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Energy Conservation Potential of Staggered Work Hours

JAMES M. WITKOWSKI AND WILLIAM C. TAYLOR

Research was performed to evaluate the potential of staggered work hours to reduce work-trip fuel consumption and to evaluate the relation between the size and location of the participating work force and the level of fuel savings. The spatial organization of a hypothetical urban area was generated by using data from the literature and a computer simulation program designed to distribute population and employment activities throughout the urban area. By using this distribution and a defined transportation network, the program then generated the work-trip travel pattern and computed the transportation fuel requirements for automobile work trips and daily transit service. A base case was generated and used as the basis for comparison of the alternative policies. Several alternative temporal distributions of work travel were used to simulate the effect of staggered-work-hour programs. Tests were designed to determine the effect on the reduction in fuel consumption of the magnitude and location of the work force participating in the staggered-work-hour programs. The simulation results indicated that staggered-work-hour programs can significantly reduce automobile work-trip gasoline consumption. The effectiveness of the staggered-work-hour policies was shown to be influenced by both the number of participants in the program and the distribution of the participants throughout the urban area. The reduction in fuel consumption increased with the number of participating work travelers. The reduction also increased as the locations of the participating employment centers became more dispersed throughout the urban area. The staggered-work-hour programs also showed a strong negative influence on work-trip bus ridership.

Evaluation of strategies to reduce automobile fuel consumption in urban areas is of particular interest to transportation planners because these trips consume approximately 34 percent of the national total transportation energy (1). These trips also account for approximately 98 percent of the fuel consumption for urban passenger travel and account for 92-95 percent of the total vehicle person trips (1).

The objective of staggered- or flexible-work-hour programs is to shift work-trip travel away from the peak demand periods. The desired results are a reduction in peak highway and transit system loading, improved transportation levels of service, and reductions in energy consumption and vehicle emissions.

The capabilities of planners to evaluate quantitatively the potential benefits of transportation system management (TSM) actions with respect to transportation fuel consumption are limited. Each urban area exhibits its own particular characteristics and needs. Confronted with the question of which action or combination of actions can be used to successfully reduce gasoline consumption for urban travel while maintaining an acceptable level of service, the transportation planner must often rely on national statistics for cities ambiguously described as small, medium, or large. Whether or not the policy actions actually yield the estimated reduction in fuel consumption depends on the characteristics of the area being studied.

Several studies (2-5) have reviewed the potential of different TSM techniques to reduce urban congestion and, subsequently, to reduce gasoline consumption. In each of these studies, staggered work hours was determined to be an effective low-cost action to reduce congestion and gasoline consumption. Another conclusion was that proper coordination of staggered work hours and transit supply strategies could improve the effectiveness of TSM actions (2,4). These studies did not define a relation between the size of the participating work force and the level of fuel consumption, nor did they indicate the magnitude of the temporal redistribution of the work trips required to effect a significant reduction in gasoline consumption.

Only a few studies (6-8) have attempted to determine the impact of staggered-work-hour programs by simulating the redistribution of work trips during the peak period. None of these attempted to relate the results to reductions in energy consumption.

The goal of this study was to improve the capabilities of transportation planners to evaluate the short-term relation between specific TSM policies and fuel consumption for urban work trips. This would enable planners to assess more accurately the potential benefits of specific policies and aid in the selection of policies for implementation. It would also aid in planning for future energy contingencies.

This research focused on the work-trip fuel-conservation potential of staggered-work-hour programs. It was hypothesized that a potentially significant reduction in transportation fuel consumption for the urban work trip would result from the implementation of a staggered-work-hour program.

The level of effectiveness of alternative work schedules appears to be dependent on (a) the level of participation in the work force, (b) the relative location of the participating employment centers, (c) the degree of coordination of transit scheduling with the work-hours program, and (d) the configuration of the highway network.

The effect of staggered work hours on work-trip fuel consumption is evaluated in this research with respect to both the size of the work force participating in the program and the location of this work force in the urban area.

SIMULATION PROCESS

The primary requirements of the modeling system for this research were the following:

1. The capability to simulate modal choice as a function of the elements of travel time and cost, such as in-vehicle travel time, walk time, and, for transit passengers, waiting time (for automobile travel, it was important that travel time be related to highway congestion levels);
2. The capability to estimate energy consumption for both automobile and transit travel;
3. The capability to model the effects of staggered work hours on highway congestion and mode choice (the model had to be capable of simulating work travel over several distinct time elements so that the sensitivity of fuel consumption to the proportion of travelers during each time element could be tested).

The modeling system used is shown schematically in Figure 1. This system was adapted from the MOD3 modeling procedure used by Peskin and Schofer (9). MOD3 is a large-scale computer model that simulates the spatial development of an urban area, forecasts the passenger travel that takes place during a single day, and computes the energy consumption resulting from that travel. In effect, the model combines the elements of land use distribution, modal choice, and network assignment with an energy consumption module for work trips. Modal choice is estimated by using a binary logit formulation. The details of the structure of MOD3 are contained in the work by Peskin and Schofer (9). Details of the modifications to the program required for this research are contained in an earlier report (10).

The broken flow line in Figure 1 represents the

Figure 1. Basic requirements of modeling systems.

