TRANSPORTATION RESEARCH RECORD 935

Analysis of Issues in Energy Planning and Energy Modeling

TRANSPORTATION RESEARCH BOARD

NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C. 1983

Transportation Research Record 935
Price $7.40
Edited for TRB by Naomi Kassabian

modes
1 highway transportation
2 public transit

subject area
17 energy and environment

Library of Congress Cataloging in Publication Data
National Research Council. Transportation Research Board.
Analysis of issues in energy planning and energy modeling.

(Transportation research record; 935)
1. Transportation–Energy conservation–Congresses.
2. Transportation–Energy consumption–Congresses. I. National Research Council (U.S.). Transportation Research Board. II. Series.
TE7.H5 no. 935 [HE152.5] 380.5s [333.79] 84-9983
ISBN 0-309-03650-X ISSN 0361-1981

Sponsorship of the Papers in This Transportation Research Record

GROUP 1–TRANSPORTATION SYSTEMS PLANNING AND ADMINISTRATION
Kenneth W. Heathington, University of Tennessee, chairman

Environmental Quality and Conservation of Resources Section
Earl C. Shirley, California Department of Transportation, chairman

Committee on Energy Conservation and Transportation Demand
Carmen DiFiglio, U.S. Department of Energy, chairman
William G. Barker, Martin J. Bernard III, Sydney D. Berwager, Melvyn Cheslow, Sidney Davis, Donald J. Gantzer, David Lloyd Greene, David T. Hartgen, Richard Hood, Charles A. Lave, Michael F. Lawrence, H. James Leach, Rasin K. Mufti, Philip D. Patterson, Milton Pikarsky, Axel Rose, William P. Schlarb, Richard H. Shackson, Richard P. Steinmann, Richard L. Strombotne, Thomas J. Timbario, Kenneth H. Voigt

Stephen E. Blake, Transportation Research Board staff

The organizational units, officers, and members are as of December 31, 1982.

Contents

ENERGY SHORTFALLS AND PEAK-HOUR TRANSIT CAPACITY PROBLEMS: THE 1979 EXPERIENCE
Daniel K. Boyle and Jeffrey R. Cantine 1

AN EVALUATION OF OPTIONS FOR FREIGHT CARRIERS DURING A FUEL CRISIS
Larry R. Johnson and Christopher L. Saricks 5

EVALUATION OF MANAGEMENT MEASURES TO REDUCE GASOLINE QUEUES AT SERVICE STATIONS: A SIMULATION APPROACH
A.G. Hobeika and S.H. Young 12

ANALYSIS OF TOTAL ENERGY USE OF URBAN TRANSPORTATION ENERGY CONSERVATION STRATEGIES
Margaret K. Singh and Sarah J. LaBelle 19

THE CALIFORNIA FREIGHT ENERGY DEMAND MODEL
Herbert Weinblatt 26

INDIVIDUAL RESPONSES TO RISING GASOLINE PRICES: A PANEL APPROACH
Roger B. Trent and Cecil R. Pollard 33

DETERMINANTS OF NEW-CAR FUEL EFFICIENCY
Ronald J. Sutherland and Andrew Ford 40

Authors of the Papers in This Record

Boyle, Daniel K., Planning Division, New York State Department of Transportation, 1220 Washington Avenue, Albany, N.Y. 12232
Cantine, Jeffrey R., Planning Division, New York State Department of Transportation, 1220 Washington Avenue, Albany, N.Y. 12232
Ford, Andrew, Los Alamos Scientific Laboratory, P.O. Box 1663, Los Alamos, N. Mex. 87545
Hobeika, A.G., Department of Civil Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Va. 24061
Johnson, Larry R., Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Ill. 60439
LaBelle, Sarah J., Center for Transportation Research, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Ill. 60439
Pollard, Cecil R., Office of Health Services Research, West Virginia University, Morgantown, W.Va. 26506
Saricks, Christopher L., Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Ill. 60439
Singh, Margaret K., Center for Transportation Research, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Ill. 60439
Sutherland, Ronald J., Los Alamos Scientific Laboratory, P.O. Box 1663, Los Alamos, N. Mex. 87545
Trent, Roger B., Department of Sociology and Anthropology, West Virginia University, Morgantown, W.Va. 26506
Weinblatt, Herbert, Jack Faucett Associates, 5454 Wisconsin Avenue, Suite 1100, Chevy Chase, Md. 20815
Young, S.H., Department of Civil Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Va 24061

Energy Shortfalls and Peak-Hour Transit Capacity Problems: The 1979 Experience

DANIEL K. BOYLE AND JEFFREY R. CANTINE

Effects of the 1979 energy shortfall on peak-hour transit capacity are analyzed. A short survey was sent to 102 transit operators in 100 urbanized areas throughout the United States; of these, 45 responses were received from 44 urbanized areas. The extent to which peak-hour capacity problems were created or heightened in the spring and summer of 1979, actions selected for 1979, the effectiveness and cost of those actions, implementation problems, and transit operators' recommendations for future crises of this nature are documented. Results indicate that systems in the Northeast and in urbanized areas with a population of more than 250,000 were most affected in terms of peak-hour capacity problems. The actions most often taken were relaxing informal operating standards, increasing park-and-ride or express bus services, using a reserve fleet of buses, changing maintenance practices, and encouraging programs for variable work hours. Changing operating standards is an excellent first move to make while other actions are being considered. Problems most often concerned finance, maintenance, personnel, and time requirements. The most effective actions tended to be the most costly.

Previous work on the effects of energy supply on transit has indicated that ridership increases significantly during energy shortfalls. Much of this increase appears to be focused in the peak hour, when most transit systems are already operating at or near capacity. This poses obvious problems for transit operators. The surge in demand not only comes at the time of day when the operator is least able to handle it but is also temporary, because ridership is significantly above normal only for the duration of the shortfall.

There is little information available concerning the response of transit operators to emergency situations when there is a surge in demand for transit services, particularly peak-hour service. Therefore, as part of a study concerning rapid increases in transit capacity, transit operators in the United States were surveyed to determine the extent of capacity problems during the 1979 energy shortfall. Operators were also questioned about the effectiveness and cost of actions carried out in 1979, problems encountered, and recommendations for future energy shortfalls.

In this paper the extent to which peak-period transit capacity problems were hightened by the 1979 crisis and the responses of transit operators to these problems are documented. A sample of 68 transit operators in 66 urbanized areas, used in a previous study on transit ridership changes during the 1979 energy shortfall (1), was augmented with 34 other systems chosen by stratified random sampling techniques to yield an overall sample representative with respect to urbanized area size and system location. Where appropriate in very large cities, more than one operator was surveyed. Of the 102 surveys distributed, a total of 45 responses from 44 urbanized areas were received. In Tables 1 and 2 response rates are broken down by region and size (2). It may be seen that the lowest response rates were for systems in very small urbanized areas, whereas systems in very large and medium-sized urbanized areas had the highest response rates. Consequently, systems in urbanized areas with more than 250,000 population are somewhat overrepresented in this sample and systems in smaller urbanized areas are underrepresented.

PEAK CAPACITY PROBLEMS

The results of the survey indicate that the 1979 energy crisis made peak-period transit capacity problems worse for certain systems. Survey results are presented in Table 3. Systems in medium-sized urbanized areas consistently reported capacity problems, whereas systems in smaller urbanized areas generally did not experience problems. If a division is made at a population of 250,000, 74 percent of systems in urbanized areas with more than 250,000 population experienced a worsening of peak capacity problems, whereas only 33 percent of systems in small urbanized areas reported such problems. In every region, systems in larger urbanized areas experienced more problems than systems in smaller urbanized areas. The Northeast reported the most problems, and the South had the least.

The conclusions to be drawn are that systems in small and very small urbanized areas and southern systems did not generally experience capacity problems in 1979. These problems were most prevalent on systems in urbanized areas with more than 250,000 population and on systems in the Northeast.

These conclusions contrast with previous work on transit capacity (3), which indicated that very large and very small systems would be least able to cope with capacity problems brought on by an energy crisis and that systems in the Northeast and the South would not have the excess capacity available to handle increased demand in a crisis. The results here show that systems in very small urbanized areas and southern systems experienced few capacity-related problems in 1979 and that not only very large systems but systems in urbanized areas of more than 250,000 (medium to very large) had problems. Both these results and those of the previous study agree on the extent of capacity-related problems in the Northeast. One possible reason for the discrepancy concerning southern systems is that the shortfall was relatively minor in southern urbanized areas contained in the sample (1).

Table 1. Response rates of transit operators by urbanized area size.

	U.S. Urbanized Areas with Transit		Surveys Sent		Surveys Received		
Urbanized Area Size	No.	Percent	No.	Percent	No.	Percent	Response Rate (%)
Very large (>1,000,000)	25	9.6	14	13.7	10	22.2	71.4
Large (500,000-1,000,000)	21	8.1	12	11.8	6	13.3	50.0
Medium (250,000-500,000)	35	13.5	12	11.8	8	17.8	66.7
Small (100,000-250,000)	96	36.9	34	33.3	13	28.9	38.2
Very small (50,000-100,000)	83	31.9	30	29.4	8	17.8	26.7
Total	260		102		45		44.1

Note: Data are from UMTA.

ACTIONS TAKEN IN 1979

The survey form listed 10 possible capacity-expanding actions and asked operators to indicate whether the action was taken, to rank its effectiveness on a scale of 1 to 4 (1 = ineffective and 4 = effective), and to estimate actual daily capacity increase and actual daily cost. A separate set of questions elicited similar information on variable work hours; because the cost of this action is generally not borne by the operator, the cost question was omitted for variable work hours. The results of this part of the survey are presented in Tables 4-7. In Table 4 the frequency of implementation, effectiveness, and cost of actions are considered, and in Tables 5-7 a breakdown of actions taken by system size and region is provided. Regional differences were not pronounced. Systems in very small urbanized areas took few actions because they generally reported no problems. Interestingly, systems in very large urbanized areas rarely increased park-and-ride or express service; presumably, these systems already operated fully developed park-and-ride and express service.

From Table 4 it may be seen that relaxing informal operating standards, increasing park-and-ride and express service, bringing retired buses back into service, readjusting maintenance practices, and encouraging variable work hours were the actions most often taken in 1979. The other actions listed in Table 4 were rarely taken.

Table 4 also gives the averages and ranges of effectiveness (rated on a scale of 1 to 4), percentage of capacity increase, and daily cost. In responding to the survey, some operators gave an absolute increase in seat capacity; this was converted to a percentage increase by finding the peak-hour vehicle requirement for the system [2 (early 1980 was the closest date for which the information was available)] and assuming 45 seats per bus. It must be noted that many operators were unable to provide figures on capacity increase and cost. In Table 4 the number of responses from which average capacity increases and costs were computed is indicated.

Relaxing informal operating standards (basically a do-nothing option) was generally effective and low in cost, although it seemed less effective in the Northeast and in large and very large urbanized areas. Increasing park-and-ride and express service was also generally effective but high in cost. Bringing retired buses back into service was moderately effective and had a high cost. Readjusting maintenance practices resulted in low benefits and high cost. Variable work hours were ranked low on the effectiveness scale but seemed to produce moderate shifts in demand out of the peak. Among actions rarely taken, speeding up the procurement of buses resulted in high benefits, but only two systems were able to do this in 1979. Similarly, only in one system was the use of school buses attempted; significant costs were reported.

Table 2. Response rates of transit operators by region.

	U.S. Urbanized Areas with Transit		Surveys Sent		Surveys Received		
Region[a]	No.	Percent	No.	Percent	No.	Percent	Response Rate (%)
Northeast	52	20.0	22	21.6	12	26.7	54.5
South	93	35.8	36	35.3	14	31.1	38.9
North Central	74	28.5	28	27.5	13	28.9	46.4
West	41	15.8	16	15.7	6	13.3	37.5
Total	260		102		45		44.1

Note: Data are from UMTA.

[a] Region definitions are based on U.S. Census divisions.

Table 3. Number of systems reporting peak-period capacity problems as a result of 1979 energy crisis.

	Northeast		South		North Central		West		All Regions	
Urbanized Area Size	No. with Problems	No. Without Problems	No. with Problems	No. Without Problems	No. with Problems	No. Without Problems	No. with Problems	No. Without Problems	No. with Problems	No. Without Problems
>1,000,000	3	1	1	1	1	1	2	0	7	3
500,000-1,000,000	0	1	1	1	2	0	1	0	4	2
250,000-500,000	3	0	2	1	2	0	0	0	7	1
100,000-250,000	1	1	1	5	2	2	1	0	5	8
50,000 100,000	2	0	0	1	0	3	0	2	2	6
Total	9	3	5	9	7	6	4	2	25	20

Table 4. Number, effectiveness, and cost of actions taken in 1979.

			Effectiveness[a]		Capacity Increase (%)			Daily Cost ($)		
Action	No. of Systems Taking Action	Percentage of Response	Range	Avg	No. of Responses	Range	Avg	No. of Responses	Range	Avg
Relax informal operating standards	17	37.8	1-4	2.9	7	0-27	9.6	6	0-300	50
Increase park-and-ride and express service	12	26.7	2-4	2.9	5	2-30	10.4	3	800-7,000	4,267
Bring retired buses out of storage	9	20.0	2-4	3.0	6	1-10	5.2	4	100-3,000	1,243
Offer variable work hours	9	20.0	1-3	2.1	5	0-18	7.6	–[b]	–[b]	–[b]
Readjust maintenance practices	8	17.8	1-3	2.5	6	1-10	5.0	4	40-5,000	1,710
Reassign buses	3	6.7	2-4	2.7	0	–	NA	0	–	NA
Turn back buses	3	6.7	2-3	2.7	1	–	4.0	1	–	240
Speed up bus procurement	2	4.4	–	4.0	1	–	15.0	0	–	NA
Lease school buses	1	2.2	–	3.0	1	–	3.0	1	–	2,860
Initiate fare differential	0	0	–	2.0[c]	0	–	–	0	–	–
Lease private buses	0	0	–	1.0[c]	0	–	–	0	–	–

[a] On scale of 1 to 4 (1 = ineffective, 4 = effective).

[b] No costs assumed.

[c] Estimated.

Table 5. Number of systems taking specific actions in 1979 and average of effectiveness ratings by size of urbanized area.

	More than 1,000,000		500,000 to 1,000,000		250,000 to 500,000		100,000 to 250,000		50,000 to 100,000		All Systems	
Action	No.	Avg Effectiveness^a	No.	Avg Effectiveness^a	No.	Avg Effectiveness^a	No.	Avg Effectiveness^a	No.	Avg Effectiveness^a	No.	Avg Effectiveness^a
Bring retired buses out of storage	3	3.0	1	4.0	3	3.0	1	3.0	1	2.0	9	3.0
Readjust maintenance practices	3	2.3	1	3.0	2	3.0	2	2.0	–	–	8	2.5
Turn back buses	2	2.5	–	–	1	3.0	–	–	–	–	3	2.7
Reassign buses	2	2.0	–	–	–	–	1	4.0	–	–	3	2.7
Lease school buses	1	3.0	–	–	–	–	–	–	–	–	1	3.0
Lease private buses	–	–	–	–	0	1.0^b	–	–	–	–	0	1.0^b
Increase park-and-ride and express service	2	3.0	3	2.7	3	3.0	4	3.0	–	–	12	2.9
Relax informal operating standards	6	2.5	2	2.5	5	3.5	4	3.3	–	–	17	2.9
Speed up bus procurement	–	–	2	4.0	–	–	–	–	–	–	2	4.0
Initiate fare differential	–	–	–	–	0	2.0^b	–	–	–	–	0	2.0
Offer variable work hours	1	3.0	2	1.5	4	2.3	2	2.0	–	–	9	2.1

[a] On scale of 1 to 4 (1 = ineffective, 4 = effective). [b] Estimated effectiveness; action not taken.

Table 6. Number of systems taking specific actions in 1979 and average of effectiveness ratings by geographical region.

	Northeast		South		North Central		West		All Systems	
Action	No.	Avg Effectiveness^a	No.	Avg Effectiveness^a	No.	Avg Effectiveness^a	No.	Avg Effectiveness^a	No.	Avg Effectiveness^a
Bring retired buses out of storage	3	3.5	2	2.0	4	3.0	–	–	9	3.0
Readjust maintenance practices	2	2.5	3	2.7	2	2.0	1	3.0	8	2.5
Turn back buses	2	3.0	–	–	1	2.0	–	–	3	2.7
Reassign buses	–	–	–	–	2	3.0	1	2.0	3	2.7
Lease school buses	–	–	1	3.0	–	–	–	–	1	3.0
Lease private buses	–	–	–	–	0	1.0^b	–	–	0	1.0^b
Increase park-and-ride and express service	2	3.0	3	3.0	5	3.0	2	2.5	12	2.9
Relax informal operating standards	6	2.6	4	3.0	4	3.0	3	3.3	17	2.9
Speed up bus procurement	–	–	–	–	1	4.0	1	4.0	2	4.0
Initiate fare differential	–	–	–	–	0	2.0^b	–	–	0	2.0^b
Offer variable work hours	1	3.0	1	2.0	4	1.8	3	2.3	9	2.1

[a] On scale of 1 to 4 (1 = ineffective, 4 = effective). [b] Estimated effectiveness; action not taken.

IMPLEMENTATION PROBLEMS

Several problems arose when transit operators attempted to carry out capacity-increasing actions. Financial considerations were emphasized in the operators' comments: Either there was no working capital available or the marginal cost of the option exceeded the marginal revenue. Personnel and union problems were also prevalent. New personnel hired during the crisis were often reported unsatisfactory. A shortage of qualified mechanics was noted, and drivers' unions occasionally objected to certain actions. Small operators generally put as many vehicles as possible into service as a standard practice and so were particularly vulnerable to peak capacity problems in a crisis. Some large operators experienced serious problems with the physical condition of the existing fleet and so were saddled with high spare ratios. These were the major problems noted along with obvious concerns as to fuel and fleet storage and fuel supply.

One operator indicated that although several actions were taken during 1979, there were no long-term solutions among the options. This may be because no way has yet been found to reduce the inefficiencies inherent in the operation of transit systems with such pronounced peaking characteristics. In this view, crises do not cause capacity problems; they only magnify the severity of the existing problems.

Unique circumstances sometimes prevented peak capacity problems from becoming worse. One system reported no true peak period, whereas another reported that its peak was unrelated to work travel. A series of fare increases counterbalanced the increased demand resulting from the energy shortfall on one system. And a system near the U.S.-Canadian border reported little shift to transit because motorists found low prices and plentiful gasoline across the border.

In general, implementation problems most frequently involved finance, maintenance, and personnel. The most common reasons for not carrying out proposed actions were financial barriers and long lead times.

OPERATOR RECOMMENDATIONS

From their experiences in 1979, transit operators were asked to recommend actions to be taken in a future energy crisis. Table 8 ranks actions by frequency of recommendation and compares the number of times an action has been recommended with the number of times it was actually put into operation in 1979. Reassigning buses and initiating a differential between peak and off-peak fares were recommended significantly more often than they were actually put into operation. The time frame and a lack of preparation may explain why a fare differential was not instituted more often. Small-scale ac-

Table 7. Increase in peak-period capacity and daily cost associated with capacity-expanding options.

Option	Area Size and Region[a]	Capacity Increase (%)	Cost ($)
Bring retired buses out of storage	VL NE	6	NA
	VL NC	5	NA
	M NE	1	270
	M NE	6	1,600
	M NC	10	3,000
	VS S	3	100
Avg		5.2	1,243
Readjust maintenance practices	VL NE	1	40
	VL S	1	600
	L W	10	NA
	M S	6	NA
	M NC	5	1,200
	S S	7	5,000
Avg		5	1,710
Turn back buses	VL NE	4	240
Lease school buses	VL S	3	2,860
Increase park-and-ride and express service	L W	3	NA
	M NE	2	800
	M S	10	NA
	M NC	30	7,000
	S S	7	5,000
Avg		10.4	4,267
Relax informal operating standards	VL S	NA	0
	VL W	NA	0
	L W	10	NA
	M NE	0	0
	M S	10	NA
	M S	0	0
	M NC	10	300
	S NE	10	0
	S W	27	NA
Avg		9.6	50
Offer variable work hours	L NC	0	–
	L W	5	–
	M NE	18	–
	M NC	10	–
	M NC	5	–
Avg		7.6	
Speed up bus procurement	L W	15	NA

Note: Where capacity increase was not given as a percentage but as a number of additional seats, 45 seats per bus were assumed and the peak-hour vehicle requirement (2) was used to compute the base.

[a] Area sizes and regions are as follows: VL, very large; L, large; M, medium; S, small; VS, very small; NE, Northeast; S, South; NC, North Central; W, West.

tions related to operations, such as reassigning buses, may be more appealing given the current fiscal state of transit. Variable work hours, ranked fifth among actions taken, is most often recommended. Again, operators may feel that now there is time to develop a program of variable work hours.

The most dramatic differences between actions taken and actions recommended involve increasing park-and-ride and express service and relaxing informal operating standards; both were taken in 1979 far more often than they were recommended for a future crisis. This is puzzling at first glance, because Table 4 indicated that both actions were rated as moderately effective. However, increasing park-and-ride and express services was the most expensive action; the cost may well have discouraged operators from recommending it. Relaxing informal operating standards is a default option, taken if nothing else is done. Although operators may have been forced to relax operating standards in 1979 because of a lack of preparedness, financial difficulties, or other reasons, their reluctance to recommend doing this indicates an awareness that riders will not tolerate overcrowded conditions for long. The list of recommendations in Table 8 also indicates the most desirable actions in the absence of time constraints, because the recommendations presume that necessary preparations can be made.

Table 8. Actions recommended for future energy crises.

Action	No. of Systems Recommending Action	No. of Systems Taking Action in 1979
Offer variable work hours	7	9
Bring retired buses out of storage	7	9
Readjust maintenance practices	6	8
Reassign buses	6	3
Initiate fare differential	6	0
Turn back buses	5	3
Increase park-and-ride and express service	3	12
Lease school buses	2	1
Relax informal operating standards	1	17
Speed up bus procurement	1	2
Lease private buses	1	0

Table 9. Summary of actions most often taken in 1979.

Action	Benefits	Cost
Relax informal operating standards	High	Low
Increase park-and-ride and express service	High	High
Bring retired buses out of storage	Moderate	High
Readjust maintenance practices	Low	High
Encourage variable work hours	Low	None[a]

[a] For operator.

SUMMARY OF SURVEY RESULTS

A majority of systems in the sample reported that peak-hour capacity problems were created or worsened during the 1979 energy crisis. Systems in the Northeast were most affected, whereas systems in the South reported few problems. Systems in urbanized areas with a population of more than 250,000 experienced more problems than did systems in small regions. Actions most often taken are listed in Table 9 along with their general effectiveness and cost. It should be noted that despite its favorable ratings in Table 9, it was rarely recommended that operating standards be relaxed; presumably the decrease in quality of service resulting from this option is considered tolerable only in the short term. Nevertheless, because operating standards can be changed immediately, it is an excellent first action to take while other actions are prepared to be carried out.

Implementation problems most often concerned finance, maintenance, personnel, and time requirements. No consensus emerged regarding recommendations.

The survey results provide information derived from the experience of transit operators in 1979 concerning two factors of interest: the effectiveness of various capacity-increasing options and the distribution of capacity problems. The effectiveness of 1979 actions provides a basis for recommending various packages or options for a future crisis (4), whereas the distribution of peak-hour capacity problems in 1979 indicates the extent to which the energy shortfall had a measurable effect on transit.

ACKNOWLEDGMENT

This paper was prepared under a grant from UMTA. We would like to thank David T. Hartgen, Alfred J. Neveu, Janis M. Gross, and Nathan S. Earlbaum for advice offered in the course of preparing this paper. At the time this paper was written, Jeffrey R. Cantine was a department intern from Union College in Schenectady, N.Y. We, of course, retain re-

sponsibility for the contents of the paper, including any errors or omissions.

REFERENCES

1. D.K. Boyle. Transit Use and Gasoline Shortages. Planning Research Unit, New York State Department of Transportation, Albany, Preliminary Research Rept. 200, Oct. 1981.
2. A Directory of Regularly Scheduled, Fixed Route, Local Public Transportation Service in Urbanized Areas over 50,000 Population. UMTA, Aug. 1980.
3. G.F. Taylor. Capacity of Urban Transit Systems to Respond to Energy Constraints. In Considerations in Transportation Energy Contingency Planning, TRB, Special Rept. 191, 1980, pp. 43-48.
4. D.K. Boyle. Rapid Increases in Transit Capacity: When to Act and What to Do. UMTA, 1983.

An Evaluation of Options for Freight Carriers During a Fuel Crisis

LARRY R. JOHNSON AND CHRISTOPHER L. SARICKS

Demand-reduction alternatives that carriers (truck, rail, air, and inland waterway) could logically adopt during a fuel emergency are examined and the fuel savings attributable to their use are quantified. Opportunities for improvement in fuel efficiency may be classified as systemwide (increasing load factors, reducing congestion) or vehicle and operation specific (adapting available technologies, improving maintenance, changing operating practices). Nevertheless, fixed and variable nonfuel costs could increase such that, for a given alternative (e.g., phased advance-technology retrofit), the payback period could exceed the duration of any shortfall, and the investment thus would not be justified on the basis of the shortfall alone. Specific alternatives under each of the five general categories of fuel-efficiency improvement are considered for each mode and a percentage of reduction in fuel consumption is estimated based on reported effectiveness and the expected degree to which such measures would be adopted systemwide. An aggregate estimate of petroleum savings (roughly 4 to 8 percent) was found to be attributable to demand-reduction alternatives that could be adopted by freight carriers without drastically curtailing service. Because carriers are moving toward improved fuel efficiency as an integral aspect of normal operations, the potential for reducing fuel demand will decline in the future.

The two predominant features of the federal emergency planning for oil supply interruptions are (a) the intent to rely on the basic economic forces of supply and demand to allocate the scarce resource and (b) the use of the Strategic Petroleum Reserve (SPR) as the principal method to mitigate the effects of an oil shortfall. Allowing the fuel price to rise during a shortfall more accurately reflects the value of the commodity, which permits consumers to make better-informed decisions concerning their use of a product in short supply. No false price signals regarding the severity of the shortage are given to the public, as would be the case with arbitrarily controlled prices. The development and use of the SPR is regarded a national insurance policy in which stored oil can be substituted for imported (or domestic) oil the flow of which has been disrupted.

In the freight transportation industry as a whole, energy contingency planning currently receives little attention. Other more pressing problems, such as the decline in traffic because of a poor economy, have been the focus of management's attention. Contingency planning, especially with the current availability of fuel, is likely to be reactivated in the event of a crisis. Wide variation, however, does exist. Some companies have extensive energy management programs and not only have plans ready in the event of a fuel supply interruption but have taken steps in their own self-interest, such as increasing their fuel storage capacity. In a more general way, most carriers have reacted to the higher fuel costs by purchasing more fuel-efficient equipment, which in turn puts them in a more favorable position (compared with that a few years ago) in the event of a fuel shortfall.

Conceptually, contingency planning for freight carriers, whether explicitly stated or implicit in their operations, covers two time periods: before the shortfall and during the shortfall.

Elements in planning before the shortfall include

1. Purchasing fuel-saving equipment,
2. Increasing fuel storage capacity and fuel stocks,
3. Providing firm contractual arrangements for fuel supplies as well as alternative fuel suppliers, and
4. Planning both the management functions and the technical requirements for an energy shortfall.

Elements of a contingency plan that a company can invoke during a shortfall will depend on the magnitude and duration of the fuel interruption but will likely be taken in the order of increasing severity. Those elements include

1. Actions that necessitate little or no increase in capital or operating expense,
2. Actions that incur higher capital costs or increases in nonfuel operating expenses or both, and
3. Actions that require significant capital expenditures and drastic operating changes that markedly affect the perceived quality of service.

CONSERVATION OR CONTINGENCY PLANNING

In identifying contingency actions, an important distinction should be maintained between contingency and conservation. Contingency actions, because of the immediate nature of the emergency situation, must be quickly instituted to be effective in reducing the impact of an oil shortfall. Energy conservation, which also has as an objective the reduction in the demand for fuel, is oriented toward efficiency improvements that can be accomplished over the long term. Many of the contingency actions identified in this analysis could rightfully be called conservation and have, in varying degrees, been instituted in the transportation industry. Under conditions of stable fuel prices and relatively abundant fuel supplies, economic and service considerations may override energy concerns. During an energy shortfall, rapidly rising fuel prices and the lack of fuel availability become the driving forces that change a carrier's perception of the practicality of actions that could reduce fuel demand. For any actions that require an increase in capital or operating expense, the payback period becomes shorter. Thus some contingency actions can be considered a subset of conservation actions.

