBD	7.2 miles	5.4	All direct and indirect effects on trip frequency	<0.5
			Direct effect on trip length	-14
			Indirect effect on trip length via average automobile speed	-4
Total			All direct and indirect effects	-33[b]

[a] Evaluated at mean VMT.
[b] Less than the sum of the individual effects, each of which is measured against the sample average VMT.

length are by far the most important contributors to variations in VMT. Transit shares are small enough that even substantial increases in ridership rates have little impact on total VMT. Average automobile occupancy does not show systematic variation with most other variables and fluctuates within a relatively small range and, therefore, exerts little influence on household VMT. (Keep in mind that these VMT estimates only cover home-based travel, i.e., trips that begin or end at home. These estimates understate total VMT by about 20 percent.)

Table 8 attempts to place in perspective the various lines of influence through which the two neighborhood urban development variables included in the analysis affect automobile VMT. The table shows the impact on household VMT of changes of one standard deviation in neighborhood density and neighborhood distance from the CBD. Such a shift would move the mean neighborhood in the sample into the top 16 percent with respect to the development characteristics that economize on automobile travel. Reference to a standardized change of this type makes it possible to compare the relative magnitude of the impacts of shifts in density and distance to the CBD.

A shift of one standard deviation may also be interpreted as a (rough) measure of the changes it is practicable to make in development patterns, at least in light of the current differences in development characteristics that are found in U.S. urban areas.

Table 8 demonstrates that neighborhood density produces its principal effect on vehicle trip frequency. As noted before, the major explanation for this impact seems to be the substitution at higher densities of walking trips for vehicle trips--a response that unfortunately could not be tested directly in our sample. Although the primary impact of density on trip frequency is a direct one, there is also an indirect effect through the lesser rates of automobile ownership that households choose when living in high-density conditions.

The direct and indirect effects of density on trip lengths are about one-third as important in their influence on automobile VMT as the impacts on trip frequency. The direct effects of density on trip length, through the clustering of destination points, are of roughly the same importance in reducing VMT as the indirect discouragement to longer trips through congestion or slower automobile speed.

The effects of density on transit ridership are conspicuous for their unimportance, at least as a means of discouraging automobile use. This suggests that the quest for high-density development and greater mass transit patronage may be relatively inefficient as a means of achieving most other urban goals.

Neighborhood proximity to the CBD has a very strong effect on automobile VMT through its effect on trip length. This influence is exerted both directly (by reducing the average distance to urban activities) and indirectly (by discouraging the long trips that greater congestion causes in trips from close-in neighborhoods).

All in all, a simultaneous shift of one standard deviation in both urban development characteristics has the effect of reducing average household VMT by approximately one-third--a substantial impact on urban automobile travel. This figure should be interpreted as an order-of-magnitude indicator of the sensitivity of automobile travel to urban development characteristics. The partially specified nature of most of the equations makes it impossible to read great accuracy into the results. In particular, the use of distance to the CBD as the only measure of job-residence separation is a practical compromise forced by data availability; the omission of other land use variables further restricts interpretation of the results. Nonetheless, Table 8 goes part of the way toward clarifying the complex interrelationships that link urban land use characteristics to travel choices and toward establishing at least a sense of the magnitude of the changes in travel behavior that can be accomplished from alterations in the urban development pattern.

To further indicate the relative importance of density and location, as well as of metropolitan variables, the range of values of the transportation characteristics is shown in Table 9 for neighborhoods in two of the metropolitan areas and in an average area. The demographic makeup in all the neighborhoods is assumed to be identical--average household income of $12 000, average household size of 3.5, and 10 percent black. Los Angeles, on the one hand, is a large, sprawling metropolis where activities are highly separated. Youngstown, on the other hand, is a much smaller and more compact area where activities are closer together. For many of the variables, there are greater variations between cities than between neighborhoods within the cities. This occurs even though the sample included no really high-density city, which indicates that large-scale activity separation is apparently more important than the local land use measures.

URBAN FORM AND TRANSPORTATION ENERGY USE

The variation in fuel use in the different neighborhoods and metropolitan areas can be derived by using Equation 3. The results are shown in Table 9. Again, there is greater variation between cities than within them. Because transit use is so low in the neighborhoods considered in Tables 9 and 10, assumptions about transit fuel use do not affect the energy calculations. At least among the neighborhoods in this sample, in no case does congestion appear to cause fuel use to increase with density. In the range of cities considered in Table 10, the more compact or dense an urban area is, the less fuel is used. The table also indicates an interesting phenomenon in which the fuel-efficiency level, measured in miles per gallon, is inversely related to fuel use. This occurs mainly because the shorter trips

Table 9. Representative travel measures for a high-income neighborhood.

Metropolitan Area	Inner High Density	Fringe High Density	Fringe Low Density
Automobile Driver Trip Length (miles)			
Los Angeles			
Work	16.4	19.3	26.3
All	12.7	14.6	17.2
Average area			
Work	7.4	8.6	11.4
All	5.8	6.6	7.7
Youngstown			
Work	3.9	4.1	5.6
All	3.3	3.5	4.1
Automobile Driver Trip Duration (min)			
Los Angeles	26.3	26.5	28.7
Average area	14.5	14.7	15.9
Youngstown	8.3	8.4	9.1
Vehicular Trip Frequency			
Los Angeles	6.2	5.9	9.1
Average area	6.7	6.7	10.4
Youngstown	7.1	7.1	11.3
Transit Use (%)			
Los Angeles	4.4	0.6	0.3
Average area	2.3	0.7	0.3
Youngstown	1.6	1.1	0.5
Automobile Vehicle Miles of Travel			
Los Angeles	49.7	56.5	103.0
Average area	24.8	28.7	52.2
Youngstown	14.7	15.6	29.3
Transit Availability			
Los Angeles	0.87	0.18	0.02
Average area	0.87	0.51	0.10
Youngstown	0.85	0.73	0.22
Automobile Driver Trip Speed (mph)			
Los Angeles	0.29	0.33	0.36
Average area	0.24	0.27	0.29
Youngstown	0.24	0.25	0.27
Automobile Ownership (cars/household)			
Los Angeles	1.8	1.9	2.6
Average area	1.8	1.9	2.5
Youngstown	1.8	1.8	2.4

Note: All figures refer to home-based internal travel only.

have a larger fraction of the travel that occurs with cold engines.

The analyses of Los Angeles and Youngstown do not give a complete picture of what happens in very dense neighborhoods in very compact cities. To give an indication of these situations, Table 11 shows the percentage changes in several travel characteristics if neighborhood land use variables were changed in different ways. One of these would have the urban area become compact, with a dense urban core--a city the size of Youngstown but with a large CBD employment such as in Washington, D.C.

Other alternatives include increasing the density by factors of three or five and placing the neighborhood one-quarter of the average distance to the CBD. (A density increase by a factor of five produces Manhattan-like concentrations.) Table 11 indicates much larger changes in the travel characteristics than those in Table 9. Now the local changes in land use have effects similar in magnitude to the areawide changes and, in the case of trip frequency, the impact is larger. One can surmise that this effect on trip frequency indicates a large switch to walking trips in the very high-density neighborhoods.

Even in these very high-density situations, transportation energy use appears always to decrease with more concentrated development. From Table 11, it appears that this result occurs because of the small changes estimated in automobile speed relative to those in trip length and frequency. One might have some doubts that speeds would remain so high because in Manhattan they are as low as 8-12 mph. These very low speeds represent a decrease from the average in the sample of more than 50 percent, much more than the model would estimate.

This observation of the possible errors in estimating speed change suggests that the analysis cannot be extrapolated accurately to these very high densities. We cannot yet be sure that a maximum density does not exist above which energy use would again start to rise.

Table 10. Representative daily energy use per household for a neighborhood.

Metropolitan Area	Inner High Density	Fringe High Density	Fringe Low Density
Daily Fuel Use (gal)			
Los Angeles	3.7	5.2	6.9
Average area	2.3	3.1	4.3
Youngstown	1.6	2.1	2.8
Average Miles per Gallon			
Los Angeles	13.3	14.2	14.8
Average area	11.0	11.7	12.4
Youngstown	9.4	9.7	10.4

CONCLUSIONS

How important are physical development characteristics in shaping urban travel behavior and energy use?

The analysis of neighborhood travel patterns presented here, coupled with previous studies, indicates that there is little uncertainty regarding the direction of effect of most urban development variables. High residential and employment densities are systematically linked with fewer vehicular trips and with greater rates of transit use. Large metropolitan populations and greater-than-average separation between residential and job locations are regularly associated with long average trip lengths. These qualitative conclusions regarding the determinants of travel behavior correspond with planners' perceptions, as reflected in planning proposals to alter travel patterns.

Previous studies have left unclear whether the physical development characteristics of cities shape transportation choices primarily at the neighborhood scale or primarily at the metropolitan scale. Of course, it is likely that both scales of influence are important. Nonetheless, it would be a much easier task to mold future urban transportation behavior if household travel choices were found to respond largely to the development characteristics of their own neighborhood and its environs. Even drastic changes in the physical planning of new developments can be contemplated without great difficulty. Transformation of the configuration of an entire metropolis is another matter. Nothing short of physical destruction or a total reversal of economic markets is likely to convert San Diego or Tucson into an exemplar of compact development.

The empirical analysis presented here has shown the impact of neighborhood development characteristics to be substantial, though frequently less important than household demographic characteristics and automobile ownership rates in influencing travel choices. The representative development scenarios used to illustrate the findings of the regression analysis involved savings of more than 40 percent in annual transportation energy use per household, when relatively high-density, centrally located development was compared to low-density fringe development in the same metropolitan region, after control for household and other characteristics.

The data set assembled for this study was not the ideal one with which to examine influences on a metropolitan scale. In the majority of instances, the regressions indicated important differences between metropolitan areas. Unfortunately, because so few metropolitan areas were included in the sample, it was impossible to pinpoint the urban-scale char-

Table 11. Changes in neighborhood travel characteristics due to modification of urban structure.

Travel Variable	Mean Value	Change SMSA to Medium Size and Compact (%)	Neighborhood Density Increase (%)		Neighborhood One-Quarter of Average Distance to CBD (%)	Combination of Two Preceding Modifications (%)
			Factor of Three	Factor of Five		
Automobile trip frequency	5.1	-13	-21	-31	-9	-44
Vehicular trip frequency	5.3	+7	-18	-25	-5	-29
Automobile trip distance	7.4	-43	-5	-8	-19	-34
Automobile trip speed	24.5	-21	-3	-5	-8	-12
Percentage transit	4.8	+370	+72	+170	+80	+354
Automobile ownership	1.2	0	-11	-15	-6	-20
Automobile occupancy	1.2	-6	+1	+1	-1	0
Fuel use	2.7	-35	-24	-35	-28	-56

acteristics that distinguished the different metropolitan regions. The analysis, however, is consistent with earlier studies that have reported that metropolitan population size, central employment concentration, and work-residence separation (for which the other two variables may be proxies) dominate travel choices at the metropolitan scale.

A word needs to be said regarding the desirability of alternative urban travel patterns. Because public costs are associated with automobile travel, many land use planners have taken the position that urban development patterns that reduce automobile travel are superior.

A careful analysis of the relative advantages of alternative development patterns must first investigate the ability of citizens to reach desired destination points and then examine both the private and public costs in doing so. There are two basic design options for providing accessibility. One is to endow the individual or the household with its own means of travel and to design urban areas to facilitate individual travel. This transportation strategy relies on personal mobility. Since World War II, this has been the overwhelmingly dominant approach to urban transportation in the United States, as embodied in the automobile and in ambitious urban road construction programs.

An alternative strategy would be to design cities so that households and destinations are in close proximity to each other, with the result that many trips can be made on foot or by mass transit. Until part way through this century, the shape of urban areas was in fact constrained by the structure of mass transportation routes and by the walking radiuses around transit stations. The availability of automobiles has freed urban development from this constraint, but one of the most common planning recommendations is to return to an urban design that would facilitate, or even require, greater use of mass transportation while diminishing use of the automobile.

A full comparison of the transportation costs associated with alternative development patterns is beyond the scope of empirical analysis at this stage of our understanding. Private costs would have to include dollar outlays, time consumed in travel, and the inconvenience of travel to the user. Public costs take the form of public capital investment, operating subsidies for mass transit systems, air pollution and other externalities generated by automobile use, and any social costs associated with gasoline consumption beyond those reflected in its price. This analysis, taken as a whole, goes some distance toward identifying and measuring these social costs. It does not, however, settle on a prescription of the optimal development pattern or attempt a cost-benefit comparison of alternative urban designs.

In this paper we limit ourselves to examining the trade-off in travel patterns and energy use associated with alternative urban development forms. It is intended to cast light on the question, "How greatly could urban transportation patterns and energy use be modified through urban land use alterations?" The related, and ultimately more important question, "Is it economically and socially desirable to rearrange urban development patterns in order to alter travel behavior?", is not answered.

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Publication of this paper sponsored by Committee on Traveler Behavior and Values.

Travel Demand and Estimation of Energy Consumption by a Constrained Model

YACOV ZAHAVI AND MELVYN CHESLOW

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.

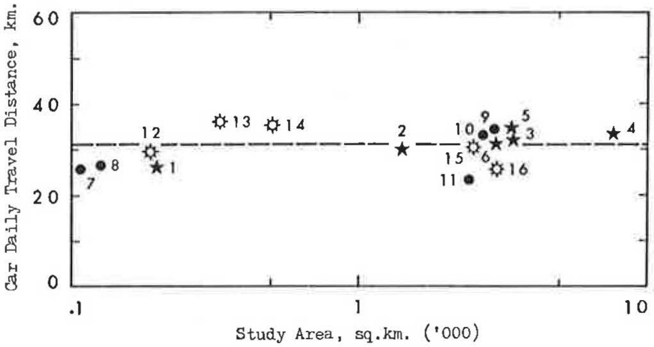
Models based on microeconomics of consumer behavior under explicit constraints of travel budgets appear to be both more true to reality and more versatile in application. One such new model is described in this paper, and examples of its application to both urban and interurban travel conditions are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



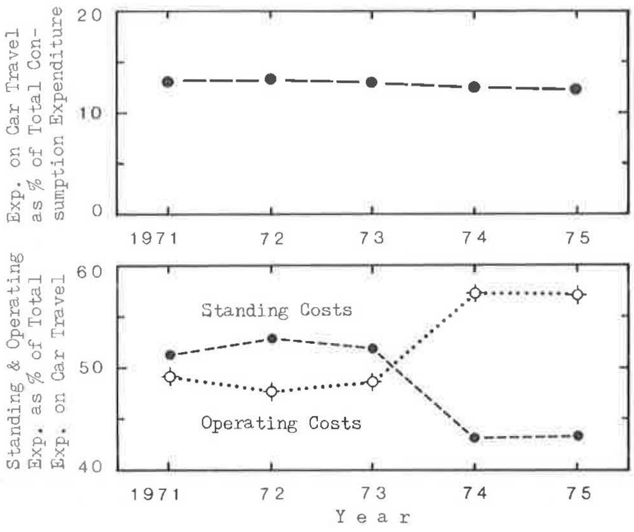
Note: 1 = Monroe, 2 = Orlando, 3 = Cincinnati, 4 = Twin Cities, 5 = Washington, 6 = Philadelphia, 7 = Kingston Upon Hull, 8 = Belfast, 9 = Nuremberg, 10 = Copenhagen, 11 = London, 12 = Tel Aviv, 13 = Kuala Lumpur, 14 = Singapore, 15 = Bogota, 16 = Bangkok.