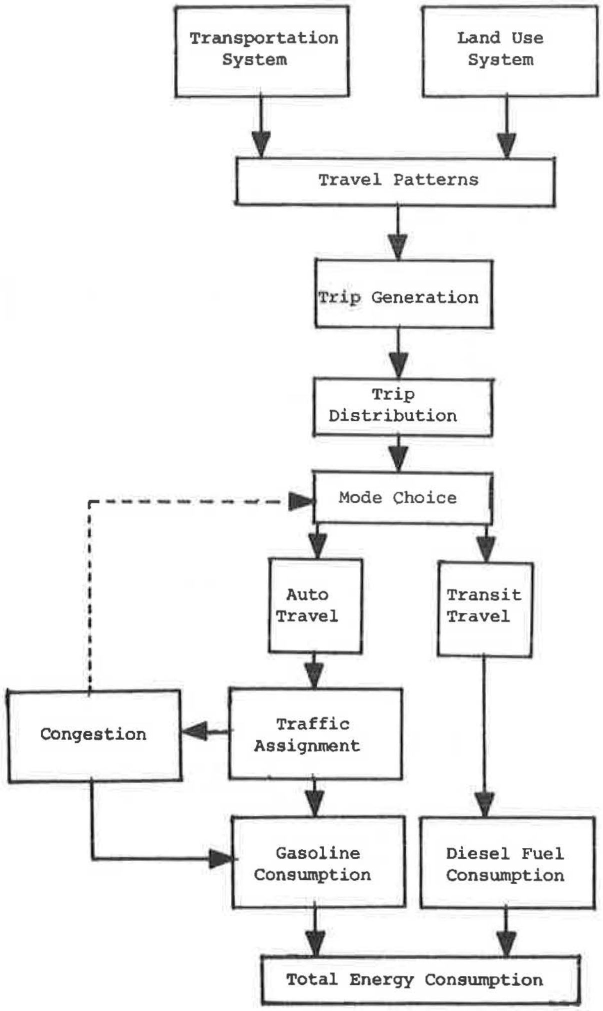
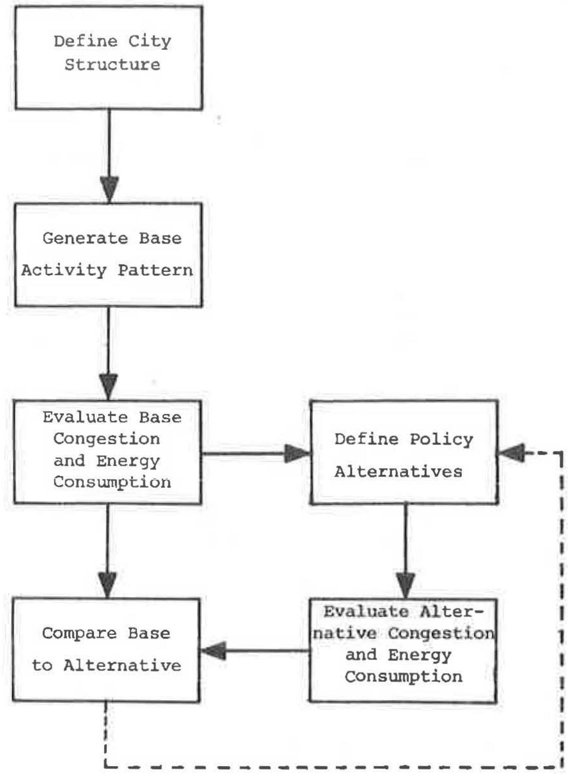


Figure 2. Overall simulation procedure.



feedback mechanism necessary to evaluate the impacts of traffic congestion on modal choice, network assignment, and energy consumption. The capability to evaluate the impacts of congestion or reductions in congestion was the heart of the modeling system. It was assumed that the overall patterns of work-trip travel demand were fixed and were unaffected by fluctuations in the cost or time required for travel. The results were interpreted as reflecting the short-term impacts that might be experienced in a situation where changes in living patterns were not immediately possible. The impacts on work-trip travel were confined to mode and route selection.

This research involved the simulation of the activity distribution and travel patterns for a hypothetical city. The overall evaluation procedure is shown schematically in Figure 2. The procedure consisted of the generation and evaluation of a base case and the evaluation of several staggered-work-hour programs in relation to base-case energy consumption. The dashed line in Figure 2 represents the feedback from policy evaluation to alternative policy selection.

City Characteristics

A concentric ring design slightly elongated along two of the major travel corridors was selected as the structure of the hypothetical city. The 52-zone structure is shown in Figure 3. The four central zones represent a central business district (CBD) with a total area of 1 mile^2. The CBD was surrounded by four concentric rings of development that had progressively increasing zone sizes toward the periphery. The total land area was approximately 100 miles^2. Total population for the test area was 100 000 and total employment was 40 000.

Population and service employment were distributed among the zones by using MOD3. The following table gives some of the input data required to describe the base activity pattern for the study area:

Item	Value
Persons working at home (%)	2.3
Value of travel time for work trips ($)	5.00
Price of gasoline per gallon ($)	1.00
Automobile occupancy rate for work trips (persons/vehicle)	1.3
Automobiles owned per household	1.3
Parking cost per day ($)	
CBD	
Work trips	2.50
Nonwork trips	1.00
Ring 2	
Work trips	1.25
Nonwork trips	.50
Elsewhere	0.00
Number of transit routes	12
Peak-period transit frequency of service (buses/h)	3
Transit bus trips per day on each route	43
Transit fare ($)	0.35
Transit transfer fare ($)	0.00
Population/employment ratio	2.5

Figure 4 shows the resultant employment distribution as generated by MOD3.

Figure 3. Zonal structure of simulated urban area.