FUEL DEMAND-REDUCTION ALTERNATIVES

Fuel conservation activities in the freight transportation industry are well recognized. Before the 1973 Arab oil embargo, fuel costs were a relatively minor expense for most carriers. Since then the steady increase in fuel prices has been an impetus for carriers to control expenses by reducing fuel use. More fuel-efficient motive power is being used to replace retired vehicles. Retrofit devices are being used to increase the efficiency of existing vehicles. Operating practices have been changed to reduce fuel consumption in both the line-haul and the local-access portions of the trip.

Nevertheless, in the event of a fuel-supply interruption, the sudden and rapid rise in fuel price will dramatically affect the economics of freight transport. As fuel costs become an even larger portion of operating expense, capital and operating changes that in normal times would not be appealing will suddenly be considered workable options. In addition to high fuel prices, spot shortages throughout the country may exist for short periods of time in which fuel may not be available at any price.

In general, the approach in this analysis was to estimate (a) the fuel-saving potential of a contingency response, (b) the percentage of participation that could be expected within the industry (considering the extent to which the actions are already being used in conservation), and (c) the net reduction in fuel demand that could be anticipated. The estimates are made at the aggregate level (e.g., for the entire trucking or rail industry). Wide variations, however, may exist for individual carriers. The consequent effects that these contingency responses have on a carrier's service (e.g., travel time) or nonfuel operating costs are qualitatively addressed. Statistical data do not exist for the number of carriers (or vehicles) within a particular industry that have adopted each of the conservation practices. As a result, estimating those parameters and the potential participation rates was done through numerous industry contacts.

INCREASING THE LOAD FACTORS

Freight transport is a service in which efficiency is often measured by the time taken to complete deliveries. As a result, carriers often are not able to fully use the available capacity of their equipment. Several factors contribute to this, including commodities that require specialized equipment, unbalanced commodity flows, and size and weight restrictions of the loads. Obviously, some empty mileage is unavoidable. However, if operating practices are changed during a fuel shortfall to increase the percentage of capacity used (by reducing the number of trips needed), carriers will be able to transport, on an aggregate basis, the same shipments with less fuel.

Truck Mode

Truck loaded miles have been estimated by the Interstate Commerce Commission (ICC) to be 80 percent when measured as vehicle miles and 73 percent when calculated as capacity miles (1). Although empty vehicles and less-than-capacity travel cannot be completely eliminated, steps can be taken to improve vehicle utilization. Recent legislation, including the Motor Carrier Act of 1980 and the Surface Transportation Act of 1982, addressed some of the more acute problems of hauling inefficiencies such as size and weight limitations, gateway restrictions, and circuitous route provisions, and excessively restrictive limitations on commodities transported and territories served were greatly eased. Also, the restrictions on intercorporate backhauling were significantly reduced. These actions should improve vehicle efficiency or utilization or both, in turn reducing the demand for fuel.

In addition to these opportunities, motor carriers could improve their load factors by utilizing tractor-trailer matching programs for the return trips and reducing their service frequency.

Computerized trailer-matching programs offer the potential for improving equipment utilization. In the trucking industry, a private company has provided this service for 4 years. The current program, known as Extra Equipment Shipment Service (XESS), handles all phases of shipping, matching the freight on dock to available trailers and motive power. XESS combines two earlier programs--Computer Interchange Substitute Service (CISS) and Computer-Assisted Load Matching (CALM). Although the service is available to carriers, brokers, and truck manufacturers, industry utilization is relatively low, perhaps because of a combination of factors, including fear of increased competition, initial reluctance to use the computer system, or lack of familiarity with the program. However, with the system in place, it could easily be expanded during a crisis.

During a fuel crisis, motor carriers are likely to find shippers more willing to consolidate their shipments in order to control their shipping costs. This in turn allows the carrier to reduce the frequency of service, beginning with the marginal shipper, while increasing the load factor. Any reduction in empty mileage will still require improved information exchange and sufficient guarantees for both the consignor and the carrier concerning rates, delays, and insurance. Even so, reductions in empty mileage of 10 percent may be all that can be expected without a drastic reduction in service frequency. [In the previously mentioned ICC study of empty truck miles it was indicated that 16.7 percent of the empty trucks in the sample could have been paired with similar empties traveling at the same time in the opposite direction but it was cautioned that the figure was not an accurate estimate of the potential savings.] With over-the-road fuel efficiency of an empty truck roughly twice that of a loaded truck, a 10 percent reduction in empty backhauls could reduce energy demand by 1.6 percent.

Air Mode

In air transport, freight is shipped either in all-cargo aircraft or in the lower deck of passenger aircraft (belly freight). During a fuel crisis, belly freight service will be affected by carrier decisions relating to passenger flights, which is beyond the scope of this study. On a revenue basis, all-cargo aircraft carry 43 percent of the air freight (2). The load factor for all-cargo flights has remained fairly constant in recent years at 61 percent. The principal means that carriers have to increase load factors is to reduce flight frequency, a response that air carriers used during the previous fuel crises. A reduction in average service frequency of 10 percent for all-cargo aircraft should yield a 2 percent increase in overall average load factors (3). The variation in energy intensity by incremental load factor would indicate a 1.6 percent reduction in average energy consumption. Reduced service frequencies would also be expected to decrease operating costs.

Rail Mode

Reduction in service frequency will be an expected result of the economic slowdown during a petroleum shortfall; further reductions would affect the railways' competitive position and are likely to be resisted unless all competing modes are subject to the same pressures. This is improbable, given the generally greater flexibility of the trucking industry, for example, to respond quickly to short-term changes in demand for service or fuel supply.

Car and shipment matching programs, through which the pairing of shipments with available empty cars is facilitated by computer data banks, may become more workable as railroads' car-tracking procedures improve, but effective car management programs are barely beyond the embryonic stage even on the largest railroads. Perhaps the most promising way to increase average rail freight load factors in a short-term fuel crisis is to reduce empty backhauls.

A 10 percent reduction in empty backhauls (28 percent of backhauls moving loaded rather than the current estimated 20 percent) would result in a net reduction of about 3 percent of average energy intensity for boxcar or gondola movements and a 2 percent reduction for piggyback movements. Net costs are reduced because revenues associated with the shipment of the additional loaded tonnage help offset the costs of moving the cars. Wait times increase slightly because of the additional time required to locate the 10 percent loaded cars to complete train consist blocks formerly filled out with empties.

Water Mode

Little opportunity to achieve significant additional fuel savings is available to barge and push-tow operations by increasing load factors. One-way bulk commodity hauls are the mainstay of river transport, and self-propelled barges are rarely dispatched outbound loaded at less than capacity. Ballast (empty) trips by these barges cannot be eliminated without substantial relocation of primary and secondary sectoral activity nationwide.

Fleet pooling of dumb (unpowered) barges is now practiced to some extent with the objective of sharing in the revenues of an outbound tow with available capacity. This strategy incidentally reduces the number of tows operating at less-than-full complement and increases average load factors generally. The average load factor for all inland waterway movements has not been directly computed because the waterway industry is unregulated and thus not subject to ICC reporting requirements. One estimate places the figure at 60 percent (4). Without additional and possibly (to the carrier) costly port calls to locate loaded barges, it is unlikely that this figure can be increased and have carrier operations remain profitable. Even so, gross tonnage per tow would only increase 10 to 20 percent for the 5 percent of the tows likely to be involved. Thus, a maximum of 1 percent reduction in energy intensity is estimated for new activity in increasing load factors of waterway movements during a petroleum shortfall.

REDUCING CONGESTION

In a shortfall congestion may be reduced because there will be less travel. However, peak-period congestion may increase if work schedules are consolidated to meet transit and carpool schedules. Where severe capacity deficiencies exist, it is likely that only capital improvements can resolve the problem (e.g., reconstruction of highways and locks and dams). In such cases, the solution is beyond the carrier's responsibility and beyond the time frame for contingency planning. Actions that the carrier could initiate, although difficult to quantify, should lead to changes in shipment time and operating costs.

Truck Mode

The long-haul portion of intercity truck travel would rarely be congested except for the portion that occurs during the morning and afternoon peak rush-hour periods in cities. Most of the congestion-induced delays are therefore likely to occur during the pickup-and-delivery (PUD) portion of the trip, which accounts for about 17 percent of the total mileage of intercity truck trips (4). However, not all of the PUD travel is congested. Furthermore, most of the PUD travel involves only movement of local goods and services. PUD of intercity freight represents less than 1 percent of the stops and only 7 percent of the intracity mileage, although it accounts for 45 percent of the tonnage (5). In effect any actions taken to relieve congestion will have the most significant impacts on the industry for urban goods movement and concomitantly on urban passenger travel; less change will be experienced by the intercity freight industry.

Shifting the hours of truck operation could significantly improve fuel efficiency during the PUD portion of the trip. However, the overall savings for intercity truck fuel consumption is expected to be less than 0.5 percent. The shift to avoid rush-hour traffic may in the process lengthen the total travel time for the mode. Little change would be expected in nonfuel operating costs due to offsetting cost trends. Nighttime labor and terminal operating costs would increase, although the shift should result in more efficient utilization of equipment and personnel by spreading out the peak operations and thus perhaps even reducing daytime operating costs. However, the ability of a carrier to alter operating hours is constrained by labor contracts, the receiver's hours, and security considerations.

Air Mode

The frequently noted congestion at airports primarily concerns passenger aircraft, scheduled for the convenience of the business traveler. Belly cargo is essentially captive to the passenger aircraft schedule; thus changes to relieve passenger congestion should work to the benefit of that portion of air freight. All-cargo aircraft generally operate when there is less congestion. To a large extent air freight operation avoids much of the congestion because it is a 24-hr/day service in which much of the handling occurs at night. Consequently, no fuel savings or fuel demand reduction is attributed to the emergency relief of congestion for air freight.

Rail Mode

Activities to reduce congestion in the rail system are applicable primarily to switchyard operations. Centralized traffic control helps to maximize the efficiency of trunk-line movements. In the yards the most important effect of congestion delays is the increase in nonfuel operating costs, chiefly labor (6).

Energy efficiency of yard operations will increase rather than decrease as car management programs improve, and modern yard operating procedures stress minimization of engine idling time by switchers. Petroleum shortfalls are likely to bring about no net increase in the volume of cars handled by yards, and the expected economic downturn likely will mean a decrease in car throughput requirement. Centralization and modernization of railway yard operations are likely to continue irrespective of the threat of a reduction in petroleum supply. For these reasons, no extra reduction in fuel demand attributable to reduced congestion is assumed for rail freight operations.

Water Mode

Congestion of traffic at locks has been cited as a problem by waterway carriers, but lock capacity and cycle time constraints that give rise to such congestion are not susceptible to remedies short of major reconstruction. In reaches that occasionally become congested, improved radio communications could enhance the efficiency of push-tow movements, but regular coordination of movements among operators would be necessary. Barge owners have indicated that fuel savings from such procedures would be negligible compared with the effect of reducing congestion at locks. Therefore, no reduction in fuel consumption is credited to this action.

ADAPTING AVAILABLE TECHNOLOGIES

The purchase of fuel-saving equipment by the various modal carriers has been accelerating since the 1973-1974 oil embargo. In general, this is a conservation not a contingency measure because it often involves a long-term, capital-intensive commitment to reducing fuel consumption. However, just as the conversion to fuel-saving technologies was spurred by rising fuel prices during the last decade, rapidly increasing fuel prices during an energy shortfall can prompt the replacement of old equipment with fuel-efficient equipment at a faster rate than would have otherwise taken place. This accelerated replacement is again limited by the extensive conservation actions that have already occurred.

Truck Mode

One of the most prominent conservation programs has been the Joint Industry-Government Voluntary Truck and Bus Fuel Economy Improvement Program. Much of the program is devoted to new equipment purchases, some of which (e.g., high torque-rise diesel engines and power train modification) are clearly beyond the scope of short-range contingency measures because of the high costs involved. A few devices have a low enough cost (including quick installation) that a payback could be achieved during a fuel shortfall as energy prices rise. These devices include temperature-controlled fans, aerodynamic devices, radial tires, and fuel heaters.

The appearance of recent articles in trade publications (7,8) concerning ways to improve truck fuel economy indicates that there is still room for further conservation and to a lesser extent contingency savings through the same actions. A rough estimate (provided by industry contacts) of the current extent of conservation is that 40 percent of the trucking companies, representing about 70 percent of the total ton miles, are extensively utilizing the widely referenced conservation techniques. For contingency planning purposes, it is estimated that of the remaining 30 percent of ton miles, approximately 20 to 40 percent may be affected by the accelerated purchase of fuel-saving equipment during an energy emergency, for a participation rate of 6 to 12 percent. The fuel-saving potential of the devices is not additive, but if the maximum savings is estimated at 10 percent, the range of fuel demand reduction is between 0.6 and 1.2 percent. Nonfuel operating cost will increase with the purchase of the devices, but the relatively short payback period should limit the operating cost increases to 0.3 to 0.6 percent, or half the rate of the fuel savings.

Air Mode

Discussions with knowledgeable people within the air freight industry have not identified any retrofit technologies that could be adapted during a short-term fuel crisis. Purchase of new fuel-efficient aircraft as replacement for older units, however, has been going on for some time and is one of the principal means that the airline industry is using to reduce their vulnerability to fuel shortages.

Rail Mode

Three types of devices or support systems, developed at least in part to limit the wasting of locomotive power and thus improve the utility of fuel consumed, are considered feasible here for addition to a railroad's repertoire of fuel-stretching measures during a shortfall. Use of this equipment is already widespread among the carriers, but the planned rate of retirement of less-efficient devices still in use could be accelerated without intolerable costs being incurred. The most promising equipment includes fiberglass air filters, improved roller bearings and seals, and slippage control systems.

Wasted heat is recovered aboard locomotives for crew service (compartment heating), but devices to convert wasted heat to useful propulsion remain at the test-bench stage of rail application. Little experimentation with such equipment in revenue operations could be expected during a fuel shortfall. Based on the evaluations of the equipment described, railroad adaptation of available energy-efficient technology during a shortfall could result in fuel savings of up to 1.5 percent.

Water Mode

Propeller pitch and blade design (together with hull hydrodynamics) determine the amount of useful thrust that can be obtained by a tug or self-propelled barge and thus the quantity of fuel expended under way. Many of the newest self-propelled barges have been fitted with controllable-pitch propellers in order to achieve the optimum angle of attack under various channel depth and flow conditions (9), but additional penetration of the fleet by such craft probably could not exceed 0.5 percent during a period of shortfall. Retrofitting of these advanced propellers has not been explored by waterway carriers but would probably not be cost effective unless a vessel were already in drydock for a major overhaul.

CHANGING MAINTENANCE PROCEDURES

During a time of scarce fuel supplies, all facets of a carrier's operation should be reexamined for new fuel-saving potential. This includes a company's maintenance program. With the rising fuel prices during the 1970s, most companies oriented their maintenance programs toward improving their fleet's fuel efficiency; the larger companies used computerized systems for scheduling preventive maintenance.

Truck Mode

Although preventive maintenance (PM) varies by company, several large carriers perform their PM inspection on their tractors after 25,000 miles (about 30 to 60 days) at which time the air filters and oil filters are changed. At 100,000 miles engine oil and transmission fluid are changed and the differential is greased. Obviously, a good PM program is required in order to maintain these service intervals. Consequently, little improvement could be anticipated during an emergency. Three types of maintenance in which there may be some room left for improvement are

1. Reducing exhaust back pressure,
2. Maintaining proper tire pressure, and
3. Using synthetic lubricants.

Current estimates of improved vehicle maintenance indicate a fuel-saving potential of 1 to 3 percent per vehicle. Given that much of the trucking industry already has good maintenance programs in place, the potential applicability of a change in maintenance procedures may be limited to 10 to 20 percent of the industry; the fuel-saving potential for the industry as a whole may be less than 1 percent.

Air Mode

Extensive maintenance programs have been common in the airline industry for many years because of the obvious safety concerns. Rising fuel prices in recent years have been another reason for increased attention to airline maintenance procedures. The focus of the maintenance improvements has been on three parts of the aircraft: airframe, engine, and instruments. Significant deterioration of both engine and airframe normally occurs during the first two or three years of an aircraft's operation, resulting typically in a 3 percent decrease in fuel efficiency (10). With routine maintenance the fuel efficiency can be held relatively constant after that initial decline. It is doubtful, however, that a fuel shortfall would produce energy savings in airframe and instrument maintenance.

Estimates of potential fuel savings from improved engine maintenance are about 3 to 5 percent; 10 to 20 percent of full implementation has currently been achieved within the industry (11). However, technological and cost constraints currently limit the detailing of cost-effective engine maintenance actions. Current research on this problem, combined with rising fuel prices during a shortfall, could stimulate an overall improvement in fuel efficiency but probably one of less than 1 percent.

Rail Mode

Locomotives are almost never put in the shop for engine retuning unless a severe operational problem has been diagnosed. Layup and labor costs preclude putting locomotives in the shop at regular intervals simply to ensure that they are running at optimum fuel efficiency; such costs will almost always be greater than any savings in over-the-road operations. However, some roads have adopted a 92-day inspection schedule for each locomotive, at which time engine performance is routinely checked. Again, the reduced demand for motive power during the economic downturn that is attendant to a petroleum shortfall will permit railroads to mothball their less efficient engines for extended periods no matter what the regular maintenance schedule. During a shortfall, all locomotives would be maintained at least once under a 92-day schedule; the resulting average fuel savings would be 3 percent (12). For the perhaps 40 percent of total locomotives in service that are affected, a net reduction in energy intensity of 1.2 percent or less could be expected.

Water Mode

Reduction in ton-mile demand attributable to the economic impact of a petroleum shortfall could free excess motive power for drydock maintenance or outright retirement in favor of more efficient craft. To some degree this has already occurred as a result of the current recession and excess power is now available. On the assumption that even closer attention to engine tuning and performance monitoring would be feasible during a shortfall, a potential fuel saving of 0.5 percent by waterway carriers is estimated for this activity.

CHANGING OPERATING PRACTICES

In a manner similar to the other fuel-saving categories that have been described, increased attention to a carrier's operating practices is likely to occur during a fuel shortfall. Again, rising fuel prices have prompted conservation along these lines, and it is likely that another crisis-induced fuel price increase would spur operational contingency efforts to reduce fuel consumption.

One particular operating strategy that applies to all carriers, and thus need not be discussed for each mode, is the use of the most efficient vehicles in the fleet. To a large extent carriers have already adopted this strategy. In the event of a fuel shortfall, the general economic decline would reduce the demand for freight transport so that excess motive power would exist for each mode. Consequently, it is likely that carriers would continue to use their most efficient equipment; thus no additional reduction in fuel demand is attributed to this action.

Truck Mode

The key to fuel efficiency improvements in the actual operation of a truck is the driver during normal or fuel-crisis periods. Consequently a number of trucking companies have initiated fuel-conservation programs that focus on the driver: teaching fuel-saving techniques, keeping accurate records, and rewarding the most fuel-efficient drivers. Although these programs are increasing in frequency, they are not universal in the industry. Even the existence of a program does not ensure compliance. Drivers can make a significant difference in fuel consumption over two critical operating modes--speed and idle--which become an important focus of attention during a fuel shortfall.

Only a few states differentiate car and truck speeds when filing their quarterly speed-monitoring reports with FHWA. Data from four states (Illinois, Minnesota, North Carolina, and Michigan) indicate that for the past few years car and truck speeds have been fairly close for almost all highway functional groupings but that truck speeds in most cases are lower than car speeds. If these states can be taken as representative (and FHWA statistics have shown increasing national conformity and speeds recently declining in western states), the data show that 47 percent of the trucks exceeded 55 mph, 13 percent exceeded 60 mph, and 2 percent exceeded 65 mph. By using midpoint speeds and the fuel-saving potential of 2.2 percent for each mile per hour above 55 (13), the maximum energy savings would be 5.3 percent, although a 50 percent compliance would be more likely. Because these speeds would apply only to the line-haul portion of the trip, 83 percent of total intercity mileage (4), an estimated potential fuel savings of 2.2 percent could be achieved with either increased voluntary adherence by drivers or increased enforcement of the posted speed limit.

Engine idling at truck stops and terminals is a frequent occurrence, especially during the winter, to keep cabs warm or because of the difficulty in restarting a cold engine. Fuel heaters can solve the latter problem and cabs can be warmed within a few minutes after a restart. An indication of the magnitude of the problem is shown in a truck-stop survey in which 55 percent of the trucks were left with their engines idling on a 34°F day in February (14). No reliable estimates of the magnitude of wasted fuel due to idling have been found, but the amounts are likely to be significant for some operators.

Air Mode

Although the airlines have achieved substantial improvements in their fuel efficiencies, marginal fuel-saving actions may not have been carried out because of consideration of other costs (especially labor) in providing their services. Rapidly rising costs of fuel during a shortfall or extremely diminished supplies in some locations (short-term spot shortages) may result in more extensive use of some generally accepted conservation actions. Two concepts offer potential fuel savings in the event of a fuel shortfall.

It is likely that all airlines have reduced the cruise speed for their jets, generally from a range of 0.82 to 0.85 Mach to a range of 0.80 to 0.82 Mach, depending on aircraft type. Nevertheless, because of other operating costs, some airlines still use a cruise speed that is about 0.2 or 0.3 Mach above the long-range cruise point, because this minimizes total operating costs. During a fuel shortfall, the demand for fuel may be reduced an additional 1.0 percent by use of the optimum cruise speed.

Air traffic control procedures require 1,000 ft of vertical separation below a flight level of 29,000 ft (FL 290) but 2,000 ft of separation above FL 290. Changing to a uniform 1,000-ft separation would double the capacity for flying at these efficient altitudes and increase the probability that individual aircraft would be able to fly at their most efficient altitude during congested periods (15). No quantifiable fuel savings have been found, but they are likely to be less than 0.5 percent.

Rail Mode

There appears to be strong concurrence throughout the rail industry that improvements in fuel inventory control will be the key to truly significant energy savings in the future. The final disposition of up to 10 percent of rail fuel is unknown; practices such as better fuel tracking after purchase, fuel storage security, automatic shutoff and spillage control during refueling, spilled-fuel recycling, and fill metering could together save a railroad at least part of this 10 percent. Modern refueling equipment has penetrated the Class I carriers extensively in recent years, but smaller roads are only now becoming active in fuel control and security. It is expected that during a shortfall the carriers responsible for 20 percent of the fuel purchased for rail operations could account for the disposition of an additional 5 percent of their initial fuel inventory, whereas the carriers that buy the remaining 80 percent could introduce measures sufficient to account for an additional 2 percent. If it is assumed that 50 percent of unaccounted fuel is profitably used, this estimate results in a net saving of 1.3 percent industrywide.

In the range of possible railway operational modifications to save fuel, the six listed below would probably be initiated or expanded during a shortfall by roads not already using them. Most of these are already in place on Class I lines, but a margin does exist for further implementation.

1. Reducing power in locomotive consists,
2. Matching consist load to locomotive power requirements,
3. Using helper engines at the more difficult grades,
4. Disengaging parasitic loads (cooling systems and so on) when not in use,
5. Eliminating unnecessary idling,
6. Eliminating cabooses where feasible, and
7. Traveling at more efficient speeds.

The combined effect of all measures to improve rail operating practices for fuel efficiency during a shortfall could provide a reduction in energy intensity of 5 percent.

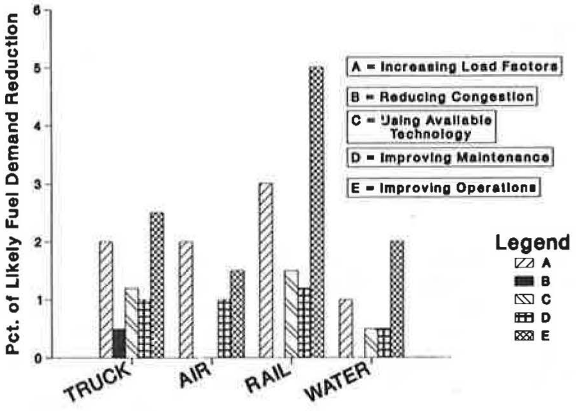
Water Mode

Forward speed adjustment as a means to reduce fuel consumption is not tractable to ready analysis in the context of waterway transport. A study of least-energy use operation of river shipping that included a means to estimate the most energy-efficient speed through water under differing channel depths and current conditions for upstream and downstream movement showed that the speed of minimum propulsion fuel consumption tends to be 3 to 5 mph less than the speed at which minimum total costs are achieved. That is, assigning the highest priority to the control of time-accrued costs such as crew wages, auxiliary fuel expense, food, depreciation, maintenance, and management may still be the key to profitability of an operation despite the high cost of fuel. As the author of the study remarks (16), "The easiest way to incur excessive cost is by going too slowly."

Although according to available information, tows and barges are currently operating on average slightly above the most fuel-efficient speeds for river operation (in discussions with the industry, midstream tow speed was reported to average 5 to 6 mph downstream and slightly less upstream), the congestion problem at locks will continue to frustrate carriers' efforts to achieve a trade-off between time costs and fuel expenditure by smoothing out trip speed profiles. Nevertheless, the lock situation provides an opportunity to cut wasteful fuel consumption at no additional cost. Some operations routinely throttle down when approaching a lock and run only enough engines to maintain steerage during intermediate delays. All engines may be shut down if extended waits are anticipated. These practices are already widespread; nevertheless, their adoption by all inland waterway operations could save an additional 1 to 2 percent of fuel.

Pilot training for efficient operation has been explored since the mid-1970s, but no formal programs appear to be in place. As noted earlier, some pilot practices can be identical but produce quite different results under apparently identical stream conditions, although the degree to which good pilots know the river does not always extend to uniform recognition of all the factors of wind and water that affect the translation of engine power to for-

Figure 1. Comparison of effectiveness of contingency responses for freight transportation.



ward thrust. Therefore, a more formalized approach to pilot education with an emphasis on energy consciousness must be considered as an option by any waterway carrier seeking to assure the best use of available fuel supplies in a shortfall. Such training is unlikely to have much payoff if it is not initiated until a shortfall occurs, but the additional benefits of prior training might save the industry up to 5 percent of normal fuel consumption if fuel cost as a percentage of total operating costs reaches the likely shortfall level of 80 percent or more and if comparison with expected results from similar training programs in the rail industry is legitimate. (Up to 5 percent reduction in propulsion-fuel consumption is attributed by many railway operations personnel to fuel-conscious education and training programs for enginemen and other train operations staff.)

CONCLUSIONS

The freight transportation industry has a maximum fuel demand reduction potential of about 4 to 8 percent, depending on the mode, without drastic curtailing of service. In Figure 1 the expected changes that each category of contingency responses could have for the various modes are summarized. Changing operating practices and increasing the load factors are the most significant options available for carriers to reduce their fuel demand during a fuel crisis. However, only an extremely severe shortfall would precipitate a fuel use restriction of this magnitude. In addition, carriers will become more fuel efficient as the rising price of fuel causes companies to replace older vehicles with energy-efficient equipment and to continue to improve their operating practices. Consequently the potential for curtailing fuel demand in the future will be less than it is now, simply because the entire freight transportation system will have become more efficient. The benchmark of fuel consumption, against which savings can be measured, will have been lowered.

On the other hand, the potential for enhancing the fuel supply during a shortfall is growing. The SPR has stored in excess of 250 million bbl of crude oil--enough to displace a 10 percent shortfall for 6 months if it were to be entirely drawn down. By the end of the decade an authorized level of 750 million bbl of storage should be reached. Private storage (company-owned stocks) of fuel may again increase after the current recession has ended, providing a further hedge against a fuel-supply interruption. Fuel extenders, many of which are experimental, may be available for use should a shortfall occur several years in the future. Alcohol fuels can be used now, but the production capacity is low.

In short the demand-reduction options are generally less significant than the alternatives to enhance the fuel supply, although both are important in developing a coordinated response to a sudden loss of fuel availability.