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).

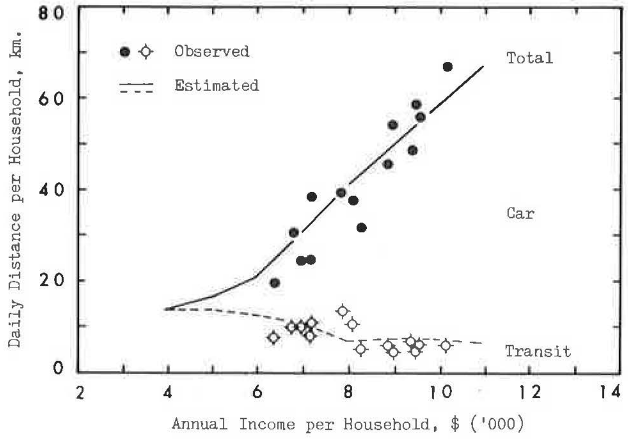
One useful way of applying travel budgets as constraints is within the microeconomic theory of consumer behavior, where consumer utilities are maximized under explicit constraints. In UMOT, the utility of the spatial and economic opportunities to which a person travels, which are conveniently represented 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

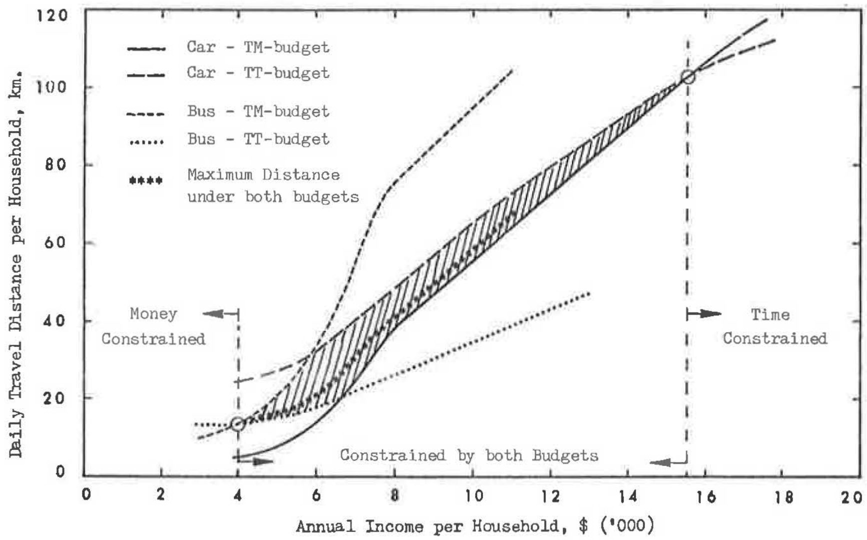


Figure 4. Maximum daily travel distance per average household versus household annual income for Washington, D.C., 1968.

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.

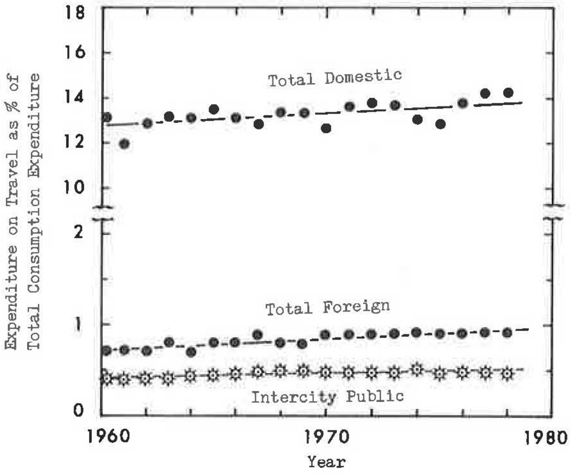
Detailed analyses of travel time budgets in a wide range of cities in both developed and developing countries suggest a rather large coefficient of variation (standard deviation over the mean) of about 0.6. Interestingly, this value was found to be quite similar both between different cities and within 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.

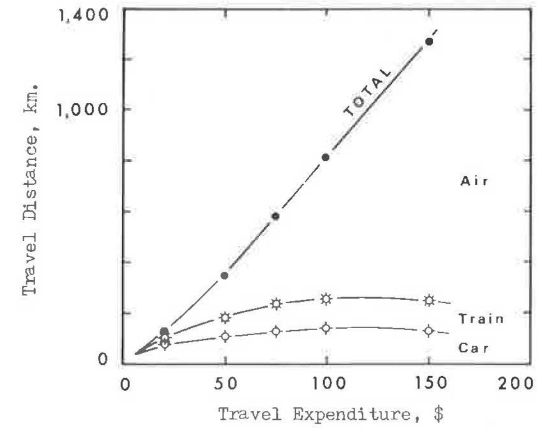
Table 3 summarizes the unit costs and outputs,

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

Characteristic	Mode	Travel Budget $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.



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

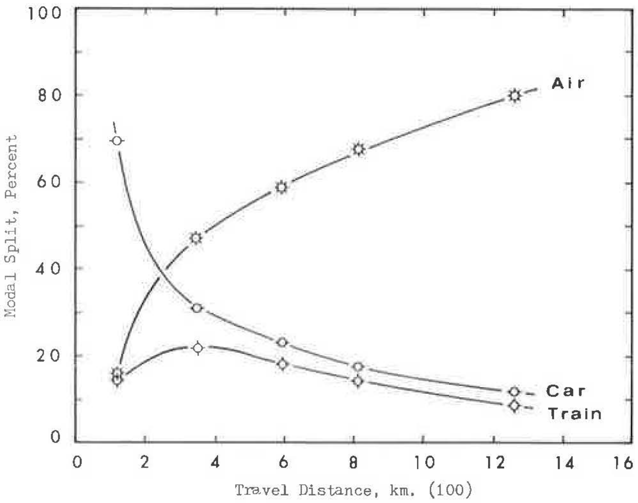
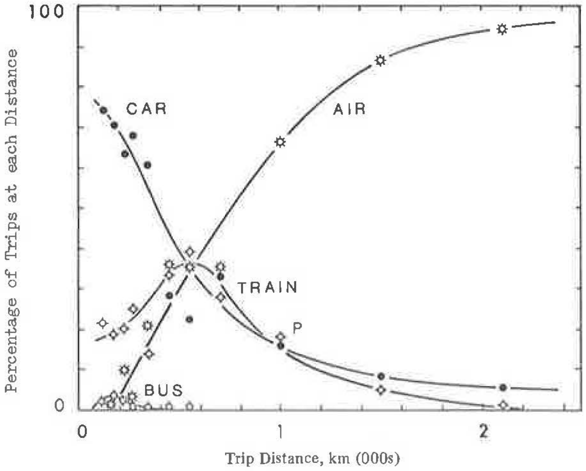


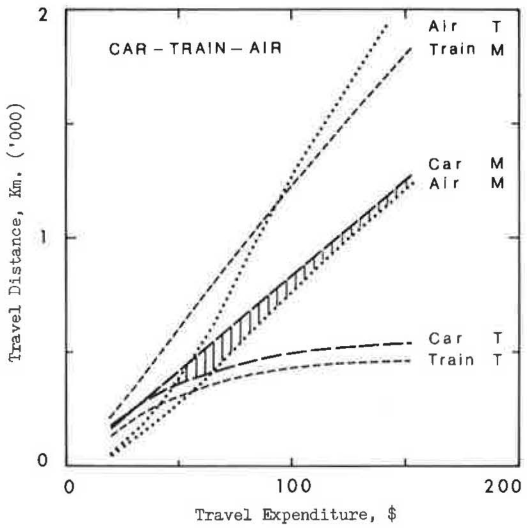
Figure 8. Trip modal split by trip distance for business trips in European intercity travel.



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.

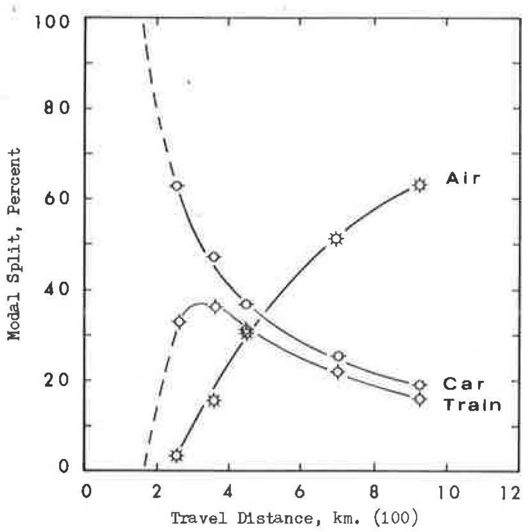


Table 5. Effect of increased train speed on travel demand for one traveler who has budgets of $100 and 330 min after one iteration.

Characteristic	Mode	Train Speed		
		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.

Mode	Absolute Values (km)			Modal Shares (%)		
	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.

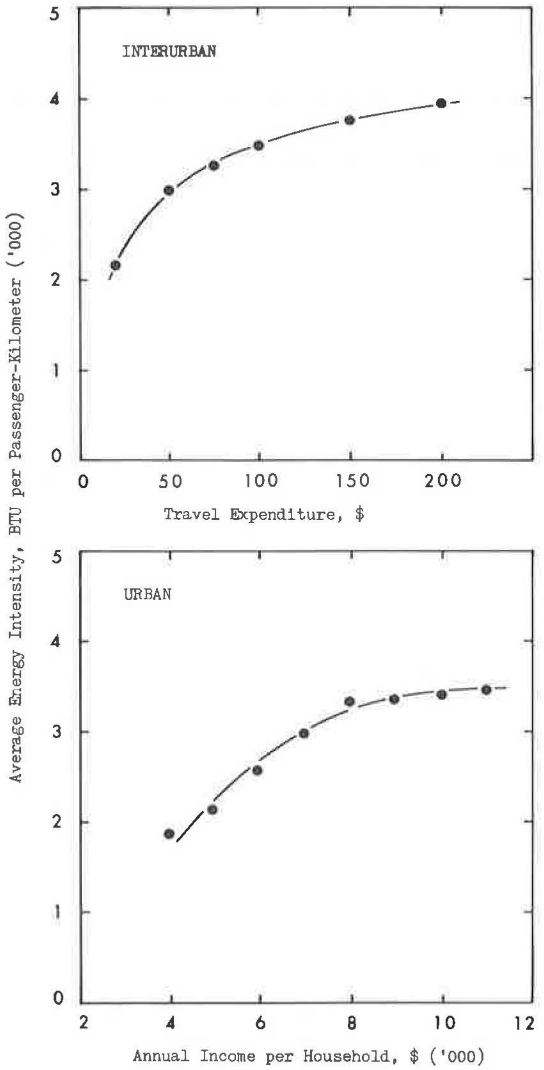
By referring to Figure 11 it may also be concluded that, ironically enough, most of the energy savings by modal shifts will be realized at the lower end of travel money expenditures (i.e., for lower-income travelers in most cases). The total nationwide savings in travel energy consumption will then depend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

ACKNOWLEDGMENT

We are grateful to Robert W. Crosby and David Kahn of the Research and Special Programs Administration, U.S. Department of Transportation, for their permission to refer in this paper to some results from an ongoing study, and to Philip D. Patterson of the Energy Research and Development Administration, U.S. Department of Energy, for his helpful comments.

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

Assessment of the Wharton EFA Automobile Demand Model

BARBARA C. RICHARDSON, D. HENRY GOLOMB, MICHAEL M. LUCKEY, AND DANIEL B. SUITS

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 an estimate of the effect of the policy.

There have been two main updates to the Wharton EFA automobile model. These are the Wharton EFA Motor Vehicle Demand Model, Mark I and Mark II (2,3). However, the initial version of the model has been the most widely used. Thus, that initial version of the model is discussed in this paper.

The construction of the Wharton EFA Automobile Demand Model was a very ambitious project that was completed under restrictive time constraints. As with any such project, unforeseen problems can arise that distort the accuracy of the model and decrease its usefulness. The limitations of this model are fairly subtle and required many hours of detailed examination to uncover. Nevertheless, these limitations severely reduce the usefulness of the model. This paper briefly presents some of the model's applications so that its past importance in policy analysis can be understood. Then the study approach and the model's structure are described. The paper concludes with a discussion of the more severe limitations of the model.

APPLICATIONS OF THE MODEL

The model has been used frequently in the U.S. Department of Transportation, particularly in the National Highway Traffic Safety Administration (NHTSA), the Office of Intermodal Transportation, and TSC. Other agencies that have used the model include the International Trade Commission in studies for the Senate Finance Committee, the U.S. Environmental Protection Agency, the Congressional Office of Technology Assessment, the Council of Economic Advisors, and the U.S. Department of the Treasury.

A variety of major policies has been analyzed; the most prominent among them are policies related to energy issues. Specifically, the model has been used by several agencies to study the economic impact of proposed automobile fuel-economy standards (4-6) and of the "gasoline guzzler" tax proposals (7). It has also been used to study the potential market impact of battery-powered automobiles (8), although the model was not designed for such a use. A more complete discussion of these documented uses of this model and other undocumented uses that deal with the impact of vehicle safety proposals, emission control standards, and other issues is presented by Saalberg, Richardson, and Joscelyn (9).

It appears that the model output has influenced the formulation of policy. There is, however, a wide variance of opinion on just how important a role the model has played. In any case, the limitations of the model have not been fully appreciated. Few, if any, analysts had time to become familiar with the structure of the model in the detail necessary to understand its performance. As a result, the model has been applied to situations it is not equipped to deal with (e.g., those that depend critically on the split between foreign and domestic shares of the market) and to situations in which reliance has been placed on inadequately qualified policy forecasts (e.g., those that involve the forecast shares of new-car sales by size class).

An analysis of the model by Golomb, Luckey, Saalberg, Richardson, and Joscelyn (10) disclosed many limitations of the model. These limitations would have been apparent to analysts in the government agencies that used the model if they had conducted an analysis of it with respect to its suitability for application to specific policy questions. However, such analyses require considerable time and money. Justifiable decisions to commit agency funds for such purposes require very close rapport and precise communications between agency managers and staff analysts capable of ascertaining the extent to which a given mathematical model is suited for application to a particular policy issue. That general problem applies to all potential uses of all models by government.