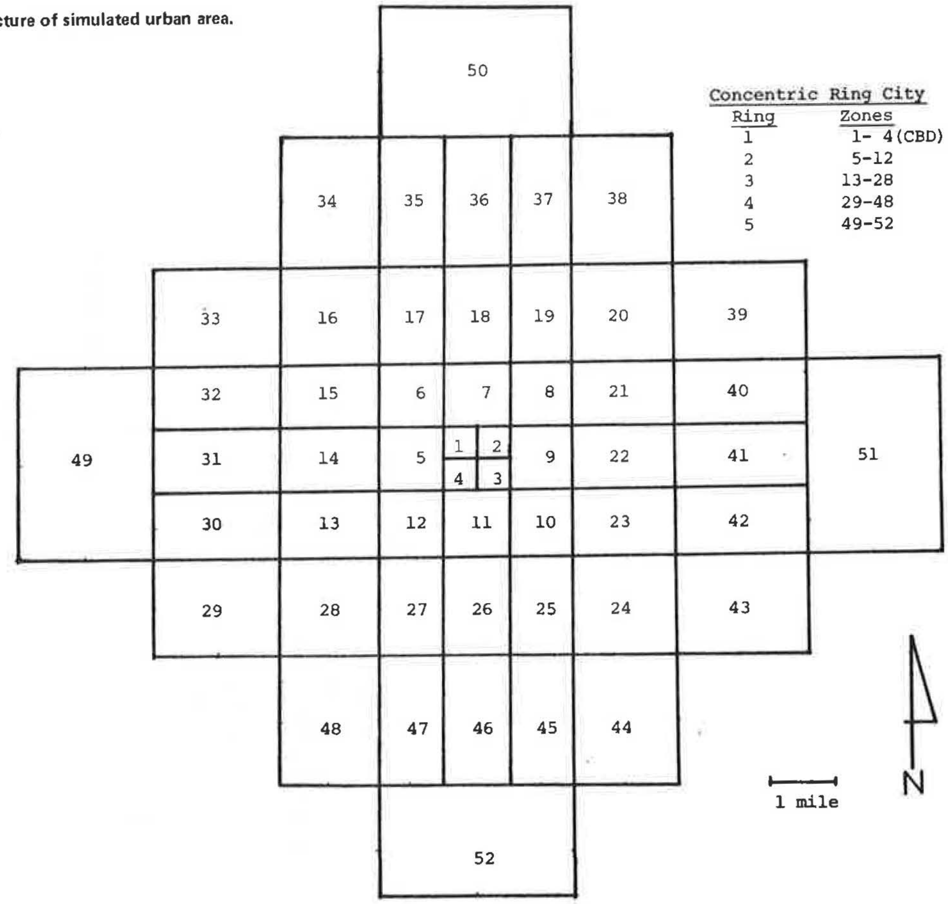


Figure 4. Total employment per zone for simulated urban area.

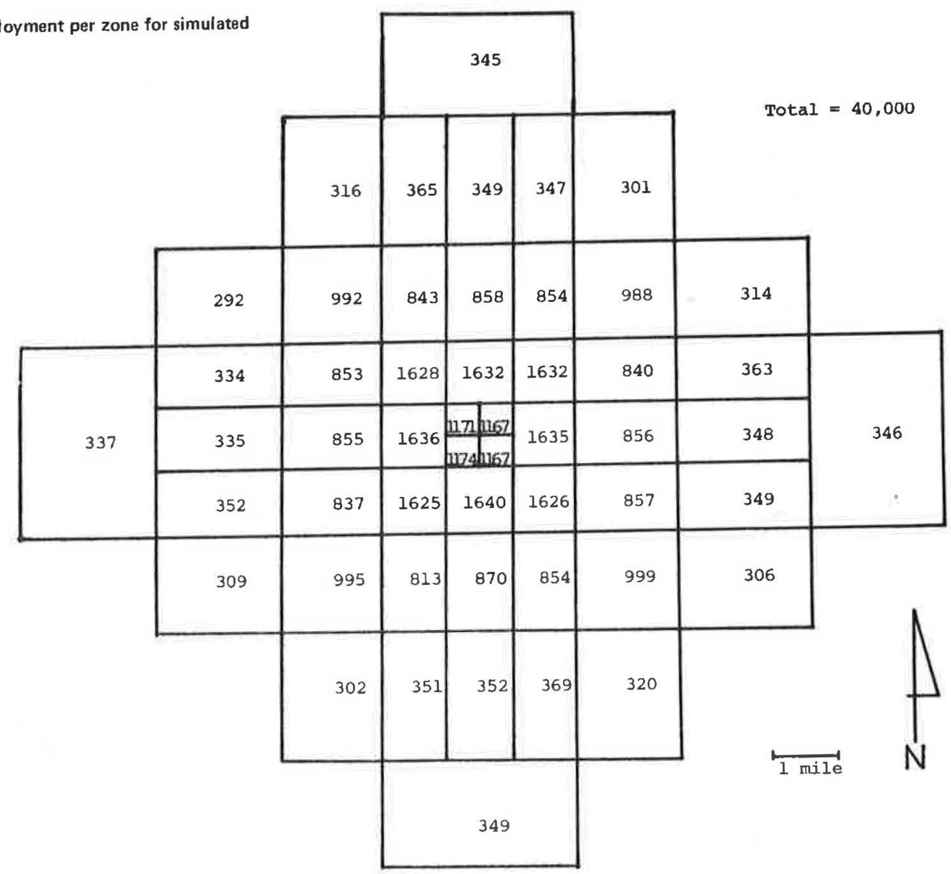
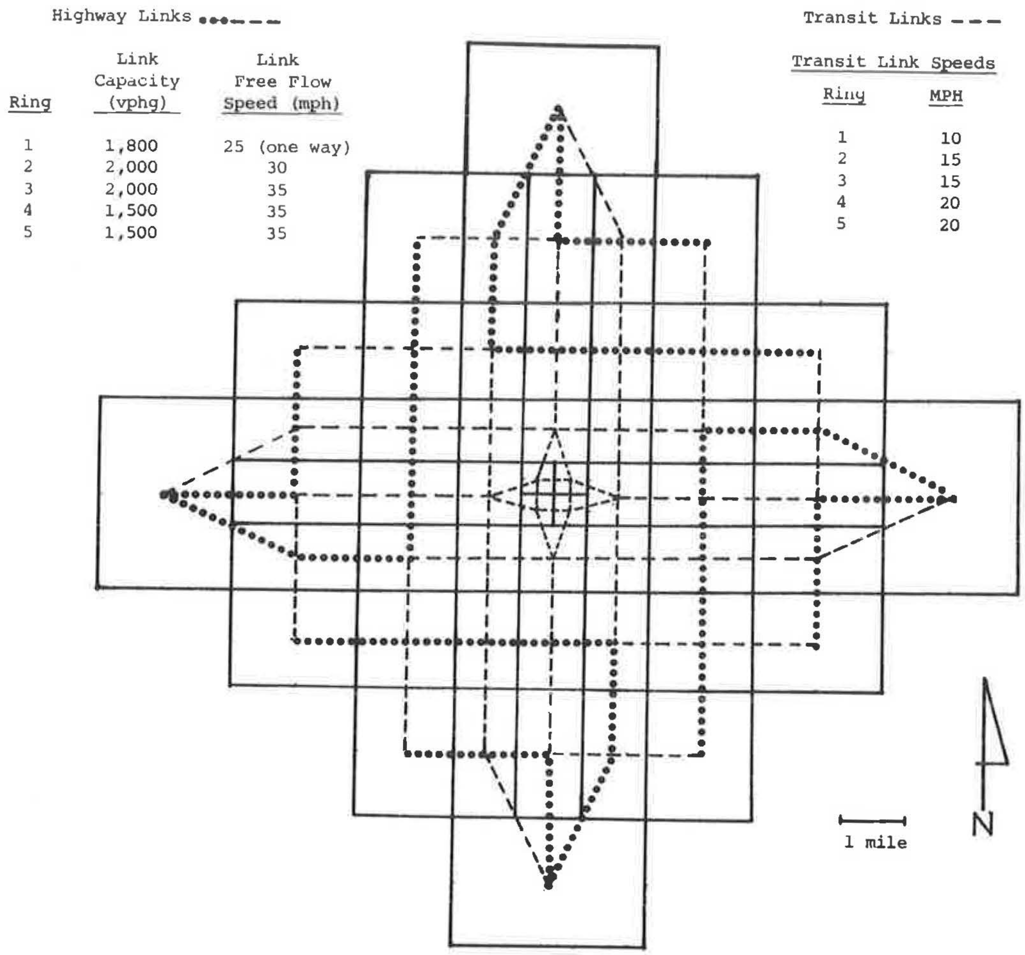


Figure 5. Highway and transit network for simulated urban area.