REFERENCES

1. Empty/Loaded Truck Miles on Interstate Highways During 1976. Interstate Commerce Commission, Washington, D.C., April 1977.
2. A.B. Rose. Energy Intensity and Related Parameters of Selected Transportation Modes: Freight Movements. Oak Ridge National Laboratory, Oak Ridge, Tenn., Rept. ORNL-5554, June 1979.
3. R.A. Mays, M.P. Miller, and G.P. Schott. Intercity Freight Fuel Use at Low-Package Densities. Presented at the 55th Annual Meeting, TRB, 1976.
4. CACI, Inc. Transportation Network Models for Energy Supply Analysis. Electric Power Research Institute, Palo Alto, Calif., Rept. EA-2324, March 1982.
5. A Primer on Urban Goods Movement: Summary Report. U.S. Department of Transportation, April 1976.
6. S.J. Petracek et al. Railroad Classification Yard Technology: A Survey and Assessment. FRA, Rept. FRA/ORD-76/304, Jan. 1977.
7. Commercial Car Journal, Sept. 1981.
8. Overdrive, Jan. 1982.
9. L. Sinclair and C.F.W. Eames. Propellers for Economy. In Proceedings of the Shipboard Energy Conservation '80 Symposium, Society of Naval Architects and Marine Engineers, New York, Sept. 1980.
10. M.B. Schwartz and A.E. Demke. Computerized Engine and Airplane Performance Monitoring Progress. In Symposium on Commercial Aviation Energy Conservation Strategies, April 1981, Washington, D.C., Office of Environment and Energy, Federal Aviation Administration, n.d.
11. R.R. Covey et al. Examination of Commercial Aviation Operational Energy Conservation Strategies. U.S. Department of Energy, Rept. SAN-2184-T2, Oct. 1978.
12. G.W. English et al. Canadian Railway Energy Conservation and Alternative Fuels. Canadian Institute of Guided Ground Transport, Kingston, Ontario, Aug. 1978.
13. The Double Nickel Challenge: Race to the Fuel Pump. U.S. Department of Transportation, Rept. NRD-20, May 1979.
14. Who or What Controls an Engine's Temperature. Fleet Owner, April 1980.
15. E.H. Price. Air Traffic Control: Its Effect on Fuel Conservation. In Symposium on Commercial Aviation Energy Conservation Strategies, April 1981, Washington, D.C., Office of Environment and Energy, Federal Aviation Administration, n.d.
16. F. Marbury. Least-Energy Operation of River Shipping. Marine Technology, Vol. 16, No. 2, April 1979, pp. 136-155.

Evaluation of Management Measures to Reduce Gasoline Queues at Service Stations: A Simulation Approach

A.G. HOBEIKA AND S.H. YOUNG

An analytical simulation model is developed in this study to evaluate gas-line management measures during interruptions in fuel supply. In the model households, vehicles, and service stations are assigned certain attributes to be compatible with their real-world counterparts. Travel activities by vehicle are stratified by trip purpose and simulated on a day-by-day basis. The next-event method is employed to simulate vehicle refilling activities, which takes a microdynamic view of the queueing system at service stations. A sensitivity analysis is conducted for two types of panic behavior during an energy crisis—topping off the tank and arriving early at the gas station. The results show that early arrivals lengthen the waiting time. To prevent this panic behavior, a so-called scattered-refill schedule is proposed. Three management measures are evaluated by the model to determine their effectiveness in reducing wait time per gallon of purchase under a hypothetical 20 percent supply interruption: the odd-even plan, maximum-minimum purchase requirements, and the proposed scattered-refill schedule. The results show that the maximum-minimum plan is an adequate one to prevent tank toppers and the scattered-refill schedule is an effective one to prevent early arrivals. The odd-even plan, although easier to put into effect, is not an effective gas-line management measure.

During the 1973 and 1979 energy shortages, waiting in line to buy gasoline at service stations was one of the most serious problems that automobile users experienced (1). Many studies (1-5) have indicated that during the past two energy crises, increased waiting time in gasoline stations was used to ration the scarce fuel supplies. However, the gasoline queue is an inefficient gasoline market clearance mechanism. No one benefits from the use of resources employed in queues (2).

When the queueing systems at gasoline stations are under energy supply restrictions, some users are affected by gasoline refilling needs, refilling times, and purchase limits in addition to the operational features of the stations such as station hours and purchase requirements.

The uncertainty about the future terms on which gasoline will be available brings a kind of speculative demand. However, the amount of gasoline that can be purchased in a gasoline station is limited by the capacity of the vehicle's tank. Regardless of the fuel level in the tank, automobile users tend to refill more frequently to maintain enough fuel for travel. This kind of tank-topping behavior, in which there is a high refilling point and small purchase size, causes an increased number of visits to gasoline stations. Thus, more time is spent to purchase the same amount of fuel than would be spent under normal conditions.

The already short fuel supply augmented by panic buying behavior soon depletes the fuel at gasoline stations. Consequently, stations close earlier, which plays an important role in drive-up waiting lines at service stations during an energy crisis. For customers early closure of the gasoline station is a strong indication of a gasoline supply shortage. Therefore, as long as they can find an open station, they refill with as much gasoline as possible if there is no limit on purchases. If after serious searching they still cannot find an open station, an early visit to the gasoline stations the next day is considered. Thus, the shortened station hours severely limit customers' scheduling flexibility in buying gasoline and force them to make early visits to gasoline stations, which result in much longer waiting times for refueling.

Another serious problem during an energy crisis is the preopening arrivals at gasoline stations, which cause extremely long waiting times for the customers. Therefore, a plan to regulate the distribution of arrivals at gasoline stations during a fuel supply interruption so that customer waiting time could be minimized would be an important asset to transportation energy contingency planning.

Daskin et al. (4) made the first model of service station queues during gasoline supply shortages. An M/G/1 queueing model was employed in this study to approximate the queueing system at service stations. The times between customer arrivals (M) were assumed to be exponentially distributed, the service times followed a general distribution (G) described by its mean and variance, and there was only one server in the system (1). Service time in the model was divided into two parts: a fixed time needed by each visitor to the service station and a pumping time, which was a function of the mean size of fuel purchase and the pumping rate. The mean arrival rate was assumed to be constant, independent of time of day. Moreover, the mean purchase size was assumed to be independent of the total amount of gasoline that each consumer demands.

The odd-even rationing plan was tested in the model by assuming a certain reduction of the mean arrival rate. Gasoline purchase requirements (maximum-minimum plan) were evaluated in the model by assuming certain upper and lower limits of the purchase size probability density functions. Tank-topping behavior was also analyzed in the model by reducing the mean purchase size.

There were several drawbacks to the structure of this model. The lack of dynamic feedback in the system is the major one. The waiting time spent at service stations does not have any impact on consumers' refilling behavior. The early depletion of fuel at stations caused by large purchases was not considered in the model. The purchase size was not constrained by the capacity of the vehicle's tank (in this study, it was assumed that the purchase size was independent of the amount of gasoline demand). In addition, the assumption that the mean arrival rate is constant and independent of time of day is not compatible with the real-world situation at service stations, in which peak demands exist at certain periods of the day. Moreover, the early arrivals were not considered in this study.

Prins et al. (1) developed a simple mathematical model to analyze gasoline-line problems. The allocation of gasoline per day represented the supply side of the system. The demand function consisted of the following independent variables: (a) the cost per gallon of gasoline, (b) the mean waiting time per visit, (c) the expected number of visits to gasoline stations per week, and (d) the average number of hours that gasoline stations are open. The average number of hours that stations are open is a function of automobile population, number of service stations, expected number of visits to service stations per week, and the service station rate (in vehicles per hour). The expected number of visits to gasoline stations per week is a function of the use rate per vehicle per day and the purchase size. The purchase size is a function of the average number of hours that gasoline stations are open, the mean waiting time in line per visit, the expected number of visits to gasoline stations per week, and the level of the gasoline shortage.

The odd-even plan and maximum-minimum purchase requirements were tested in the model. This study concluded that the odd-even plan minimized aggregate wait time as well as wait time per visit more than maximum-minimum purchase requirements. This conclusion is just the opposite of the one made by Daskin et al. The sensitivity analysis of the model showed that the waiting time was not sensitive to the length of time that the stations are open or to the purchase size. This result is not compatible with two findings: (a) early station closures shorten the refilling period (and thus shorten times between arrivals and consequently lengthen waiting times) and cause early arrivals (which lead to much longer waiting times), and (b) the smaller purchase size that results from panic buying (tank-topping behavior) increases the waiting time per gallon of purchase. The inappropriate set-up of these two critical factors in the model (i.e., the length of time that the station is open and the purchase size) might be one of the reasons for those inadequate findings (6). The exclusion of the vehicle's tank capacity and the impact of early arrivals could be the other reasons.

Hobeika et al. (7) have developed a simulation model to evaluate the impacts of several fuel supply restriction measures on gasoline consumption during energy shortages. The major entities in the model are households, automobiles, and service stations. The major components of the model are household attribute assignments, vehicle attribute assignments, station attribute assignments, trip assignments, travel routine, search routine, queueing routine, fill-up routine, and summary routine.

The model was built with a detailed activity simulation approach, where events include all types of travel activities detailed as to trip start time, end time, distance, and speed. This kind of simulation uses a great deal of computer execution time. Because most vehicles do not refill every day, it is not necessary to simulate all trips. Moreover, in this study it is assumed that refilling occurs only at the end of a trip, which is not necessarily true for all users.

PURPOSE AND OBJECTIVES

The purpose of this study is to develop an analytical dynamic simulation model that can adequately analyze gasoline queue problems and evaluate various gasoline-line management measures for possible use by decision makers before and during an energy crisis. To accomplish this the specific objectives of this study are identified as follows:

1. To provide a better understanding of the quantitative effects of panic behavior (such as tank topping and arriving early) on gasoline queues,
2. To identify an effective scheme that helps to prevent early arrivals during an energy crisis, and
3. To evaluate the effectiveness of several gasoline-line management measures in reducing gasoline queues.

METHODOLOGY

Model Entities

The major entities being simulated in the gasoline retail market are the vehicles owned by households and the gasoline service stations in the study area. In most commodity purchase queueing systems the consumers are identified as the entities on the demand side. However, with regard to fuel consumption, a vehicle is more appropriate to work with in a simulation model because it is easier to count vehicles than persons at gasoline stations.

According to Dave Catterton of the Virginia Petroleum Jobbers Association (March 16, 1982) and James Heizer of the Virginia Gasoline Retailers' Association (March 15, 1982), the gasoline at service stations is consumed mostly by vehicles owned by households; the major group of customers at service stations is therefore the household vehicle owners. Also, because household-owned vehicles consume more than half of the motor fuel in this country (8) and their consumption of fuel exhibits greater flexibility than that of other modes, the fuel that can be conserved by vehicles owned by households during an energy crisis deserves more attention than that carried by other modes. Vehicles in this model are assigned certain attributes to meet the characteristics of their real-world counterparts. At the same time they are assigned to specific households to serve the travel needs of a group of people who live together and share the same vehicle. Therefore in this study the household is employed as the unit for travel demand. Each household is assigned certain attributes that would affect the level of travel made by the vehicle or vehicles that it possesses.

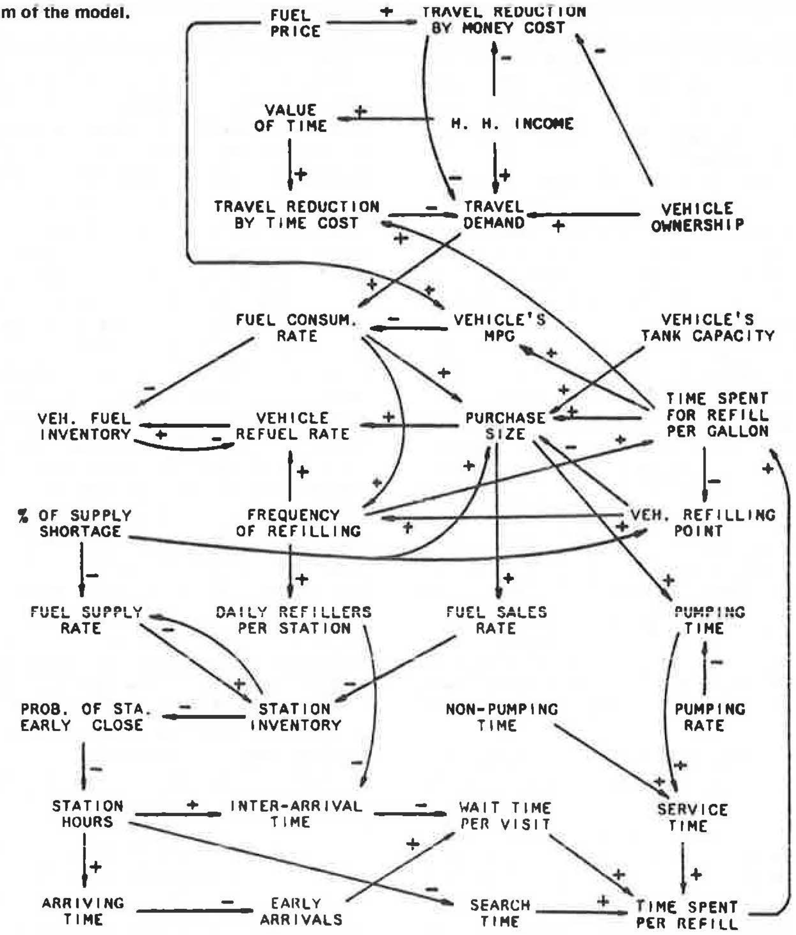
Similarly, service stations are established in the model that represent the supply side of the system and have characteristics compatible with those of their real-world counterparts. A ratio of stations to household-owned vehicles is identified for the region under study. It is then multiplied by the number of household-owned vehicles in the model to estimate the number of stations that should be established. These stations are designed to have the ability of carrying out the various station-related gasoline-line management measures under investigation.

Household-owned vehicles are not the only arrivals at service stations. Other vehicle types are also considered in the simulation model, which includes their number, size, and fuel consumption characteristics. The fuel consumed by these vehicles is then subtracted from the total to indicate the remaining fuel available for consumption by household-owned vehicles.

Events

In a simulation model the status of the system changes when an event occurs. The changes associated with the travel-related events are the changes in time, fuel, and the number of customers in service stations that occur when any event is promoted from the next event to the current event. Only the critical events are considered in the model to minimize the complexity of the system. Because most vehicles do not refill every day and because the refillings do not necessarily take place at the end of a trip, it is not necessary to simulate all trips in a day. Therefore, only refilling-related events are simulated in the model by the next-event approach. By this approach, the simulation model keeps track of the times at which each distinct status-changing event will occur. It then chooses the time at which the next event will occur, moves forward in the simulation to that time, and alters the status of the system in accordance with the conditions dictated by the occurrence of that event. The basic concept underlying this approach is that there is no need to

Figure 1. Conceptual causal diagram of the model.



view the system at times other than those at which critical events occur. In this research, the next-event approach is only used to simulate the events associated with the refueling activities. All the travel activities are simulated on a day-by-day basis.

Station Hours

Gasoline station service hours played a significant role during the past energy crises in limiting the refueling flexibility of customers and in causing panic behavior among vehicle drivers with regard to the severity of the shortage of fuel. Thus, the station hours in the model are designed to reflect gasoline depletion or early closure conditions or both.

The major causal relationships in the model are summarized in Figure 1. In this diagram the direction of the linkage represents the direction of the influence. A positive sign (+) is used when changes in both variables are in the same direction (both increasing or both decreasing). A negative sign (-) implies that changes in both variables are in opposite directions (one increasing and the other decreasing, and vice versa).

The relationships between variables are briefly described as follows. A high fuel-consumption rate leads to low fuel inventory in a vehicle's tank, which leads to a high vehicle refuel rate (also to larger purchase size or greater refill frequency or both). The size of purchase is larger if the tank is bigger or the fuel-consumption rate is higher but is smaller if the refill point is higher. The purchase size increases with the level of shortages in the model.

The refill frequency is greater when the refill point of the fuel-consumption rate is higher. Greater frequency of refilling leads to more who refill daily and thus shorter times between arrivals, which cause longer wait time per visit and large purchase size. The increase in those who refill daily per station results in higher fuel sales rate and consequently lower station fuel inventory, which in turn increases the probability of fuel depletion and thus early station closure. The shortened station hours cause early arrival time, shorter times between arrivals, and longer search time. Shorter times between arrivals and more early arrivals cause longer wait times per visit.

On the other hand, larger purchase size and lower pumping rate result in longer pumping time and thus longer service time. The time spent per refill increases when search time, wait time, or service time increases. But smaller purchase size and higher refill frequency lead to longer time spent for per-gallon refill of gasoline.

The fuel inventory at the station increases with a higher fuel supply rate and decreases with a higher fuel sales rate. When the fuel inventory at a station is low, more fuel supplies are requested. However, the supply is reduced whenever there is an energy shortage. The fuel inventory in a vehicle's tank is raised with the vehicle's refuel rate and is reduced with the fuel-consumption rate.

The demand for travel increases with income but decreases with travel hardship such as the increase in travel time and travel cost. The increase in travel time has a greater impact on those with high incomes, whereas the impact of travel cost is greater for those with low incomes because they have limited budgets.

THE MODEL

To illustrate the application of the model for medium-sized urbanized areas, the city of Richmond, Virginia, was selected as a case study. Area-specific data were obtained from Richmond; national data were used in the general part of the model.

Household Attribute Assignments

In the model, households were stratified by income, vehicle ownership, and size. The joint probabilities of these three household attributes were used to stratify households into 60 strata (5 income levels, 3 vehicle ownership classes, and 4 household size groups).

Assignment of Vehicle Attributes

Four attributes were assigned to the vehicles in the model: fuel-efficiency rate, tank capacity, plate number, and refilling point. The fuel-efficiency rate and tank capacity were directly related to the size of the vehicle. In the model vehicles were categorized into four classes: class 1, subcompact vehicles; class 2, compact vehicles; class 3, intermediate-sized vehicles; and class 4, full-size vehicles. The sizes of vehicles were assigned according to household income.

Assignment of Household Annual Vehicle Miles of Travel

The assignment of household annual vehicle miles of travel (VMT) in the model was based on a recent study by Gorman (9) in which the data of the 1977 Nationwide Personal Transportation Study (NPTS) (10) were used to analyze household characteristics and the determinants of travel behavior. Annual VMT were assigned to households according to their income and vehicle ownership.

Assignment of Daily VMT by Trip Purpose

After all households in the model had been assigned an annual VMT, the daily VMT by trip purpose was then assigned to vehicles owned by these households as follows:

1. Adjustment of annual household VMT by month: Because the model was developed for analyzing the problems of an energy crisis, the analysis period was short by nature. Because travel varies in different months of the year (9), annual VMT data cannot be used directly in the model for short-term analysis. Therefore, the data were adjusted by the months during which the energy shortages occurred.
2. Assignment of household annual work-trip VMT: Although the VMT varies on a monthly basis, the VMT for the work trip was assumed to be unvaried throughout the year. In the model the data from the 1977 NPTS were used to allocate the percentage of annual work-trip VMT. This percentage was assigned to each household according to its income level. The assigned household annual work-trip VMT was then divided by 52 to obtain household weekly work-trip VMT. On the other hand, household weekly non-work-trip VMT was obtained by subtracting household weekly work-trip VMT from household weekly VMT for all trip purposes. The assigned household weekly non-work-trip VMT was further categorized as shopping, social or recreational, personal business, and other trip purposes according to the data from the 1977 NPTS. The same data source was used to allocate the household weekly VMT by various trip purposes to different days of the week to obtain household daily VMT. Consequently the model assigned the daily VMT to the vehicles owned by the household.

Assignment of Station Attributes

Before attributes were assigned to service stations in the model, the number of stations to be established for the 500 vehicle-owning households in the model was discussed. According to the 1981 National Petroleum News Fact Book (11), there were 3,436 service stations in Virginia in 1981. Because the total number of households in Virginia for that year was about 1,923,000 (12), the ratio of households to stations is 560:1. After an adjustment by carless households, only one service station was needed for 500 vehicle-owning households. Nevertheless, the model consisted of two service stations and reduced the number of pumps in each station by half to provide the consumers the opportunity to make selections between stations based on the differential in gasoline prices.

There were eight attributes assigned to the service stations in the model: station hours, an initial amount of fuel, tank capacity, replenishment schedule, replenishment amount, average price of fuel, pumping rates, and the nonpumping time for services other than refueling.

Assignment of Refill Time

The travel component of the system was simulated on a daily basis. The fuel in the tank of each vehicle was correspondingly checked on a day-by-day basis to see whether the vehicle needed to be refilled (according to its current refilling point). When that point had been reached, the vehicle was ready to be sent to the service station for refueling. The time to visit the service station still had to be determined.

No existing data were available on the demand distribution of gasoline purchases at service stations. So a survey was conducted to determine the demand distributions at service stations in Richmond, Virginia. The results of the survey showed that

1. Most of the stations had similar demand distributions,
2. Usually the busiest times were on Monday from 7:00 a.m. to 9:00 a.m. and on Tuesday through Friday from 4:00 p.m. to 6:00 p.m., and
3. The busiest times on Saturday and Sunday were from 12 noon to 1:00 p.m.

However, the data obtained from this survey were only for normal situations. As mentioned before, early arrivals occurred during the past energy crises. An algorithm was thus developed in the model to assign arrival times to vehicles that are refilling under crisis conditions. It included two steps. The first step was to assign vehicles with a normal arrival time. The second was to shift the normal arrival time to an earlier time according to the degree of crisis.

Refill Routine

The refill routine was simulated by the next-event approach. It consisted of several steps: searching for a station, joining a queue, being served, and updating the status of the system. The structure of the refill routine is illustrated in a simplified flowchart as shown in Figure 2, in which the SEARCH subroutine determines the time spent searching for a gasoline station and the decision to enter a station. The search time is a function of the station open hours. The decision to enter a station depends on the prices of gasoline and the queue lengths at the stations. The probability of entering a station is lower for a station with higher fuel prices or longer gasoline queues. The JOIN subroutine assigns the refilling vehicle to one of the channels of the station it entered. The TSER subroutine is then called to determine the service time needed to serve the newly arrived vehicle according to its purchase

Figure 2. Simplified flowchart of the refilling routine.

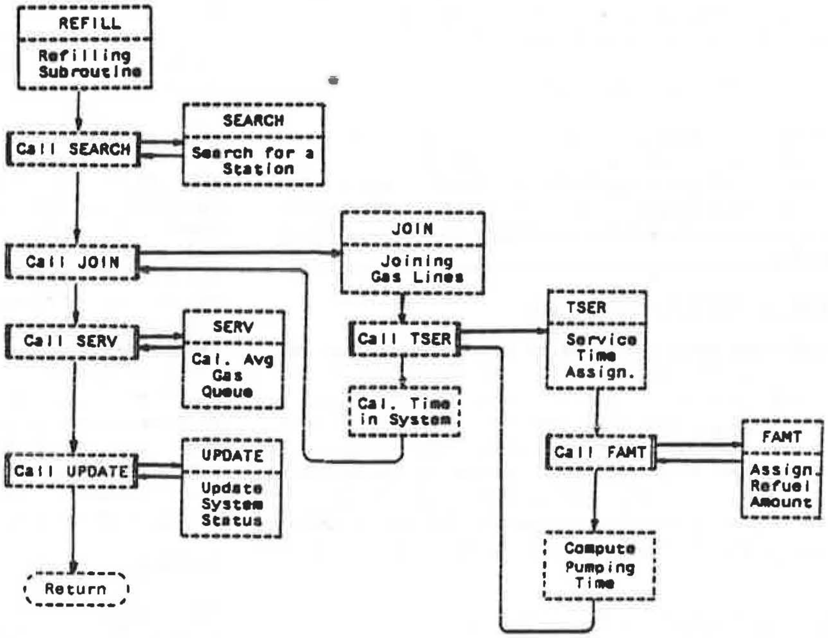
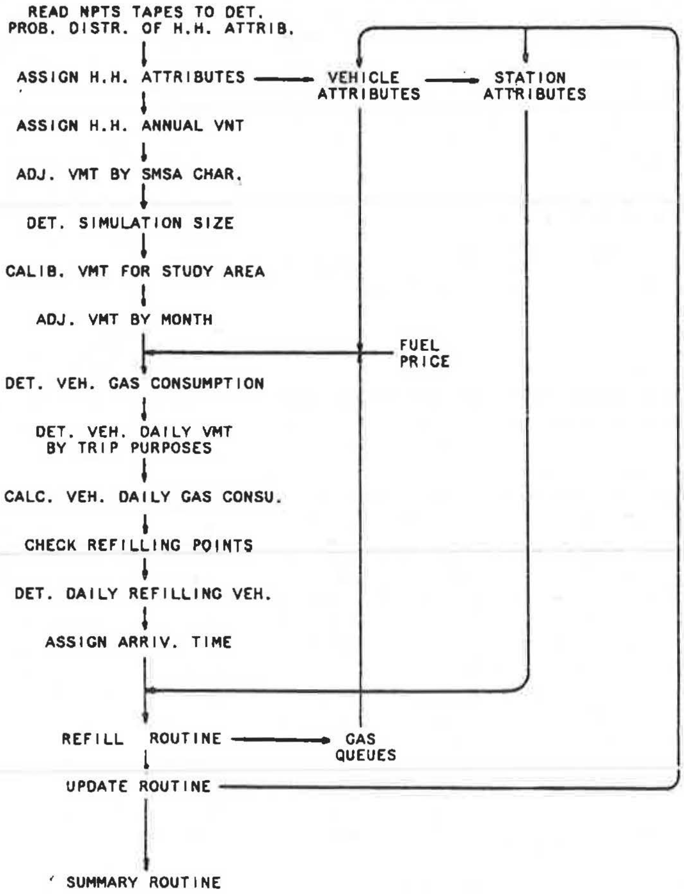


Figure 3. Simplified model formation flowchart.



size, whereas the purchase size is assigned by calling the subroutine FAMT. The time that the new arrival spent in queue is then calculated by calling the subroutine SERV, which sums up the time needed to serve all the customers in front of this new arrival. Average gasoline-queue and waiting time are also updated. When the vehicle has finished its refilling, the subroutine UPDATE is called, which changes the following status of the system:

1. The amount of fuel at the station is reduced by the amount of fuel pumped to the vehicle,
2. The amount of fuel in the vehicle's tank is increased by the amount of fuel purchased,
3. The number of customers in the channel is reduced by 1,
4. The number of customers in the station is reduced by 1,
5. The simulation clock is advanced by the amount of time spent servicing this vehicle, and
6. The simulation time attached to this vehicle is advanced to a value greater than 24, which is the end of a simulation day.

The formulation of the model is summarized in a simplified flowchart, shown in Figure 3. A more detailed description of the model may be found in Young's work (13).

MODEL VALIDATION AND CALIBRATION

Because the model employs the Monte Carlo technique to assign attributes to its entities, it was run with a sufficiently large sample size and various random number seeds to reduce the nonrandom bias. The results showed that an adequate size to run the model was 500 households (about 1,000 vehicles). The outputs showed that the model was functioning in the manner intended. The fuel-efficiency rates were adjusted in the model to make the fuel consumption compatible with the Virginia data.

SCATTERED-REFILL SCHEDULING

A scheme is proposed in this study to prevent excessive waiting by early arrivals at gasoline stations. Its basic concept is to diversify refilling activities so that waiting time can be minimized. This scheme is not a new idea. It is widely applied at universities during registration, when students are assigned registration times according to the initials of their last names to minimize waiting time.

Under this scheme a vehicle can refill at assigned times on the basis of the last digit of its license plate number. There are several times during which a vehicle can visit stations. For example, for stations that operate from 7:00 a.m. to 10:00 p.m. there are three 5-hr periods. For the first two periods, each hour is scheduled for vehicles with the designated last two digits. There is no restriction on digit requirements in the third period. Thus, this scheme gives refillers a certain flexibility to their refill schedules. Moreover, the tourist industry, which suffered seriously from the odd-even plan, will not be affected much by this scheme, because long-distance travelers have three chances a day to refuel their automobiles and complete their trip.

Because there is no easy way to prevent the panic that causes early arrivals at gasoline stations during an energy crisis, this scheme, although a little complicated in its administration, could be much more effective than other line-management measures such as the odd-even plan. The scheme can also be administered with minimum or maximum purchase requirements whenever tank-topping occurs.

MODEL APPLICATION

Simulating Panic Buying Behavior

The panic buying behavior during an energy crisis--tank-topping and arriving at the gasoline station early--is simulated by the model to examine the impact of such behavior on waiting time. Tank topping is formulated in the model by raising the refilling points of all vehicles in the model. The panic behavior of early arrivals is formulated in the model by making vehicle refilling times earlier. The results of these simulations are shown in Table 1, in which a 13 percent fuel supply shortfall and 40 percent gasoline price increase are given as the crisis conditions.

From the results shown in Table 1 it can be seen that the impact of early arrivals on average waiting time is more significant than that of the tank-topping behavior. In addition, for both types of panic behavior, the impact on average waiting time becomes more significant as the degree of severity becomes greater.

Scenarios and Tests

In this study, gasoline-line management measures are evaluated under four different scenarios. Each scenario is a combination of the following crisis situations: the level of the energy supply shortfall, the percentage of increase in fuel prices, and the degree of panic behavior (tank topping and arriving early).

In the first scenario it is assumed that a 13 percent fuel supply shortfall and a 40 percent gasoline price increase exist and that both types of panic buying behavior occur as well. This scenario describes the height of the 1979 energy crisis in New York State as observed by Hartgen and Neveu (14). In the second scenario a shortfall similar to that of the 1979 energy crisis is defined but a 100 percent increase in fuel prices is hypothesized, which leads to minor panic buying behavior. In the third scenario a 30 percent fuel supply shortage and a 100 percent gasoline price increase are postulated and there is medium-level panic buying behavior. In the fourth scenario a 30 percent supply disruption and serious panic buying situations are considered; the price of fuel is assumed to have risen 40 percent.