STUDY METHOD

The model analysis was divided into the following steps: analysis of the model structure, equation reconstruction, performance of the model in forecasting, and sensitivity testing. The analysis method used was based in part on the method presented by Dhrymes and others (11). Flow charts were constructed, and the computer program of the model was examined in detail to understand the structure of the model. An attempt was made to reconstruct the key time-series equations of the model. The historical data tapes that had been delivered to TSC by Wharton EFA were used in this attempt. In order to study the forecasting ability of the model, both the complete model and subsets of the complete model were run over the historical fit period of the model. Statistics on model errors were generated over these historical periods. Similarly, both the full model and subsets of it were used to perform sensitivity tests on the model. In these tests, policy-sensitive independent variables were changed by small percentages, and changes in the output variables were observed. In all tests performed, the computer program of the model and the data used were those developed by Wharton EFA and obtained from TSC. The interested reader is referred to Golomb and others (10) for a complete description of the study method used and the results of the analysis. This paper highlights only some of the findings of the analysis.

MODEL STRUCTURE

The model is essentially divided into six computational blocks. The blocks employ both exogenous and endogenous variables to generate a set of outputs. The major outputs and required exogenous inputs for each block are listed in Figure 1 (10, pp. 21-23), and the relationships among the blocks are shown in Figure 2 (10, p. 24).

In block A, estimates of fuel economy or miles per gallon for each of five size classes of new cars (defined on the basis of wheelbase length and price) are generated. Independently of block A, block B produces estimates of total purchase price for new cars by class and for each of the four components that make up the purchase price: transportation charges, base price, expenditures for options, and purchase taxes.

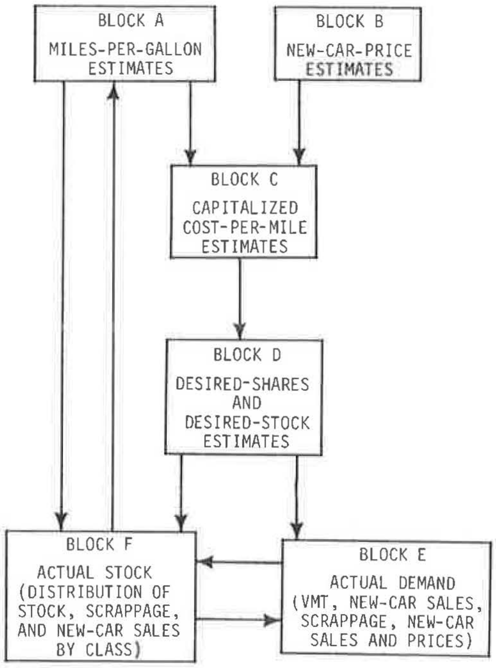
Blocks A and B feed into block C to calculate the capital cost per mile for each class of car. The capital cost per mile is essentially the present value of all costs associated with the purchase, sale, and operation of a car that has a 10-year lifetime. Essentially, block A, which has an exogenous gasoline price per gallon, provides the fuel cost component of the operating costs, and block B provides the estimate of purchase costs.

The capital cost-per-mile estimates are used in block D to calculate the desired stock of vehicles and the desired shares of stock for each of the five size classes. These estimates are of critical importance to the model because they constitute the targets toward which existing stock would move under the conceptual framework of the stock-adjustment process. Computation of the desired-share and desired-stock estimates is complex; it is done on

Figure 1. Wharton EFA Automobile Demand Model exogenous input and model output by block.

Model Exogenous Input	Model Output
Auto Characteristics Assumptions Curb Weight by Class Engine Displacement by Class Fraction of Cars with 4 Cylinders by Class Fraction of Cars with 6 Cylinders by Class Fraction of Cars with Overdrive by Class Fraction of Cars with Automatic Transmission by Class MPG Efficiency Factors by Class Economic Activity Assumption Ratio of City to Total Vehicle Miles Traveled	BLOCK A Miles Per Gallon Estimates for New Cars by Class • City • Highway • Combined • EPA Estimates
Economic Activity and Price Assumptions Transportation Price Index Foreign Auto Export Price Base Price Ratio of Class to Fixed Weight Average Index of Input Costs Consumer Price Index Real Disposable Income Maximum Price of Installed Options by Class Total State and Local Taxes on New Cars by Class Demographic Assumptions Number of U.S. Families	BLOCK B New Car Price • Transportation Charges by Class • Base Price by Class • Expenditures on Options by Class • Purchase Taxes by Class • Total New Car Price by Class
Economic Activity and Price Assumptions Finance Charge Discount Factor Gasoline Price Insurance Cost Index Tire Cost Index Parking, Tolls Cost Index Motor Oil Cost Index Repair Cost Index Policy Variable Total State and Local Taxes on New Cars by Class	BLOCK C Capitalized Cost Per Mile • Capitalized Cost Per Mile by Class
Economic Activity and Price Assumptions Ratio of Total Retail Outlets to Foreign Retail Outlets Real Disposable Income Demographic Assumptions Percent People Living in Metropolitan Areas Ratio of Pacific Population to Total Population Ratio of Mountain Population to Total Population Ratio of New England Population to Total Population Ratio of West South Central Population to Total Population Ratio of Resident Population, 20-29, to Total Number of Families Ratio of Families with 3 and 4 Members to All Families Number of U.S. Families Ratio of Families with 5 or More Members to All Families Licensed Drivers Per Family Transportation Mode Assumption Persons Traveling to Work by Non-Auto Means	BLOCK D Desired Shares and Desired Stock • Desired Shares by Class • Desired Shares/Domestic and Foreign • Desired Stock Per Family
Economic Activity and Price Assumptions Gasoline Price Real Disposable Income Unemployment Rate Scrap Metal Price Index Rate of Decline in Used Car Prices by Size Class	BLOCK E Actual Demand • Total Stock • Total Vehicle Miles Traveled • New Car Sales • Scrappage • Used Car Sales by Class • Used Car Prices by Class • Number of Trade-Ins by Age
Economic Activity and Price Assumptions Domestic Share of New Car Sales by Size Class Total Number of Makes of Cars by Class Real Disposable Income Number of Makes by Class Number of Dealers by Class Demographic Assumptions Number of Persons 25 Years and Older with 4 or More Years of College Ratio of Resident Population, 20-29, to Total Families Percent of Population in Metropolitan Areas Ratio of Pacific Population to Total Population Ratio of East North Central Populations to Total Population	BLOCK F Actual Stock • Scrappage Adjustment Factor • Scrappage Probabilities by Age • Shares of New Cars by Class • Cars in Operation by Class • Scrappage of Cars by Class • Shares of Cars by Class after Scrappage • Expected Scrappage for Older Cars • Mid-Year Stocks by Age • Average Age of Stock • Vintage-Weighted VMT

Figure 2. Flow diagram of Wharton EFA Automobile Demand Model.



the basis of the relative costs of different cars, the relationships of these costs to family income, and various other economic and demographic factors. The estimate of total desired stock is derived on the basis of desired shares, weighted capital cost per mile, family income, the number of licensed drivers, the number of U.S. families, and other economic and demographic variables.

In block E, total new car sales, scrappage, total stock, and total vehicle miles traveled are estimated. Each of these estimates is dependent on the other three, which makes the estimates highly simultaneous. New-car sales and scrappage also depend on the estimates of desired stock derived in block D as well as on variables of block F.

Block F contains two sets of equations: one to predict the stock of cars by class and by age and the other to predict the number of new cars by class. The predictions for the total stock by age depend on new-car sales estimated in block E and a vehicle-survival model that determines the scrappage of cars by age. The scrappage estimates in the vehicle-survival model depend on the total scrappage estimate of block E. The estimation of new-car sales by size class depends on the desired-stock share estimates generated in block D and on the actual or existing number of cars on the road of that size class after scrappage, which is predicted within block F. The estimation of the foreign and domestic shares of new-car sales by size class is made exogenously.

MODEL LIMITATIONS

Desired Stock

Basic to the Wharton EFA automobile model is its treatment of the demand for automobiles as if, given prices, incomes, and other factors, society desired to own a specified total number of vehicles. The number of new cars purchased in any year is then treated as dependent on the difference between the number of cars desired and the number already registered and on the road. Of course, it is not implied that automobile buyers actually think in such terms. Rather, the stock-adjustment process is employed as a statistical shortcut to embody the effect of used-car prices on new-car demand.

The net cost of a new car to a buyer is the difference between the price he or she must pay for the new car and what he or she can get for a used car as determined by supply and demand on the used-car market. In general, the larger the number of cars already on the road, the lower the price of used cars and, hence, the greater the cost of trading. For this reason, the supply of used cars already in operation acts as a back pressure on the demand for new cars, and this back pressure is captured by the stock-adjustment representation of new-car demand.

The use of the stock-adjustment mechanism in the Wharton EFA automobile model is damaged, however, by the way in which the desired stock was estimated. The Wharton EFA authors fitted automobile ownership per family to price and income data drawn from a cross section of states. Unfortunately, the small variation in new-car prices among states makes it difficult, if not impossible, to obtain an accurate estimate of price elasticity by this procedure. The problem shows up clearly in the Wharton EFA calculation for desired stock:

$$\ln(\text{desired stock per family}) = -1.910\ [0.796] + 0.563[0.180]\ \ln(\text{real permanent income per family}) - 0.101\ [0.052]\ \ln(\text{index of income distribution}) - 0.200\ [0.238]\ \ln(\text{average cost per vehicle mile driven}) + 0.421\ [0.137]\ \ln(\text{licensed drivers per family}) - 0.054\ [0.036]\ \ln(\text{nonautomobile commuters per family}) + 0.099\ [0.062]\ (\text{percentage of persons living in metropolitan areas}),$$

where $\bar{R}^2 = 0.461$. In this calculation, permanent income is the income that a family can expect in the long run, as distinguished from what is received during any particular year. The index of income distribution is the ratio of the number of families that have incomes of at least $15 000 to the number that have incomes under $15 000. Average cost per vehicle mile driven is the present value of the total cost per mile of owning and operating a vehicle, discounted over the lifetime of the car. It includes the price of the new car as well as all operating costs, insurance, and repairs. The other variables in the equation are self-explanatory.

Figures in brackets are standard errors of the respective coefficients. In keeping with the small state-to-state variation in prices, the price effect is measured with the least accuracy of all the variables in the calculation. Indeed, the coefficient is not statistically different from zero. In other words, the estimated equation provides no evidence that desired stock responds in any way to changes in price.

An additional difficulty with the desired-stock equations as measured is that the estimation procedure focuses entirely on the number of cars, to the exclusion of the age distribution of the stock of cars owned. The wide state-to-state differences in the age distribution of cars on the road is not taken into account.

Desired Stock by Size Class

To produce estimates of new-car sales by size class, the Wharton EFA automobile model partitions total desired stock into shares by size class. This procedure has neither basis in theory nor validity as an empirical shortcut. The stock-adjustment process is widely used in the modeling of automobile demand and performs well in its shortcut role as long as attention is fixed on total demand; however, it is unclear that the demand for new subcompacts, for example, is usefully represented as deriving from a gap between the desired stock of subcompact cars and the number already registered. One need only consider the present situation to see the weakness of the idea. Uncertainty of fuel availability and price have increased the demand for very small, fuel-efficient cars. But the would-be buyers of these cars are owners of large cars that must be traded. Despite the small size of the existing fleet of subcompact cars on the road, a substantial back pressure is being exerted on the purchase of subcompact cars by the reluctance of buyers of used cars to purchase additional large cars. However, note that there are variables in the desired-stock-share equation that will lessen this back pressure. Specifically, these variables allow trading among size classes.

Block D contains a system of five equations designed to generate the desired stock of the five classes employed in the model. The most-important variables that affect these proportions are discounted operating cost per mile of the respective car sizes and average family income relative to the average cost per mile of all cars.

Like total desired stock, the share equations are fitted to data from a cross section of states, again employed without taking account of differences in age structure. In view of the ability of prospective buyers to choose not only among a range of sizes and prices of new cars but also among a range of ages and prices of used cars, the validity of using an observed cross section to predict market shares is open to serious question.

Effect of New-Car Prices on New-Car Sales

New-car prices enter the Wharton EFA automobile model via the equation of new-car sales (calculation 2) in two ways. According to this calculation, total sales depend on the desired stock of cars, which already embodies the price of new cars. In addition, the Wharton EFA equation makes new-car sales dependent on the rate of increase in new-car prices:

$$\ln(\text{new sales per projected stock}) = -2.915 + 3.793\ [0.383]\ \ln(\text{desired stock per projected stock}) + 6.039\ [0.728]\ \ln(\text{permanent income per current income}) - 1.267\ [0.367]\ (\text{rate of increase in new-car prices}) - 0.225\ [0.103]\ (\text{dummy for strikes}),$$

where $\bar{R}^2 = 0.864$. Projected stock is the number of cars that would be found on the road in the absence of any new-car sales. It is equal to the total stock as of the end of the preceding year less scrappage. Standard errors are in brackets.

The way new-car prices appear in the calculation creates additional weakness in the model. Aside from its insignificant contribution to desired stock, the only way the price of new cars appears in the automobile-demand equation is as its rate of increase. The theoretical background of this variable is unclear, yet the model will apply this coefficient to any increase in price expected from policy actions and will automatically attribute to such actions an initial, substantial, but temporary impact on sales of new cars.

The only role for the level, as distinguished from the rate of increase, of new-car prices is via the desired stock. The price of new cars represents approximately one-half of the discounted operating cost, but, as shown above, the effect of operating cost on desired stock is not measured with precision, nor even with statistical significance.

The combination of these two highly uncertain components of the new-car sales equation will produce cyclical responses by the model to any one-time change in prices of the sort expected from most policy decisions. The model will translate any one-time price increase into an immediate reduction of new-car sales, via the rate of increase variable. In all following years, however, when prices are stabilized at the higher level, rate of change drops to zero and the large negative impact is removed. But the temporary drop in sales has been so great that the model will find actual stock deficient relative to desired stock, and the forecast of total sales will rebound above the base level despite the higher level of prices.

Price differences play a minimum role in the allocation of new-car sales among size classes. Once the model determines total sales, it assigns them to size classes exclusively on the basis of the composition of the size class of desired stock relative to the composition of existing stock. Price enters only in the partitioning of desired stock. Analysis of the size composition of new-car sales demands a more complex and sophisticated treatment than the stock-adjustment mechanism can provide, and it is no surprise to find that the performance of the Wharton EFA automobile model is substantially weaker in predicting the composition of new-car sales than it is in predicting the overall total.