The highway network used in the simulation is shown in Figure 5. The network was a grid pattern and consisted solely of arterial streets connecting zone centroids. Local streets were assumed to handle intrazonal trips and therefore are not depicted. The vast majority of the highway network consisted of two-way links; the exceptions were those one-way links connecting the CBD zones. Freeway links were omitted from the city structure since, for cities of the size simulated, there are usually few, if any, freeway links used for intraurban travel. It was assumed that 90 percent of the specified link capacity was available for work trips during the peak period and that an average of 50 percent of traffic-signal cycle time was green on each arterial.

The transit network, also shown in Figure 5, is representative of urban bus routes in U.S. cities in terms of route spacing and average link speeds. The focal point of the network was the CBD, and the network was designed so that each zone had access to transit. All routes began and ended at the city periphery. Where possible, the use of multiple routes serving any single zone was avoided to enhance the capability of monitoring changes in interzonal transit ridership that resulted from individual policy alternatives.

Peak-Period Travel

To facilitate the testing of staggered-work-hour programs, the total evening peak travel period was segmented into five discrete time elements and the work-trip travel for each time element was simulated. Trip interchanges were multiplied by a factor of two to represent morning and evening peak-period travel. The sum of the energy consumed during these five time elements represented the total for both peak periods.

The peak travel period was specified to have a length of 2.5 h and was divided into five half-hour periods. Half-hour time periods were selected for three basic reasons:

1. Half-hour periods are adequate to describe the peaking characteristics of urban work travel. Simulating more time periods of a shorter duration would have resulted in only a small increase in descriptive capability at a substantial increase in computer costs.
2. O'Malley and Selinger (11) stressed that a travel time period shift of at least 30 min was necessary with a staggered-work-hour program to obtain a definite change in commuting habits.
3. The use of half-hour time periods eliminated the potential problem of vehicles from different time periods interacting on the network. This condition could not be accounted for by MOD3.

The base-case temporal distribution of evening work travel is shown in Figure 6 for computer run 1. The general shape of the distribution is similar to the distributions found in studies of urban work trips (7,11), although the peaking characteristic of the base case is slightly less exaggerated than that found in the literature. It was found that loading the simulated network with more than 50 percent of the total work trips during a half-hour period re-

Figure 6. Staggered-work-hour simulation runs.

Run No.	Zones Involved	Percent Participation	Temporal Distribution for Zones Involved: Time Period 1	2	3	4	5	Temporal Distribution for All Zones: Time Period 1	2	3	4	5
1	ALL	Base Case	--	--	--	--	--	.10	.15	.50	.15	.10
A1	ALL	60	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20
A2	1-4	10	.10	.175	.45	.175	.10	.10	.153	.494	.153	.10
A3	1-4	30	.125	.20	.35	.20	.125	.103	.156	.482	.156	.103
A4	1-4	50	.175	.20	.25	.20	.175	.109	.156	.470	.156	.109
A5	1-4	60	.20	.20	.20	.20	.20	.112	.156	.464	.156	.112
A6	1-12	10	.10	.175	.45	.175	.10	.10	.161	.478	.161	.10
A7	1-12	30	.125	.20	.35	.20	.125	.111	.172	.434	.172	.111
A8	1-12	50	.175	.20	.25	.20	.175	.133	.172	.390	.172	.133
A9	1-12	60	.20	.20	.20	.20	.20	.144	.172	.368	.172	.144
A10	1-28	10	.10	.175	.45	.175	.10	.10	.170	.460	.170	.10
A11	1-28	30	.125	.20	.35	.20	.125	.120	.190	.380	.190	.120
A12	1-28	50	.175	.20	.25	.20	.175	.160	.190	.300	.190	.160
A13	1-28	60	.20	.20	.20	.20	.20	.180	.190	.260	.190	.180
A14	1-48	10	.10	.175	.45	.175	.10	.10	.174	.452	.174	.10
A15	1-48	30	.125	.20	.35	.20	.125	.124	.198	.356	.198	.124
A16	1-48	50	.175	.20	.25	.20	.175	.172	.198	.260	.198	.172
A17	1-48	60	.20	.20	.20	.20	.20	.197	.198	.210	.198	.197
B1	ALL	NA						.112	.156	.464	.156	.112
B2	ALL	NA						.133	.172	.390	.172	.133
B3	ALL	NA						.144	.172	.368	.172	.142
B4	ALL	NA						.160	.190	.300	.190	.160
B5	ALL	NA						.109	.156	.470	.156	.109
C1	6,10,14, 15,16,17, 22,23,24, 25,30,31, 32,33,39, 40,41,42, 43,49,51	10	.10	.20	.45	.15	.10					
	8,12,13 18,19,20, 21,26,27, 28,34,35, 36,37,38, 44,45,46, 47,48,50, 52	10	.10	.15	.45	.20	.10					
	1,2,3, 4,5,7, 9,11	10	.10	.175	.45	.175	.45	.10	.175	.45	.175	.10

NA = Not Applicable

sulted in unrealistically high levels of congestion.

The highway congestion index (HCI) was used as a measure of average network congestion. The HCI is the mean of all the congestion indices computed for each link of the network. The congestion index for each link is defined as the ratio of the link free-flow travel speed to the link travel speed when adjusted by the link volume of traffic. As the level of congestion increases, so does the HCI.

Policy Analysis

Staggered-work-hour policies were designed to evaluate the relations between both the magnitude of the participating work force and the level of urban work-trip fuel consumption. These policies were divided into two groups:

1. Group A--Shift travelers away from the peak half-hour in increments of 10, 30, 50, and 60 percent of the peak half-hour demand and vary the zones involved; and
2. Group B--Apply the total temporal distribution of work travel resulting from group A policies to all of the zones in the study area.