The following gasoline-line management measures are assessed according to their effectiveness in reducing waiting time: odd-even plan, maximum and

Table 1. Simulating panic buying conditions.

Panic Level by Behavior		
Tank Topping	Arriving Early	AWTPR[a] (min)
None	None	7.94
Minor	None	9.24
Medium	None	12.13
Serious	None	17.35
None	Minor	9.19
None	Medium	15.11
None	Serious	28.25

Note: Crisis conditions are 13 percent supply shortage and 40 percent price increase.

[a] Average wait time per refill (assuming that the average purchase size is 8 gal) of the last 28 simulation days (considering the first 7 days as the warm-up period).

minimum purchase requirement, and scattered-refill scheme. The do-nothing alternative will serve as the basis for evaluating these measures. In addition a combination of the maximum-minimum plan and the scattered-refill scheme is also tested. These scenarios and measures are shown in Table 2. The results of these measures are shown in Table 3.

In addition to the average wait time per refill (AWTPR), the indicator HARD is also employed in the evaluation process to reflect the hardship that automobile users encountered under a certain scenario and a certain management measure. The value of HARD is determined by (a) the percentage of vehicles being rejected at service stations (when a vehicle needs to be refueled but cannot enter the service station because of an unmatched plate number, size of purchase, or the early closure of the service station, it is defined as rejected by the station) and (b) the percentage of the potential reduction of fuel demand caused by increased fuel prices and waiting times. This indicator reflects not only the degree of inconvenience imposed on automobile users by the measures but also the hardship level of the scenario itself. However, the value of this indicator should be referred to only on a comparative basis.

The effect of fuel price increases on waiting time is also evaluated in the model. The short-run price elasticities estimated by Archibald and Gillingham (15) and Charles River Associates (16) are employed in the model to reduce fuel consumption as gasoline prices increase. The results show that increases in fuel price have little impact on waiting time.

DISCUSSION AND ANALYSIS

The results of the model show that the scattered-refill scheme has proved effective in reducing the long waiting time caused by serious panic behavior. Nevertheless, its effectiveness in reducing waiting time is not much greater than that of the odd-even and maximum-minimum purchase requirement under less serious panic situations. Moreover, its hardship on automobile users is always less than that of the other plans, especially under serious panic situations. Tests other than the four scenarios just described have shown that if tank topping is contagious among refillers, the resulting long waiting time would not be effectively reduced by the scattered-refill scheme alone.

Table 2. Scenarios and measures.

Scenario	Supply Shortage (%)	Fuel Price Increase (%)	Panic Level by Behavior		Measure
			Tank Topping	Arriving Early	
1	-13	+40	Serious	Serious	All
2	-13	+100	Minor	Minor	All
3	-30	+100	Medium	Medium	All
4	-30	+40	Serious	Serious	All

The effectiveness of the maximum-minimum purchase requirement ranks next to that of the scattered-refill scheme in minimizing gasoline queues. However, tests other than the four scenarios have shown that if the panic behavior of early arrivals is serious, the effectiveness of this plan is significantly weakened.

The odd-even plan is as effective as the maximum and minimum purchase requirements in reducing waiting times under serious tank-topping situations. Although the odd-even plan is the easiest one to administer, it imposes the most inconvenience on consumers, especially those who are heavy automobile users and long-distance automobile travelers.

All the tests show that the do-nothing alternative has the longest average waiting time under all scenarios. However, the values of HARD indicate that some other alternatives impose more inconvenience cost to automobile users than the do-nothing ones, especially the odd-even plan.

Thus, in order to effectively and adequately minimize the waiting times at service stations caused by both types of panic behavior, a combination of the maximum-minimum purchase requirement and the scattered-refill scheme is needed. It is recommended that the former be employed first for its easier administration. If the panic behavior, especially the early arrivals, continues, the scattered-refill scheme should be adopted.

OTHER POTENTIAL APPLICATIONS

As indicated in contingency theory for management science, in order to fit changing and uncertain situations, the goal of a management plan varies according to the needs. Because it is likely that the prices of fuel will still not be allowed to clear the market during a future energy supply shortage (17), gasoline queues might be employed again as the market clearance mechanism. However, excessive waiting time is a pure loss to individuals and society. The usual goal of minimizing waiting times at service stations could be changed to selecting adequate action that allows gasoline queues to grow to the point where the level of supply shortfalls should be reflected. How to properly reduce excessive waiting time and employ the remaining waiting time to clear the market can be a challenge to all energy contingency planners. The model, if supplied with sufficient data, would be a potential tool.

The current maximum-minimum purchase plans all have fixed purchase limits. Variation in tank capacity among different vehicles is not considered. Under this type of fixed-limit plan, vehicles with smaller tank capacity are treated inequitably. Because the tank capacity of each vehicle is specified in the model, purchase requirement plans with vari-

Table 3. Test results.

Measure	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	AWTPR	HARD[a]	AWTPR	HARD	AWTPR	HARD	AWTPR	HARD
Do nothing	33.72	0.81	15.20	0.53	18.63	0.63	35.10	0.90
Odd-even plan	20.84	0.90	8.87	0.64	12.57	0.79	25.13	0.98
Maximum-minimum plan[b]	19.29	0.73	5.23	0.58	8.23	0.70	28.68	0.77
Scattered-refill scheme	6.85	0.14	4.12	0.23	6.09	0.26	7.34	0.16
Both[c]	4.29	0.59	3.92	0.50	4.55	0.59	3.84	0.60

[a] For definition of HARD, see text.

[b] Maximum limit, 10 gal; minimum limit, 8 gal.

[c] Both maximum-minimum plan and scattered-refill scheme.

able limits can be easily simulated by the model to determine the optimal purchase limits for vehicles of various size classes.

REFERENCES

1. V. Prins, R.A. Wolfe, and S.R. Lerman. Simple Analytical Model for Understanding Gasoline Station Lines. TRB, Transportation Research Record 764, 1980, pp. 43-49.
2. Y. Sheffi and V. Prins. Dual Price System for Management of Gasoline Lines. TRB, Transportation Research Record 801, 1981, pp. 60-67.
3. N.S. Dorfman and I.E. Harrington. Evaluating the Costs and Benefits of Plans to Reduce Gasoline Queues. TRB, Transportation Research Record 764, 1980, pp. 26-32.
4. M.S. Daskin, S.E. Shladover, and K.L. Sobel. An Analysis of Service Station Queues Under Gasoline Shortage Conditions. Computers and Operations Research, Vol. 3, 1976.
5. H. Muhmassani and Y. Sheffi. Queueing and Search Delays Due to Gasoline Station Closings: A Simple Equilibrium Framework. TRB, Transportation Research Record 764, 1980, pp. 32-38.
6. W.B. Tye. Review of Analytical Models of Gasoline Demand During an Energy Emergency. TRB, Transportation Research Record 764, 1980, pp. 49-53.
7. A.G. Hobeika, S.H. Young, and D. Seeman. Simulation for Evaluating the Impact of Supply Restriction Policies on Gasoline Consumption. TRB, Transportation Research Record 870, 1981, pp. 55-60.
8. J.N. Hooker. Effect of a Sudden Fuel Shortage on Freight Transport in the United States: An Overview. TRB, Special Rept. 191, 1980, pp. 71-81.
9. R. Gorman. Household Characteristics and Determinants of Travel Behavior. TRB, Special Rept. 181, 1980, pp. 135-138.
10. 1977 Nationwide Personal Transportation Study, Rept. 3: Purpose of Vehicle Trips and Travel. FHWA, Dec. 1980.
11. NPN Fact Book Issue. National Petroleum News, Hightstown, N.J., 1981.
12. Newsletter Spring-Summer 1978. Virginia State Data Center, Tayloe Murphy Institute, Charlottesville, Va., 1978.
13. S.H. Young. An Analytical Model for Contingency Management of Gasoline Lines Under Motor Fuel Supply Interruptions: A Simulation Approach. Department of Civil Engineering, Virginia Polytechnic Institute and State Univ., Blacksburg, Ph.D. dissertation, Aug. 1982.
14. D.T. Hartgen and A.J. Neveu. The 1979 Energy Crisis: Who Conserved How Much. New York State Department of Transportation, Albany, April 1980.
15. R. Archibald and R. Gillingham. An Analysis of the Short-Run Consumer Demand for Gasoline Using Household Survey Data. Review of Economics and Statistics, Vol. 62, No. 4, Nov. 1980.
16. Price Elasticities of Demand for Transportation Fuels. Office of Transportation Research, Federal Energy Administration, May 1976.
17. O. Schueftan and R.H. Ellis. Federal, State, and Local Responses to 1976 Fuel Shortages: Summary Report. Office of the Secretary, U.S. Department of Transportation, Feb. 1981.

Analysis of Total Energy Use of Urban Transportation Energy Conservation Strategies

MARGARET K. SINGH AND SARAH J. LaBELLE

As part of a technology assessment project sponsored by the U.S. Department of Energy, an evaluation was made of total energy consumption by fuel type resulting from local travel (by urban households) for 1980, 1990, and 2000 in two scenarios and under three alternative policies. Energy consumed in vehicle operation, fuel production, vehicle production, and infrastructure construction was projected, and the relative impact of each policy was also evaluated. A substantial decline in total energy use in national urban passenger travel from 1980 to 2000 was projected for both scenarios and all three policies. However, the analysis also indicated that indirect energy use required to support the policies can offset some of their direct energy savings. Further, the scenario that resulted in the greatest total energy savings did not save the greatest amount of petroleum.

In a project sponsored by the U.S. Department of Energy, Technology Assessment of Productive Conservation in Urban Transportation (TAPCUT) (1), several alternative strategies promoting energy conservation in urban transportation were assessed to determine their energy, environmental, and economic impacts. The alternative strategies were tested in three cities for 1980, 1990, and 2000. They represented policies and technology developments designed to conserve urban transportation energy while maintaining a productive economy. They were set within two socioeconomic scenarios that differed in terms of growth rate of gross national product (GNP), social organization, retail fuel price, total metropolitan population, average household income, environmental regulations, and types of fuel available for transportation. The expected energy impacts, both direct and total, of these alternative strategies are related here.

PROJECT STRUCTURE

To evaluate the energy impacts of the alternative strategies properly, the strategies themselves, scenarios, vehicle characteristics, and fuel supply and prices assumed in this study need to be briefly described. The three conservation strategies analyzed were termed the in-place policy, group travel policy, and individual policy. As a baseline, the in-place policy was established as the extension to the year 2000 of all programs and plans in place in 1980 that affected urban transportation. For the three case-study cities used in this analysis, the in-place policy was defined in terms of existing state, regional, and local plans. By contrast, the group travel policy promoted mass transit and ridesharing with no improvements to automobile technology relative to the in-place policy. In general, the group travel policy involved large-scale changes in level of service for transit, as measured by service frequency, line-haul travel time, and system coverage in each case-study region. The individual policy focuses on automobile technology improvements as the means to decrease transportation energy use while maintaining mobility. Research and development on engines, vehicles, and fuels was increased, and new-car fuel economy improved even more than expected under the in-place policy.

These policies varied by the scenario in which they were expected to have the greatest effect. For example, scenario 1, which projected a wealthy economy with high technological success, was assumed to be capable of supporting rail transit service expansion under the group travel policy. Scenario 3, on the other hand, a relatively poor economy with low technological success, emphasized reduced transit fares and express bus service, including busway construction, under this policy. No analysis was conducted for scenario 2.

In this analysis, automobile and transit vehicles were characterized by size class, engine type, fuel economy, emissions profile, purchase price, operating costs, materials composition, and (for personal vehicles) performance. Three different sets of vehicles were used: set C, the expected technologies, was used for the in-place policy and group travel policy in both scenarios; set A, designed as the the best technology for both conservation and performance, was tested for the individual policy in scenario 1; the third set, a modification of set C, was tested in scenario 3 under the individual policy.

Fuel supply varied across scenario and price across scenario and policy. In particular, synthetic fuels were expected to play an important role in scenario 1 and no role in scenario 3. Base average market crude prices were higher in scenario 3 than in 1 [$61/barrel (1975$) versus $46 in 2000]. The retail fuel prices derived from these base fuel prices were varied among the policies; imposition of stiff automobile fuel taxes under the group travel policy was the key variable. The retail gasoline price was $1.89/gallon under the in-place policy and $3.78 under group travel in scenario 1 in 2000, whereas in scenario 3 it jumped to $3.82 under group travel from $2.55 under the in-place policy.

NATIONAL PROJECTIONS OF DIRECT ENERGY USE IN URBAN VEHICLE OPERATION

Method Overview

The travel demand analysis conducted for TAPCUT resulted in estimates and projections of total daily direct energy consumption by fuel and vehicle type for home-based local passenger travel in automobiles and vans in three case-study cities. For the energy analysis these projections were expanded to national annual totals for urban passenger transportation, including non-home-based travel in automobiles and vans. The expansion was based on TAPCUT expansion factors for the three case-study cities and on regional surveys indicating the relationship of non-home-based to home-based travel and of average weekday to weekend travel. The description of the method developed for this analysis may be found in a technical memorandum by Singh (2).

Energy consumption by fuel type in mass transit operation was estimated separately for TAPCUT and was not included in the summaries of direct energy use in this section. Currently only about 2 percent of all urban travel is made on mass transit. Even under the group travel policies in the two scenarios, national energy consumption by mass transit rose to 0.2 quad annually compared with 0.1 quad now. The highest value forecast for 2000 represented 8 percent of the direct energy consumption of automobiles and vans in urban passenger travel in that year.

Direct Energy Use

Purchased Fuels

The forecast annual automobile travel in metropolitan areas is shown in Table 1. Under the group travel policy in both scenarios, total urban passenger vehicle miles of travel (VMT) by 1990 drops below that of 1980 and continues to drop slightly by 2000. Under the in-place and individual policies in scenario 3, urban passenger VMT in 1990 and that in 2000 are almost equal to that of 1980. Under the in-place and individual policies in scenario 1, urban passenger VMT in 1990 is approximately 9 percent above that of 1980 and in 2000 approximately 17 percent above the 1980 level. In scenario 1, the VMT increase is slightly greater than the 16 percent increase in metropolitan area population. Population growth in scenario 3 is only 4.6 percent over the 20 years; VMT growth lags population, probably because of a slight rise in the cost of travel.

Table 1 presents direct energy consumption by purchased fuel type in addition to VMT on each fuel in national urban passenger travel. The fuels include gasoline, diesel fuel, electricity, gasohol, methanol, and a combination of diesel fuel and methanol (diesel-methanol). Electricity is measured in this analysis as the input energy required at the power plant to meet the electricity requirements for charging and operation of an electric vehicle (EV). Gasohol, which is projected to be available only in scenario 1, is an approximately 90-10 blend (87-13 was used in this analysis) of gasoline and coal-derived methanol (actually methyl fuel).

The diesel-methanol combination occurs only in scenario 1 in 2000. No specifications currently exist for a blend of diesel fuel and methanol or for an engine to burn it, but it was assumed that in scenario 1 this fuel type might become available for use in diesel-powered vehicles. These may operate on a variety of blend ratios or alternate between 100 percent methanol and 100 percent diesel fuel. In aggregate, the fuel distribution assumed for the diesel-methanol combination is 70 percent diesel fuel and 30 percent methanol.

From Table 1 and Figure 1 it can be observed that all policies result in a decline from 1980 to 2000 in direct energy consumed in urban passenger travel. (Although information is provided on direct energy consumption in 1975, the base year for purposes of this analysis is 1980.) As might be expected, the greatest absolute declines occur under the group travel policy in both scenarios. The amounts of energy consumed in scenarios 1 and 3 under the group travel policy are virtually the same by 2000 and represent about 47 percent of the 1980 energy consumed in urban passenger travel. The smallest absolute decline by 2000 occurs in scenario 1 under the in-place policy; the 3.2 quads consumed under this policy represent about 63 percent of the 1980 levels.

Gasoline energy consumption is still predominant in 2000 among the fuels used. However, energy consumption in the form of other fuels grows through 2000. In scenario 1 by 2000, energy consumed in the form of gasohol represents approximately 25 percent of total energy consumption under all policies. Under the individual travel policy of scenarios 1

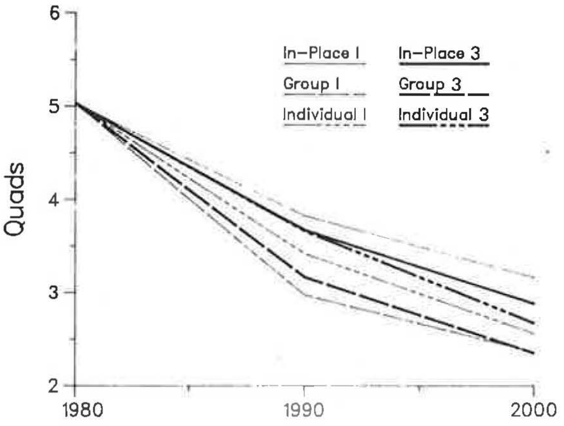
Table 1. Total direct energy consumed by purchased fuel type and total VMT for each fuel in national urban passenger travel.

Year, Scenario, and Policy	Gasoline		Gasohol		Methanol		Diesel		Diesel-Methanol		Electricity		Total	
	10^{15} Btu	10^{11} VMT[a]	10^{14} Btu	10^{10} VMT	10^{14} Btu	10^{10} VMT	10^{14} Btu	10^{10} VMT	10^{13} Btu	10^{9} VMT	10^{13} Btu[b]	10^{9} VMT	10^{15} Btu	10^{11} VMT
1975	5.996	5.269	–	–	–	–	–	–	–	–	–	–	5.996	5.269
1980	5.014	5.142	–	–	–	–	0.185	0.291	–	–	–	–	5.032	5.171
1990, scenario 1														
In place	3.183	4.548	3.336	5.050	–	–	3.065	5.564	–	–	0.065	0.114	3.824	5.611
Group	2.510	3.899	2.633	4.332	–	–	1.996	3.457	–	–	0.127	0.221	2.975	4.680
Individual	2.923	4.852	3.066	5.391	–	–	1.849	2.721	–	–	0.238	0.464	3.417	5.668
2000, scenario 1														
In place	1.886	3.447	8.478	16.41	1.745	3.830	1.985	4.308	5.554	14.82	0.417	0.863	3.164	6.059
Group	1.405	2.652	6.318	12.63	1.301	2.947	1.261	2.789	3.968	10.51	2.654	5.498	2.360	4.649
Individual	1.306	2.910	5.872	13.86	1.209	3.233	4.287	11.079	9.292	28.73	2.399	5.590	2.560	6.070
1990, scenario 3														
In place	3.456	4.971	–	–	–	–	2.134	3.827	–	–	0.090	0.158	3.671	5.346
Group	2.985	4.301	–	–	–	–	1.802	3.099	–	–	0.202	0.349	3.167	4.614
Individual	3.471	4.971	–	–	–	–	1.881	3.287	–	–	0.123	0.212	3.660	5.302
2000, scenario 3														
In place	2.613	4.789	–	–	–	–	2.666	5.592	–	–	0.244	0.504	2.882	5.353
Group	2.147	3.899	–	–	–	–	1.735	3.720	–	–	2.811	5.799	2.349	4.329
Individual	2.348	4.532	–	–	–	–	2.991	6.986	–	–	2.455	5.109	2.672	5.282

[a] Excluding mass transit vehicles.

[b] Converted at 10,400 Btu/kW·hr.

Figure 1. Direct energy consumed in national urban passenger travel by scenario and policy, 1980-2000.



and 3, diesel-fuel energy consumption is more than 10 percent of total energy consumption by 2000. In scenario 1 under all policies in 2000, approximately 5 percent of the total energy consumption is in the form of neat methanol. Energy consumption in the form of electricity for EVs, however, is at most only 1 percent of total energy consumption. This level occurs in both scenarios in 2000 under the group travel and individual policies.

Table 2 is derived from the results presented in Table 1. It illustrates the generally steady increase in the on-the-road fuel economy of urban passenger vehicles operating on various fuels under all policies in each scenario. Further, it illustrates that by 2000 in both scenarios the group travel policy results in fuel economy similar to that under the in-place policy. Concurrently, the individual policy in both scenarios results in greater fuel economy, the highest levels of which are achieved in scenario 1. The average (over all fuel types) on-road fuel economy and that for gasoline vehicles only are plotted in Figure 2 for scenario 1.

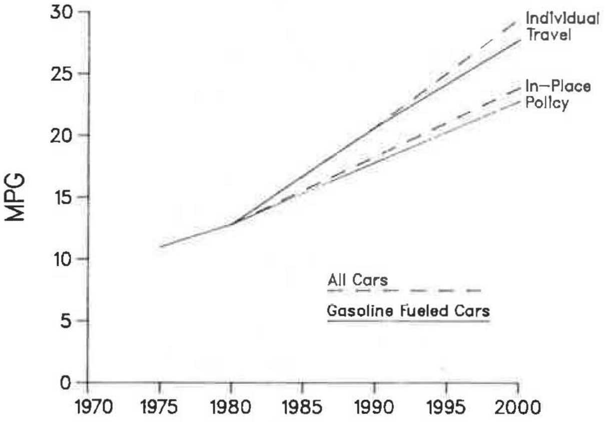
Resource Fuels

For the comparison of total energy use it is necessary to further disaggregate the energy consumption by fuel-type totals shown in Table 1. The amount of (a) gasoline used in gasohol, diesel fuel in the diesel-methanol combination, and methanol in both gasohol and the diesel-methanol combination; (b) resource fuels for the gasoline and diesel fuel (petroleum, oil shale, and coal); (c) resource fuels for methanol; and (d) resource fuels used to generate electricity is specified in order to allow analysis of the total energy required to produce these fuels.

Table 3 presents the results of this disaggregation: total energy consumed in urban transportation by primary fuel type and resource fuel. As defined here, the primary fuel types are gasoline and diesel fuel combined, methanol, and electricity. The resource fuels for gasoline and diesel fuel are assumed to be the same in this analysis rather than assign a particular input fuel (crude oil, coal, shale) to each of these refined products. Energy for production of these refined products is estimated for the average national refinery in each scenario and applied to diesel and gasoline Btu in the same manner. Thus these two fuels are aggregated here. The proportion of gasoline and diesel fuel produced from petroleum, shale oil, and coal in each scenario was assumed part of the TAPCUT scenarios; by applying these proportions to the gasoline and diesel totals, the absolute amounts of petroleum-derived, shale-oil-derived, and coal-derived gasoline and diesel fuel are determined. The resource fuels for electricity and methanol are similarly assumed in the TAPCUT scenarios.

From the results of Table 1, it is clear that the use of petroleum-derived fuels decreases substantially between 1980 and 2000. Table 3 shows that the use of petroleum-derived fuels is substantially less in scenario 1 than in scenario 3 in 1990 and 2000 under all three travel policies. By 2000 the use of petroleum-derived gasoline, diesel fuel, and electricity in scenario 1 represents about 70 percent of the total petroleum used in scenario 3. This occurs despite the 10 percent difference at most between total direct energy consumption in the two scenarios. The chief reason, of course, is the use

Figure 2. On-road fuel economy for urban vehicles in scenario 1 under in-place and individual policies.



of gasoline derived from oil shale and coal and diesel fuel in scenario 1 but not in scenario 3; to a lesser extent, the substitution of coal-derived methanol for gasoline in scenario 1 also accounts for some of the difference. The direct use of petroleum for urban travel is plotted in Figures 3 and 4 for each scenario.

TOTAL ENERGY REQUIRED TO SUPPORT TAPCUT SCENARIOS AND POLICIES

Total Energy and Petroleum Use

Total energy use for urban transportation is the sum of direct and indirect energy use. Indirect energy includes energy required to produce the fuels used in vehicle operation, to produce the automobiles and transit vehicles used by urban travelers, and to construct the infrastructure (highways, busways, and rail systems) necessary to support the transporta-

Table 2. Average on-the-road fuel economy of urban passenger vehicles by fuel type.

Year, Scenario, and Policy	Gasoline (mpg)	Gasohol (mpg)	Methanol (mpg)	Diesel (mpg)	Diesel-Methanol (mpg)	Electricity[a] (Btu)
1975	10.99	–	–		–	–
1980	12.82	–	–	21.92	–	–
1990, scenario 1						
In place	17.86	17.86	–	25.23	–	21.86
Group	19.41	19.41	–	24.07	–	21.73
Individual	20.75	20.75	–	20.46	–	24.40
2000, scenario 1						
In place	22.85	22.85	15.58	30.59	31.50	25.90
Group	23.59	23.59	16.09	30.73	31.25	25.89
Individual	27.84	27.84	18.99	35.92	36.48	29.13
1990, scenario 3						
In place	17.98	–	–	24.93	–	21.88
Group	18.01	–	–	23.91	–	21.56
Individual	17.90	–	–	24.30	–	21.63
2000, scenario 3						
In place	22.91	–	–	29.16	–	25.77
Group	22.70	–	–	29.81	–	25.79
Individual	24.13	–	–	32.47	–	26.02

[a] Converted at 10,400 Btu/kW·hr and at 125, 000 Btu/gal.

Table 3. Total direct energy consumed in national urban passenger travel by primary fuel type.

Year, Scenario, and Policy	Petroleum to Gasoline and Diesel (10^{15} Btu)	Shale Oil to Gasoline and Diesel (10^{15} Btu)	Coal to Gasoline and Diesel (10^{15} Btu)	Coal to Methanol (10^{15} Btu)	Coal to Electricity (10^{12} Btu)	Uranium to Electricity (10^{12} Btu)	Petroleum to Electricity (10^{12} Btu)	Natural Gas to Electricity (10^{12} Btu)	Other[a] to Electricity (10^{12} Btu)	Total[b] (10^{15} Btu)
1975	5.99562	–	–	–	–	–	–	–	–	5.9956
1980	5.03234	–	–	–	–	–	–	–	–	5.0323
1990, scenario 1										
In place	3.23948	0.36666	0.17388	0.04323	0.33	0.18	0.11	0.02	0.01	3.8239
Group	2.51877	0.28510	0.13520	0.03413	0.64	0.36	0.22	0.05	0.01	2.9746
Individual	2.89196	0.32733	0.15523	0.03973	1.19	0.67	0.41	0.09	0.02	3.4166
2000, scenario 1										
In place	2.16357	0.50588	0.18863	0.30155	1.80	1.67	0.55	0.12	0.02	3.1638
Group	1.59651	0.37329	0.13919	0.22421	11.44	10.67	3.50	0.77	0.16	2.3597
Individual	1.74899	0.40895	0.15249	0.22568	10.34	9.64	3.17	0.70	0.14	2.5601
1990, scenario 3										
In place	3.66972	–	–	–	0.45	0.26	0.16	0.03	0.01	3.6706
Group	3.16515	–	–	–	1.01	0.57	0.35	0.07	0.02	3.1672
Individual	3.65877	–	–	–	0.61	0.35	0.21	0.04	0.01	3.6600
2000, scenario 3										
In place	2.87988	–	–	–	1.05	0.98	0.32	0.07	0.01	2.8823
Group	2.32092	–	–	–	12.11	11.30	3.71	0.82	0.17	2.3490
Individual	2.64698	–	–	–	10.58	9.87	3.24	0.71	0.15	2.6715

[a] Hydroelectricity and pumped storage.

[b] Rows do not always sum because of rounding.

Figure 3. Direct use of petroleum for urban transportation in scenario 1.

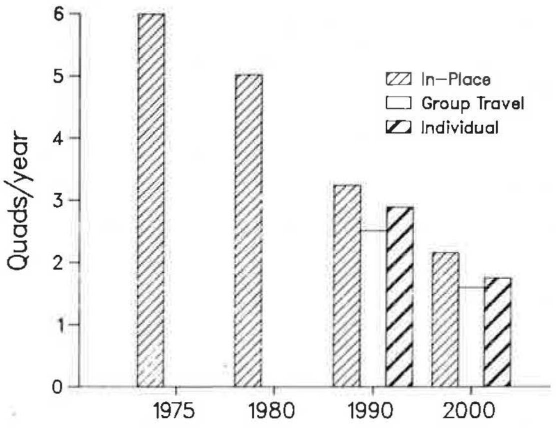
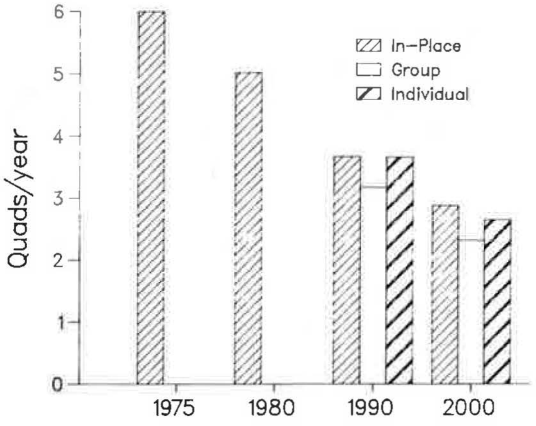


Figure 4. Direct use of petroleum for urban transportation in scenario 3.



tion level of service under each policy. These energy requirements were estimated with the methods developed for TAPCUT (2-7). The limits to the energy accounting have been described in a technical memorandum (2). The results of these analyses represent the indirect energy use under the TAPCUT policies and are combined with the results of the direct energy analyses in Table 4 to show the estimated total energy by fuel type for urban travel. Estimates for 1990 were also derived but are not presented in this table.