Imports Versus Domestic Production

In the initial version of the Wharton EFA automobile model, the imported share of U.S. new-car sales by size class is a preassigned input. In other words, despite the substantial share of sales of small cars that have long been imported by U.S. consumers, the model is incapable of forecasting how imports respond to new conditions. Inasmuch as an important function of the model is supposed to be the prediction of market shares by size classes, inability to forecast the imported share of the market raises serious additional questions about its utility. This problem has been addressed in revised versions of the model; however, it is raised here because the model has been used in one instance, by the International Trade Commission, to forecast the split between foreign and domestic shares when, in fact, the foreign-domestic split of each size class was set exogenously (7,12).

Forecasting Performance of the Model

When the performance of the model is tested against data for the period 1960-1974 (included in the data to which the statistical equations were fitted), sales of new cars were found to be predicted with errors that average about 9 percent. Forecasts of vehicle miles traveled per family were more accurate; those errors averaged about 5 percent. In contrast, however, predictions of market shares by size class were uniformly poor. Errors in forecasts of market shares ranged from an average of about 14 percent for luxury vehicles and 37 percent for full-size cars up to 54 percent for midsize and 97 percent for subcompact models. Errors for all size classes were larger than would be produced by a naive sample mean model, even over the data to which they were fitted. Error statistics for eight key output variables of the model are shown in Table 1 (10, p. 173). The remarkably poor performance of the model in forecasting market shares is in keeping with the stock-adjustment nature of the Wharton EFA automobile model and with the use of state-by-state data to develop estimates of desired composition of automobile ownership.

POLICY RESPONSES OF THE MODEL

The response of the model to changes in policy is most easily represented by the percentage change in forecast that results from a percentage change in a policy-sensitive input variable. These are calculated by first obtaining a base forecast from the model in the absence of any change. The policy change is then incorporated in the exogenous input and a second forecast is made. The difference between the two forecasts represents the effect of the policy as predicted by the model.

The structure of the model embodies two general classes of policy-sensitive variables:

1. Variables that affect the selling price of new cars. This includes, for example, excise taxes on new vehicles, transportation charges, and prices of options. The most important of these, the index of automobile production costs, is generally representative of the others.
2. Variables that affect costs per mile of operation independently of initial purchase price. This class of variable includes automobile characteristics, insurance rates, tire prices, and parking fees. The price of gasoline is the most important variable in the class and is generally representative.

To understand the effect of these variables in the model, it is necessary to follow each set of forecasts over a period of years.

Tables 2 and 3 cover a 15-year period of forecast responses to changes in each of these two key policy variables. To provide a historical context, each of the analyses is examined as if the policy change had been initiated in 1960, and impacts are followed through 1974.

Production Cost of Automobiles

According to the model, a 1 percent increase in production costs would reduce total sales by 1.46 percent in the initial year, but for 8 years thereafter would raise sales above levels that would have prevailed at lower prices. Beyond year 9, however, total sales would again be slightly lower than otherwise. In terms of the number of cars sold, the model predicts that, following the initial decline, sales during the remaining 14 years would total 0.3 percent more cars than would have been

Table 1. Error statistics for the within-sample period 1960-1974.

Variable	Mean	Root-Mean-Square Error	100 x Root-Mean-Square Error/Mean
Sales	8.693	0.8234	9.47
Scrappage	6.171	0.8958	14.52
Vehicle miles traveled per family	12.38	0.6358	5.134
Subcompact car	0.1339	0.1300	97.08
Compact car	0.1697	0.0572	33.68
Midsize car	0.2520	0.1356	53.81
Full-size car	0.3628	0.1294	35.66
Luxury car	0.0814	0.0113	13.90

Table 2. Percentage response to a 1 percent increase in automobile production costs.

Year	Total New Car Sales	Size Composition of New Sales					Vehicle Miles Traveled
		Subcompact	Compact	Midsize	Full-Size	Luxury	
1	-1.46	0.75	-0.30	0.01	-0.45	-0.01	-0.07
2	0.77	0.12	0.06	-0.03	-0.14	-0.01	-0.23
3	0.05	0.17	-0.02	-0.02	-0.13	-0.01	-0.13
4	0.02	0.19	-0.04	-0.02	-0.12	-0.01	-0.09
5	0.12	0.43	-0.14	-0.00	-0.28	-0.01	-0.08
6	0.09	0.46	-0.13	0.01	-0.32	-0.01	-0.04
7	0.09	0.61	-0.17	0.02	-0.45	-0.01	0.08
8	0.10	0.76	-0.17	0.01	-0.58	-0.02	0.03
9	0.09	0.85	-0.18	-0.03	-0.61	-0.03	0.06
10	-0.00	0.84	-0.21	-0.04	-0.57	-0.03	0.09
11	-0.07	0.72	-0.18	-0.03	-0.50	-0.02	0.10
12	-0.17	0.73	-0.02	-0.01	-0.33	-0.02	0.09
13	-0.11	0.24	0.03	0.02	-0.27	-0.01	0.06
14	-0.15	0.19	0.05	0.03	-0.26	-0.01	0.04
15	-0.14	0.16	0.04	0.02	-0.21	-0.01	0.02

Table 3. Percentage response to a 1 percent increase in gasoline prices.

Year	Total New Car Sales	Size Composition of New Sales					Vehicle Miles Traveled
		Subcompact	Compact	Midsize	Full-Size	Luxury	
1	-0.20	0.09	0.05	0.01	-0.15	0.00	-0.20
2	-0.22	0.06	0.05	0.00	-0.11	0.00	-0.21
3	-0.23	0.07	0.04	0.00	-0.11	0.00	-0.22
4	-0.07	0.06	0.03	0.00	-0.10	0.00	-0.24
5	0.01	0.10	0.00	-0.00	-0.11	0.00	-0.25
6	0.06	0.12	0.00	0.00	-0.12	-0.00	-0.25
7	0.07	0.12	-0.00	0.01	-0.12	-0.00	-0.24
8	0.05	0.17	-0.01	0.00	-0.15	-0.00	-0.23
9	0.04	0.16	-0.01	-0.01	-0.14	-0.00	-0.21
10	-0.01	0.17	-0.02	-0.01	-0.13	-0.00	-0.20
11	-0.02	0.14	-0.02	-0.01	-0.10	-0.00	-0.19
12	-0.05	0.12	-0.01	-0.01	-0.10	-0.00	-0.19
13	-0.07	0.11	-0.00	-0.00	-0.10	-0.00	-0.19
14	-0.08	0.09	0.01	0.00	-0.10	-0.00	-0.20
15	-0.09	0.13	0.01	0.01	-0.14	0.00	-0.21

sold in the absence of a price increase.

Increased production costs also generate a shift in the forecast composition of sales, and the sale of subcompacts increases, largely at the expense of full-size cars. Again, a cyclical pattern over the experiment period is in evidence as the increase in subcompact share declines from an initial 0.75 percent to only 0.12 percent in the year following, then rises again by year 9 to exceed the initial gain, only to decline to 0.16 percent in the 15th year. Similar cycles appear in the compact and full-size share of the market.

The model's projection of vehicle miles traveled is particularly unrealistic. Initial levels are below and later levels are above what would be found in the absence of any change in automobile production cost.

Price of Gasoline

In response to a 1 percent increase in the price of gasoline, the model again generates cycles over the experimental period. New-car sales are depressed for four years, followed by five years at levels above what would have prevailed with cheaper gasoline, then lower levels recur. With higher gasoline prices, the model shifts the composition of sales in the direction of small cars, but once more in a characteristic cyclical pattern. A particularly strange aspect of the predicted size distribution is that the principal trade-off occurs between subcompacts and full-size cars. Compacts and mid-size cars show little change, and luxury cars show practically no change.

Based on the evidence available, one cannot say whether the model will continue to generate cycles in the longer term. It may be that this behavior dampens out in future years. However, in the applications of this model, 15 years has been a typical forecast period. Therefore, these cycles pose serious problems for the model users.

CONCLUSIONS

Like any large econometric model, the Wharton EFA Automobile Demand Model is intended to approximate the complex interrelationships in an economic subsystem. A successful approximation is capable of processing large amounts of data to produce detailed forecasts of policy impacts. In view of the growing complexity of policy issues, there is every reason to believe that government agencies and others will continue to employ such models and will expand the area of their application.

But the validity of any model depends on how closely its structure matches that of the system it is supposed to approximate. Even a model that, in retrospect, forecasts well over the data to which it has been fitted will produce substantial errors in future forecasts and generate misleading policy analyses if it contains structural elements that are seriously at variance with reality.

Unfortunately, this is the case with the Wharton EFA automobile model; it is seriously deficient in at least two key respects: The model employs prices in an unrealistic manner in the generation of total new-car sales, and total sales are partitioned into size classes by a structure that is worse than no model at all, even over the sample data.

Since practically all applications made of the Wharton EFA automobile model depend critically on one or both of these features, policymakers who intend to employ the model in their analyses are advised to be on guard. Note that this advice applies not only to users of the Wharton EFA automobile model but also to users of all policy models. Every model has its limitations, and these should be recognized by model users.

ACKNOWLEDGMENT

Development of this paper was supported by an unrestricted grant from the Motor Vehicle Manufacturers Association (MVMA). We wish to thank the MVMA, the staff of Wharton EFA, Inc., and the Transportation Systems Center of the U.S. Department of Transportation for their cooperation. The assistance and advice of colleagues at the University of Michigan is also gratefully acknowledged.

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

Forecasting Equilibrium Motor Vehicle Holdings by Means of Disaggregate Models

CHARLES F. MANSKI AND LEONARD SHERMAN

This paper reports on the development of a methodology to forecast the fuel efficiency of household motor vehicle holdings in the United States. Forecasts are made by using a new partial equilibrium model of the operation of the motor vehicle market. In a break with the prevailing aggregate stock-adjustment approach, the approach described here incorporates household-level discrete choice models to explain vehicle holdings and scrappage decisions. Given assumptions on the design and prices of future new vehicles and fuel prices, the behavior of a demographically weighted sample of households is simulated and equilibrium conditions for the vehicle market are solved each year in the forecast period. The paper presents predictions of household vehicle holdings, new-vehicle sales, used-vehicle scrappage, and the resulting average vehicle fuel efficiencies under two future scenarios.

The years ahead will be characterized by significant changes to the motor vehicle market. In particular, the federal vehicle fuel-economy standards enacted in 1975 have stimulated domestic manufacturers to launch major programs of vehicle redesign. At the same time, fuel prices are expected to rise considerably. A further development that affects the vehicle holdings is the projected shift in the demographic mix of the population toward an older, more affluent profile and more small households.

Because the gasoline used by household motor vehicles constitutes a substantial fraction of American oil consumption, forecasts of vehicle fuel efficiencies are clearly relevant to the formation of a national energy policy. Our work addresses two forecasting questions:

1. Given the currently envisioned changes in vehicle design, what is the likely path of sales-weighted new-vehicle efficiencies through 1985?
2. Given the same design assumptions, how will the average efficiency of all vehicle holdings change over time?

To answer the first question, one must predict the composition of new-vehicle sales. To answer the second, one must predict not only the mix of new-vehicle sales but also the volume of new-vehicle sales and the rate of used-vehicle scrappage as well. The forecasts to be presented here are the output of a new partial equilibrium model of the operation of the motor vehicle market and machinery for forecasting with this model.

Our approach to forecasting vehicle sales, scrappage, and holdings breaks completely with the aggregate stock-adjustment framework that has long prevailed. Aggregate stock-adjustment models generally contain three elements:

1. A system of aggregate demand models predicts desired vehicle holdings,
2. Descriptive models predict used-vehicle scrappage, and
3. Stock-adjustment equations predict new-vehicle sales.

This three-step procedure was first suggested, independently, by Chow (1) and by Nerlove (2). Wharton Econometric Forecasting Associates (3) presented a particularly sophisticated application, and Ayres and others (4) and Mellman (5) provided literature reviews.

Our decision to reject the aggregate-stock-adjustment paradigm for the approach used here follows from a comparison of basic elements of model structure. Stock-adjustment models characterize desired vehicle holdings as the classical demands of a representative consumer. We, in contrast, model holdings as the discrete choices of a population of heterogeneous consumers. Stock-adjustment models explain new-vehicle sales as the fractional reduction of discrepancies between desired and actual vehicle stocks. We treat new-vehicle sales, used-vehicle scrappage, and used-vehicle prices as jointly endogenous variables that solve a set of market equilibrium conditions. In these and other regards, our forecasting system, although itself idealized, provides a more realistic representation of the vehicle market.

CONSUMER BEHAVIOR

The owners of motor vehicles participate in the operation of the vehicle market in two ways:

1. Through their demand for new and used vehicles from the market and
2. Through their supply of used vehicles to the vehicle and scrap markets.

Often, although not always, the demand and supply roles occur in conjunction. In particular, when a consumer trades in a used vehicle for a new one, he or she is simultaneously acting as a vehicle demander and supplier. On the other hand, when someone decides to add a vehicle to current holdings, he or she acts only as a demander; when one decides to subtract a vehicle, he or she acts only as a supplier. In what follows, models of the demand and supply aspects of consumer behavior are described.

Vehicle Demand

The household's choice of a quantity of vehicles to own, its selection among alternative types of vehicles, and its subsequent use of the vehicle selected should, in principle, be modeled as an interrelated complex of decisions. Our efforts were more limited in scope. The absence of data on vehicle use by our household sample precluded any attempt to model use or its relation to vehicle holdings, as in Lerman and Ben-Akiva (6). Moreover, in modeling vehicle holdings, we found it desirable to focus resources on the problem of modeling household selection among vehicle types conditional on choice of a vehicle quantity. Correspondingly, we restricted our efforts to explain vehicle quantities to the development of a reduced-form model. This allocation of research priorities followed from a belief that projected vehicle design and price changes will have their major impact on the composition of vehicle holdings. But we, on the contrary, expect that the number of vehicles that households choose to own will be largely determined by socioeconomic and demographic forces.

The model that explains vehicle quantities yields the probability that a household characterized by a given income, size, residential location, number of workers, age of head, and previous year ownership level will currently hold zero to three vehicles. A multinomial logit form was estimated from a sample of 810 households surveyed in June 1978. A detailed description of this model can be found in Sherman, Manski, and Ginn (7).

Our model of the household's choice among alternative vehicle types, plus the related model of vehicle scrappage decisions, form the heart of the model of the motor vehicle market. Because the vehicle choice model has been described in detail in Manski and Sherman (8), we limit ourselves here to a summary of the specification and results.

Two vehicle submodels were estimated--one to explain vehicle choices in households that hold a single vehicle, the other to explain the composition of holdings in two-vehicle households. In each case, we view the household as making yearly evaluations of its current vehicle holdings and updating these as desired. The utility of any vehicle, or vehicle pair, is assumed to be a function of vehicle seating capacity, luggage capacity, weight, acceleration time, noise level, scrappage probability, price, operating cost, and a search-transaction cost associated with entering the vehicle market. Search-transaction costs can be avoided by staying out of the vehicle market, that is, by retaining current holdings. Household size, age, education, income, number of workers, and residential location condition the utility function.