Group A policies served a dual purpose. The first was to evaluate the relation between the magnitude of the participating work force and work-trip fuel consumption. The basic test structure was to shift work travelers away from the peak half-hour period incrementally and evaluate the change in fuel consumption resulting from the temporal shift. Trips were shifted to the time periods immediately adjacent to the peak half-hour in equal amounts until the adjacent time periods each contained approximately 20 percent of the work trips originating from the zones involved in the staggered-work-hour program. Additional shifts from the peak half-hour were made in equal amounts to the half-hour periods beginning one hour before and after the beginning of the peak half-hour period. For example, as shown in Figure 6 for run A2, a total of 10 percent of the peak half-hour trips originating from zones 1-4 were shifted to the adjacent time periods 2 and 4. Areawide, 49.4 percent of the total work trips still occurred during the peak half-hour for this run, where all zones except zones 1-4 maintained the base temporal travel distribution. Similarly, for run A3, 30 percent of the work trips originating in zones 1-4 during the peak half-hour were shifted to other time periods. This was continued until a uniform temporal distribution of work travel was created for the participating zones.

The second purpose of group A policies was to test the impact of the location of the participants on fuel consumption. The simulation began with only the CBD zones (zones 1-4) participating (runs A2-A5) and progressed outward from the CBD, adding adjacent rings of zones to the staggered-work-hour program in successive program runs. For example, in Figure 6, run A8 involved the distribution of a total of 50 percent of peak half-hour trips to other time periods for zones 1-12 (rings 1 and 2). Areawide, this resulted in 39 percent of the work trips being made during the peak half-hour compared with 50 percent for the base case.

The purpose of policy group B was to test the impact of concentrating the staggered-work-hour program in selected zones as opposed to dispersing the same overall temporal distribution of trips over all zones. For five cases (runs B1-B5), the overall temporal distribution of work travel that resulted from the staggered-work-hour simulations for selected group A policies (runs A4, A5, A8, A9, and A12) was applied to all zones. For example, as shown in Figure 6, the overall temporal distribution for run B5 is the same as that generated for run A4. For run B5, all zones had the travel distribution specified in Figure 6, whereas in run A4 all zones except zones 1-4 had the base temporal trip distribution shown for run 1.

A variation of the staggered-work-hour policies was designed to coordinate the staggered-work-hour shift along selected transit corridors. This is policy group C. The purpose of this variation was to enhance the influence of the transit system on work travelers involved in the variable-work-hour program.

For run C1, 10 percent of the travelers originating in the zones along the five transit routes that traverse a general east-west direction were shifted from time period 3 (the peak half-hour) to time period 2. The same percentage of travelers originating in zones along the five transit routes that traverse a general north-south direction were shifted from time period 3 to time period 4. Zones that had transit routes along both major corridors (zones 1-4, 5, 7, 9, and 11) were given a 5 percent shift of peak half-hour travelers to both time periods 2 and 4. This run is also described in Figure 6. The policy structure described for run C1 was also used in later experiments as a basis for comparing the results of combined staggered-work-hour and transit policies.

POLICY EFFECTS ON FUEL CONSUMPTION

The total work-trip energy calculation contained data on transit fuel consumption for an entire day's travel. Since transit energy consumption is computed by MOD3 as a daily total, the contribution of transit energy consumption from each individual time element cannot be specified. However, this is not a major drawback in the analysis because the daily transit energy consumption was only 3 percent of the combined energy consumption for daily transit and automobile work trips.

The results of the simulation of the staggered-work-hour programs on automobile work-trip and daily transit energy consumption (hereafter referred to as total energy consumption) are shown in Figure 7. The results show that there is a strong relation between the percentage of work travelers shifting away from the peak half-hour period and the percentage decrease in total energy consumption. The smooth curve shown was manually fitted to the data and represents the approximate relation between work-trip travel-time shift and potential energy savings. This relation asymptotically approaches a 12.2 percent energy savings for work travel at the point where the temporal distribution of work travel is uniform over the length of the peak period.

The curve in Figure 7 indicates that the potential for energy savings from staggered-work-hour programs appears higher than the 1 percent savings indicated by previous research (3). For example, a 10 percent shift of work travelers away from the peak half-hour resulted in a 4 percent savings in energy. A 10 percent shift appears to be a realistic goal for such a program based on earlier studies (6,11).

The results also indicate that a greater savings in energy can be realized through a staggered-work-hour program that covers a dispersed area of influence rather than being concentrated in a small area. For example, in Figure 7, the data points marked by the symbol "+" represent group B policies. Group B policies have the same total number of participants in the staggered-work-hour program as specific group A policies. However, group B policies are applied to the entire urban area whereas those in group A are concentrated. In four of five simulations, the citywide program resulted in a greater reduction in energy consumption than the associated program in a more concentrated area. The magnitude of the difference between the group A and group B policies decreases as the total area of participation for group A policies increases.

The influence of a dispersed program compared with a concentrated program is more clearly shown in Figure 8. Here, the curves represent the trend of energy consumption versus percentage of traveler shift for each successive ring of zones added to the program. As successive rings of zones were included in the staggered-work-hour program, the trend was for a greater reduction in energy use for a given percentage shift in travelers from the peak half-hour. This difference became less pronounced as a larger percentage of travelers participated in the program. However, there was virtually no change in energy consumption with increased participation in staggered work hours when the program was concentrated in the CBD (ring 1).

The anomaly of the relation between staggered-work-hour participation and energy use for the CBD can best be explained by the fact that the majority of the simulated work trips to these zones were relatively short in length (generally only to the second or third ring) and were routed over only a few highway links. In addition, the highway links within the CBD were relatively uncongested. The combination of short trips and uncongested links resulted in no change in energy consumption. This result is consistent with the literature, which suggests that the effect of a concentrated program on congestion is lost within approximately 2 miles of the program location (8,12).

Similar results were obtained when congestion was treated as the dependent variable. All staggered-work-hour programs tested had a direct impact on highway congestion except those policies concentrated in the CBD zones, as shown in Figure 9. The percentage reduction in congestion resulting from staggered-work-hour policies increased as the program became more dispersed and included more zones. The maximum decrease in mean network congestion (based on the HCI) was approximately 44 percent.