The results, which are further illustrated in Figures 5 and 6, show a substantial decline between 1980 and 2000 in energy use devoted to urban passenger transportation even when indirect energy (i.e., energy for fuel production, vehicle manufacture, and infrastructure construction) is included in the analysis. In scenario 1, the decline by 2000 in total energy use from the 6.6 quads estimated for 1980 ranges from 1.0 quad under the in-place policy to 2.4 quads under the group policy, or 16 to 36 percent. Most of this decline is achieved by 1990. In scenario 3, the decline in total energy use is even more dramatic. It is nearly halved by 2000 under the group travel policy; i.e., there is a 3.0-quad reduction in total energy use. This is much greater than the savings of 2.2 quads forecast under the in-place policy. The individual policy is identical to the in-place policy, also saving 35 percent relative to 1980. Much of the difference between scenarios is due to the greater amount of energy required for fuel production under scenario 1. In particular, more energy is required to produce gasoline and diesel fuel from the coal and oil shale used in scenario 1 than from petroleum, which in scenario 3 is the only resource fuel for gasoline and diesel fuel.

Although scenario 3 shows the greatest decline in total energy use, scenario 1 shows the greatest decline in petroleum use (see Figures 5 and 6). From the 1980 level of 5.6 quads of petroleum use in direct vehicle operation and associated indirect energy, petroleum use under the scenario 1 policies declines 3.2 to 3.8 quads, i.e., from 56 to 67 percent, by 2000. In scenario 3, petroleum use declines 2.4 to 3.0 quads, or 43 to 54 percent, by 2000. Petroleum consumption shown in Table 4 is not complete, however, because a portion of the unspecified external subsidies in fuel production is petroleum itself and these subsidies by 2000 represent 13 to 16 percent of the total energy requirement for urban passenger travel. However, any likely disaggregation of these subsidies should not alter the fact that scenario 1 leads to greater petroleum savings than does scenario 3.

The energy supply forecasts assumed in TAPCUT can be used as indicators of the changes in energy use under the alternative policies. The absolute levels of energy supply that are forecast in each scenario are not directly related to the demand analysis undertaken in TAPCUT. The forecast indicating that scenario 1 has a greater energy supply than does scenario 3, for example, does not support a conclusion regarding a lower need for conservation, nor are these forecast levels of supply equivalent to an official forecast of supply.

It is important, however, to look at urban transportation energy use in the context of the rest of the energy users in the economy. Thus the results of the direct and indirect energy analyses shown in Table 4 are compared here with the TAPCUT fuel supply assumptions. In 1980 the 6.6 quads of energy required directly and indirectly for urban passenger transportation represent approximately 8.3 percent of total national energy consumption of 80 quads. By 2000 in scenario 1 and depending on the policy, total energy consumption in urban passenger transportation represents 3.7 to 4.9 percent of the forecast national total of 114 quads. In scenario 3, total energy consumption in urban passenger transportation represents from 3.8 to 4.7 percent of the forecast national total of 94 quads.

In 1980 the 5.6 quads of petroleum required directly and indirectly for urban passenger transportation represent approximately 16.1 percent of the total national petroleum consumption of 35 quads. By 2000 in scenario 1, total petroleum consumption in urban passenger transportation represents 7.0 to 9.4 percent of the forecast national petroleum total of 26 quads. In scenario 3, total petroleum consumption in urban passenger transportation represents from 7.7 to 9.5 percent of the forecast national petroleum total of 34 quads.

Direct Versus Indirect Energy Use

The distribution of fuel types consumed in urban passenger transportation changes both directly and indirectly between 1980 and 2000, particularly in scenario 1. Excluding the external subsidies, in 1980 the total energy consumption is 90 percent petroleum, 5 percent coal, and 5 percent other fuels. By 2000 under scenario 3, the distribution changes modestly to 80 to 85 percent petroleum and 7 to 9 percent coal; the remainder is other fuels. By 2000 in scenario 1, however, petroleum consumption represents just 49 to 53 percent of the total energy consumption, coal jumps to 23 to 25 percent, and oil shale 13 to 15 percent; the remainder is other fuels. Obviously this change is largely because of the use of coal and oil shale as sources of gasoline and diesel fuel.

The relative importance, in terms of energy, of the individual components of urban passenger transportation (vehicle operation, fuel production, vehicle manufacturer, and infrastructure construction) changes over time and with scenario. The distribution of energy use by these components under the in-place policy in scenario 1 is shown in Figure 7. In 1980 direct energy use for vehicle operation represents 76 percent of the total energy use associated with urban passenger travel. By 2000 in

Table 4. Total direct energy consumed in urban passenger travel by primary fuel type and resource fuel.

Energy Need	Fuel (10^{15} Btu) Petroleum	Shale Oil	Coal	Natural Gas	Uranium	Hydro-electricity	Other	External Subsidies[a]	Total	Percentage of Total Energy
1980										
Vehicle operation	5.0323	–	–	–	–	–	–	–	5.0323	76.2
Fuel production	0.4479	–	–	–	–	–	–	0.3598	0.8077	12.2
Vehicle manufacture	0.0862	–	0.2640	0.1999	0.219	0.0238	0.0032	–	0.5990	9.1
Infrastructure construction	0.0607	–	0.0588	0.0416	0.0020	0.0015	–	–	0.1646	2.5
Total	5.6271	–	0.3328	0.2415	0.0239	0.0253	0.0032	0.3598	6.6036	
Percentage of total energy without external subsidies	90.1	–	5.2	3.9	0.4	0.4	0.0	–		
2000, Scenario 1, In-Place Policy										
Vehicle operation	2.1641	0.5059	0.4920	0.0001	0.0017	–	–	–	3.1638	56.8
Fuel production	0.1926	0.2029	0.2949	–	0.0004	–	–	0.8861	1.5769	28.3
Vehicle manufacture	0.0769	–	0.2802	0.2584	0.0859	0.0365	0.0109	–	0.7488	13.4
Infrastructure construction	0.0286	–	0.0304	0.0198	0.0032	0.0005	0.0003	–	0.0828	1.5
Total	2.4622	0.7088	1.0975	0.2783	0.0912	0.0370	0.0112	0.8861	5.5723	
Percentage of total energy without external subsidies	52.6	15.1	23.4	5.9	2.0	0.8	0.2	–		
2000, Scenario 1, Group Policy										
Vehicle operation	1.6000	0.3733	0.3748	0.0008	0.0107	0.0001[b]	–	–	2.3597	55.7
Fuel production	0.1424	0.1497	0.2203	0.0002	0.0025	–	–	0.6567	1.1718	27.7
Vehicle manufacture	0.0608	–	0.2215	0.2049	0.0684	0.0290	0.0089	–	0.5935	14.0
Infrastructure construction	0.0352	–	0.0424	0.0262	0.0047	0.0007	0.0004	–	0.1096	2.6
Total	1.8384	0.523	0.859	0.2321	0.0863	0.0298	0.0093	0.6557	4.2346	
Percentage of total energy without external subsidies	51.4	14.6	24.0	6.5	2.4	0.8	0.3	–		
2000, Scenario 1, Individual Policy										
Vehicle operation	1.7522	0.4090	0.3885	0.0007	0.0096	0.0001	–	–	2.5601	50.7
Fuel production	0.1560	0.1640	0.2268	0.0001	0.0023	–	–	0.7004	1.2496	24.7
Vehicle manufacture	0.0748	–	0.2873	0.2839	0.1098	0.0338	0.0192	–	0.8088	16.0
Infrastructure construction	0.1335	–	0.1730	0.1088	0.0154	0.0024	0.0014	–	0.4345	8.6
Total	2.1165	0.5730	1.0756	0.3935	0.1371	0.0353	0.0206	0.7004	5.0530	
Percentage of total energy without external subsidies	48.6	13.2	24.7	9.0	3.2	0.8	0.5	–		
2000, Scenario 3, In-Place Policy										
Vehicle operation	2.8802	–	0.0010	0.0001	0.0010	–	–	–	2.8823	65.7
Fuel production	0.2563	–	0.0002	–	0.0002	–	–	0.5899	0.8466	19.3
Vehicle manufacture	0.0594	–	0.2313	0.1978	0.0463	0.0326	0.0102	–	0.5776	13.2
Infrastructure construction	0.0283	–	0.0304	0.0194	0.0022	0.0007	0.0004	–	0.0814	1.8
Total	3.2242	–	0.2629	0.2173	0.0497	0.0333	0.0106	0.5899	4.3879	
Percentage of total energy without external subsidies	84.9	–	6.9	5.7	1.3	0.9	0.3	–		
2000 Scenario 3, Group Policy										
Vehicle operation	2.3246	–	0.0121	0.0008	0.0113	0.0002	–	–	2.3490	65.4
Fuel production	0.2069	–	0.0018	–	0.0027	–	–	0.4767	0.6881	19.1
Vehicle manufacture	0.0479	–	0.1865	0.1595	0.0374	0.0263	0.0083	–	0.4659	13.0
Infrastructure construction	0.0305		0.0337	0.0211	0.0024	0.0008	0.0004	–	0.0889	2.5
Total	2.6099	–	0.2341	0.1814	0.0538	0.0273	0.0087	0.4767	3.5919	
Percentage of total energy without external subsidies	83.8	–	7.5	5.8	1.7	0.9	0.3	–		
2000, Scenario 3, Individual Policy										
Vehicle operation	2.6502	–	0.0106	0.0007	0.0099	0.0001	–	–	2.6715	61.7
Fuel production	0.2359	–	0.0016	–	0.0023	–	–	0.5434	0.7832	18.1
Vehicle manufacture	0.0710	–	0.2679	0.2412	0.0555	0.0409	0.0118	–	0.6883	15.9
Infrastructure construction	0.0658	–	0.0680	0.0443	0.0047	0.0015	0.0008	–	0.1851	4.3
Total	3.0229	–	0.3481	0.2862	0.0724	0.0425	0.0126	0.5434	4.381	
Percentage of total energy without external subsidies	79.9	–	9.2	7.6	1.9	1.1	0.3	–		

[a] Fuels, electricity, materials, and equipment required to operate and construct the fuel-production system. Resource fuels are not included.

[b] All energy listed as "other" in Table 3 is assumed to be hydroelectricity in this analysis.

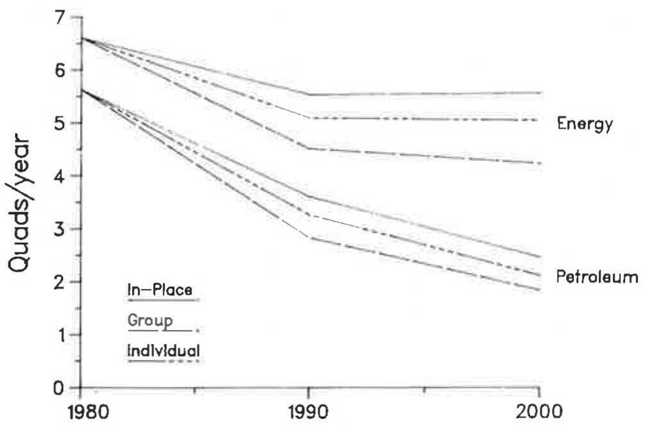


Figure 5. Total energy required for urban passenger transportation versus total petroleum in scenario 1.

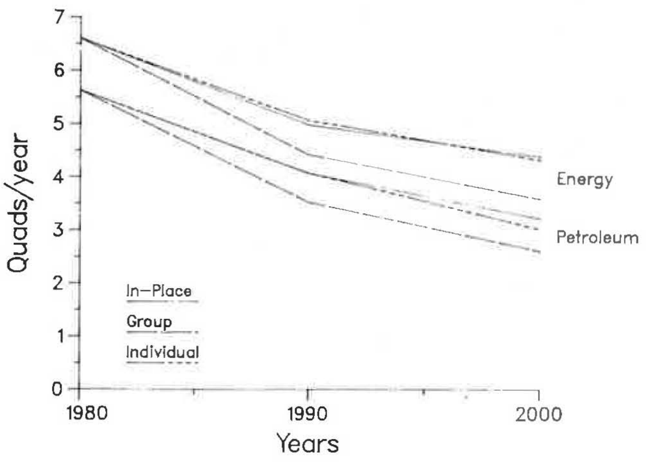


Figure 6. Total energy required for urban passenger transportation versus total petroleum in scenario 3.

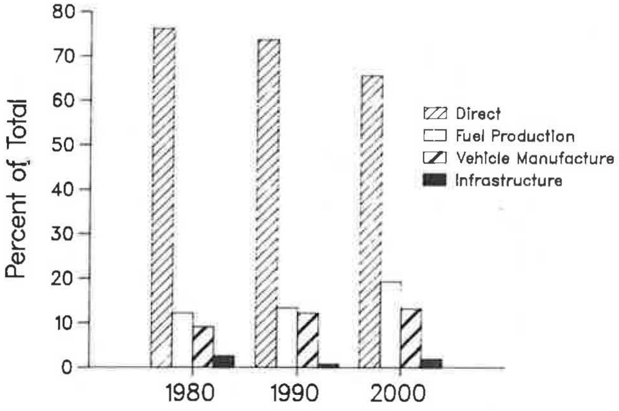


Figure 7. Urban travel energy use by type under in-place policy in scenario 1.

scenario 1, vehicle energy use drops to 51 to 57 percent of the total, depending on the policy; in scenario 3 the decrease is to 62 to 66 percent of the total. Energy required for fuel production represents 12 percent of the total energy use in urban passenger transportation in 1980. By 2000 fuel production energy in scenario 1 increases to 25 to 28 percent of the total; in scenario 3 it increases to 18 to 19 percent of the total. Energy required for vehicle production is 9 percent of the total in 1980; by 2000 this increases to 13 to 16 percent of the total energy in both scenarios. This share increases because of the increased number of vehicles manufactured in the scenarios rather than because of an increase in the energy required to produce each vehicle, which declines from 1980 to 2000. Energy for infrastructure construction represents 2.5 percent of the total energy use in 1980. Only under the individual policy in both scenarios does it increase to 4.3 to 8.6 percent by 2000.

The scenario 1 totals for each phase of indirect energy under each policy are almost always higher than the scenario 3 totals for the equivalent policy in both 1990 and 2000. (The only exception is the energy required for vehicle manufacture in 1990 under the individual policy.) This higher indirect energy total generally explains why the scenario 1 total energy consumption is always higher than that of scenario 3 in spite of the similar effect on each scenario, for direct energy consumption alone, of these policies. The major difference among the scenarios occurs in the energy required for fuel production. As indicated earlier, energy required to produce fuel under all policies for both scenarios is almost always the greatest proportion of the indirect energy in both 1990 and 2000. (In 1990 under the group travel and individual policies of scenario 3, energy for vehicle manufacture is slightly higher.) As stated previously, the totals for fuel production are much higher for scenario 1 than for scenario 3 because of the use of coal and oil shale in the derivation of gasoline and diesel fuel and because of the use of coal-derived methanol in scenario 1.

CONCLUSIONS

Some distinct changes are expected to occur in urban travel energy use to the end of this century. Energy conservation strategies can affect the forecast patterns of energy. These projected patterns have been examined here. Many assumptions are built into all phases of the analysis; changes in any of these assumptions would obviously affect the specific totals generated. However, the general results would probably not be greatly affected. The most important of these results are the following:

1. A substantial decline in direct energy consumed in national urban passenger travel is projected from 1980 to 2000. The 1980-2000 decline occurs in both scenarios under all energy-saving strategies.
2. Even when indirect energy (energy for fuel production, vehicle production, and infrastructure construction) is included, a substantial decline between 1980 and 2000 in energy use devoted to urban transportation occurs.
3. The scenario that results in the greatest savings of petroleum does not save the greatest amount of energy. This occurs in wealthy scenario 1 largely because more total energy is required to produce gasoline and diesel fuel from oil shale and coal (and to a lesser extent to produce coal-derived methanol, which substitutes for gasoline) than is required to produce gasoline and diesel fuel from petroleum. In other words, petroleum savings achieved through fuel substitution exact a price in the form of higher consumption of other fuels, particularly coal.
4. By contrast, petroleum savings achieved through improved vehicle efficiency are not balanced

against any increase in energy for vehicle production. This situation has come about because of the large decrease in vehicle weight that occurs by 2000, which compensates for the forecast increase in energy per pound of vehicle inherent in the new materials and production processes used in the more fuel-efficient cars.

5. The relative importance of individual components of urban transportation will change over time in either economic scenario. In particular, by 2000 indirect energy requirements are projected to account for at least 34 percent without synfuels and up to 49 percent with synfuels of the total energy required for urban passenger transportation as opposed to 24 percent in 1980. The opportunities for energy saving in fuel production in particular should be identified now to lessen the impact of the shift to alternative fuels.

6. Indirect energy use can offset some of the direct energy savings projected in urban transportation. Total indirect energy consumption increases between 1980 and 2000 under the in-place policy in one scenario and under the individual policy in both scenarios. Thus, when the implications of various transportation strategies on direct energy use in vehicle operation are examined, the energy consumed indirectly must be considered.

ACKNOWLEDGMENT

The effort reported in this paper would not have been possible without the help of other participants in the TAPCUT project, each lending his or her special expertise as needed. In particular, we would like to acknowledge the efforts of those who characterized the vehicle and fuel production technologies and infrastructure construction: Charles Hudson, now with EE&G, Santa Barbara, California; Evelyn Putnam, now with Priority Research, Santa Barbara; and Roy Hildestad, now with General Research Corporation, Santa Barbara. We would also like to acknowledge the efforts of those who provided the forecasts of population, travel demand, and automobile ownership: Bruce Peterson, Oak Ridge National Laboratory; Marc Kaplan, now with Bell Laboratories, in New Jersey; and Chris Saricks, Argonne National Laboratory. Last, but certainly not least, we owe our thanks to David O. Moses, U.S. Department of Energy, the sponsor of the TAPCUT project.

REFERENCES

1. S.J. LaBelle and D.O. Moses. Technology Assessment of Productive Conservation. Argonne National Laboratory, Argonne, Ill., Final Rept. ANL/ES-130, Nov. 1982.
2. M.K. Singh. Energy Consumption Due to Local Travel by Urban Households under Three Alternative Policies: 1980-2000. Center for Transportation Research, Argonne National Laboratory, Argonne, Ill., Rept. ANL/EES-TM-12, Nov. 1981.
3. A.J. Frabetti. Application of Net Energy Analysis to Consumer Technologies. Energy Research and Development Administration, U.S. Department of Energy, Feb. 1977.
4. A.J. Frabetti. A Study to Develop Energy Estimates of Merit for Selected Fuel Technologies. Office of Research and Development, U.S. Department of Interior, Sept. 1975.
5. A.G. Melcher. Net Energy Balance Study of Fossil Fuel Resources. Colorado Energy Research Institute, Golden, Colo., April 1978.
6. E.M. Dickson et al. Impacts of Synthetic Liquid Fuels Development: Assessment of Critical Factors, Volume II: Analysis, Energy Research and Development Administration, U.S. Department of Energy, and U.S. Environmental Protection Agency, Rept. ERDA 76-129/2, 1976.
7. T.O. Wagner et al. Diesel Fuel Ups Energy Efficiency. Oil and Gas Journal, Vol. 79, Jan. 4, 1981, p. 1.

The California Freight Energy Demand Model

HERBERT WEINBLATT

The freight model of the California Energy Commission transportation model system is designed to analyze rail and truck competition and to produce detailed projections through 2002 of activity and energy consumption within California of all trucks and of rail-freight operations. The model is also designed to analyze the potential effects of public policy on such transportation activity and energy consumption. A slightly simplified description of the entire model as it is now planned plus projections produced by the phase-1 model are presented. The phase-1 model consists of the truck-transportation components of the entire model plus a limited capability for projecting aggregate rail-freight energy consumption. Rail and truck competition and a more disaggregate rail-freight sector have been introduced in the phase-2 version of the model.

The California Energy Commission (CEC) transportation model system consists of a freight model (1), an automobile model (2), and a transit model (3). The freight model is designed to analyze rail and truck competition and to produce detailed projections through 2002 of activity and energy consumption within California of all trucks and of rail-freight operations. The model is also designed to analyze the potential effects of public policy on such transportation activity and energy consumption.

The freight model was implemented in two phases. The first was completed in August 1982, and the second was completed in June 1983.

A slightly simplified description of the entire model as it is now planned plus projections produced by the phase-1 model are presented. The phase-1 model consists of the truck-transportation components of the entire model plus a limited capability for projecting aggregate rail-freight energy consumption. Analyses of rail and truck competition and a more disaggregate rail-freight sector were implemented in early 1983.

In the first section of this paper various ways are described in which the basic variables of the model are disaggregated. In the second section the estimation of the base-year data used by the model is described. The operation of the model and a summary of the base-case projections produced by the phase-1 model are covered in the third and fourth sections, respectively.

THE BASIC VARIABLES

In the freight model single-unit trucks are classified into six size categories:

Class 1: up to 6,000 lb gross vehicle weight (GVW),
Class 2: 6,001 to 10,000 lb GVW,
Classes 3-5: 10,001 to 19,500 lb GVW,
Class 6: 19,501 to 26,000 lb GVW,
Class 7: 26,001 to 33,000 lb GVW, and
Class 8: more than 33,000 lb GVW.

In addition three categories of tractor-trailer combination vehicles are distinguished by the model: single trailer, double trailer, and triple trailer. Triple trailers are not permitted in California now but could be in the future.

Within each size category, three to five of the following body types are distinguished:

1. Pickup,
2. Van,
3. Platform or flatbed,
4. Dump or garbage,
5. Tank,
6. Cement mixer,
7. Utility vehicle (e.g., jeep or similar vehicle), and
8. Other.

In all, a total of 40 different size and body-type combinations are classified. In Table 1 the numbers identify the sequence in which data relating to the 40 vehicle types are stored in the model. For each size category, the "other" body type is used for all body types not separately identified for that size category (e.g., "other class-1 vehicles" consists of all class-1 vehicles except pickups and utility vehicles).

In addition to vehicle type, trucks and vehicle miles of travel (VMT) are classified by

1. Activity or commodity,
2. Fuel type,
3. Local or nonlocal operation,
4. Age, and
5. Region.

The activity or commodity indicator distinguishes vehicles by use. The 17 activities or commodities so distinguished are shown in the following:

1. Fruits and vegetables,
2. Agricultural products,
3. Construction and mining,
4. Timber and lumber,
5. Food products,
6. Paper products,
7. Chemicals,
8. Primary metals,
9. Machinery,
10. Other manufacturing,
11. Household goods movement,
12. Motor homes,
13. Retail trade,
14. Wholesale trade,
15. Utilities,
16. Services, and
17. Personal-use trucking.

The first 10 activities include a significant commodity-transport component, which receives special consideration in projecting the demand for trucking and rail-truck competition. The 17 activities consist of 15 commercial activities plus household goods movement (category 11) and other personal-use trucking (category 17). (Category 1 is not distinguished separately in the phase-1 model.)

Truck fuel types distinguished by the freight model are gasoline, diesel fuel, liquefied petroleum gas (LPG) and liquefied natural gas (LNG), and methanol. Eleven age categories are distinguished; all vehicles 10 or more years old are combined into a single category. Finally, for purposes of all projections, the state of California is divided into five multicounty regions: San Francisco, Los Angeles, San Diego, Sacramento, and the rest of state.

Railroad traffic is measured in ton miles and classified by railroad car type, commodity, and region. Seven types of railroad car are distinguished: conventional boxcar, refrigerated boxcar, tank, gondola, hopper, automobile rack, and trailer on flatcar (TOFC). The commodities distinguished are the first 10 shown in the list given previously. The stock of railroad cars is not explicitly represented within the model.

BASE-YEAR DATA

The base-year data used by the freight model provide the starting point from which all projections are developed. There are four categories of base-year data used by the freight model proper:

1. The stock of single-unit and combination trucks based in California,
2. The VMT in California by each category of truck,

Table 1. Vehicle size and body-type categories.

	Body Type							
Size Category	Pickup	Van	Platform or Flatbed	Dump or Garbage	Tank	Cement Mixer	Utility	Other
Truck								
Class 1 (<6,000 lb GVW)	3						1	4
Class 2 (6,001 to 10,000 lb GVW)	5	6	7				2	8
Classes 3-5 (10,001 to 19,500 GVW)		9	10	11				12
Class 6 (19,501 to 26,000 lb GVW)		13	14	15				16
Class 7 (26,001 to 33,000 lb GVW)		17	18	19				20
Class 8 (>33,000 lb GVW)		21	22	23		24		25
Combination								
Single trailer		26	27	28	29			30
Double trailer		31	32	33	34			35
Triple trailer		36	37	38	39			40

Note: Numbers identify sequence in which data are stored in the model.

3. The volume of truck and rail freight movements (in ton miles) in California of commodities 1-4 (as defined previously) and of nonlocal movements of commodities 5-10, and
4. The stock and VMT of commercial-use automobiles.

The base year used for all data except the automobile data is 1977. For compatibility with the automobile model, the base year used for automobile data is 1980. The development of the base-year data used by the freight model is described in the following.

Trucks and Combinations

The number of trucks and tractors registered in California in the base year (1977) was obtained by size category, fuel type, vintage, and region from R.L. Polk and Company data supplied by CEC (4-7). The 1977 Light Truck File was used as the basis for class-1 and class-2 trucks; and the 1977 Domestic Car File and Import Car File were used as the basis for class-1 and class-2 passenger vans. Because 1977 data were not directly available for medium and heavy trucks, 1977 registrations were estimated from data in the 1978 and 1979 Medium and Heavy Truck Files on the basis of 1978 registrations and attrition rates inferred by comparing 1978 and 1979 data.

Data from the 1977 Truck Inventory and Use Survey (TIUS) (8) were then used to scale these vehicle counts so that they would represent the number of vehicles based in California (and in each of the five regions) rather than the number of vehicles registered there. Polk and TIUS data were used to distribute class-1 and class-2 trucks over the various body types distinguished by the model, and TIUS data were used to perform corresponding distributions for single-unit trucks of classes 3-7. The body-type distribution of combinations and class-8 trucks was also inferred primarily from TIUS but also reflects commodity information obtained from the 1977 Commodity Transportation Survey (CTS) (9).

Vehicles were distributed by activity or commodity and normal range of operation (local and nonlocal) on the basis of TIUS data. Vehicles were allocated to the 17 activity and commodity uses on the basis of TIUS distributions of California vehicles by major use and commodity carried.

In the resulting matrix of base-year vehicle stock, California-based trucks are distinguished by

1. Vehicle type (40),
2. Normal activities or commodities carried (17),
3. Fuel type (4),
4. Normal range of operation (local or nonlocal),
5. Age (11), and
6. Region (5).

It is readily determined that the base-year vehicle stock matrix contains 299,200 distinct cells (many of which are empty). Although much of the data is derived from Polk's census of vehicle registration data, the activity or commodity and range of operations attributes were derived entirely from the TIUS data for California-based vehicles, and for medium and heavy trucks, the body-type distributions were derived from TIUS as well. TIUS contains results from a survey of 3,534 vehicles. Accordingly, this matrix, and matrices derived from it, should not be inspected unless suitable aggregation has first been performed.

Ton Miles

The volume of base-year truck transport of manufactured products measured in ton miles was derived from a special tabulation of data from the 1977 CTS that had been performed by the U.S. Bureau of the Census for the Transportation Systems Center (TSC) of the U.S. Department of Transportation (9). This tabulation contains the CTS in a form that identifies origins and destinations by 173 Bureau of Economic Analysis (BEA) economic regions.

The base-year estimates of truck transport of manufactured products in California were derived from CTS data on shipments originating or terminating in the state or both. (Truck transport through California of goods that both originate and terminate elsewhere was assumed to be negligible.) Estimates of ton miles transported within each of the five California regions were derived by identifying the routes within California that would most likely be used for transport between BEA region pairs, estimating average mileage within each region for each route, and combining this information with the CTS data on tons transported between BEA region pairs.

The results of these analyses are estimates of the volume of manufacturing shipments transported by seven commodity groups (nos. 4-10) and five regions. The types of vehicles used for transporting each commodity group were inferred from national TIUS data and then modified on the basis of California TIUS data to reflect the greater use of double trailers in California than nationally. The shipments were assigned to vehicle types on the basis of this distribution and split between local and nonlocal movements on the basis of California TIUS data.