The empirical analysis was based on a national random sample of households drawn in 1976 from the Survey Research Center's rotating consumer panel. This sample contained 430 usable observations on vehicle choices by one-vehicle households and 445 on those by two-vehicle households.

The Survey Research Center's sample contained only 150 households that owned three or more vehicles. It was decided that this sample was too small to support an estimation of a model of vehicle choice by such multiple-vehicle households. In producing our forecasts, coefficients estimated in the two-vehicle model were used to predict the vehicle choices of households that own three or more vehicles.

From a variety of sources, we developed a vehicle-attributes file that provides the relevant design, performance, and price data for the various makes, models, and vintages of passenger automobiles and light trucks available in the United States in 1976. Multinomial logit models were used to probabilistically describe each household's choice among vehicle alternatives. A household's choice set would, in general, contain all vehicles or vehicle pairs available on the marketplace plus whatever vehicles are currently held by the household. The latter are characterized by a zero search-transaction cost.

Among the many empirical results, one prominent finding is that the marginal utility of additional vehicle seats varies considerably with household size. Moreover, households that own two vehicles tend to want smaller ones than do single-vehicle households. Heavy vehicles are found desirable by older households but weight is of no concern to younger ones. As expected, luggage space is viewed as a positive characteristic.

We find that most aspects of vehicle performance have little effect on choices but, counterintuitively, sluggish vehicles appear to be strongly preferred to quick ones. No convincing explanation for this result has yet emerged, although it has been suggested by some that the model's omission of measures of maintenance cost might make quick vehicles appear undesirable.

Vehicle costs, including price, fuel costs, and search-transaction costs, are all found to be important determinants of vehicle utility. Of some interest is the fact that the impact of fuel costs seems to vary considerably among socioeconomic and demographic groupings. This variation may mask differential vehicle-use patterns among the groups. The large magnitudes of the search-transaction cost coefficients in the estimated models indicate that, if all else is equal, retention of one's current holding is much to be preferred to entrance into the vehicle market. Households enter the market only when the gains from doing so exceed the costs incurred.

Vehicle Supply and Scrappage

We assume that the household that is disposing of a vehicle faces a binary choice between scrappage and sale on the vehicle market. Scrappage yields a price R_j and market sale yields a price P_j. The household scraps the vehicle if $P_j < R_j$; otherwise, it sells it. It is assumed that there is no linkage between a household's decision about vehicle holdings and the sales-scrappage price the household can realize from disposal of currently held vehicles. It can be shown that decisions about holdings are in fact independent of disposal prices if two conditions are satisfied:

1. Household utility functions should exhibit constant marginal utility of money and
2. The price received for disposal of a vehicle should not depend on the identities of any other vehicles simultaneously disposed of or purchased; that is, market transactions should not be package deals.

The market price (P_j) undoubtedly depends on the mechanical condition, body quality, and installed optional equipment of vehicle j. Although such detailed vehicle attributes and their effects on price may be known to the vehicle owner, they were not available to us. Rather, the only price statistics in our possession were the Red Book prices (9), published measures of the average realized sales prices for each make, model, and vintage of vehicle.

Given this, we formulated a simple probabilistic scrappage-model conditioning based on the known Red Book (9) price. Specifically, by letting V_j be vehicle j's Red Book price, we assumed that

$$\text{Prob}\,[P_j < R_j] = \alpha R_j / V_j \qquad (1)$$

for some $\alpha > 0$. This model can be derived from more basic assumptions, but its greatest virtues are its reasonable qualitative properties and its simplicity.

Since scrappage prices vary relatively little among vehicles, we further assumed that $R_j = R$, a constant for all j. The scrappage probability then reduces to β/V_j where $\beta = \alpha R$. Given data on make-model-vintage-specific scrappage and sales frequencies in the United States, β can be estimated by least-squares regression. The point estimate obtained was $\hat{\beta} = 250$. A check on the reasonableness of the estimate and of the model more generally emerges if we observe that, under the model, V_j should never fall below β. In fact, the lowest vehicle Red Book prices are around $300, so that $V_j > \hat{\beta}$ always.

Organizations, including police forces, utilities, taxi companies, rental car agencies, and numerous other government agencies and private firms collectively account for significant fractions of motor vehicle holdings, purchases, sales, and scrappage. Little is known about the determinants of organizational vehicle-holdings behavior or about the extent to which the organization and household sectors of the motor vehicle market are interconnected. Casual observation does, however, suggest that organizations usually buy new vehicles rather than used ones and that the used vehicles they do purchase are generally bought from other organizations rather than from households. On the other hand, organizations often sell used vehicles to households; thus the organization sector becomes a net supplier of used vehicles to the household sector of the vehicle market.

It is estimated that, in recent years, organizations have supplied about 1.5 million vehicles/year to households. For forecasting purposes, we have assumed that the rate of supply will grow by 0.05 million vehicles each year through 1985 and that the composition of supply is identical to that in the overall used-vehicle fleet.

The firms that supply new motor vehicles and the consumers who purchase them are not treated symmetrically in the market model. As was indicated earlier, we assume that, at the beginning of each sales year, manufacturers make new-vehicle design and pricing decisions that are then fixed for that year. With the new-vehicle offerings specified, new-vehicle supplies are assumed to be perfectly elastic until the end of the sales year, when production ceases.

The above assumptions are fairly, although not totally, realistic. Certainly vehicle designs, once embodied in production facilities, are not easily altered. Moreover, when production facilities are in place, marginal costs of production are relatively constant over a wide range of quantity levels. As long as constant marginal costs prevail, the assumption of perfectly elastic vehicle supplies is reasonable, at least up to a point. There are limitations to production capacity that ultimately constrain vehicle supply. And, in fact, with the rapid conversion of manufacturing plants to gear them for the production of more fuel-efficient vehicles, order backlogs and delivery delays are becoming more frequent occurrences for popular models. Perhaps least realistic is our assumption that prices of new vehicles are fixed over the sales year. Although price setting by manufacturers is an administered process, prices are not rigid. Mid-year changes in wholesale and retail prices are being observed with increasing frequency. In addition, dealers often adjust wholesale to retail markup levels as market conditions change.

Abstracting from their realism, the assumptions are necessary for analytic tractability. The problem of modeling the operation of the vehicle market would be substantially complicated if we allowed manufacturers to make supply adaptations during the yearly market period. It is far simpler to model the market dynamic as a sequential process in which manufacturers act, then consumers bring the market to a temporary equilibrium, then manufacturers act again. The model can, of course, be exercised on a quarterly rather than yearly simulation cycle, were the issue of mid-year price adjustments of sufficient concern to justify the added costs of a computer run. As stated earlier, a scenario rather than a formal model forms the basis for our projections of future manufacturer design-pricing behavior.

MARKET EQUILIBRIUM

The motor-vehicle market shares with the housing and certain other durable-goods markets a number of complex features. First, vehicles are multidimensionally differentiated and spatially located commodities. In fact, every used vehicle, because of its unique body and mechanical condition and location, represents a distinct good. Second, vehicle trade occurs in an environment of very limited information. Potential sellers and buyers are often not aware of each others' existence. Moreover, buyers generally have only partial knowledge of vehicle attributes, and learning is costly. Third, the trading process usually involves one-on-one negotiations, whose outcomes can depend on the strategic behavior of participants.

Clearly, practical modeling of the market's operation requires considerable idealization. An obvious approach is to assume that, given new-vehicle designs and prices, used-vehicle prices adjust until the demand for used vehicles equals the available supply. Specifically, let A_u represent the universe of extant used-vehicle types and let $V = [V_a,\ a \epsilon A_u]$ be the vector of selling prices for these vehicles [selling prices here are identified with the Red Book statistics (9)]. Let $B_a(V)$ be aggregate household purchases of vehicles of type a under prices V, let $W_a(V)$ be aggregate scrappage, and let $S_a(V)$ be aggregate sales. Also let X_a be the exogenous number of vehicles supplied by organizations to the household sector. Then the vehicle market can be said to be in (temporary) equilibrium when V is such that the conditions

$$B_a(V) + W_a(V) = S_a(V) + X_a \qquad a \epsilon A_u \tag{2}$$

are jointly satisfied.

With approximately 600 distinct makes, models, and vintages delineated by our vehicle-holdings model, solution of a set of 600 nonlinear equations is required to determine a market equilibrium. In the forecasting context, where each prediction exercise involves a sequence of yearly market periods, this task clearly poses an unacceptable burden.

What is feasible, on the other hand, is to impose a relatively small subset of equilibrium conditions. That is, we may impose only the conditions

$$\sum_{a \epsilon A_{ud}} B_a(V) + W_a(V) = \sum_{a \epsilon A_{ud}} S_a(V) + X_a \qquad d \epsilon D \tag{3}$$

where A_{ud}, $d \epsilon D$ is a collection of subsets of A_u. Through judicious selection of the subsets A_{ud}, the most-important features of equilibrium might be preserved through a relatively small set of such conditions. The extreme nontrivial case, of course, is to impose only the aggregate demand-equals-supply condition:

$$\sum_{a \epsilon A_u} B_a(V) + W_a(V) = \sum_{a \epsilon A_u} S_a(V) + X_a \tag{4}$$

If this is done, the problem of solving a system of

600 nonlinear equations is reduced to that of solving a single such equation.

When Equations 1-3 constitute a proper subset of the equilibrium conditions, multiple price vectors (V) will exist that solve these equations. To resolve this nonuniqueness, side constraints on V may be imposed. Assume that for each $a \varepsilon A_u$, $V_a = f(X_a, \gamma)$ where f is a specified function of observed vehicle attributes X_a and of the free parameter vector γ of length $|D|$. In conventional jargon, $F(X, \gamma)$ is a hedonic price index. Given sufficient regularity in the equation system, an at least locally unique solution γ^* to Equations 1-3 will now exist. A particularly simple version of this approach, appropriate when the subsets A_{ud}, $d \varepsilon D$ are mutually exclusive and exhaustive, is to set $V_a = X_a + \gamma_{d(a)}$, where X and γ are now scalars. Here, X_a is a benchmark price for vehicle a and $\gamma_{d(a)}$ is a shift factor that moves the prices of all used vehicles in the same class as a uniformly relative to those of new vehicles. Conditions of this kind are imposed in our forecasting system.

The major components and linkages of the model of the motor vehicle market are shown schematically in Figure 1. The figure depicts, for a single year, the process that generates purchase of new vehicles, transfers of used vehicles among households, and used-vehicle scrappage.

FORECASTS OF HOUSEHOLD MOTOR VEHICLE HOLDINGS

A forecast may be made with a model as complex as ours only if a simulation approach is adopted. The simulation system developed for use in this study operates on a sample of 1063 households from the 1976 Survey Research Center panel weighted so as to represent the U.S. household population. Preliminary tests of the sensitivity of the simulation to random number seed indicated excessive variability of results with this sample size. We, therefore, cloned each household into a pair of households that share all demographic attributes but whose random numbers are drawn independently. This procedure effectively doubled the sample size to 2126 and reduced the seed sensitivity to acceptable levels.

The Forecasting System

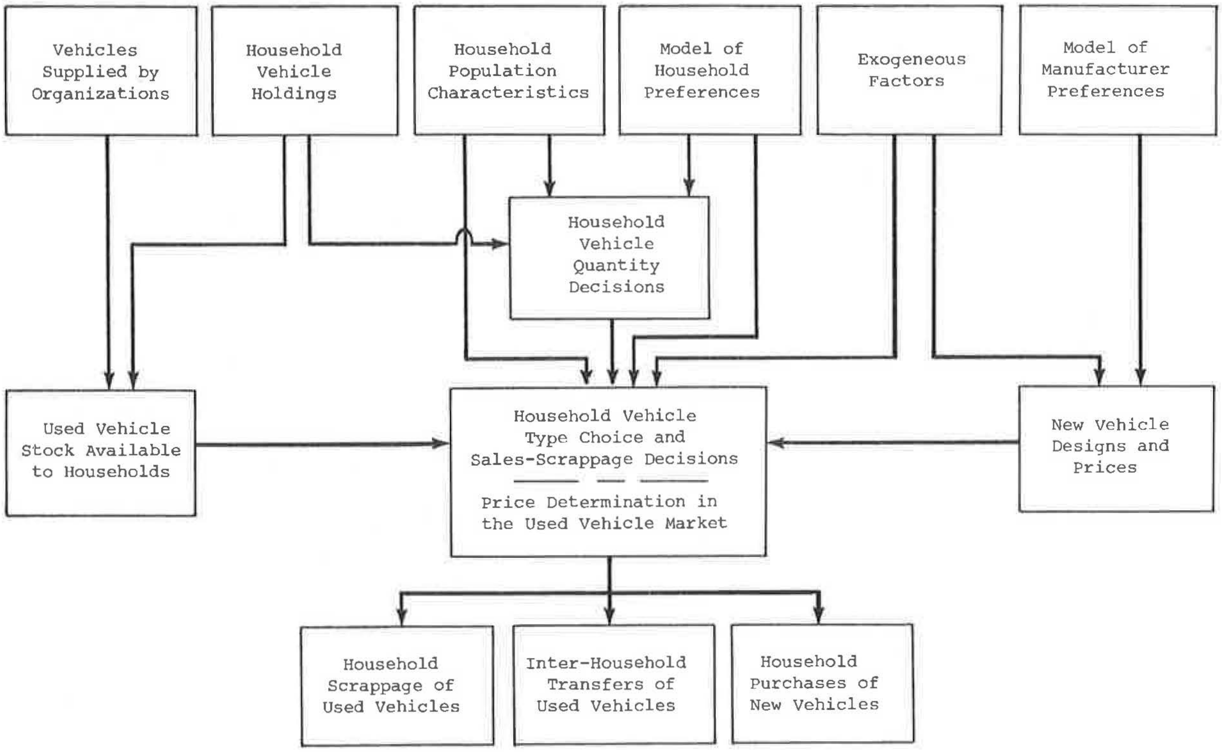
The first step in a given year's simulation is to apply the vehicle quantity model to predict the number of vehicles each household in the sample will own. Given any set of vehicle prices, the vehicle choice model then predicts the composition of holdings for each household. The scrap-sell model determines the manner in which vehicles are disposed. The final step in the year's simulation is, therefore, to search for a set of vehicle prices that generates desired holdings, sales, and scrappage that solve a practical set of equilibrium conditions.

At present, four equilibrium conditions are imposed. These are that household purchases plus scrappage should equal household plus organization vehicle sales for each of the following classes of vehicles:

1. Used passenger automobiles less than 10 years old,
2. Used passenger automobiles 10 or more years old,
3. Light trucks (pickup trucks, vans, and utility vehicles) less than 10 years old, and
4. Light trucks 10 or more years old.