The relation between highway congestion and energy consumption generated by the simulation is shown in Equation 1. This regression relation exhibits a strong linear tendency, resulting in an r^2 value of 0.97 (using the data from all of the simulation runs):

$$y = 0.20 + 0.27x \quad (1)$$

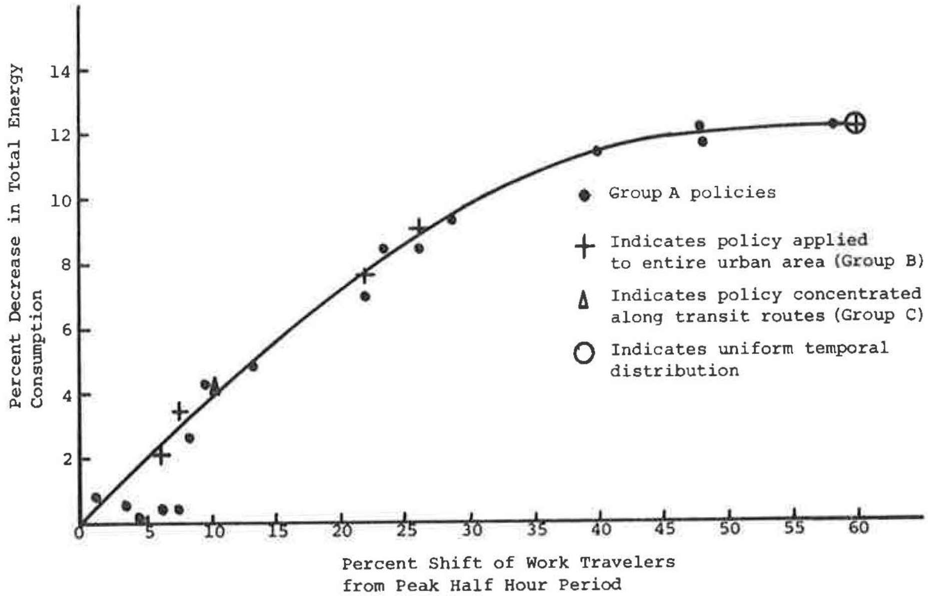


Figure 7. Impact of staggered-work-hour policies on total energy consumption.

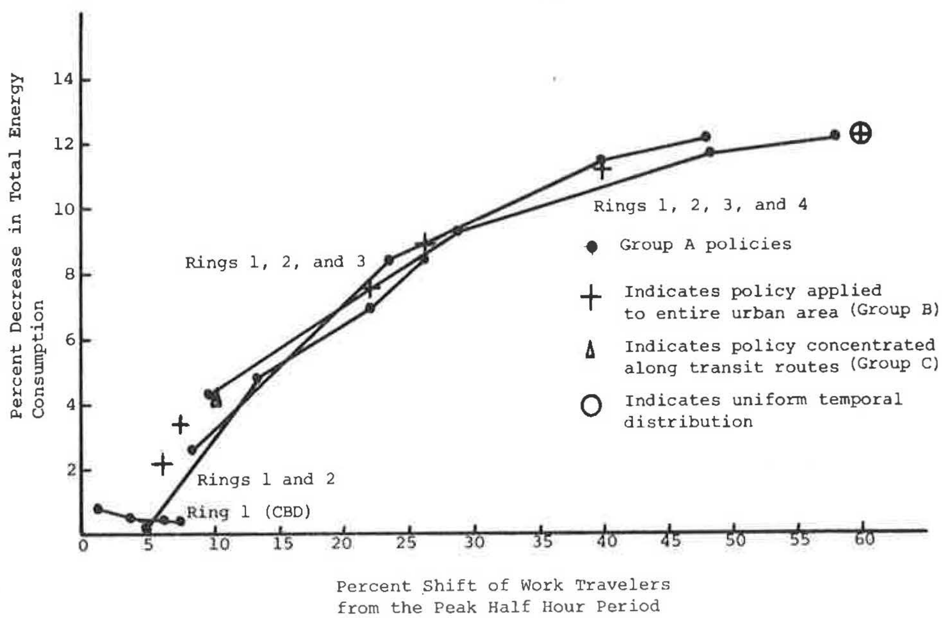


Figure 8. Impact of staggered-work-hour policies on total energy consumption by location of participating zones.

where $\hat{y}$ is the estimate of the percentage reduction in total energy consumption and x is the percentage decrease in the weighted mean HCI. The maximum reduction in energy consumption was approximately 12 percent for a reduction of 44 percent in the HCI.

The reduction in the HCI would have resulted in an even greater decrease in energy consumption had a modal shift to automobile travel not occurred as a result of the decrease in network congestion. The relation between the percentage change in bus ridership and the percentage change in the HCI generated by all of the simulation runs can be expressed by the following linear regression equation:

$$\hat{y} = -0.65 + 0.21x \quad (2)$$

where $\hat{y}$ is the percentage change in bus ridership and x is the percentage change in the weighted mean HCI.

The regression analysis resulted in an r^2 value of 0.91, which indicates good linear correlation. This result indicates that a decrease in congestion due to the implementation of a staggered-work-hour program would have a negative impact on work-trip bus ridership unless steps were taken to deter the modal shift. The possibility still exists that during an energy shortage transit ridership would increase even with the implementation of a staggered-work-hour program. Under conditions of normal fuel availability, this does not appear likely.

Automobile work trips were affected by the reduction in congestion resulting from the staggered work hours. The parameters most affected by the staggered-work-hour policies were automobile work-trip time and speed. Figure 10 shows the relation between the percentage of work travel shifted during the peak half-hour period and the decrease in automobile work-trip travel time. The family of curves

again suggests that concentrating these programs in a small area (the CBD) is less effective than a more dispersed approach. There is a distinct advantage in reduced work-trip travel time through the implementation of staggered-work-hour programs. The amount of the decrease in travel time depends on both the location of the program and the number of participants.

The relation between the reduction in mean automobile work-trip travel time and the savings in energy resulting from the simulated staggered-work-hour programs is as follows:

$$\hat{y} = 0.02 + 0.74x \quad (3)$$

where $\hat{y}$ is the percentage decrease in total energy

Figure 9. Impact of staggered-work-hour policies on highway congestion.