These results were supplemented by estimates of the volume of transport of goods in the nonmanufacturing sectors (agriculture, construction and mining, and transport of household goods) derived from estimates of VMT by heavy-duty vehicles (combinations and class-8 single-unit trucks) in these sectors. The VMT estimates were derived from California TIUS data and converted to ton miles on the basis of average effective payload by vehicle type and range of operation. All estimates of base-year truck-transport volume were then scaled to be consistent with the final estimates of base-year VMT (see next section).

Estimates of ton miles transported by rail are being developed by commodity and region from 1977 railroad waybill data (10) with a procedure similar to that used for the CTS data.

VMT

The base-year estimate of VMT was derived as a composite of estimates from three independent sources. The first set of estimates was based on the estimates of base-year vehicle stock derived from California Polk and TIUS data. These estimates were multiplied by estimates of average VMT (by vehicle type, fuel type, age, and range of operation) derived from national and California TIUS data. The result was a set of VMT estimates for each of the vehicle categories represented in the model.

A second set of VMT estimates was based on the estimates of base-year ton miles of manufacturing shipments by motor carrier derived from CTS data. It was assumed that virtually all shipments of manufactured products would be made in class-8 trucks and single- or double-trailer combinations. For each commodity category, the relative amount of VMT of each of the corresponding vehicle types was inferred from national TIUS data and from the annual VMT estimates and then adjusted on the basis of California TIUS data to reflect the greater use of double trailers in California. The actual amount of VMT required for each of these commodity categories was then derived by dividing the ton-mile estimates by average effective payload estimates by commodity and vehicle type derived from data from the Truck Weight Study (11,12) and from the study of empty versus loaded trucks by the Interstate Commerce Commission (ICC) (13). The result was a second set of VMT estimates for commodities 4-10 transported in heavy vehicles.

The Polk and TIUS data were judged to yield better estimates of VMT than the CTS data. The CTS data, on the other hand, provided substantially better identification of the manufactured commodities carried. Accordingly, the CTS estimates of VMT by commodity were scaled by vehicle type to Polk or TIUS control totals of VMT of heavy trucks transporting manufactured goods. The resulting VMT estimates for commodities 4-10 transported in heavy trucks were then combined with the original Polk or TIUS VMT estimates for the remaining commodities and vehicle types to provide a complete set of VMT estimates corresponding to the base-year vehicle stock.

The 1980 fuel-consumption implications of the resulting VMT estimates were then determined and compared with estimates of truck fuel consumption derived from data on annual highway fuel consumption in California (14) and from automobile model (2) and transit model (3) fuel consumption estimates. On the basis of this comparison, these estimates were further scaled by reducing all values of average VMT so that freight model projections of 1980 diesel fuel consumption would be consistent with that derived from the other data sources.

Commercial-Use Automobiles

For the CEC transportation model system, commercial-use automobiles are defined as automobiles in fleets of four or more that are garaged at a company facility. Such vehicles are assumed to be vehicles that are used entirely or primarily for company purposes and hence whose use may be appropriately projected on the basis of forecast changes in the California economy. Vehicles not garaged at a company facility are assumed to be primarily automobiles used for personal as well as company purposes and whose characteristics can best be projected by the automobile model. The base year for commercial-use automobile data was taken to be 1980 for consistency with that used by the automobile model.

Estimates of the average mileage and age distribution of commercial-use vehicles and of the number of vehicles in fleets of 10 or more were developed from survey data collected in late 1981 by the Bobit Publishing Company under contract to CEC (15). The number of automobiles in fleets of 4 to 10 was estimated as the ratio of the national 1980 population of these vehicles (16) to the national 1980 population of privately owned automobiles (17) multiplied by the California 1980 population of privately owned automobiles (17). The age and average annual mile distributions for fleets of 4 to 10 were assumed to be the same as those for fleets of 10 or more. The resulting estimates were taken to be an appropriate representation of the 1980 population of commercial-use automobiles in California. (Because of the low rate of growth in the automobile fleet in recent years and the uncertainty of the population estimate, it was not thought worthwhile to scale from 1981 totals to 1980 totals.)

MODEL OPERATION

Projections by economic sector of growth in production, shipment value, or employment within California have been developed in a parallel CEC effort. These projections are used as the basis for projecting growth in freight volume by commodity and growth in VMT of commercial-use class-1 through class-7 single-unit trucks by economic sector. Growth in commercial-use automobile VMT is similarly projected by the freight model for use by the automobile model; these projections are developed on the basis of projected growth in employment in the service and retail and wholesale trade sectors. Projected changes in the vehicle stock and VMT of personal-use class-1 and class-2 trucks are developed by the automobile model for use by the freight model.

The VMT projections allow for some replacement over time of class-2 and class-3 trucks by class-1 and class-2 trucks and of class-6 and class-7 trucks by class-7 and class-8 trucks. The rate of such downsizing and upsizing is user specified. Otherwise, the freight model assumes that for each economic sector, the distribution of use for trucks of classes 1-7 by vehicle type, range of operation, and region will remain the same as that observed in the base year.

A modal-diversion capability for the model is now being developed. The modal-diversion analysis will be applied by commodity to all traffic that is truck or rail competitive. Shifts in mode split will be projected on the basis of changes in relative modal costs and estimates of the overall sensitivity of the modal choice of each commodity group to changes in relative cost. Changes in modal costs will reflect projected changes in fuel efficiency as well as exogenous projections of the real cost of fuel, taxes, and other components of modal cost and exogenous specification of changes in truck size and weight limits. The results of this analysis are estimates of truck and rail traffic in California by commodity and region for competitive movements. This traffic is then assigned to truck type and railroad-car type on the basis of base-year distributions. The VMT of trucks transporting such commodities will be determined by dividing by average effective payload.

Projections of truck stock are developed in each year by applying age-specific survival rates to the preceding year's stock, multiplying by annual VMT (by vehicle type and age), subtracting the resulting estimates of VMT of the existing vehicle fleet from the projections of total VMT (by vehicle type), and determining the number of new trucks required. The survival rates used for medium and heavy trucks and tractors are adapted from those estimated by Kenworth Trucking Company from R.L. Polk and Company data as quoted by Energy and Environmental Analysis (EEA) (18). Those for light trucks were derived by EEA (19) from NHTSA (20).

The number of new methanol vehicles by type is determined on the basis of exogenous projections, and the number of new LPG or LNG vehicles is determined so as to maintain their relative importance in each vehicle category. The fraction of the remaining new vehicles that will be diesel is then estimated as a function of the fraction that were diesel in the previous year, an exogenous trend, and the lagged change in the relative cost of gasoline and diesel fuel.

Fuel consumption of trucks is projected by multiplying estimated VMT times fuel efficiency by vehicle type, fuel type, and vintage. For class-8 single-unit trucks and all combinations, payloads are also considered in this calculation. Fuel consumption of rail transport is projected on the basis of estimated ton miles transported and average fuel efficiency by car type.

The fuel efficiency of pre-1978 gasoline and diesel trucks of classes 1-7 was derived by vehicle type and vintage from TIUS data. The fuel efficiency of pre-1978 combinations and class-8 trucks as a function of payload was derived from data used in

Table 2. Projected improvement in fuel efficiency.

	Improvement Rate (%)									
	Gasoline					Diesel				
Period	Class 1	Class 2	Classes 3-5	Class 6	Classes 7, 8	Class 1	Class 2	Classes 3-5	Class 6	Classes 7, 8
1978-1982	7	4	1.3	1	2	4	4	1.3	1	3
1983-1985	5	5	1.3	1	2	4	4	1.3	1	3
1986-1990	3	3	1.3	1	1.3	4	4	1.3	1	1.3
1991-1995	2.5	2.5	0.5	0.5	0.8	1.5	1.5	0.5	0.5	0.8
1996-2002	1	1	0.1	0.1	0.2	1	1	0.1	0.1	0.2

Note: Efficiencies projected for model year 2002 in miles per gallon are as follows. Gasoline: class 1, 29.2; class 2, 21.4; classes 3-5, 8.9; class 6, 6.6; classes 7 and 8, dependent on payload. Diesel: class 1, 36.9; class 2, 31.2; classes 3-5, 13.4; class 6, 9.8; classes 7 and 8, dependent on payload.

Table 3. Truck ton-mile projections.

	Volume Projected (billions of ton miles)			
Commodity Group	1977	1980	1990	2002
Agricultural products	8.13	8.36	10.12	11.02
Construction and mining	9.46	9.28	10.60	10.74
Timber and lumber	1.52	1.52	1.57	1.59
Food products	2.12	2.18	2.64	2.87
Paper products	1.47	1.72	2.14	2.72
Chemicals	0.59	0.62	0.74	0.97
Primary metals	0.32	0.36	0.50	0.62
Machinery	0.21	0.26	0.50	0.90
Other manufacturing	2.20	2.35	3.21	4.05
Household goods movement	0.35	0.38	0.46	0.51
Total	26.38	27.02	32.48	36.00

Table 4. VMT projections by commodity group.

	VMT Projected (millions of vehicle miles)			
Commodity Group	1977	1980	1990	2002
Agricultural products	3,134	3,223	3,898	4,245
Construction and mining	3,206	3,092	3,788	3,843
Timber and lumber	396	400	414	417
Food products	238	244	296	322
Paper products	179	208	259	330
Chemicals	74	79	95	124
Primary metals	113	125	173	215
Machinery	39	47	93	166
Other manufacturing	699	747	1,019	1,286
Household goods movement	419	448	550	611
Motor homes	196	228	139	162
Retail trade	2,154	2,508	3,153	3,917
Wholesale trade	1,960	2,282	2,818	3,014
Utilities	570	664	843	868
Services	3,761	4,380	6,174	7,801
Personal-use trucks	20,248	26,101	24,987	35,281
Total	37,385	44,777	48,699	62,600

the Truck Size and Weight Study (21) as was the fuel efficiency of rail transport by car type. Projected rates of improvement in fuel efficiency for 1978 and subsequent years are provided to the model exogenously. Those now in use are shown in Table 2. The improvement rates shown for light trucks are the same as those used in the automobile model; those shown for heavy trucks are based on projections developed by EEA (22) through 1985 and by Argonne National Laboratory (23). Fuel efficiencies for methanol vehicles are assumed to be 0.6 times those of corresponding gasoline vehicles, and those of LPG or LNG vehicles to be 0.95 those of gasoline vehicles.

RESULTS

In this section a summary of the base-case projections produced by the phase-1 freight model for 1977-2002 is given. The complete projections for selected years (1977, 1980, 1982, 1985, 1990, 1995, 2000, and 2002) are contained in the appendix to the freight model report (1).

Freight Volume

Projections of the volume of freight traffic transported by truck are shown in Table 3 for the first 11 commodity groupings. These projections, like all those produced by the model, represent transport occurring within California and include an estimate of the California portion of Interstate transport. The figures represent the estimated volume of all transport in tractor-trailer rigs and class-8 single-unit trucks of the first four commodity groups [agricultural products (groups 1 and 2), construction and mining, and timber and lumber] as well as nonlocal transport in these vehicles of the remaining seven commodity groups.

As can be seen from Table 3, two-thirds of the transport of these commodities consists of agricultural products and construction and mining products. (Mining products transported by truck in California, in terms of tonnage, consist primarily of construction materials such as sand and gravel and crushed stone, so these products have been combined with construction materials within the model.)

The projections in Table 3 show slight growth in the transport of timber and lumber through 2002 and greater growth in the transport of the other commodities (although a slight dip was estimated for construction and mining materials between 1977 and 1980). The growth rates are projected to be greatest for several manufacturing products; truck transport of machinery is projected to quadruple in the 25-year period covered. Overall, truck freight volume is projected to increase by 36 percent through 2002. All projections shown in Table 3 are based primarily on CEC economic projections by sector.

VMT

Projections of VMT for trucks in California are shown in Table 4 for 16 activities and commodities, the first 10 of which correspond to the 10 commodities given in Table 3. The other six categories are motor-home use, personal-use trucking, and four commercial activities.

The projections shown in Table 4 represent VMT of all trucks, not just the combinations and class-8 trucks represented in Table 3. The projections for VMT of commercial-use vehicles, however, like the freight-volume projections of Table 3, are based primarily on CEC economic projections by sector. Accordingly, growth in VMT of commercial-use trucks exhibits much the same pattern as growth in freight volume. The VMT projections for personal-use trucks

Table 5. VMT projections by vehicle category.

Vehicle Category	VMT Projected (millions of vehicle miles) 1977	1980	1990	2002
Truck				
Class 1				
Pickup	13,245	16,061	20,354	28,904
Utility	1,055	1,442	827	1,092
All other	5,653	7,509	5,534	7,679
Class 2				
Pickup	7,468	8,570	9,460	10,843
Utility	229	262	227	233
Van	3,470	4,172	3,821	4,167
All other	199	242	320	357
Classes 3-5	338	291	302	301
Class 6	1,043	1,093	1,270	1,295
Class 7	110	148	308	499
Class 8				
Dump or garbage	181	197	246	282
All other	294	323	414	486
Combination				
Single trailer				
Van	1,589	1,770	2,271	2,666
Platform or flatbed	464	497	614	697
Dump or garbage	183	182	211	218
Tank	282	312	400	471
Other	76	83	107	125
Double trailer				
Van	794	886	1,129	1,325
Platform or flatbed	335	350	422	462
Dump or garbage	178	180	213	225
Tank	140	144	172	186
Other	59	63	78	88
Total	37,385	44,777	48,699	62,600

Table 6. Vehicle stock projections by vehicle category.

Vehicle Category	Stock Projected (thousands) 1977	1980	1990	2002
Truck				
Class 1				
Pickup	1,256	1,546	1,707	2,250
Utility	99	135	76	90
Other	529	685	478	602
Class 2				
Pickup	746	899	962	974
Utility	20	23	25	23
Van	258	312	319	304
Other	25	31	44	43
Classes 3-5	39	33	24	18
Class 6	83	87	78	73
Class 7	8	9	15	24
Class 8				
Dump or garbage	9	10	12	13
Other	11	12	15	17
Tractor	86	89	110	121
Total	3,169	3,873	3,863	4,553

are developed by the automobile model and those for class-1 and class-2 motor homes are inferred from automobile model projections.

VMT of personal-use trucks are estimated to account for 54 percent of total truck VMT in 1977 and, despite a dip between 1980 and 1990, this percentage is projected to rise to 56 percent in 2002. Largely because of relatively rapid growth in the non-goods-movement sectors, greater growth in VMT between 1977 and 2002 (67 percent) is shown in Table 4 than is shown for traffic transported by trucks (36 percent) in Table 3.

In Table 5 the VMT projections are given by vehicle category. Light trucks accounted for 84 percent of total VMT in 1977, and this percentage is projected to increase slightly to 85 percent in 2002. Steady growth in VMT is projected for most vehicle categories, although a dip is projected for several categories of class-1 and class-2 trucks between 1980 and 1990, and as a result of continued downsizing, VMT of trucks in classes 3-5 is projected to decline throughout this period. The greatest percentage of increase in use is projected for class-7 trucks, which, as a result of upsizing of class-6 trucks, are projected to contribute about 4.5 times as much VMT in 2002 as in 1977.

Vehicle Stock

Projections of California truck and tractor stock by vehicle category are shown in Table 6. The projections produced by the model indicate that vehicle stock will grow somewhat more slowly than VMT. This is primarily because of a projected increase in the use of diesel trucks and an assumption, embedded in the model's structure, that the average annual VMT of commercial-use vehicles is determined by the vehicle type, fuel type, age, and whether they are primarily used locally but not by other use characteristics. To the extent that other use characteristics affect average VMT, the model may underestimate the effect on the average VMT of diesel vehicles of their increasing substitution for gasoline-powered vehicles. Accordingly, the truck stock projections may be understated in those categories in which a significant conversion to diesel trucks is projected (classes 1-6).

As shown in Table 6 a substantial decline is projected in trucks of classes 3-5 (largely as a result of upsizing), and more moderate declines are projected in the number of class-6 trucks (as a result of downsizing) and in class-1 utility vehicles (e.g., jeeps). On the other hand, substantial increases are projected in the number of class-7 trucks (as a result of upsizing) and in the numbers of class-1 pickups and miscellaneous class-2 vehicles. The decline in the number of utility vehicles and the increase in the number of pickups are largely caused by a projected shift in the relative personal-use popularity of these two vehicle types. Overall, vehicle stock is projected to increase by 44 percent between 1977 and 2002, and the number of light trucks is projected to rise from 92.5 percent to 94 percent of the total.

Fuel Consumption

Projections of California gasoline and diesel-fuel consumption by truck category are shown in Table 7 along with projections of diesel-fuel consumption by rail-freight operations. Despite a 67 percent increase in truck VMT between 1977 and 2002, total truck fuel consumption (in gallons), exclusive of the rail-freight component, is projected to decline by 20 percent between 1977 and 2002. This decline is caused by improved fuel efficiency (especially among light-duty trucks) and the greater fuel efficiency of diesel engines.

The model, which prints fuel consumption projections for each year between 1977 and 2002, estimates that gasoline consumption by trucks in California peaked in 1980 at 3.3 billion gal and will decline to 1.35 billion gal in 2002. Diesel-fuel consumption is expected to grow from 1.2 billion gal in 1977 to 2.1 billion gal in 2002.

It can be seen that a switch to diesel fuel is projected for all categories. By 2002, gasoline consumption by combinations and class-8 single-unit trucks is projected to drop to almost zero, and diesel fuel is also projected to become the dominant fuel for class-6 and class-7 trucks. An increasing portion of fuel consumed by light-duty (classes 1 and 2) and medium-duty (classes 3-5) trucks is also

Table 7. Projected gasoline and diesel-fuel consumption by vehicle category.

Vehicle Category	Fuel Consumption Projected (millions of gallons)			
	1977	1980	1990	2002
Truck				
Class 1				
Gasoline	1,553	1,824	1,136	855
Diesel fuel	0.03	16	130	395
Class 2				
Gasoline	1,132	1,218	809	468
Diesel fuel	0.6	1.5	71	206
Classes 3-5				
Gasoline	51	41	26	10
Diesel fuel	0.2	0.2	7	16
Class 6				
Gasoline	179	161	48	12
Diesel fuel	7	21	107	125
Class 7				
Gasoline	15	13	8	3
Diesel fuel	10	16	39	64
Class 8				
Gasoline	12	8	1	0.1
Diesel fuel	88	94	99	104
Combination				
Gasoline	36	33	7	0.7
Diesel fuel	828	854	849	880
Railroad				
Diesel fuel	245	255	304	348
Total				
Gasoline	2,977	3,298	2,036	1,349
Diesel fuel	1,179	1,257	1,606	2,138

projected to be diesel fuel. The increased use of diesel fuel reflects, in part, CEC projections of an increasing real price difference between gasoline and diesel fuel and thus may be slightly overstated.

REFERENCES

1. Jack Faucett Associates, Inc., and System Design Concepts, Inc. California Freight Energy Consumption Model: Phase I Report. California Energy Commission, Sacramento, Aug. 1982.
2. Cambridge Systematics, Inc. Vehicle Ownership and Usage: An Integrated System of Disaggregate Demand Models. California Energy Commission, Sacramento, Aug. 1982.
3. System Design Concepts, Inc. California Transit Energy Model. California Energy Commission, Sacramento, Aug. 1982.
4. 1977 Light Truck File (magnetic tape). R.L. Polk and Co., Detroit, Mich., n.d.
5. 1977 Domestic Car File (magnetic tape). R.L. Polk and Co., Detroit, Mich., n.d.
6. 1977 Import Car File (magnetic tape). R.L. Polk and Co., Detroit, Mich., n.d.
7. 1978, 1979 Medium/Heavy Truck Files (magnetic tape). R.L. Polk and Co., Detroit, Mich., n.d.
8. 1977 Truck Inventory and Use Survey (magnetic tape). Bureau of the Census, U.S. Department of Commerce, n.d.
9. Commodity Transportation Survey (magnetic tape). Transportation Systems Center, U.S. Department of Transportation, Cambridge, Mass., 1977.
10. 1977 Waybill File (magnetic tape). Federal Railroad Administration, n.d.
11. 1977 Truck Weight Study (magnetic tape). FHWA, n.d.
12. 1978 Truck Weight Study (magnetic tape). FHWA, n.d.
13. Empty/Loaded Truck Miles on Interstate Highways During 1976. Interstate Commerce Commission, April 1977.
14. Travel and Related Factors in California: Annual Summary--1980. California Department of Transportation, Sacramento, 1980.
15. Completed Fleet Vehicle Census and Survey Results of California-Based Fleets. Bobit Publishing Co., Redondo Beach, Calif., Jan. 27, 1982.
16. Automobile Fleet. Bobit Publishing Co., Redondo Beach, Calif., April 1981.
17. Highway Statistics 1980. FHWA, 1981.
18. Energy and Environmental Analysis, Inc. Medium and Heavy-Duty Truck Fuel Demand Module. U.S. Department of Energy, final rept., May 1980.
19. Energy and Environmental Analysis, Inc. Technical Analysis of the Light-Duty Truck Fuel Economy Standards for 1985 Model Year. U.S. Department of Energy, May 1980.
20. Rulemaking Support Paper Concerning 1981-1984 Passenger Auto Average Fuel Economy Standards. NHTSA, July 1977.
21. D. Knapton. Truck and Rail Fuel Effects of Truck Size and Weight Limits. In An Investigation of Truck Size and Weight Limits, Technical Supplement Volume 3, U.S. Department of Transportation, July 1981.
22. Energy and Environmental Analysis, Inc. Medium and Heavy-Duty Truck Fuel Demand Module Update and Calibration of the Highway Fuel Consumption Model. U.S. Department of Energy, Dec. 18, 1980.
23. M. Millar et al. Baseline Projections of Transportation Energy Consumption by Mode: 1981 Update. Argonne National Laboratory, Argonne, Ill., Rept. ANL/CNSV-28, April 1982.

Individual Responses to Rising Gasoline Prices: A Panel Approach

ROGER B. TRENT AND CECIL R. POLLARD

A panel survey design is used to study how individual motorists responded to rising gasoline prices during the latter half of the 1970s. Data on past and future responses to rising gasoline prices were obtained in 1975, 1976, and 1980; the responses were coded into three categories: drive less, other economy measures, and no change. Almost all drivers reported some effect of gasoline prices, and by 1980 most drivers were prepared either to drive less or to pay up to $2.00/gal to maintain their current level of driving. Analysis of trend data suggests that many drivers do eliminate some of their discretionary driving when gasoline prices rise, particularly when the rate of increase is faster than the increase in inflation.

This research is an attempt to describe the patterns of responses made by drivers as gasoline prices rose sharply during 1974-1980. Some responses cope with costs by making travel more efficient, whereas others simply limit travel without making it more efficient. Some information on changing travel patterns is available in the form of aggregate data, such as overall gasoline consumption and changes in transit ridership from one year to the next. These aggregate trends will be examined, and so will the trends in individual travel behavior in a panel of respondents. The panel data will allow the examination of individual responses in some detail. Moreover, because these respondents were interviewed up to three times during the period under examination, it will be possible to determine which coping strategies are attempted for a short time and then abandoned and which are more resilient in that respondents continue to use them. Thus, it will be possible to differentiate long-term from short-term responses to rising gasoline prices.

METHODS AND DATA

In a transportation survey in the spring of 1975, the researchers asked respondents a series of questions about their travel behavior, among them, how they would respond if the price of gasoline rose to $1.00/gal. In surveys in 1976 and in 1980, more questions concerning travel behavior and response to rising gasoline prices were asked. These data are the basis of the analysis in this paper.

The study design is a panel survey in which the respondents in the first survey (1975) are reinterviewed in the second and third surveys (1976 and 1980). This design allows direct assessment of how individuals change over time in contrast to the normal cross-sectional survey that allows only assessment of changes in aggregates. The panel is the preferred design for microanalysis of change.

In 1975 a representative sample of 305 nonstudent adult householders in an Appalachian city of about 38,000 population (1), including its surburban fringe, was selected. Students, whose travel patterns, car ownership rates, and length of tenure in the local area tend to be distinct from those of the nonstudents, were excluded from the survey. In 1976, 221 of the original 1975 sample plus a supplementary sample of 102 new respondents were reinterviewed. The panel was continued in 1980 when 195 of the total of 323 respondents from the 1976 survey were reinterviewed. In essence, a panel of respondents was followed over the 5-year period; each respondent was interviewed two or three times. The shrinkage in the sample represents those who moved from the area, died, refused to be reinterviewed, or could not be located. The combined result of panel shrinkage and the drawing of supplementary samples is a series of sample sizes, depending on which pair of surveys is compared. Sample size is also affected by the exclusion of respondents who do not own vehicles.

Before the panel data are analyzed, the trends in the changing gasoline prices and the possible responses on the part of the driving public will be examined. This analysis uses two kinds of aggregate trend data. Whenever possible, local or regional data are used. In cases where local or regional data are either unavailable or inappropriate, national data are used as an approximate indicator of the local situation. In a subsequent section, panel data from the survey region on individual responses to gasoline price increases are examined.

CHANGING TRAVEL SITUATION: 1974-1980

The Gasoline Crisis

The gasoline crisis consists of gasoline shortages and rising prices following the Arab oil embargo of 1973. Shortages appeared to have had only a temporary effect on gasoline consumption (2), but it is not clear what effect rising prices had. The years following the embargo witnessed rising gasoline prices and persistent inflation in prices of other commodities as well. Although "creeping inflation is generally characterized by a reduction in discretionary expenditure" (3), these reductions are not the same in all purchase categories. Differential reductions in consumption, or substitution effects, will occur for items the prices of which become dearer relative to the prices for other items (4). Substitution effects inevitably occur, because inflations always alter the relative prices of goods and services (5). In the case of gasoline this implies, first of all, that the portion of a consumer's gasoline purchases that is used for discretionary driving should show a higher elasticity than gasoline purchases for nondiscretionary driving. To the extent that motorists make both discretionary and nondiscretionary trips, gasoline may be elastic to the point where most discretionary driving is eliminated, after which point it may become inelastic. This argument will be pursued later.

A second implication of the relativity of substitution effects during inflation is that motorists probably base their purchase decisions over time not on gasoline prices per se but rather on relative gasoline prices [i.e., prices adjusted by the consumer price index (CPI)]. Both nominal (pump) prices and inflation-adjusted prices are given in Figure 1 to show the difference between the two types (6). (Figure 1 shows average national prices because accurate and relevant localized prices were unavailable for the study area.)

First consider the retail pump price, the uppermost trend line in Figure 1. The price rises experienced by drivers during this period are much greater after 1978 than before. The price of gasoline in 1974 was $0.52/gal, but the price was up to $0.63 in 1977. This represents a yearly annual increase of about 5 percent. As shown in the graph, the price rose sharply from 1977 to 1980 (a 32 percent annual increase). The lower trend line in Figure 1 is the retail pump price of gasoline adjusted by the CPI ("real" price). Whereas the upper trend line represents the numbers on the gasoline pumps that motorists faced every week, the lower trend line represents the relative cost of gasoline compared with other typical consumer expenditures. Interestingly, the real price of gasoline actually declined slightly from 1974 to 1978. From 1978 to 1980 the real price jumped 46 percent from $0.50 to $0.73/gal in 1974 dollars.

If, in the case of gasoline, consumers repond to nominal prices, it would be expected to find some decrease in gasoline demand throughout the period encompassed by this research, with perhaps a sharp decrease after 1978. These decreases would correspond to the successful implementation of various strategies to cut travel costs by individual consumers. On the other hand, if consumers respond to relative prices, any decrease in gasoline sales would not be expected until after 1978, when a modest decrease might be evident. In either case there can be a considerable lag in consumer response to gasoline prices because some saving strategies (e.g., buying a more gasoline-efficient automobile) require more time to carry out than others (e.g., cutting down on discretionary driving).

Figure 1. Nominal and adjusted prices for regular (leaded) gasoline (1974 = 100 CPI) (6, p. 186).

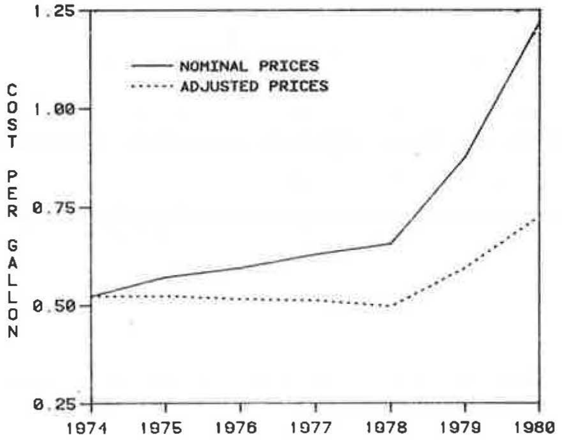
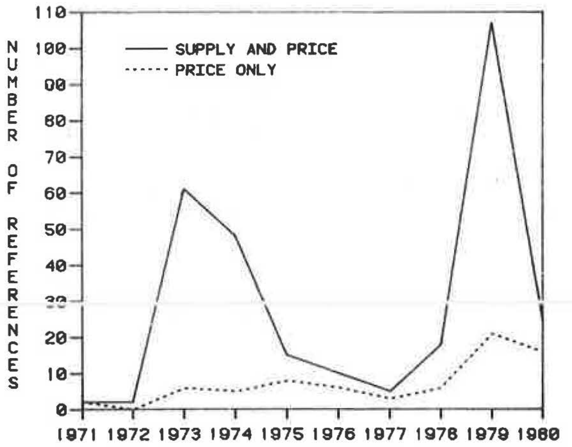


Figure 2. Regional graph of references to gasoline situation in American periodicals (7).