The side constraints are that, within every class, the price of each vehicle type be the sum of two terms. One of these is an exogenously given base price for the type, computed as price when new minus an age-specific depreciation amount. The other is an endogenous shift factor common to all vehicles in the class. Under this specification, solution of the equilibrium conditions requires determination of

Figure 1. Model of the household motor vehicle market.



equilibrium values for the four shift factors.

The decision to impose these equilibrium conditions was made after experimentation with other options, including the simple setup in which only the aggregate condition (Equation 4) is imposed. It was found that the conditions and side constraints ultimately chosen consistently produced results in which demands were acceptably close to supplies when vehicles were categorized by vintage, size class, and other criteria. At the same time, the computational costs of solving the set of four conditions were reasonable. The algorithm used generally finds a set of equilibrium shift factors within three to four iterations. We note that, in general, uniqueness of the equilibrium is not theoretically guaranteed. However, uniqueness can be proved in the case when only the single condition (Equation 4) is imposed.

New-Vehicle Design and Price Projections

Available evidence indicates that, during the next several years, domestically produced passenger automobiles will weigh less, have less interior space, and have smaller engines than those now being produced. Some of the projected weight reduction will be achieved by material substitution and some will follow from a continuation of the "downsizing" trend begun in 1977. Downsizing is the attempt to reduce the dimensions of a vehicle with as little as possible accompanying loss of interior space. It is expected that, as vehicle weights are lowered, engine sizes will be reduced so that acceleration is left roughly constant but fuel efficiency is increased.

The primary impetus for the rather dramatic expected changes in domestic vehicle designs comes from the federal fuel-economy standards mentioned earlier. Penalties for noncompliance are substantial--a non-tax-deductible $5/vehicle for each 0.1 gal/mile below the standard. Since the sales-weighted mean fuel efficiency of 1978 domestic models was only 20.5 miles/gal but the standards call for 27.5 miles/gal by 1985, the need for design changes is clear. Foreign manufacturers, on the other hand, by and large meet the 1985 standards already. Relatively little change is expected in the designs of their vehicles. Likewise, we assume only a small modification in pickup truck, van, and utility-vehicle designs. Token weight reductions and minor reductions in engine size were assumed for these vehicles.

Within the forecasting system, the projected vehicle designs for each future year are represented as revisions to the designs of a base year, taken here to be 1978. Based primarily on material in a Corporate Tech Planning, Inc., report (10), a most-probable scenario for the extent and timing of the weight changes to be made by the domestic manufacturers of passenger automobiles has been formulated. With each projected weight change, there are associated projected changes in seating capacity, luggage space, and fuel efficiency for each affected base-year vehicle. Other attributes of the affected vehicles as well as all attributes of unaffected vehicles are held constant at their 1978 values.

In addition to vehicle designs, we must predict the prices of new vehicles. Consideration of the cost consequences of projected design changes suggests a 2 percent/year real increase in the prices of domestic automobiles. The projected rise reflects cost increases due to materials substitution and retooling as partially balanced by cost decreases from reductions in vehicle size. The prices of foreign automobiles and light-duty trucks are predicted to remain at 1978 levels in real terms.

The design-price scenario just set out is, of course, only a point prediction of events about which considerable uncertainty exists. The scenario discounts the possibility of fuel-saving technological advances in engine design and of cost-saving advances in the use of light body materials. We also ignore possible manufacturer manipulation of vehicle prices as an instrument for affecting the fraction of sales that goes to relatively fuel-efficient vehicles. It should be emphasized that our forecasting system can represent a wide range of design-pricing scenarios. Exploration of the sensitivity of the forecasts to variations in the scenario constitutes an important direction for future work.

Forecasts

In this section we present forecasts of household vehicle holdings, new-vehicle sales, used-vehicle scrappage, and vehicle fuel efficiencies through 1985. We have produced forecasts under two different assumptions about fuel prices:

1. Prices will remain at the level of $1.00/gal in 1979 dollars throughout the forecast period and
2. Prices will rise in equal yearly increments from $1.00/gal in 1980 to $2.50/gal in 1985, again in 1979 dollars.

The performance of forecasts under two such different assumptions serves two purposes. First, the spread from $1.00 to $2.50 brackets a reasonable range of values for a quantity about which considerable uncertainty exists. Second, with two values of fuel price, we can execute a useful controlled experiment in forecasting. As will be seen, the comparison of forecasts made under different assumptions about fuel prices while all other inputs are held constant reveals much about the structure of the forecasting system and, more importantly, about subtleties in the operation of the real motor vehicle market.

The first step in the forecasting process is to predict household vehicle-ownership levels for each of the sample households. The prediction is that total vehicle holdings will rise from 118.6 million in 1979 to 132.5 million in 1985. During this period the number of households is predicted to rise from 78 million to 87 million, which implies that the number of vehicles per household will remain stable at 1.52.

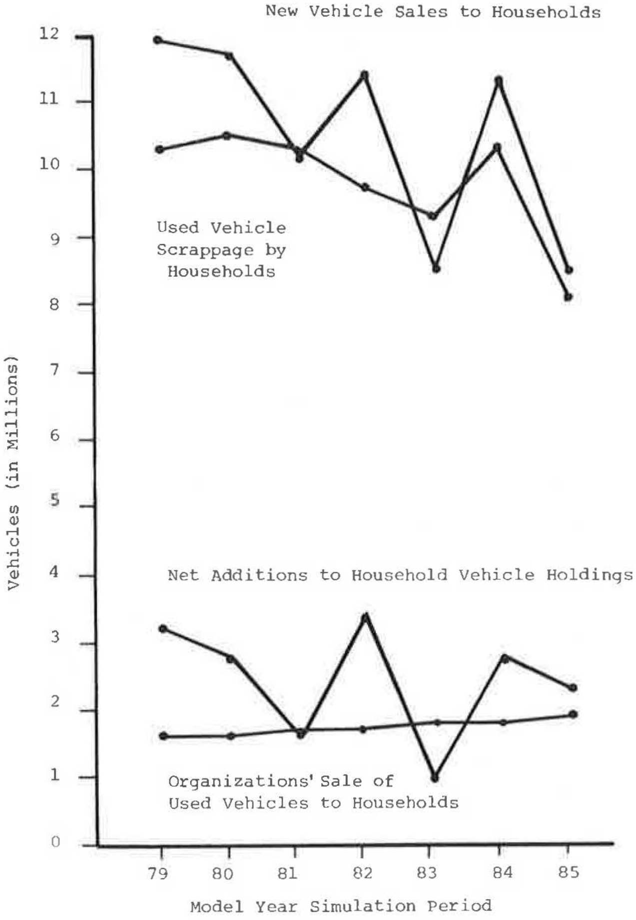
In predicting vehicle-holding levels each year, we also determine net additions to holdings, the path of which is shown in Figure 2. The makeup of net additions is, however, not yet determined. Net additions satisfy the identity

$$\Delta H \equiv \sum_{a \epsilon A_n} S_a(V) - \sum_{a \epsilon A_u} W_a(V) + \sum_{a \epsilon A_u} X_a \qquad (5)$$

where ΔH designates net additions and A_n is the set of new-vehicle offerings. If we hold as fixed the exogenous contribution ΣX_a of organization-supplied vehicles, a given quantity of net additions is compatible with a combination of high new-vehicle sales (ΣS_a) and high used-vehicle scrappage (ΣW_a) or with a low sales-scrappage mix.

The combination of new-vehicle sales and used-vehicle scrappage that produces the required net additions is determined by the characteristics of new- and used-vehicle offerings and by the condition that the used-vehicle market be in equilibrium. To visualize the process, consider a situation in which new-vehicle offerings are found to be relatively desirable by households. In this case, the equilibrium prices of used vehicles will be relatively low, equilibrium scrappage relatively high,

Figure 2. Composition of net additions to household vehicle holdings.



and equilibrium new-vehicle sales high. On the contrary, a situation in which new vehicles are not liked but all other things remain the same leads to an equilibrium characterized by high used-vehicle prices, low scrappage, and low new-vehicle sales.

Figure 2 gives our point prediction for the sales-scrappage composition of net additions under the lower-bound assumption that gasoline prices remain at the $1/gal level through 1985. A striking finding is that new-vehicle sales tend to decrease over the period and fall from a high of 11.9 million units in 1979 to a low of 8.5 million in 1985. At the same time, scrappage declines from 10.3 million units at the beginning of the period to 8.1 million at the end. As a consequence, the age of vehicle holdings tends to increase. Our results indicate that, in 1979, 52 percent of all vehicles are at least five years old, and in 1985 the corresponding figure is 62 percent.

The trends our forecasts indicate for new-vehicle sales and scrappage are not monotonic, but the downward tendency is nonetheless unmistakable. Qualitatively, the movements in new-vehicle sales closely track those in net additions. The definite negative correlation in sales in adjacent years may also have a structural explanation. High new-vehicle sales one year accompanied by high scrappage implies that the age distribution of used vehicles will be more skewed toward young vehicles the next year. The result is lower scrappage and sales in the next year.

The most straightforward explanation for the series of findings is that, when the price of gasoline is $1/gal, households do not find the increased fuel efficiency of the new vehicles to be offered in the coming years worth the reduction in dimensions and increases in prices associated with downsizing. In this context, the prices of the larger inefficient vehicles produced up to the late 1970s are bid up with an attendant fall in scrappage and in new-vehicle sales relative to the levels that have prevailed recently. Note that this forecast rests in part on the interpretation of weight in the vehicle choice model. To some extent, weight proxies for comfort, ride quality, and safety. It is probable that impending changes in vehicle design will reduce vehicle weights without proportional decreases in these underlying consumer concerns. To the extent that this is true, our model will overpredict adverse consumer reaction to reductions in vehicle weight.

The above results have the interesting consequence that sales of new, more-efficient vehicles can be stimulated by increases in gasoline prices. Simply put, the higher gasoline prices are, the more attractive the new vehicles appear relative to older, less-efficient ones; hence, the lower are equilibrium used-vehicle prices, the higher is scrappage, and the higher are new-vehicle sales. The quantitative impact of gasoline prices on sales is shown well in our forecasts made under the upper-bound assumption that gasoline price rises in equal yearly increments from $1.00/gal in 1980 to $2.50/gal in 1985. In this scenario, new-vehicle sales for the years 1981-1985 are 10.5, 12.0, 9.3, 12.2, and 9.8 million units. These figures are 0.3, 0.6, 0.8, 1.0, and 1.4 million units higher than those shown in Figure 2.

Some caveats are required here. Our forecast that in 1985 a $2.50/gal gasoline price generates 1.4 million more units sold than does a $1.00/gal price ignores the effect of such a large price increase on the consumer's budget problem at the micro level and on economic activity at the macro level. Although the macro effects of the price increases are difficult to predict, the micro effect probably is to reduce total desired holdings of vehicles, with consequences for new-vehicle sales and used-vehicle scrappage. Possible limitations of demand for fuel-efficient vehicles due to considerations of production capacity are also ignored.

Figure 3 presents predictions of sales-weighted harmonic mean fuel efficiencies in units of miles per gallon. The harmonic mean is appropriate for calculations of fuel consumption because federal fuel standards are stated in these terms. The sales-weighted harmonic mean efficiency of vehicles in a class A_d is defined to be

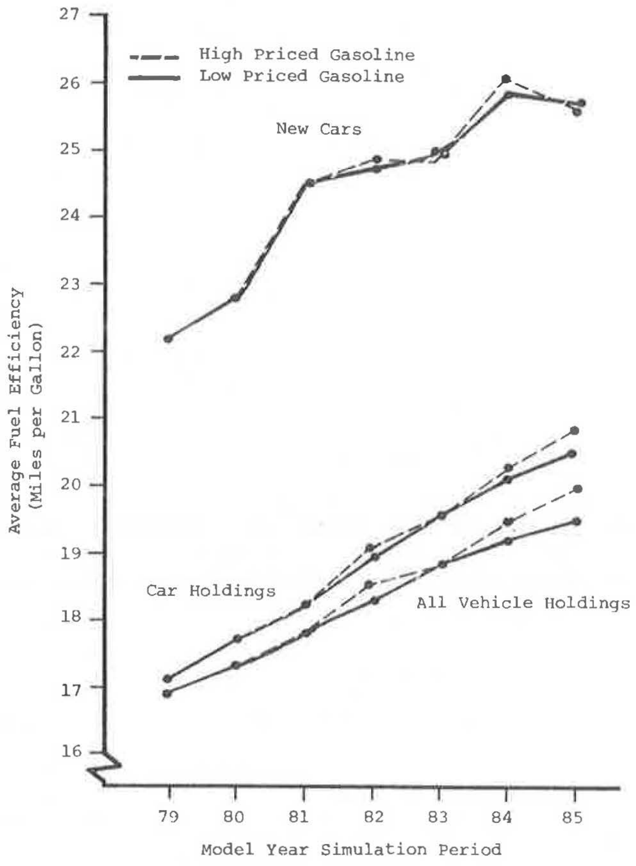
$$\bar{E}_d = \sum_{j\in A_d} N_j / \sum_{j\in A_d} (N_j/E_j) \qquad (6)$$

where N_j is the number of units sold of vehicle type j and E_j is its efficiency in miles per gallon.

The qualitative features of the predictions are easy to interpret. All of the curves slope upward over time because the fuel efficiency of new vehicles improves with time and households purchase the new, more-efficient vehicles. This same fact explains why the efficiencies of vehicle holdings lag behind those of new vehicles. The curves for new-car efficiency lie above those for all new vehicles because the latter includes the fuel-inefficient light-truck vehicle class.

Observe that the average efficiency of new vehicles and of vehicle holdings are higher under the $2.50/gal gasoline price schedule than under the $1.00/gal scenario. On the other hand, car efficiencies are not significantly affected by an increase in fuel prices. Examination of the detailed forecasting results reveals the source of this seem-

Figure 3. Average vehicle fuel efficiencies.



ingly counterintuitive finding. That is, when fuel costs rise, there is a small shift in new-vehicle sales from the larger, less-efficient automobiles to the smaller, more-efficient ones but a much more substantial shift from the very inefficient light trucks to the only moderately efficient intermediate-sized automobiles. It is, in principle, possible for the average fuel efficiency of all vehicles to rise, yet for the efficiency of cars to fall. In particular, this would happen if the increase in fuel prices caused owners of light trucks to switch to full-sized cars in sufficient numbers.