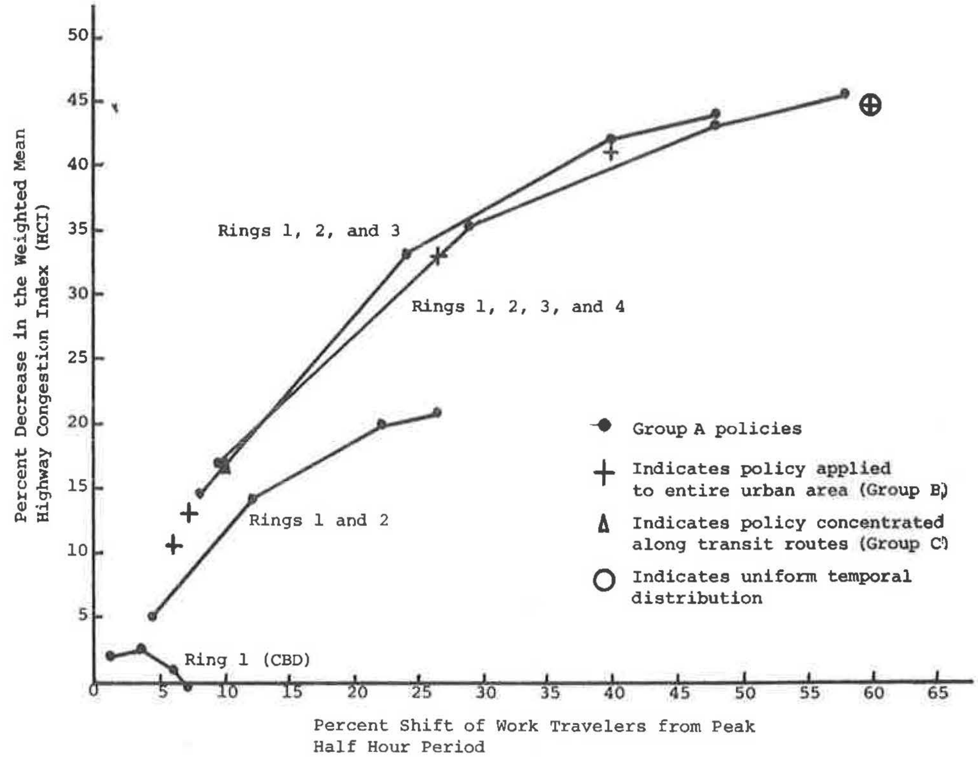
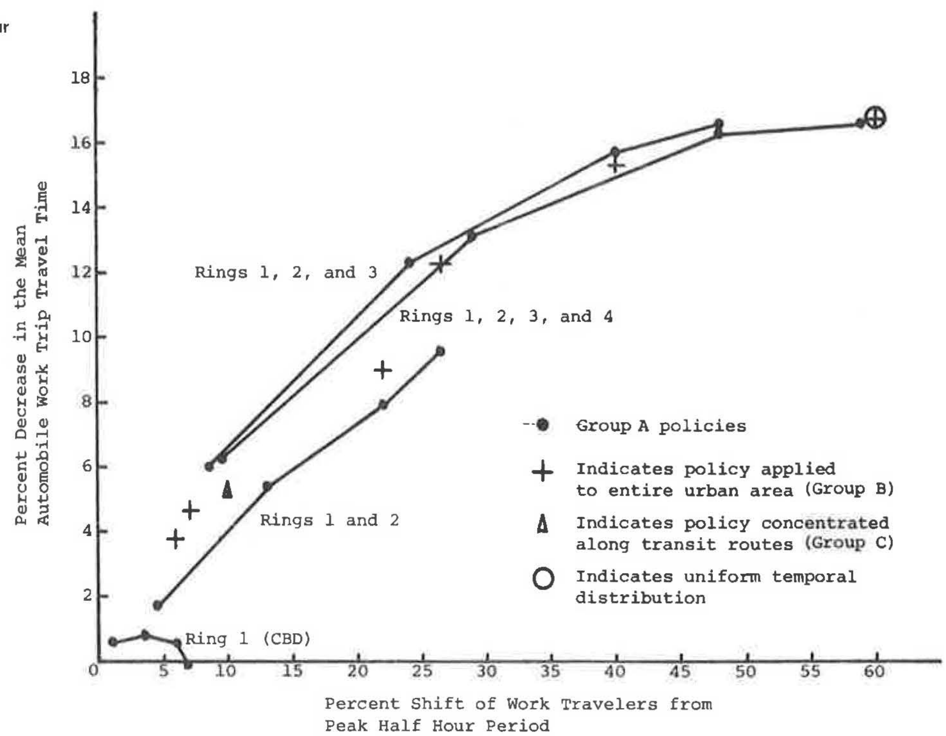


Figure 10. Impact of staggered-work-hour policies on automobile work-trip travel time.



consumption work trips and x is the percentage decrease in mean automobile work-trip travel time. The r^2 value for this relation was 0.96.

SUMMARY

For the activity pattern simulated by this research, it has been shown that staggered-work-hour programs can reduce highway network congestion and hence reduce automobile work-trip energy consumption. The reduction in total energy consumption (automobile work trips plus daily transit) was a maximum of approximately 12 percent with a uniform temporal distribution of work trips. A more realistic goal of a 4 percent reduction in total energy could be achieved with only a 10 percent shift in work travelers away from the peak period.

However, the effectiveness of a variable-work-hour program also depended on the location of the program. It has been shown through simulation that concentrating the program in a small area, such as the CBD, was less effective (approximately 85 percent) in reducing energy consumption than a program that involved the same number of travelers working at locations that were evenly dispersed over the urban area. This result is consistent with other research efforts (8,12) that have indicated that the effectiveness of a staggered-work-hour program was lost within approximately 2 miles of the workplace.

Under the conditions simulated, staggered-work-hour programs had a negative impact on work-trip transit ridership. The decrease in congestion during the peak half-hour period resulted in a proportional decrease in automobile travel time, which in turn resulted in a modal shift to the automobile. A 10 percent shift in travelers from the peak half-hour resulted in a 12-17 percent change in the HCI, depending on the location of the staggered-work-hour program. This resulted in a 2-3 percent decrease in work-trip bus ridership. The maximum decrease in transit ridership was approximately 9 percent as a result of the uniform temporal distribution of work travel.

This research study involved several limitations that may restrict the application of the results. The limitations stem primarily from the simulation technique and its scope of application. Details of these limitations are contained in earlier reports (9,10).

A hypothetical urban structure was used for the simulation. The shape and size of the area simulated may have had an impact on policy effectiveness. This possibility was not investigated in the study. Whether or not the policies tested would be more or less effective for a larger urban area, or in an area that had a different spatial distribution of population and employment, is unknown.