Media Response

If some relationship is assumed between media coverage and public perception of the gasoline price situation, trends in media coverage can be examined to gauge the impact of events on the American public. Figure 2 is a regional graph showing trends in the number of articles discussing the gasoline situation. The data source is the Reader's Guide to Periodical Literature (7). The space under the upper trend line represents the total number of articles published in a large number of American periodicals on the topics of gasoline prices, rationing, supplies, and conservation. The lower region shows the number of articles dealing solely with prices out of the total number of articles published each year. If Reader's Guide citations are a reasonably valid indicator of consumer exposure to issues, it may be seen that the issue of gasoline prices was never forcefully raised until 1979, and even then only 20 percent of the articles on the gasoline situation had to do with prices.

If the price issue was not a focus of media attention during these years, what issues relevant to the gasoline situation were raised? Of all the articles cited from 1971 to 1979, 74 percent concerned either supply or rationing of gasoline. In other words the issue of price was dwarfed by the issues of supply and rationing. If gasoline were a highly elastic commodity (i.e., one for which the price would have a strong relationship to demand), it would be expected that much public attention would be given to the price issue. Instead issues of supply and rationing received much more media exposure. The pattern hints, first of all, that gasoline may be a relatively inelastic commodity and second that savings strategies may be in response to other issues, particularly the perceived availability of gasoline.

Some Aggregate Trends in Travel Behavior

When automobile drivers are confronted with the gasoline situation (higher prices and occasional shortages), they can respond in three major ways to defend their mobility or their standard of living. First there are both individual and aggregate changes that can increase the efficiency of private automobiles. Scores of magazine articles have advised drivers to increase efficiency by getting more frequent tune-ups, properly inflating tires, avoiding fast driving, cutting warm-up times, and limiting use of automobile air conditioners. On the aggregate level, efficiency can be improved by enforcing speed limits, timing traffic lights, and creating one-way streets. All these actions serve to make automobiles more fuel efficient regardless of the average load factor per vehicle.

Second there are strategies to change the average load factor to achieve greater efficiency without necessarily increasing the mileage efficiency of individual vehicles. One of these is ridesharing. Another is using some form of public transit rather than a private automobile. Both of these strategies allow one to be mobile at less net cost and without making vehicles more fuel efficient.

If one chooses not to adopt any of these strategies for defending mobility, he or she can decide to sacrifice mobility in defense of standard of living. In other words, one strategy for drivers who face a gasoline shortage is to drive less and therefore travel less. Unlike the alternatives discussed above, this strategy will have an effect on the number of miles traveled as well as on aggregate gasoline consumption. Like the second alternatives--use of transit and ridesharing--driving less will reduce per-capita aggregate gasoline consumption and highway mileage. Only fuel-efficiency measures, such as buying high-mileage automobiles and enforcing speed limits, would be expected to decrease gasoline consumption independent of miles driven.

To what extent have American drivers adopted fuel-efficiency measures? This question will be answered by focusing on fuel-efficiency ratings of new automobiles rather than on other factors such as tune-ups. Probably the overall efficiency of automobiles has a much more profound effect on mileage than do keeping automobiles tuned and keeping their tires properly inflated. Furthermore there are concrete data on automobile efficiency provided in the mile-per-gallon (mpg) ratings by the U.S. Environmental Protection Agency (EPA) of automobiles sold in recent years. Figure 3 shows the trend in EPA ratings of new automobiles from 1974 through 1980 (8). Obviously the average efficiency of automobiles has increased a great deal. The 1980 average mpg of 23.3 is a 66 percent increase over the 1974 mpg of 14.0. Of course the actual mileage of all cars driven in a given year is a complex mix of cars of varying efficiencies being driven various distances under varying conditions, but the tendency for consumers to buy more efficient cars is clear. It may be assumed that this trend represents consumer preferences, because Detroit's underestimation of the consumer demand for smaller, more efficient automobiles is widely considered a major cause of the recent rise in sales of imported automobiles at the expense of domestic automobiles. On the other hand, consumers buying a car at random in 1980, for example, would have obtained a more efficient car than they would have in 1979 simply as a function of the greater efficiency of all automobiles available. Although it cannot be determined to what extent Corporate Average Fuel Economy (CAFE) standards forced shifts to more efficient automobiles in spite of consumer preferences, the strong revealed preference for fuel-efficient imported automobiles leads one to believe that consumers really wanted more efficient automobiles.

Figure 3. EPA mileage ratings of new cars sold in the United States (8).

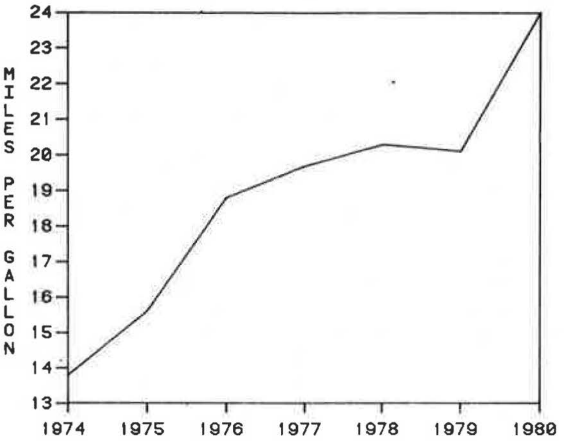
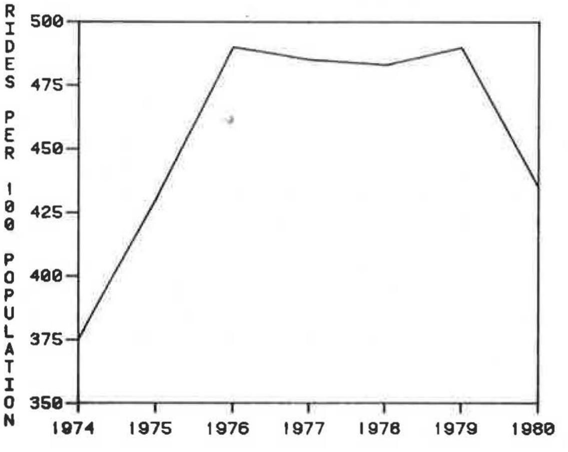


Figure 4. Rides on municipal bus system per 100 population.



Another strategy for maintaining mobility and reducing cost is to switch to public transit. Nationally ridership on public transit increased during the 1970s. In general, transit use in the study area is low. The Morgantown municipal bus system is quite small, and relatively few townspeople travel on the Morgantown downtown people mover located on the campus of West Virginia University. Figure 4 shows rides per 100 population on the municipal bus system, according to data from the Morgantown Municipal Transit. The increase between 1974 and 1976 may reflect in part the system's acquisition of a new bus in 1974. The total number of route miles has remained fairly constant since 1974. Whatever the cause of the increase between 1974 and 1976, patronage leveled off until 1979, when it dropped. However one might wish to interpret the rise or the subsequent drop in ridership, there is no evidence that the gasoline shortage spurred transit use in the study region (this generalization may not hold in urban areas with more extensive transit systems). Recall that adjusted gasoline prices actually declined when local transit use increased (from 1974 to 1976), and when adjusted gasoline prices finally rose after 1978, transit use dropped locally.

Another way to maintain mobility while holding the line on cost of travel is to increase the load factor in private vehicles, i.e., to share rides. In standard metropolitan statistical areas (SMSAs) surveyed by the Census Bureau in 1975, 21 percent of the automobile and truck commuters reported that they shared a ride to work (9). In the study region, a metropolitan area much smaller than any SMSA, 34 percent of the automobile and truck commuters reported that they shared a ride to work with at least one other person, and the average load factor in this sample is 1.54 persons per vehicle (10). Evidently ridesharing is a popular strategy for maintaining mobility while reducing cost.

Vehicle miles traveled (VMT), monitored by the West Virginia Department of Highways, can serve as an indicator of the extent to which drivers reduce vehicle travel or increase the average load factor per vehicle. Thus, to the extent that people drive less, ride share, or use public transit, VMT will be affected (on the other hand, VMT will not be affected by changes in fuel efficiency as drivers switch to automobiles that have high mpg ratings).

VMT in the study region, shown in Figure 5, increased over the study period except for declines in 1975 and in 1979, the last year for which data are currently available. The drop in 1975 is hard to explain. There were no serious gasoline shortages during that year. The price of gasoline did climb in 1976, but the adjusted price actually declined. It cannot be determined whether the 1975 drop was a short-lived response to unadjusted price increases, but by 1976 an upward trend in VMT began that continued until 1978. It will be seen that the decline

Figure 5. VMT per mile of road (x1,000), Monongalia County, W. Va.

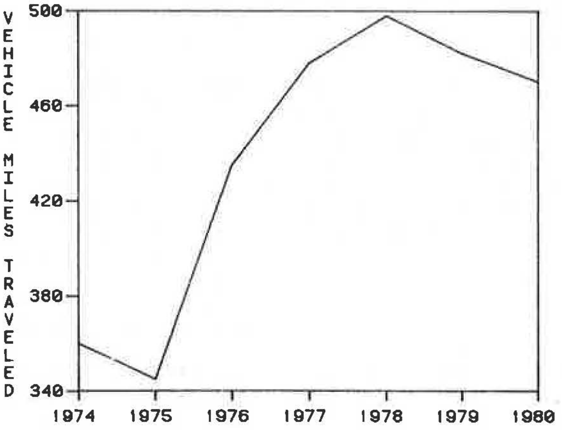
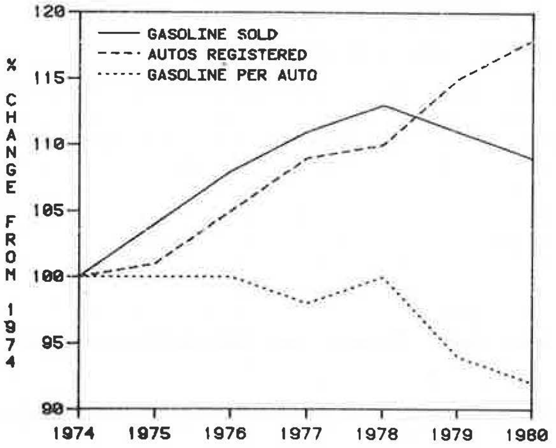


Figure 6. Changes in automobiles registered and gasoline consumed, 1974-1980 (11, p. 107).



in VMT after 1978 parallels a drop in actual gasoline consumption that occurred nationally as well as in the study region. Thus it seems likely that automobile travel has decreased since 1978, and in the study region the decrease cannot be attributed to increased transit use, because transit use actually declined after 1979. Moreover changes in the overall efficiency of automobiles on the road could not explain such an abrupt decline. Evidently automobile travel had actually dropped. This is most likely the result of more ridesharing and less discretionary travel.

Consumption of Gasoline

Changes in consumption of gasoline reflect a mix of changes in all of the strategies discussed so far, assuming that actual shortfalls do not occur. Other factors will affect gasoline consumption; some are too minor to warrant much attention (frequency of tune-ups, for example) and others are not under consumer control (increased efficiency of new automobiles in general). Figure 6 shows national trends in total gasoline consumption, number of automobiles registered, and gasoline consumption per registered automobile, all calculated as percentage changes from 1974 through 1980 (11). Total gasoline consumption closely paralleled the increase in number of automobiles through 1978. In 1979 and 1980 gasoline consumption dropped even though the size of the national automobile fleet continued to grow at about the same pace as before. The effect of these combined changes is seen in the lower trend line; gasoline consumption per automobile declined after 1978.

This drop in gasoline consumption is probably not simply a function of the greater fuel efficiency of newer cars. For one thing the growth in mpg rating of new automobiles is not rapid enough to explain this sudden and sharp decline in gasoline consumption. Although the new cars have been increasingly more efficient, the impact on the national average mpg rating has been slight (12). In addition the decline in VMT in the study region has been seen to parallel the drop in gasoline consumption. Therefore, people must be driving their vehicles less than before, either because they are sharing rides or because they are limiting their discretionary travel.

In summary, during the latter part of the 1970s a gasoline crisis occurred. Gasoline prices rose dramatically, as did prices in general. Although pump prices rose, adjusted gasoline prices did not increase appreciably until after 1978. Similarly the media responded to the gasoline situation mainly in terms of supply and rationing until 1978 when the number of articles dealing with gasoline prices rose rapidly, paralleling the increase in adjusted gasoline prices. After 1978 there was also a substantial deline in VMT and gasoline consumption. The data appear to indicate that neither changing vehicle efficiency nor changing transit ridership can adequately account for reduced VMT and gasoline consumption after 1978. It appears that drivers were actually driving less in response to the rising adjusted price of gasoline.

PANEL-SURVEY ANALYSIS

In the previous section the gasoline situation as it developed after the Arab oil embargo in 1973 was examined. These changes in gasoline availability and price led to a complex set of aggregate responses on the part of consumers, transportation policymakers, and transportation markets. In this secton individuals rather than aggregated responses will be used to examine the problem-solving processes consumers use to adjust to changing market conditions. Because the samples are relatively small, it will not be possible to examine age, socioeconomic factors, and other subpopulations in this analysis.

Citizens Assess Their Travel Options

At the time of the first survey in the spring of 1975, panelists were asked, "If gasoline goes up to $1.00/gal, what will you do?" Their responses were recorded in the order that they were given. Everyone in the sample gave some response to this question. Thus in 1975, with the Arab oil embargo still fresh in the public's mind, the respondents were able to articulate how they would react to what appeared to be a large increase in the price of gasoline.

Answers to questions on how respondents would cope with higher gasoline prices were coded into three categories: drive less, other economy measures, and no change. Drive-less respondents are those whose only reaction to higher prices is to drive less and therefore travel less. Other economy measures included any answer, such as ridesharing, buying a more efficient automobile, and bus riding, that indicates an attempt to maintain mobility by economizing in some way other than by simply driving less. No-change respondents asserted that they would not change their travel patterns.

We have seen that respondents have strategies in mind as they contemplate rising gasoline prices. Do different behaviors result when prices actually do go up? The individual behavioral data required to answer this question are not available; so self-reported behavior must be substituted. In 1975 respondents chose one of three strategies to cope with $1.00/gal gasoline: 39 percent said they would drive less, 27 percent said they would employ one of the economy strategies, and 33 percent predicted they would make no change. (These and all the other percentages discussed in the following are based on turnover tables of respondents who provided answers to a pair of questions on two of the three surveys; sample size will vary as a consequence.) In the following tabulation, respondents reported whether gasoline prices had affected their driving by 1976 according to the reaction they had predicted in 1975 (during this 1-year interval the pump price of gasoline rose from about $0.57 to $0.59/gal, but the price adjusted for inflation remained virtually stable):

	Predicted Reaction to $1.00 Gasoline in 1975 (%)		
Effect in 1976?	Drive Less (N = 89)	Economy Measure (N = 51)	No Change (N = 64)
Yes	44	49	19
No	56	51	81

About one-third reported an effect as of 1976. The percentage of respondents who predicted they would drive less or use an economy strategy was evenly split in 1976 between reporting an effect and reporting no effect. But of those who had predicted that $1.00 gasoline would have no effect on their driving behavior, only 19 percent reported an effect. In other words about half of those who had said that they would take positive steps reported having done so, whereas those who had said that they would not take steps generally did not.

In the next tabulation remembered effects of gasoline prices in 1980 are given according to respondents' 1975 predictions:

	Predicted Reaction to $1.00 Gasoline in 1975 (%)		
Effect in 1980?	Drive Less (N = 56)	Economy Measure (N = 32)	No Change (N = 40)
Yes	70	75	43
No	30	25	58

In this 5-year span, the overall proportion of those who remembered any effect of rising gasoline prices is 63 percent (compared with only 37 percent for the 1975-1976 interval). Once again, a remembered effect is much more likely among those who either had predicted they would drive less (70 percent) or would use an economy strategy (75 percent) than among those who in 1975 had said that they would not change (43 percent).

Taken together, the preceding tabulations demonstrate that

1. More people believe that they have been affected by rising gasoline prices, especially over the 5-year span;
2. In both the short run and the long run, those who had predicted that they would respond to higher gasoline prices with a positive strategy (either driving less or economizing) were more likely to remember having made a response to gasoline prices than those who had initially stated that they would make no change; and
3. Even among those who in 1975 had predicted that they would not respond to higher gasoline prices, almost half reported having made some change by 1980.

Having established the prevalence of reported effects of price increases, let us turn to a more precise description of differences between respondents who had initially selected different ways of coping. Respondents will be compared according to how they answered the question of their response to $1.00/gal gasoline in the short run, i.e., from 1975 to 1976. As an aid to interpreting the following tabulation, note that if respondents always reported the same strategies--that is, if there was no shifting of strategies whatever--all of the cases would lie on the diagonal, running from the upper left to the lower right:

	Predicted Reaction to $1.00 Gasoline in 1975 (%)		
Actual Reaction in 1976	Drive Less (N = 81)	Economy Measure (N = 45)	No Change (N = 55)
Drive less	56	40	18
Economy measure	13	29	16
No change	31	31	66

Actually, there is a great deal of shifting manifest in the data in spite of the relative stability of the marginal proportions. Of those who in 1975 had selected a drive-less strategy, a few (13 percent) changed to an economy strategy, but almost one-third switched to a no-change position. Of those who had initially selected an economy strategy, 40 percent later said that they would drive less if gasoline rose to $1.00/gal, and 31 percent moved to the no-change category, which left only 29 percent maintaining their original position. Those who had initially said that $1.00 gasoline would not change their travel habits were most likely to reiterate their stance 1 year later with 66 percent stability.

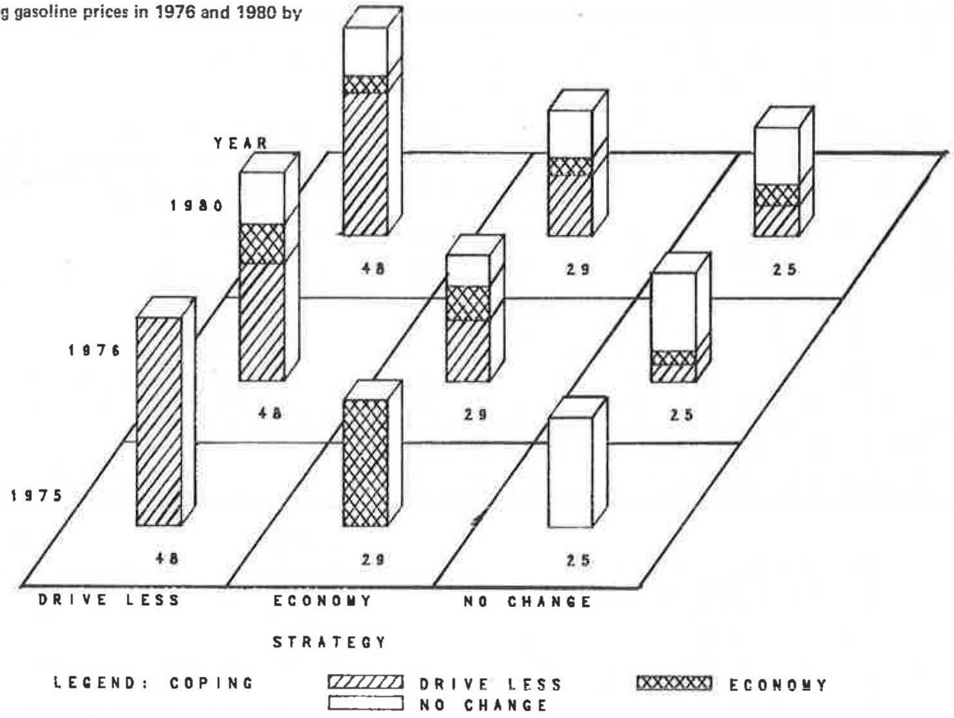
More shifting is evident in this last tabulation, which shows long-run changes in coping strategies (the 1980 data are based on the reaction of the respondent to a rise in price to $2.00/gal because the $1.00 standard used in 1975 and 1976 had become obsolete):

	Predicted Reaction to $1.00 Gasoline in 1975 (%)		
Actual Reaction in 1980	Drive Less (N = 29)	Economy Measure (N = 32)	No Change (N = 49)
Drive less	31	50	67
Economy measure	21	13	8
No change	48	38	24

Of respondents who in 1975 had chosen a drive-less strategy, almost half by 1980 predicted that they would not change their habits any more if gasoline increased to $2.00/gal. Only 21 percent said that they were prepared to shift to some economy strategy. Those who had initially chosen an economy strategy were, by 1980, mostly ready to drive less (50 percent) or make no change (38 percent). Finally, respondents who had initially said that they would make no change were prepared in 1980 to begin driving less (67 percent) to save gasoline, a few (8 percent) would select an economy option, and 24 percent would continue to resist any change in travel habits.

The long-term changes shown in the previous tabulation can be summarized briefly if it is assumed

Figure 7. Predicted responses to rising gasoline prices in 1976 and 1980 by predicted strategy in 1975.



that respondents who in 1980 reported that they would make no changes to accommodate $2.00 gasoline are mostly those who had already put one or more strategies into effect. Thus both the drive-less and the economy respondents in 1975 were quite likely to say that rising prices had affected their travel behavior both in 1976 and in 1980. A difference between those two groups is that although only 21 percent of the drive-less respondents would shift to an economy strategy, 50 percent of the economy respondents would shift to a drive-less strategy. Most of the economy strategies either require a substantial life-style change (such as using more public transportation) or involve a one-time change (such as buying a smaller car) that will not allow a scaled response to gasoline prices. From this perspective, driving less appears to be a more flexible response. Indeed the 1975 no-change respondents contributed a great deal to the predominance of the drive-less category in 1980 because a full 67 percent of those who would not change their response to $1.00 gasoline in 1975 had decided by 1980 that if the price of gasoline became $2.00/gal, they would drive less. So, again, it may be seen that over the long run respondents can always turn to limitation of driving as an easy-to-implement strategy.

If it is true that one's early reaction to gasoline prices can structure one's subsequent options, it may also be true that some options are more durable than others in the sense that they are the most likely to be used in the long run. In particular, driving less might be expected to be the response of choice initially and even more as time goes on.

The data in Figure 7 were assembled to see how each response option--drive less, economy, or no change--either leads to another option or remains a feasible option for the respondent. The first row of bars shows all respondents according to the options they chose in 1975, the baseline. For each of the baseline groups, the second and third rows of bars show respondents' choices of options in 1976 and 1980. During one year a significant minority of the drive-less group (left column) switched to one of the other categories. By 1980 it is clear that for most respondents driving less is the preferred response, even though some felt that they would make no more changes. Perhaps they had already reduced their driving to a level approaching an irreducible minimum.

The population of respondents who had initially picked an economy response (center column) had by 1980 largely changed to the drive-less category. Smaller groups stayed with an economy response or asserted that they would change no more. In other words, respondents who had initially decided to cope with some other strategy than driving less either switch to driving less or, by remaining in the no-change category, assert that their demand for gasoline is inelastic up to $2.00/gal.

The right-hand column in Figure 7 shows the 1975 no-change respondents as they move through the 5 years of the study. By 1976 a few of them had decided that they would try one of the positive strategies, and by 1980 this proportion had increased to not quite half, which means that not changing is a fairly resilient response to rising gasoline prices.

CONCLUSIONS

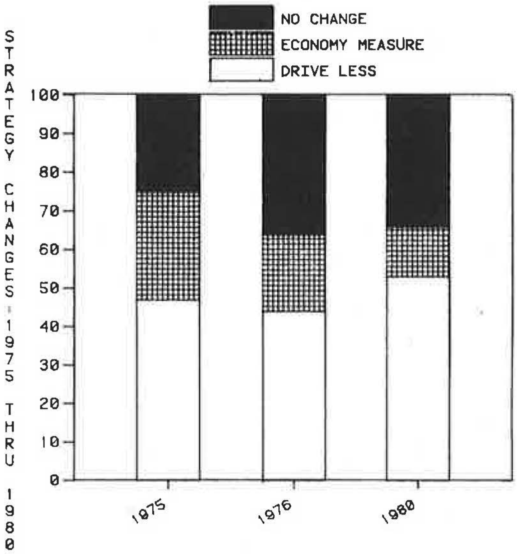
During the latter half of the 1970s, gasoline prices rose in the study region as well as in the nation as a whole. But it was not until 1979 that gasoline prices began to rise rapidly compared with prices for other consumer goods and services. It has been shown that gasoline consumption fell as the adjusted price of gasoline rose. This reduction in gasoline consumption paralleled a drop in vehicle miles traveled in the study region, which leads to the belief that the real price increase in gasoline caused drivers to limit their use of personal vehicles.

Panel data were used to examine specific changes in consumer behavior that are marked by the aggregate trends. Thus, by repeated questioning of respondents, it was possible to examine the processes by which consumers adjusted their behavior to different price schedules. It was found that on the individual level one's response to gasoline prices has a history.

Under what circumstances is gasoline an inelastic commodity? In other words, under what circumstances do rising gasoline prices fail to result in reduced consumption? Most obviously, the price increases have to be real. If the rise in gasoline prices is no greater than the rise in the CPI, the proportion of a consumer's budget spent on gasoline remains about the same. But when a real price increase does occur, as in 1979, a consumer's response depends on the available options. Those respondents who had initially said that they would not respond to a higher price ($1.00/gal) were quite likely to reiterate their stance over the 5 years of the study with only a gradual decline in the proportion who resisted changing their travel habits. These respondents could either be those for whom money is no object for a broad range of gasoline prices or they could be those for whom options--in the form of reduced driving or alternative transportation modes--were unacceptable or unavailable. In contrast, those respondents who did start out with a positive strategy (either driving less or economizing) tended to gravitate into the category of no further change. Apparently options can be used up, so that respondents make adjustments and then have little freedom to make more adjustments without paying a high personal cost, perhaps in mobility or in change in life-style. It could also be that some options prove to be more costly in terms of inconvenience than they appear to be initially. In either case, some respondents appeared to be discovering that they had little incentive to make further adjustments in their behavior even if gasoline prices rose to $2.00/gal.

Among the respondents who initially predicted that they would take positive action in response to $1.00/gal gasoline, it was found that different strategies resulted in different behavior sequences as gasoline prices did rise. Those who had initially classified themselves in the economy category (that is, all savings strategies except driving less) tended to abandon these strategies, so that by 1980 most of them reported that they would either drive less or not change in response to another large price increase. In contrast, those who had initially said that they would drive less were likely to continue saying that they would drive less in 1976 and 1980. By 1980 23 percent were in the no-change category and only 8 percent fell in the economy category; 69 percent of the initial drive-less respondents were still considering that option as of 1980.

Figure 8. Prevalence of strategies for coping with higher gasoline prices in 1975, 1976, and 1980.



Now that the turnover data have been examined in detail, the overall trends, presented in Figure 8, can be summarized. At all points in this study, respondents clearly preferred driving less as a strategy to cope with high gasoline prices. By 1980 the predominance of this strategy was clear; the majority chose it. In 1975 slightly more than one-fourth of the panelists chose one of the economy strategies. By 1980 only 13 percent chose this option. Finally, the proportion of respondents who said they would make no further changes grew from one-fourth to about one-third because respondents who had initially chosen other strategies either changed their minds or actually used up their options so that they predicted no further change in their travel behavior.

These findings are in contrast to those of a cross-sectional study conducted in New York State (13). The authors of that study found driving less to be one of the least consequential strategies employed by consumers. However, the region studied here had a more dispersed population and much less transit service. In rural areas and small towns, driving less may be the best option for many consumers who cannot find alternative means for essential work and shopping trips. Indeed, a study conducted in South Carolina (2) found that one-third of the respondents coped with gasoline shortages by limiting discretionary travel. The effect of the availability of options in various regions has yet to be determined.

To return to the original question of whether gasoline is an elastic commodity, it can be said that many, at least in this study region, still have enough slack in their personal automobile use to cut back in the face of rising prices. On the other hand, the economy strategies, which include the much publicized options of ridesharing and public transit, now appear less feasible than they did when gasoline prices began to rise dramatically. With a large proportion in 1980 saying that a rise to $2.00/gal would not change their travel behavior, a plateau may have been reached. Apparently gasoline prices would have to increase more than 100 percent and other options would have to become much more attractive before drivers could be expected to respond to prices by any means other than cutting their discretionary driving. Gasoline prices may have to rise greatly relative to other consumer goods and services before they have any effect on drivers other than to limit their driving and thereby their mobility. This would not necessarily be true in urban regions where alternatives to private automobile use are more easily accessible than in our study area.