It is of interest to ask whether automobile manufacturers will meet the federal fuel-economy standards if they make the design and pricing changes assumed in our scenario. The standards call for each manufacturer to achieve sales-weighted harmonic average efficiencies of 19, 20, 22, 24, 26, 27, and 27.5 miles/gal in 1979-1985, respectively. Our point predictions for the average efficiencies of all new cars are 22.2, 22.8, 24.5, 24.7, 24.9, 25.9, and 25.7 miles/gal in the $1.00/gal gasoline price case and almost identical figures in the $2.50/gal case. Thus, in the aggregate, the standards are not met from 1983 on.

The aggregate figures do not, however, tell the full fuel-efficiency story. More disaggregated forecasts indicate that, in the later years of the period, domestic manufacturers generally approach and, in some cases, surpass the standards. On the other hand, foreign manufacturers experience a drop in average fuel efficiencies over time and therefore fail the standards by increasing amounts. This seemingly perverse result has a straightforward explanation. As time passes, the assumed constant real costs of imports make them increasingly a bargain relative to domestic cars. In particular, the larger, relatively fuel-inefficient imported models that compete with the larger domestic cars are forecast to increase in sales substantially. Sales of small imports also increase, but to a lesser degree. Hence, in toto, import sales shift to a less-efficient mix of vehicles.

In interpreting these results, two caveats must be made. First, it is unlikely that foreign or domestic manufacturers would maintain our projected design strategies if it became clear that their resulting sales mixes were falling below mandated standards. Thus, the forecasts should not be interpreted as a statement that selected manufacturers cannot meet federal fuel-economy standards in an absolute sense, but only that design-price strategies that differ from those currently envisioned may have to be employed.

The second caveat is that our predictions about fuel economy exclude new-vehicle sales to organizations. These sales have been estimated to constitute up to 20 percent of total sales. To the extent that fleet sales are skewed toward larger or smaller vehicles than those purchased by households, our fuel-economy estimates will be biased upward or downward.

To close this discussion, let us emphasize that, although the federal fuel-economy standards apply to new vehicles, the national concern is with the fuel efficiency of all vehicle holdings. Our forecasts indicate that, in each year through 1985, the average efficiency of holdings will lag behind that of new vehicles by 3.5-4.0 miles/gal. In the absence of further increases in the efficiencies of the new vehicles offered after 1985, it is likely that holdings will not reach the efficiency of new 1985 vehicles until sometime in the mid-1990s.

CONCLUDING REMARKS

How accurate are the forecasts presented here? Our view is that it is important to distinguish between the reasonableness of our point-estimate forecasts and the ultimate usefulness of the model system for policy analysis. From both these perspectives, our results can be interpreted on several levels.

On the most benign level, even if one accepts the market structure as represented in our model, the specifics of our forecast scenario assumptions are open to question. In developing the forecasting system, our primary concern was with ensuring that the models were fully sensitive to policy--to manufacturer design strategies, to demographic influences, and to government policies that affect vehicle prices or fuel efficiencies. Two scenarios were evaluated and reported on here. Are they realistic? Probably not. As was noted earlier in the paper, manufacturers will undoubtedly develop their design-price strategies in an evolutionary manner, cognizant of year-by-year market transactions. This element of conditional decision making was beyond our research scope, but clearly not beyond the capabilities of the model system. Indeed, our simulation approach is designed to operate on a year-by-year basis, and outcomes in any year depend strongly on previous year's sales and holdings. What the actual most likely scenario will be is a difficult question, since the future depends on the outcomes in a complex market where numerous manufacturers develop strategies in secret. Our model can only respond to the question, What if the motor vehicle market were defined in our scenario?

In view of the above, our fuel-efficiency forecasts, for example, must not be interpreted as an absolute statement that selected manufacturers will not meet mandated 1985 fuel-economy standards. The results reported here are really just a starting point for consideration of the impacts of alternative government policy and manufacturer strategies aimed toward improving vehicle fuel efficiency.

A major distinction between our disaggregate approach and the numerous aggregate approaches applied to vehicle forecasting is that the latter's explanation of new-vehicle sales through stock-adjustment equations does not capture the joint endogeneity of new-vehicle sales, used-vehicle scrappage, and used-vehicle prices. Our forecasting system, although simplified for computational application, certainly provides a more realistic representation of the operation of the vehicle market.

In summary, our initial research on developing and applying a disaggregate modeling approach to forecasting future motor-vehicle sales and holdings has proved highly encouraging. Our results are really the beginning of an ongoing need to analyze and monitor the motor vehicle market through the 1980s. We have applied our modeling approach to just two future scenarios.

Additional forecasts are called for as manufacturers' strategies evolve. With an eye toward improvement of our models, future work should seek to further illuminate the linkages that connect household behavior in choosing motor vehicles and other vehicle-related decisions. In particular, a joint analysis of ownership level, the composition of holdings, and vehicle use would be a valuable contribution.

ACKNOWLEDGMENT

The research reported here was performed at Cambridge Systematics, Inc. The many contributions to this study of J. Royce Ginn are gratefully acknowledged. This work was supported by the National Highway Traffic Safety Administration and the National Science Foundation. We have benefited from discussions with Moshe Ben-Akiva, Steven Lerman, and Nick Schaeffer. Responsibility for the contents of this paper rests solely with us.

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

Transportation System Management Actions: A Study of the Energy Costs

GERALD S. COHEN

Transportation system management (TSM) actions often save energy, primarily through diversion. They also incur energy costs of construction, maintenance, and operation. This paper examines the magnitude of such costs. Selected TSM actions that are scheduled for implementation in New York State are examined to determine the aspects of the projects that generate energy costs. Appropriate energy factors (equivalent gallons of gasoline per dollar of project cost) are given for many types of actions and there is a brief discussion of procedures for determining these factors. Estimates are provided for the cost of typical TSM projects. On the average, energy costs represent approximately 15 percent of energy savings. Actions such as encouragement of ridesharing have the smallest energy costs, and actions that result in additional transit vehicle miles of travel have the largest.

The federal government requires transportation system management (TSM) actions to be a component of urban transportation plans. These actions are intended to increase the capacity and efficiency of the existing transportation system by improving traffic flow, smoothing out peak-period loads, and diverting drivers to high-occupancy modes of travel. General categories of TSM actions include the following:

1. Actions to ensure efficient use of road space,
2. Actions to reduce vehicle use in congested areas,
3. Actions to improve public transit service, and
4. Actions to improve transit management efficiency.

Such actions can often reduce vehicle miles of travel (VMT) and increase vehicle speeds in congested areas, which will bring about a reduction in energy consumption, improved air quality, and reduced traffic without limiting transportation services.

As part of a project funded in part by the New York State Energy Office, the Planning Research Unit of the New York State Department of Transportation examined the energy savings that could be obtained by implementing many types of TSM projects. The report (1) considered both the energy savings and costs. This summary document describes the estimate of costs. Additional information can be found in the main report.

METHOD

The most complete source of data on the energy costs of transportation actions is Energy and Transportation Systems (2), hereafter referred to as the California Department of Transportation (Caltrans) manual. Although many numbers in that document are based on California's experience, sources that contain information for all states (3) generally show the energy costs to be similar. Thus, the use of California numbers should give acceptable results for planning purposes elsewhere.

Note that numbers that reflect manufacturing energy costs will yield energy costs that truly reflect energy for New York State only when all manufacturing is done in New York. Normally, some equipment will be manufactured outside the state. In that event, the energy cost is a cost to the nation in general, though not necessarily to New York. Such possibilities, however, are not considered here.

The information provided in terms of energy cost per dollar does not generally use current (1978) dollars but those from some other given year. Therefore, they have been converted by using the formula

$$\text{Energy/dollars (1978)} = [\text{energy/dollars (given year)}] \times [\text{CPI (given year)/CPI (1978)}] \quad (1)$$

where CPI is the consumer price index. Unless otherwise stated, all numbers in this report are in 1978 dollars. If, for example, it is decided to make an energy estimate in 1980 dollars by using a number in 1971 dollars, the formula would be

$$\text{Energy/dollars(1980)} = [\text{energy/dollars(1971)}] \times (\text{CPI 1971/CPI 1980}).$$

Energy cost numbers as published are generally given in British thermal units (Btus) or kilowatt hours (kW•h). Energy savings and costs are usually most readily obtainable as equivalent gallons of gasoline (1 gal of gasoline = 125 000 Btu). At a power plant, efficiency is approximately one-third, so that it takes slightly more than three units of input energy to produce one useful unit of output. Published numbers of energy costs generally specify energy in this way.

The methodology used for estimating costs is very simple. There are four key steps in the process. These are as follows:

1. Consider aspects of the action or project that result in the consumption of energy,
2. Estimate the life of the project,
3. Determine the appropriate energy factors, and
4. Apply the basic formula.

The basic formula is

$$\text{Annual average energy construction cost} = \text{energy cost per unit} \times \text{number of units} \times (1/\text{service life of project}) \quad (2)$$

An additional annual maintenance or operating cost should be added in order to obtain the total annual energy cost.

Published values for energy cost per unit generally reflect the total energy cost. If it is deemed appropriate to amortize these costs annually, it is necessary to know the life of the project. The table below gives estimates of service life for a range of actions (4).

Improvement	Maximum Service Life (years)
Right-of-way, obstacle removal	100
Major structures	30
Major geometrics--change of intersection configuration and curve flattening	20
Concrete barrier (median or half section)	20
Minor geometrics--left-turn lanes and channelization	15
Lighting	15
Major sign structures	15
Metal median barrier	15
Signals and flashing beacons	10
Resurfacing (2.5 in)	10
Minor signing	10
Metal guide rail	10
Armor coat (1 in)	7
Concrete pavement grooving	
Annual average daily traffic (AADT) < 10 000 per lane	7
AADT > 10 000 per lane	5
Delineators and guide markers	5
Asphalt pavement grooving	
AADT < 10 000 per lane	5
AADT > 10 000 per lane	4
Oil and stone	4
Shoulder stabilization	4
Pavement markings--thermoplastic	
Minimum	3
Maximum	7
Pavement markings--paint	0.5

Our study simply assumed that if the life of the project is, for example, 25 years, the annual energy cost associated with construction is one-twenty-fifth of the total energy figure.

The first step in the process (determining sources of energy consumption) requires research by the analyst and (ideally) extensive knowledge of the project or action. A reasonably good estimate, suitable for an environmental impact statement (EIS), can be made by using information about similar projects. It is easy to overlook certain sources of energy consumption, but such errors made by a careful analyst should be insignificant.

Many of the actions that we will look at in the paper have similar energy-producing components. For example, many different types of projects may require signs, construction of bus shelters, or widening of roads.

Table 1 gives a useful list of appropriate energy factors for TSM projects. The numbers were obtained from the literature or phone conversations with experts or were derived for this study. As an example we will look at the derivations of some of the cost factors for construction.

Cost of major signs per lane mile = 1 billion Btu
÷ lane mile [energy cost from Caltrans manual]
x (1 gal/125 000 Btu) [conversion factor]
x (1/15 years) [life from preceding table]
= 533 equivalent gal/lane mile.

Table 1. Annual energy cost factors.

Action	Energy Cost
Construction	
Road widening and TOPICS construction	3.9 gal/$1000
Toll booths	75.4 gal/toll booth
Roadways for access ramps	8.9 gal/$1000
Standard sidewalks	6.96 gal/linear ft
General structures, pedestrian bridges	3.3 gal/$1000
Class 1 bikeway	410 gal/lane mile
Class 2 barriers for bikeways	28.9 gal/100 ft
Parking lot	1.74 gal/parking space
Bus shelter	59.5 gal/shelter
Equipment manufacture and installation	
Signals and illumination	5.9 gal/$1000
Simple ramp metering	8.8 gal/ramp
Small signs	0.84 gal/10 signs
Major roadway signs	533 gal/lane mile of road
Minor roadway signs	0.042 gal/ft^2 of sign
Rubber pylons	0.384 gal/pylon
Printing and distribution of leaflets	1.5 gal/1000 leaflets or 91 gal/$1000
Construction of buses	544 gal/bus
Electrical equipment	30 gal/$1000
Construction equipment	30.8 gal/$1000
Operations	
Operation of traffic signals	398 gal/intersection
Additional increment for computerized traffic system	6.6 gal/intersection
Ramp metering–simple system	16 gal/ramp
Ramp metering–elaborate system	478 gal/ramp
Truck running 10 miles/day	230 gal/year
Local buses	0.277 gal/vehicle mile
Express buses	0.233 gal/vehicle mile
Elaborate electrical signs	239 gal/sign
Minibuses	0.154 gal/vehicle mile
Administration	127 gal/$1000
Advertising	46 gal/$1000
Traffic and advertising	174 gal/$1000
Maintenance	
Traffic signals	2 gal/intersection
Roadway	320 gal/lane mile
Bikeway	104 gal/lane mile
Parking lots	1.008 gal/parking space
Building and grounds	263 gal/$1000
Bus	0.105 gal/vehicle mile or 88 gal/$1000 if high labor cost or 117 gal/$1000 if low or average labor cost

Note: Annual costs use 1978 dollars. Total cost for a project can be obtained by multiplying by the service life.

Annual operation cost of truck to pick up pylons
= 10 miles/day x 5 days/week x 52 weeks/year
x 1.104 [conversion from diesel to gasoline]
x 0.08 gal/mile [gasoline consumption of truck]
= 230 equivalent gal of gasoline.

Further details can be found in the major study document (1).

DESCRIPTION OF ENERGY COSTS FOR SELECTED TSM ACTIONS

An examination of the project reports for the Traffic Operations Program for Increasing Capacity and Safety (TOPICS) projects examined by this analysis indicates that, in general, project implementation costs can be broken down into two cost components: (a) those costs attributable to the physical construction of the proposed improvement and (b) those costs attributable to the installation of new traffic control and other devices.

Maintenance costs of traffic lights are trivial, but their operation uses a fair amount of energy. Calculations based on examination of electric bills suggest that there is an annual consumption per intersection of approximately 388 equivalent gal of gasoline. The Caltrans manual gives a number for the energy cost per dollar for road widening projects that is a useful factor for TOPICS projects. Other energy costs arise from the manufacture of the electrical equipment.

Computerized Traffic Signals

The TSM project involves coupling traffic signals so that they respond to demand and ensure a smooth flow of traffic. The Department of Signals and Traffic Operations in New York City indicated that additional equipment needed at each intersection resulted in an incremental increase in power consumption of 30 W/h. On an annual basis, this implies that approximately 7 equivalent gal of gasoline are consumed. Additional energy costs arise from the manufacture and installation of electrical equipment.

Ramp Metering

There are a number of types of ramp-metering projects. The first (type 1) is a very simple device of the approximate complexity of a traffic light. An example is a pressure-activated system that changes to green briefly every 10 s so as to release one car. The operational energy per ramp is used by the two light bulbs, each of 67 W, that are the major component of the device. The dollar cost of installation and equipment of such a device is approximately $1500.

In addition to the operational component of a type 1 system, an energy cost is associated with the construction (manufacture) of the equipment itself.