ACKNOWLEDGMENT

Data reported in this paper were collected under grants from West Virginia University and the U.S. Department of Transportation. We gratefully acknowledge the support of Samy Elias of the Washington Metropolitan Area Transit Authority and Ray Koppelman of West Virginia University.

REFERENCES

1. Current Population Reports. Bureau of the Census, U.S. Department of Commerce, Series P-25, No. 787, Jan. 1979.
2. J.F. Sacco. Impact of the Energy Shortage on Travel Patterns and Attitudes. TRB, Transportation Research Record 651, 1976, pp. 1-11.

3. G. Katona. Psychological Economics. Elsevier, New York, 1975.
4. E. Mansfield. Economics. Norton, New York, 1974.
5. R.G. Lipsey and P.O. Steiner. Economics, 4th ed. Harper and Row, New York, 1978.
6. World Almanac and Book of Facts: 1981. Newspaper Ehterprise Association, Inc., New York, 1981.
7. Reader's Guide to Periodical Literature. H.W. Wilson Co., New York, 1979.
8. Transportation Energy Conservation Data Book, 3rd and 4th eds. Oak Ridge National Laboratory, Oak Ridge, Tenn., 1979 and 1980.
9. Selected Characteristics of Travel to Work in 21 Metropolitan Areas, 1975. Current Population Reports, Bureau of the Census, U.S. Department of Commerce, Series P-23, No. 68, Aug. 1979.
10. N. Stout-Wiegand, R.B. Trent, and D.K. Smith. Residents' Attitudes Toward Proposed Energy Related Developments in an Appalachian Community. Presented at the Second International Forum on the Human Side of Energy, Edmonton, Alberta, Canada, Aug. 1981.
11. Ward's Automotive Yearbook. Wards Communications, Detroit, Mich., 1980.
12. Social Indicators III. Bureau of the Census, U.S. Department of Commerce, Dec. 1978.
13. D.T. Hartgen and A. Neveu. The Energy Crisis: Who Conserved How Much? Planning Research Unit, New York State Department of Transportation, Preliminary Res. Rept. 173, April 1980.

Determinants of New-Car Fuel Efficiency

RONALD J. SUTHERLAND AND ANDREW FORD

The determinants of new-car fuel efficiency during the period 1976-1981 are examined statistically with cross-sectional data on new automobiles. A significant improvement in overall fuel economy is found during this period. Most of the increased fuel economy from 1976 through 1979 is because of weight reduction, but from 1979 through 1981 the improvement came about primarily because of additional measures. Variables such as domestic versus foreign manufacturer, horsepower, and performance are not statistically related to fuel economy during this period.

In 1973 the price of gasoline increased sharply as a result of the Arab oil embargo, which prompted a shift in automobile demand toward more fuel-efficient cars. The Energy Policy and Conservation Act, passed by Congress in 1975, mandates incremental fuel economy increases until 1985, at which time average fleet fuel consumption of each manufacturer must be at least 27.5 mpg. The interest in fuel efficiency shown by Congress, automobile consumers, and automobile producers encourages the examination of the recent history of fuel-efficiency improvements in the automobile fleet.

In a Mellon Institute report, Shackson and Leach (1) document several ways in which vehicles can be made more fuel efficient. Downsizing reduces vehicle weight, thus improving fuel efficiency, but fuel efficiency also can be improved by more efficient engines, tires with less rolling resistance, improved aerodynamics, and other means that do not affect vehicle weight. Shackson and Leach forecast that fuel consumption relative to weight of new automobiles will diminish significantly in the future as a result of these measures. Their forecast is depicted graphically in Figure 1, which shows the relationship of fuel consumption to curb weight expected in future years. The downward rotation of the line depicts fuel economy improvements caused by measures other than weight reduction, whereas movement along a line results entirely from reducing vehicle weight. Figure 1 shows the expectation that future fuel economy will be achieved by further weight reduction and by complementary measures. Automobile manufacturers have now had a few years' experience in attempting to improve fuel efficiency. By quantifying the effectiveness of the recent history of fuel economy efforts, the reasonableness of the Mellon and other forecasts can perhaps be judged.

THREE HYPOTHESES

The interest in fuel-efficiency trends in this study can be stated in terms of three hypotheses:

1. Recent improvements in fuel economy are due almost entirely to vehicle weight reduction,
2. The rush to reduce vehicle weight has had secondary punitive effects on fuel economy, and
3. Weight-reduction efforts have been complemented by other fuel-efficiency efforts.

These alternative hypotheses are depicted graphically in Figures 2-4. The sample mean curb weight and corresponding gasoline consumption for the 1976 and the 1981 model years are shown in Figures 2-4.

In Figure 2 the relationship between gasoline consumption and curb weight estimated with 1976 new-car data corresponds closely to the same relationship estimated with 1981 data, even though 1981 cars are lighter and more fuel efficient. In this case the improvement in fuel efficiency is due to weight reduction, as stated in hypothesis 1. In Figure 3 the relationship of fuel consumption to curb weight estimated with 1981 new-car data lies above the 1976 relationship. In Figure 3 weight reduction has improved fuel economy, but the improvement efforts have been offset partly by secondary punitive effects. For example, in an effort to make small cars more appealing, manufacturers have offered them with more options such as air conditioners, which diminish fuel economy. Figure 4 shows the hypothesis that weight-reduction efforts have been complemented by other fuel economy efforts. The mean curb weight and corresponding fuel consumption in 1981 (and in 1976) are the same in Figures 2-4. However, the downward shift in the relationship of fuel consumption to weight depicts the effect of fuel economy improvements in addition to weight reduction.

During the sample period of 1976 through 1981, the fuel efficiency of new cars has indeed improved. The objective here is to define statistically the reasons for this improvement, specifically, the extent to which fuel efficiency is due to weight

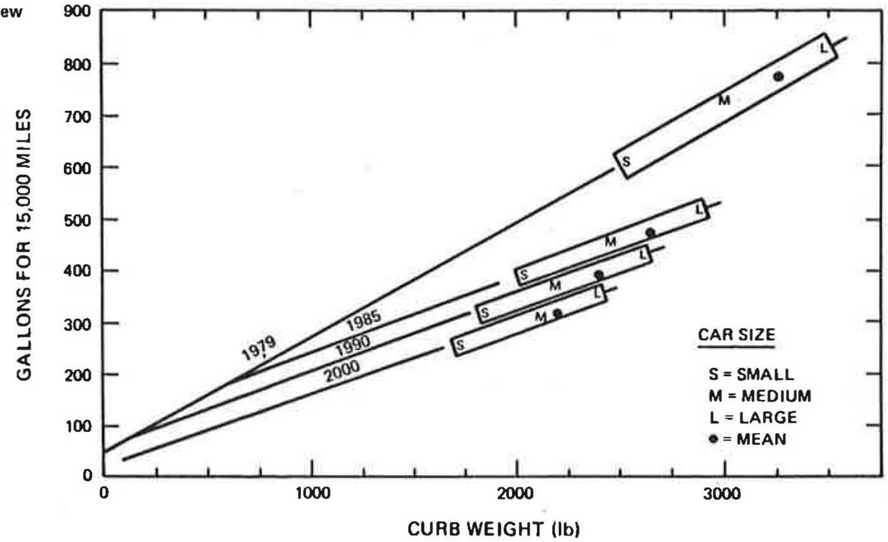


Figure 1. Mellon forecast of fuel consumption by new automobile fleet.

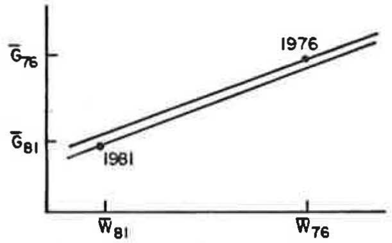


Figure 2. Hypothesis 1.

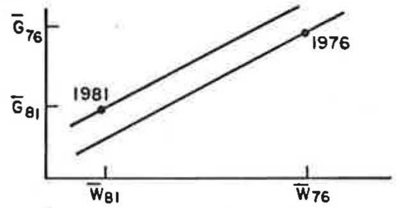


Figure 3. Hypothesis 2.

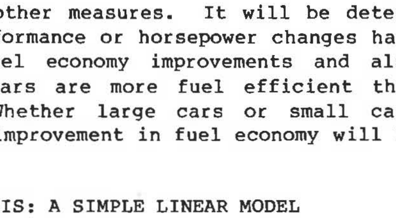


Figure 4. Hypothesis 3.

reduction versus other measures. It will be determined whether performance or horsepower changes have contributed to fuel economy improvements and also whether foreign cars are more fuel efficient than domestic cars. Whether large cars or small cars have shown major improvement in fuel economy will be examined.

STATISTICAL ANALYSIS: A SIMPLE LINEAR MODEL

This statistical analysis is based on annual samples from 1976 through 1981 of new cars appearing on the U.S. market. Some fuel-efficiency analyses have considered the market share of various car classes. Instead, an unweighted sample of new cars is used here because the interest in this study is in the effectiveness of the automobile producers' efforts to improve fuel efficiency. Extensive and successful efforts by producers to improve efficiency could be mitigated by a shift in demand toward high-consumption vehicles such as vans or light trucks. Alternatively, average fleet fuel efficiency could increase dramatically as a result of a demand shift toward efficient cars, even if automobile producers made no attempt to improve fuel efficiency.

The sample of new cars in this study included each make and model listed in the 1976 to 1981 editions of Consumer Reports. If two cars were virtual twins or a car had more than one engine choice, one car was sampled. Data were also obtained from Consumer Reports on automobile curb weight, horsepower, transmission type, and whether the producer was domestic or foreign. Mile-per-gallon estimates for city driving were obtained from the annual Gas Mileage Guide published by the U.S. Department of Energy and the U.S. Environmental Protection Agency (EPA) (EPA's city mpg estimates were used because composite city-highway estimates are not available for each year from 1976 to 1981). The annual sample size, as shown in Table 1, varied from 38 to 53 automobiles, which is the maximum number of observations obtained from the sources just mentioned after the sample had been adjusted for twins and multiple engine types. Although the sample included five classes of automobiles (subcompact, compact, intermediate, full size, and luxury), it is weighted toward small cars. In 1981 there were only four or five luxury cars on the market but more than 20 subcompacts.

It is postulated first that fuel efficiency of an automobile is primarily a function of its curb weight. Fuel efficiency may be indicated by miles per gallon or required fuel to travel, say, 15,000 miles. Fuel consumption to travel 15,000 miles is used because the relationship between fuel consumption and weight is more likely to be linear than the relationship between miles per gallon and weight (2, p. 40). A simple linear cross-section regression estimate between fuel consumption of the ith car in year t (G_{it}) and its curb weight (W_{it}) was obtained for each year from 1976 to 1981 and for the composite period. The results are given in Table 1. The weight coefficients are positive and significant, as expected. The coefficient for the composite period of 0.232 indicates that an automobile weight reduction of, say, 100 lb reduces fuel consumption for a

Table 1. Regression estimates of gasoline consumption and curb weight of new vehicles.

		Weight Coefficient					Gasoline Consumption		Weight	
Year	Intercept	Tons	t-Value	R^2	SE	Sample Size	Gallons	SD	Pounds	SD
Composite	77.2	0.232	38.38	0.845	86.9	238				
1976	201.5	0.203	15.72	0.843	92.3	48	864.8	230.6	3,270.5	1,044.1
1977	77.7	0.236	22.81	0.911	71.6	53	805.2	237.3	3,088.3	961.4
1978	18.2	0.254	13.66	0.813	109.9	45	797.3	251.0	3,063.8	890.1
1979	98.1	0.231	16.76	0.859	71.3	48	776.4	188.2	2,933.3	754.3
1980	93.1	0.221	11.92	0.785	82.9	41	719.5	176.4	2,833.4	706.8
1981	61.2	0.215	18.73	0.907	47.5	38	646.3	153.5	2,723.2	680.3

Table 2. Regression estimates of expanded model of gasoline consumption.

		Weight Coefficient		Ratio of Horsepower to Weight		Dummy Producer Variable		Dummy Transmission Variable			
Year	Intercept	Tons	t-Value	Ratio	t-Value	Coefficient	t-Value	Coefficient	t-Value	R^2	SE
Composite	55.57	0.232	37.05	753.09	0.59	-11.35	-0.85	4.34	0.30	0.843	87.18
1976	115.24	0.204	13.73	2,006.69	0.63	-2.25	0.07	21.01	0.47	0.831	-94.94
1977	159.64	0.231	21.41	-782.88	0.28	-26.44	-0.94	-43.46	-1.50	0.908	-72.08
1978	67.47	0.253	12.59	-857.29	0.26	-7.06	0.15	-19.72	-0.43	0.795	113.56
1979	144.48	0.227	14.93	-299.8	0.10	-1.70	0.06	-29.24	-0.90	0.850	72.89
1980	286.36	0.210	11.26	-3,349.76	0.91	-64.74	-2.05	-31.16	-0.99	0.791	80.63
1981	-37.39	0.223	17.67	1,660.65	0.73	5.81	0.27	33.67	1.66	0.908	46.65

Notes: The dummy producer variable is 1 for domestic, zero for foreign. The dummy transmission variable is zero for automatic, 1 for manual. R^2 is the coefficient of determination adjusted for degrees of freedom. SE is the standard error of the regression equation.

trip of 15,000 miles by 23.2 gal. Overall, this simple model has a high degree of explanatory power and the weight coefficients appear stable and are highly significant.

The last four columns in Table 1 give the sample mean gasoline consumption, its standard deviation, the sample mean curb weight, and its standard deviation on an annual basis. The average weight of new cars declined consistently throughout the period and, as expected, so did fuel consumption. The standard deviations of these variables also have diminished over time. New cars are becoming more fuel efficient over time, and they also are becoming more homogeneous in terms of weight. This observed decrease in variability of new-car weight over the sample period supports the Mellon forecast shown in Figure 1.

The mean gasoline consumption of a 1976 automobile was 864.8 gal, which declined to 776.4 gal in 1979 and 646.3 gal in 1981. This improvement in fuel economy is the result of both weight reduction and other measures, the relative importance of which is determined in the next section.

MULTIVARIATE STATISTICAL ANALYSIS

A simple linear model was postulated to determine the statistical credibility of a model based only on curb weight. Other variables were examined to see whether the statistical explanation of fuel efficiency could be improved by considering a more completely specified model. Because gasoline consumption may be influenced by engine horsepower, this variable was added and the model was reestimated. The horsepower coefficients are insignificant for each year and for the composite period. For this reason and because performance (horsepower divided by weight) may be a more appropriate variable, these results are not reported in detail. [The ratio of horsepower to weight is often used as a measure of automobile acceleration, which in turn is sometimes taken as a performance measure, according to a report in September 1976 by the Federal Task Force on Motor Vehicle Goals Beyond 1980.]

Performance is a measure of acceleration capability and it is considered a statistical determinant of fuel consumption. EPA mileage data indicate that cars with three- or four-speed manual transmissions obtain an improvement of about 1 to 3 mpg over those cars with automatic transmissions. A dummy transmission variable was set equal to zero for cars with an automatic transmission and equal to 1 for those with a manual transmission. Foreign-made cars have the reputation of being more fuel efficient than domestic cars. Although the superior fuel efficiency of foreign cars is partly because of their light weight and partly because of their use of manual transmissions, tests were done to determine whether foreign cars are more fuel efficient when the model is adjusted for weight and type of transmission. A second dummy variable was introduced to denote whether the manufacturer was domestic or foreign. Fuel consumption may have been influenced by other variables, such as radial tires, but data limitations restricted our model to the foregoing variables. Regression estimates of this expanded model for each year and the composite period are given in Table 2.

A comparison of Tables 1 and 2 shows that the weight coefficients are not affected much by additional variables, and they continue to be the most significant determinant of fuel consumption. In contrast, the performance indicator and the transmission variable are insignificant in each year. The synergistic effect between weight and horsepower suggested by Gray and von Hippel (3, p. 58) apparently has not been operative during this period. If the synergistic effect means that smaller cars will use lower-performing engines (whose performance is defined as the ratio of horsepower to weight), this synergistic effect has not contributed to improved fuel economy. However, this effect may be interpreted as lighter cars using smaller engines (with perhaps equal performance), the performance of which may remain constant. Automobiles and their engines have become smaller over the last 6 years, but the ratio of horsepower to weight is statistically unrelated to fuel economy.

The coefficient for the producer dummy is negative in each year except 1981, but it is only significant in 1980. Foreign cars tend to be compacts or subcompacts; hence, there is a high inverse correlation between weight and the producer dummy variable. As a consequence of multicollinearity, the regression coefficients and their standard errors become unreliable. This, plus the failure of the producer dummy to be significant during several years, means that the hypothesis cannot be rejected that domestic and foreign cars are equal with respect to weight-adjusted fuel efficiency.

The coefficients of determination in Table 2 have been adjusted for degrees of freedom so they can be compared with those in Table 1. For 4 of the 6 years and the composite period, the explanatory power of the expanded model is lower than that of the simple model. Thus, it may be concluded that the main statistical determinant of gasoline consumption of a new automobile is its curb weight and that this variable by itself explains most of the variation in fuel consumption.

RELATIVE IMPORTANCE OF WEIGHT REDUCTION

A close statistical association between curb weight and fuel consumption has been shown, but it has not been possible to demonstrate the significance of additional variables. The importance of other variables can be demonstrated as a composite but not individually by identifying changes in the relationship between fuel consumption and weight. The simple model is used for this analysis because the expanded model has no additional explanatory power.

If the simple model were statistically stable over the sample period, fuel-efficiency efforts other than weight reduction would apparently be random and probably unimportant. This possibility is hypothesis 1, which is shown in Figure 2. Alternatively, perhaps the statistical results in Table 1 contain significantly different intercepts or slopes or both or the coefficients contain time trends. If the slope or intercept coefficients diminished in size over the period, non-weight-reduction fuel economy efforts would have been complementary. This possibility is our third hypothesis and is shown in Figure 4. Furthermore, in the event of an unstable relationship between fuel consumption and weight, the nature of the instability is important. If fuel economy efforts other than weight reduction were concentrated in large cars, the regression line would rotate clockwise and the intercept would be unstable. Alternatively, an unstable intercept but constant slope implies that the relationship between fuel consumption and weight of all cars has changed about equally. A conventional statistical analysis is now employed to determine the statistical stability of the slopes and intercepts in Table 1 and to determine the presence of any time trends.

An analysis-of-variance (ANOVA) test was used to determine whether the individual regression estimates in Table 1 could be interpreted as being drawn from the same sample. The estimated F-statistic is 4.376, which is significant at the 1 percent level. The regression estimates for the individual years are significantly different, which implies that some type of fuel economy effort in addition to weight reduction has been important during this period.

Further ANOVA tests were conducted to determine whether the intercepts or slopes were statistically different. Testing for the equality of slopes produced an F-value of 1.875, which is significant at the 10 percent level but not at the 5 percent level. With a similar test, it was found that the intercepts in the simple models were significantly different at the 1 percent level. [The Biomedical Computer Programs used do not contain a procedure to test equality of intercepts directly. Therefore an intercept dummy variable was added for each year from 1976 to 1981 and tests were made to see whether the extra sum of squares caused by regression was significantly larger than without the dummy variables. This ANOVA test is described by Draper and Smith (4, pp. 67-69).] This result allows the rejection of the first hypothesis, that fuel economy improvement efforts have been due entirely to weight reduction. The relative stability of the slope coefficients and instability of the intercepts implies that the relationship between gasoline consumption and weight has shifted rather than rotated. The composite influence of fuel economy efforts has apparently been approximately uniform across car classes rather than concentrated on small or large cars.

Although differences in intercepts do not necessarily imply a time trend, a significant positive or negative time trend would allow the determination of whether non-weight-reduction fuel-efficiency efforts have been complementary or punitive. Therefore the simple model was rerun and a time trend in which the intercept decreases by equal increments each year but the slopes remain uniform was allowed for. The estimated regression equation is

$$G_{it} = 129.20 + \underset{(38.164)}{0.227W_{it}} - \underset{(-4.821)}{14.865t} \qquad R^2 = 0.857 \tag{1}$$

where the time-trend coefficient is negative and highly significant. Since 1976, cars from each successive model year have required, on the average, about 15 fewer gallons to travel 15,000 miles. This improved efficiency is in addition to that achieved through weight reduction. The significant negative time trend confirms hypothesis 3, that fuel economy efforts other than weight reduction have been complementary (see Figure 4).

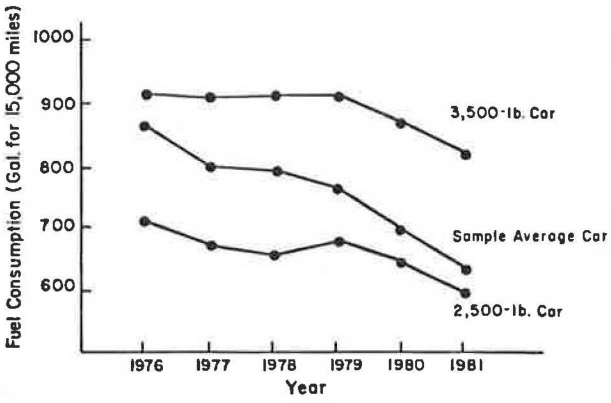
The specification of Equation 1 presumes a linear decrease in gasoline consumption in addition to the weight reduction effect. The nature of this trend is depicted graphically by assuming a car of given weight and using the regression results in Table 1 to estimate its fuel efficiency. The estimated gasoline consumption of a relatively large car of 3,500 lb and a small car of 2,500 lb is shown in Figure 5. The sample mean car weight and its corresponding fuel consumption (obtained from Table 1) are also shown in Figure 5 to illustrate the influence of all measures on average fuel consumption.

Fuel-consumption figures for a constant-weight car are compared with the sample mean fuel-consumption estimates that reflect the composite influence of weight reduction and all other measures of fuel economy. Overall, required gasoline consumption decreased from 864.8 gal in 1976 to 776.4 gal in 1979, a difference of 88 gal. During this time the improved fuel economy of a 3,500-lb car was only 12 gal. The major improvement in fuel economy achieved during the period 1976-1979 is therefore a consequence of weight reduction. From 1979 to 1981 an average new car required 130 fewer gallons to travel 15,000 miles; a 3,500-lb car required 87 fewer gallons. Most of the fuel economy achieved from 1979 to 1981 is because of measures other than weight reduction.

POSSIBLE BIAS DUE TO EPA MEASUREMENT PROCEDURE

The preceding results are based on EPA fuel-efficiency estimates, which are transformed into gasoline consumption. EPA tests are conducted with a

Figure 5. Estimated fuel consumption for 3,500-lb car, 2,500-lb car, and sample average car by year for 1976-1981.



dynomometer, so mileage estimates are simulated, not actual road mileage. EPA estimates have been criticized as being biased upward. At issue here is the nature and extent of the bias and particularly how the use of actual road mileage would have affected the regression results in Tables 1 and 2.

In an unpublished report for the U.S. Department of Energy, B. McNutt and R. Dulla in 1979 compared on-road fuel efficiency with EPA mileage for each year from 1974 to 1977. They used a linear relationship between EPA and on-road miles per gallon and concluded that on-road mileage falls short of EPA certified mileage. Although the EPA and on-road equations were different for each year, a time trend in that difference was not observed.

A more recent study for the Department of Energy by Energy and Environmental Analysis (5) reexamined the EPA and on-road mileage estimates and adopted a reciprocal equation in lieu of the linear relationship. Their so-called master equation for passenger cars for 1951 to 1980 is

$$\mathrm{MPG}_{\mathrm{Rd}} = \mathrm{MPG}_{\mathrm{EPA}}/(0.0237\mathrm{MPG}_{\mathrm{EPA}} + 0.76) \qquad (2)$$

where $\mathrm{MPG}_{\mathrm{Rd}}$ is on-road miles per gallon and $\mathrm{MPG}_{\mathrm{EPA}}$ is EPA miles per gallon.

If Equation 1 is used to define the relationship between on-road and EPA miles per gallon during the period under consideration, it can be determined how the regression results would have looked had on-road fuel consumption been used as the dependent variable. An important property of Equation 2 is that it represents each year in the time period and it contains no time trend. Although EPA mileage estimates may be biased estimates of on-road mileage, there is no time trend in this bias. Thus the results of this paper concerning weight-adjusted fuel efficiency over time are not sensitive to the use of EPA or on-road mileage.

Equation 2 can be transformed from a mileage equation to a fuel-consumption equation by first replacing miles per gallon by miles divided by gallons and inverting to obtain

$$\mathrm{G}_{\mathrm{Rd}}/\mathrm{M} = [(0.0237\mathrm{M}/\mathrm{G}_{\mathrm{EPA}}) + 0.76] \div (\mathrm{M}/\mathrm{G}_{\mathrm{EPA}}) \qquad (3)$$

in which M is miles. Multiplying through by the denominator on the right, letting M equal 15,000, and solving for G_{Rd} gives

$$\mathrm{G}_{\mathrm{Rd}} = 356 + 0.76\mathrm{G}_{\mathrm{EPA}} \qquad (4)$$

where $\mathrm{G}_{\mathrm{EPA}}$ is the dependent variable in the regression model used in this paper. Equation 4 implies that the EPA estimate of gallons of gasoline necessary to travel 15,000 miles underestimates actual on-road required gallons, at least over the relevant range (less than 1,941 gal). For the purposes of this study, the important property of Equation 4 is its linearity. A graphic picture of the fuel-economy trends in Figure 5 by using on-road gallons is simply a linear transformation of those trends. In an extensive analysis of on-road versus EPA mileage estimates, Murrel (6) also concludes that the bias has been about constant since 1976. The overall conclusion that fuel-economy improvements from 1976 to 1979 are due to vehicle weight reduction and that improvements during 1980 and 1981 are due mainly to other factors is not sensitive to the use of EPA or on-road gasoline consumption. [The simple linear model used here (and reported in Table 1), which is $\mathrm{G}_{\mathrm{EPA}} = \hat{\alpha} + \hat{\beta}\mathrm{W}$, can be transfered into a simple linear model with on-road gallons as the dependent variable by substituting the equation into Equation 4. The resulting equation is $\mathrm{G}_{\mathrm{Rd}} = 356 + 0.76\hat{\alpha} + 0.76\hat{\beta}\mathrm{W}$, where where $\hat{\alpha}$ and $\hat{\beta}$ can be obtained from Table 1.]

CONCLUSIONS AND IMPLICATIONS

An apparently negative conclusion is that variables such as horsepower, performance, transmission type, and domestic versus foreign manufacturer are not associated significantly with gasoline consumption. Foreign manufacturers have been interested in fuel economy for several years. Their efforts apparently consist of building small cars but not cars that are more efficient on a per-pound basis than U.S. cars. American small cars are likely to be competitive with foreign-made cars, at least in terms of operating costs. The failure of the performance variable to be significant implies that fuel economy has not been attained at the expense of reduced ratios of horsepower to weight.

In addition to becoming lighter, new cars have become more homogeneous in terms of weight. A disadvantage of small cars is their lack of safety in collisions with larger cars. The trend toward more homogeneous car weights may imply an improvement in the safety of new cars.

Initially in this paper, some fuel economy projections by the Mellon Institute were noted that are the results of weight reduction and other measures. The examination of recent automobile industry efforts to achieve economy here indicates that such efforts have been successful. Furthermore, the recent trends in automotive fuel economy efforts are in the direction that the Mellon Institute forecasts for the next two decades (see Figure 1). New cars are becoming lighter and therefore more fuel efficient. The first phase of fuel-efficiency improvements was completed in 1979 and consisted primarily of weight reduction. In 1980 and 1981 a second distinct phase was observed that has been more successful than the first phase and that includes primarily fuel-efficiency improvements in addition to weight reduction. These efficiency improvements have apparently been shared about equally by all car classes.

ACKNOWLEDGMENT

The work reported in this paper was performed under the auspices of the U.S. Department of Energy.

REFERENCES

1. R.H. Shackson and H.J. Leach. Maintaining Automotive Mobility: Using Fuel Economy and Synthetic Fuels to Compete with OPEC Oil. Mellon Institute, Arlington, Va., Interim Rept., 1980.

2. J.K. Tien, R.W. Clark, and M.K. Malu. Reducing the Energy Investment in Automobiles. Technology Review, Feb. 1975, pp. 39-43.
3. C.L. Gray and F. von Hippel. The Fuel Economy of Light Vehicles. Scientific American, Vol. 244, No. 5, May 1981, pp. 48-59.
4. N.R. Draper and H. Smith. Applied Regression Analysis. Wiley, New York, 1968.
5. Energy and Environmental Analysis, Inc. The Light Duty Vehicle Fuel Consumption Model. U.S. Department of Energy, 1980.
6. D. Murrell. Passenger Car Fuel Economy: EPA and Road. Motor Vehicle Emissions Laboratory, U.S. Environmental Protection Agency, Ann Arbor, Mich., 1980.