A much more elaborate project (type 2) is an expressway-surveillance system. This includes television surveillance, variable message signs on the road, loop detectors on the expressways and ramps, and additional ramp-metering stations. Detailed information on the operational energy consumption of such a project is not available at this time, but a very conservative and very rough estimate can be made by assuming that, at each of the ramps of the projects, a minimum of 2 kW of power is required. The Caltrans manual notes that one or more interconnected signals require a controller whose estimated rating is 2 kW.

Contraflow Lanes

One significant energy construction cost associated with exclusive or contraflow lanes is the installation of signs and rubber pylons in order to reduce the danger of accidents. The Caltrans manual has a number for signs (freeway rural) of 1 billion Btu/lane mile. The note says that this figure is "based on a study of eight-lane highway sections and includes major sign-carrying structures spanning the road." Thus, the number is appropriate for typical projects.

An additional cost might result if the road was widened or a barrier was put in between lanes. If an additional lane is built and has to be maintained, there are annual maintenance costs.

There are also operational energy costs. In many cases, both exclusive and contraflow lanes will feature rubber pylons put out for the morning and afternoon peak-hour periods. It is reasonable that the truck used for this purpose runs 10 miles/day and consumes 0.08 gal of fuel/mile.

Preferential Access at Toll Booths

The energy costs of implementation of this project would be highest if additional toll booths are built. Such construction might be necessary in order to avoid major traffic jams. Conversations with the New York State Thruway Authority indicate that a toll both costs $18 000-$20 000 to construct. Regardless of whether or not an additional toll booth is needed, additional signs and barriers will have to be installed. There is also an annual energy cost for maintenance of the toll booth.

Preferential Access to Arterials for High-Occupancy Vehicles

A typical project might involve the construction of a bus-priority ramp to be constructed or the widening of an existing ramp. Highway construction uses a good deal of energy. If the dollar figure is known, the Caltrans number for urban arterial construction of 3.34 million Btu/$ is appropriate. If the length of the project is known, the Fels number (5) for construction of highways of 4.6 million kW·h/lane mile can be used. There are also maintenance costs for the roadway and additional installation of signs.

The addition of a bypass lane for high-occupancy vehicles and its associated metering equipment is another appropriate action under this classification. Electronic equipment that may vary in complexity would be used. The Caltrans manual gives a figure for signals and illumination of 736 000 Btu/$. A 10-year life is appropriate. This number can be used to obtain the costs for manufacture and installation. A conservative estimate of operating cost could be made by assuming that the equipment at each ramp is rated at 2 kW.

Bus Preemption Signals

Possible energy costs for this type of action would arise from the manufacture and installation of signs, the manufacture and installation of bus preemption signals, and the possible widening of the road.

TSM Pedestrian Actions

The energy cost associated with TSM pedestrian actions arises from the construction of specialized facilities, such as pedestrian bridges, or from lesser actions, such as signings. The Caltrans manual gives a structure figure of 1.24 million Btu/$. Pedestrian bridges typically cost approximately $3000/linear m. Thirty years is an appropriate service life.

The implementation of a pedestrian facility may require the construction of pedestrian bridges and shelters. It may also require additional construction of sidewalks. Desirable design standards would be 8 ft wide and 4 in thick. A 30-year life is possible but resurfacing would have to be done every decade.

TSM Bicycle Actions

Although the potential for energy savings from bicycle facilities is limited, energy costs can result from their implementation and operation. The energy cost for bikeways varies considerably, depending on the terrain and the class of the bikeway. Class 1 bikeways feature a completely separated right-of-way; class 2 is on a restricted right-of-way, probably marked off by signs and markings; and class 3 denotes a shared right-of-way designated by signs and markings. Representatives of the New York State Department of Transportation (NYSDOT) indicate a cost of $50 000/mile for class 1 bikeways. The TSM manual (6) gives a barrier cost of $2500/mile for certain class 2 bikeways. In addition, there are estimated signing costs of approximately $500/mile for class 1, 2, and 3 bikeways. Conversations with the traffic and safety staff at NYSDOT indicate that $50 is a reasonable figure for the cost of construction and installation of a small sign.

Fels (5) writes that class 1 bikeways are often constructed to a considerably lower standard than are roads designed for the automobile. Her estimate is that the construction energy for a bikeway is approximately one-sixteenth that of a highway of the same length.

The difference stems from the narrower bikeway lane, thinner surface of the bikeway, and the fact that bikeways generally follow the terrain, but roadways require the leveling of hills and the filling of valleys.

Class 2 and class 3 bikeways will have the same energy costs (those that are associated with signs) unless there is a barrier for the class 2 bikeways that results in higher costs. The energy cost varies with the cost of the barrier.

The Caltrans manual provides values for such possibilites as concrete railing, metal beam with road posts, and chain-link fencing. The bikeway must be maintained. Maintenance costs vary with the nature of the facility.

Vanpooling

The major capital energy cost would occur if vans or minibuses are purchased. In addition, a ridesharing program may include promotional booklets or leaflets. Vans consume approximately 0.15 gal/vehicle mile.

Automobile-Restricted Zones

The energy cost of such a project may be large if a good deal of construction is needed to make these zones desirable for pedestrians. This includes bus shelters, additional pavement work, and signs. The type of analysis needed is similar to that for pedestrian malls.

Park-and-Ride and Express Bus

Energy costs for this TSM action arise from several different sources. Buses will not normally have to be purchased for park-and-ride service, but the manufacturing energy is approximately 1.02 billion Btu/bus. Maintenance costs are 13 142 Btu/vehicle mile and fuel consumption varies with the speed and the grade of the roads. The Caltrans manual provides a figure of 0.257 gal/mile for the average vehicle in metropolitan transit operations. Another source (7) gives a range of 0.167 gal/mile (diesel) to 0.386 gal/mile (diesel) for a 51-passenger bus that travels at 20 mph, depending on the grade. At 35 mph, fuel consumption drops to 0.173 gal/mile (diesel) at a 2 percent grade.

Park-and-ride service usually uses existing parking lots. If this is the case, the construction of new lots is not needed. If parking lots are constructed, the figure for concrete pavement is 9.79 million Btu/ft^3. Design standards suggest a thickness of 4 in and 200 ft^2 for each parking space. Maintenance for parking lots, including signs and resurfacing, is approximately 6300 Btu/ft^2. Ten years is an appropriate lifetime for the sign and 30 years for the pavement.

Many park-and-ride lots feed existing transit services and so there is no increase in transit VMT. Where new bus service is provided to serve a park-and-ride lot, the energy cost of increased transit service and maintenance can be calculated. Where lot construction is required, its energy cost should be included.

Bus operation energy cost can be computed by using the formula

$$\text{Cost} = (\text{transit VMT}/\text{average transit miles per gallon}) \times 1.104 \quad (3)$$

Figures for average bus miles per gallon are generally available for metropolitan areas. A federal study (8) indicates that the national average for transit buses is 4.6 miles/gal. In certain cases, it is preferable to use a statewide average mile per gallon figure. Average bus miles per gallon in most areas in New York State is below the national average; 4.0 is an appropriate figure. Since transit buses use diesel fuel, a conversion factor is included in the equation. One gallon of diesel fuel is equal to 1.104 equivalent gallons of gasoline.

The change in transit travel distance and construction and maintenance costs can be determined for each specific action. A change in transit VMT will require a corresponding increase in maintenance of the transit vehicles. The corresponding energy loss can be calculated as follows:

$$\text{Energy loss due to maintenance} = \Delta \text{ transit VMT} \times 0.105 \quad (4)$$

where 0.105 gal/mile is the energy (in equivalent gallons of gasoline) required for maintenance per additional vehicle mile.

Passenger Amenities

This broad classification covers a wide range of actions. Some of these actions, such as the purchase of new modern buses, require a large consumption of energy. A new bus that has an estimated life of 15 years has a vehicle manufacture energy cost of approximately 1.02 billion Btu. Other actions include the purchase of additional bus shelters. The number used in this study for structure construction is 1.24 million Btu/$. Bus shelters last perhaps 10 years, require little maintenance, and cost perhaps $6000.

As an aid to computing the energy cost for other passenger amenities, such as improving the approach of train stations, adding air conditioning to buses, and perhaps adding elevators and similar equipment to train stations, there are published energy costs for maintenance construction, a figure for railroad construction (e.g., track laying), and costs of manufacturing elevators and air conditioners. The operation of this equipment would introduce an unknown but significant energy cost.

Demand-Responsive Transit

The energy arises from the operation of the bus, the manufacture of the bus, and electronic equipment needed for communication.

Improved Bus Maintenance

If we consider only small-scale actions, such as better record keeping, including the use of computers to keep track of a bus maintenance record, the energy cost would result from the manufacture and operation of electronic equipment. A program may include the purchase of maintenance equipment. A comparable figure in the Caltrans manual would be that for construction machinery. Very large equipment consumes energy at the equivalent rate of a few gallons per hour. If small changes are made in the building plant, the maintenance construction figure of 2.88 million Btu/$ is appropriate. A 10-year service life is reasonable for actions considered under this topic.

Hurley (3) gives different types of numbers. He shows numbers of 1.47 million Btu/$ for maintaining service equipment and 3.29 million Btu/$ for maintaining buildings and grounds. For administration the figure is 1.59 million Btu/$ and for insurance and safety it is 1.56 million Btu/$.

Hurley's numbers can be generally applied in upstate New York but are probably somewhat inappropriate in the tri-state area. The numbers were based on a management study of a Florida bus operation. In New York City, labor costs are a much larger share of the maintenance dollar than they are in upstate areas and in Florida. Thus, a dollar spent on maintenance in New York City will result in the expenditure of much less energy than is used upstate. The Holthoff report (9) indicates that employee costs are 85-92 percent for New York City operations and only 77-82 percent for Rochester, a typical upstate area. Operating costs per vehicle mile are 2.5 times larger for the Manhattan and Bronx Surface Transit Operating Authority than they are for the Capital District Transportation Authority, although a large part of this difference reflects the lower speed in New York City. It does appear that the Hurley number is too high for application in the tri-state region, and our judgment is that a number 75 percent as large, or 1.11 million Btu/$, is more appropriate.

One problem in using these Btu per dollar factors is determining the budget figure to which they should be applied. The TSM action being advocated is improved maintenance, not maintenance. Obviously an area can not claim credit for ordinary maintenance but rather for improvements in procedures.

Transit Monitoring

Monitoring includes many managerial actions. An improved monitoring program might include the use of better records and the use of computers to maintain various parameters. If the computer is already available and does not have to be manufactured and installed, the costs are mainly administrative. In this case, an approximate energy cost can be obtained by using the Hurley (3) number of 1.59 million Btu/$ for administration. This number is presumed to reflect the light bills and operation of office equipment.

If the computer must be manufactured and installed, the Caltrans electrical number of 3.72 million Btu/$ can be used. This number can be applied to equipment for communications systems. A 10-year service life is appropriate.

DETERMINING ENERGY FACTORS

Energy factors for highway construction can be derived by using information available from the Federal Highway Administration (FHWA). The procedure is described with great clarity in a document produced for the Maryland Department of Transportation by Hittman Associates (10). At timely intervals, the FHWA published four documents (11-14) that give highway use factors for different raw materials for each state per million dollars of construction costs. Thus, for example, one finds for the period 1975-1977 that New York State used an average of 19 000 tons of aggregate for each $1 million of Interstate urban highway construction. For comparison purposes, the national average was 24 000 tons, California used 33 000 tons, and Kentucky used 11 000 tons. Similarly for each $1 million, New York used 46 000 gal of petroleum for urban Interstate construction; the national average was 49 000 gal.

Energy is consumed in processing these basic materials. The Maryland document gives a list of sources that show some variance in their value. The energy number for aggregates is approximately 21 kW•h/ton and for petroleum is 40 kW•h. The procedure for determining the cost is to use the formula given in the Maryland Department of Transportation book:

Energy used in highway construction = [energy of material production/(total cost × number of units per dollar of construction costs for material 1)] × energy processing factor for material 1 + . . . + number of material units per dollar of construction costs of material N × energy processing factor for material N + [energy of construction operations/(number of gallons of petroleum per dollar of construction × 40 kW·h per ton per gallon)] (5)

There are many published figures that give values for fuel consumption by buses. For other items, such as traffic signals or lighting, typical projects can be used to determine energy costs. The estimate for signs used in this report was based on the Caltrans number for cold rolled steel and information from NYSDOT experts on the amount of steel in a sign and the energy needed for installation.

The energy costs considered in this paper are limited to the costs that arise from operations, maintenance, and the construction or manufacture of needed equipment or facilities. There are secondary costs. If one takes a transit bus to work instead of driving, there are savings since the car is not used for the work trips. However, there are energy costs that arise from the use of the car left home. The energy costs from the use of the car left home are discussed by Gross (15). Other costs of this nature are discussed in the study group's main report (1).

SUMMARY AND CONCLUSIONS

As indicated in the introduction, the cost analysis was only one component of a larger study that dealt with both the energy savings and costs of implementing TSM actions. It should be noted that, in most cases, the projects that have the largest energy costs also generate the largest energy savings. Detailed information on the forecasting of energy savings can be found in the major study document (1).

By analyzing the costs as well as the savings, it was possible to determine that such projects as automobile-restricted zones, construction of bikeways, and demand-responsive service are questionable projects if energy savings are the prime goal. They may, of course, be justifiable on other grounds.

By using the factors in the table, the basic formula, and the analyst's best estimate of the relevant factors, the analyst can determine good estimates of the energy costs of implementing TSM actions. On the average, energy costs for TSM actions represent about 15 percent of energy savings. Several projects, such as reductions in parking spaces, work-hour policies, and ridesharing activities, have no or relatively small energy costs. In general, transit actions that generate additional bus mileage have relatively high energy costs per gallon saved. Most often the energy cost is associated with the manufacture, construction, installation, operation, and maintenance of the facilities and equipment needed to successfully develop and operate the action. For example, for bikeways there can be cost of construction and maintenance of the bike path and the manufacture and installation of signs. The energy costs of TSM actions must be determined so that a fair assessment of their energy impacts is made. It must be emphasized that TSM actions that do not show a net energy saving are often justifiable on social equity, safety, or other grounds. On the other hand, if we do not consider the energy cost we may exaggerate the potential energy savings from proposed actions and find ourselves faced in the future with unforeseen energy shortages.

ACKNOWLEDGMENT

I received useful suggestions from many members of the planning research staff. Valuable research assistance was given by Hamid Daneshmand. The cooperation of many New York State and New York City Department of Transportation personnel, who were able to obtain numbers for me, was essential to the successful completion of this project. This project was supported in part by the New York State Energy Office. Special thanks are given to Wilma C. Marhafer, Diane E. Davis, and Linda Unangst, who typed this paper.

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