The relation between policy effectiveness and alternative transportation infrastructures also remains to be investigated. Changes in the highway network structure or the addition of expressways may alter policy effectiveness. This may also be true for alterations in the transit network structure, such as changes in route configuration or the addition of a rapid transit system. Changes in transit supply and efforts to coordinate supply changes with the staggered-work-hour program could also affect the results.

The algorithm for transit fuel consumption did not explicitly consider the number of transit stops per mile or the effect of highway congestion on transit speed. These considerations could alter work-trip modal choice, although the direction of this impact is unknown.

Planning for energy contingencies is a complex process. The evaluation of many policy alternatives is necessary for each individual urban area. The results of this research indicated that staggered-work-hour programs could be a valuable tool in reducing work-trip energy demand and should be given consideration as an operationally inexpensive method of reducing gasoline consumption.

The high potential for energy savings through implementation of staggered work hours indicated by this study suggests that further research should be done to expand on these results. This should be done with the objective of answering the questions raised by the limitations of the research, to further expand the modeling system, and to test other TSM policy alternatives individually and in combination.

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Energy Impacts of Transportation System Improvements

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A quick-response methodology for estimating the energy impacts of transportation system capital and operational improvements is presented. The method considers both energy consumed by vehicles and energy consumed in the construction and maintenance of facilities. Unlike many earlier energy impact estimation procedures, this methodology explicitly considers induced and diverted travel resulting from a transportation improvement and the effect of this travel on the level of service of transportation facilities. Application of the manual methodology takes less than 4 h and uses readily available data. The results are very sensitive to baseline operating conditions on the facilities that are affected by an improvement. The methodology was applied to 20 sample projects and produced results that were frequently counterintuitive. Highway expansion and new construction sometimes result in increased energy consumption both because vehicle fuel economy generally decreases at speeds above 35 mph and because of the energy consumed by induced travel. However, because the fuel consumption of congested travel is extremely high, projects that eliminate stop-and-go conditions frequently reduce energy consumption in spite of induced travel and in spite of the energy consumed in constructing and maintaining the expanded facility. Ramp metering and traffic signal improvements are generally effective in reducing energy consumption.

This paper describes quick-response methods for evaluating the energy impacts of transportation projects. The procedures were developed for the California Energy Commission (CEC) to evaluate projects considered for inclusion in the California State Transportation Improvement Program (STIP). The STIP is a five-year programming document that sets priorities for the allocation of state transportation funds among candidate projects. The STIP is reviewed and updated on an annual basis by the California Transportation Commission (CTC). The annual update is based on recommendations provided by the state and regional offices of the California Department of Transportation (Caltrans) and by regional planning agencies. Project rankings are based on a wide variety of technical and nontechnical factors, including project cost, expected benefits (e.g., reduced delay or congestion, reduced travel time, improved facility use, and improved safety), and equity (frequently based on the distribution of highly ranked projects by political jurisdiction and/or geographic location).

One benefit that is frequently stressed by project proponents is the potential reduction in energy consumption that will result from a proposed project. For the most part, these benefits are not rigorously justified. The energy impact assessment method described in this paper consists of an incremental, elasticity-based set of models that enables a technician or transportation planner to determine the net change in energy consumption that will occur as a result of a candidate STIP project.

The development of the energy impact estimation procedures was the product of a joint agreement between Caltrans and the CEC. This cooperative venture is intended to increase the ability of Caltrans and the CEC to respond to the energy concerns represented by the CEC. The estimation procedures were developed to conform to several important specifications:

1. The method is quick response so that a large number of projects can be evaluated; a typical project analysis takes from 2 to 4 h to complete.
2. The procedures make extensive use of standard existing project data sources. This ensures that projects can be analyzed quickly and facilitates comparisons between projects because the variability that might result from incompatible data sources is eliminated.
3. The procedures handle a wide range of project types, from extensive new freeway construction to TSM pricing or marketing strategies. Both transit and highway projects can be analyzed. The procedures can also be used to estimate the impacts of various combinations of project types [e.g., express bus service on a new reserved high-occupancy-vehicle (HOV) lane]. This is critical because only rarely is a project implemented in total isolation from other transportation system changes.

SOURCES OF ENERGY CONSUMPTION

The energy impact assessment procedures calculate the effect of a proposed project on the following three broad areas of energy consumption:

1. Energy consumed by moving vehicles;
2. Energy consumed in the construction or implementation of a facility or project; and
3. Additional energy consumed in the yearly maintenance of an improved or expanded facility.

Simplified procedures for estimating the second and third areas of energy impacts have been developed by Apostolos, Shoemaker, and Shirley (1). However, quick-response procedures for calculating the first category of energy consumption (vehicle energy impacts) have been inadequate for the reasons described below.

When a project is implemented, there are three sources of change in vehicle energy consumption:

1. Vehicles currently traveling on the facility or facilities to be improved may experience changes in their speed and traffic-flow characteristics. Usually, travel speeds will be increased, delays and idling time will be reduced, and/or congested stop-and-go traffic will be relieved. These changes will affect the energy consumption characteristics of the vehicles themselves.
2. An improvement on one facility may divert traffic from other facilities of the same mode. A new highway bypass will attract vehicles from an existing arterial; a new transit route may draw patronage away from other routes that have similar service areas. Because the level-of-service characteristics (e.g., travel speed) of the competing routes may be different, this diverted travel can result in a change in energy consumption.
3. A transportation improvement may induce new travel. These new trips represent entirely new travel generated as a result of increased accessibility between points served by the improved facility. These new trips consume additional energy and therefore affect total energy consumption.

Several earlier procedures for estimating energy impacts (1,2) deal with the first of these three sources of change in vehicle energy consumption. These other methods do not, however, consider the level of induced and diverted travel and the impact of this travel on the level of service of affected facilities. The procedures described here explicitly calculate these impacts. Trips diverted away from a particular facility or mode result in a net energy savings for this facility or mode; trips induced on or diverted to a facility incur energy costs on that facility. Equilibration is performed on all affected facilities to account for supply and

demand interaction to ensure the accuracy of the results.

OVERVIEW OF METHOD

A simplified view of the structure of the method is shown schematically in Figure 1. The first step is to identify those trips that will be affected by a given improvement. These trips may be on one or more highway facilities and on one or several transit routes. In this critical step of the process, the analyst must exercise careful judgment to identify facilities that may be in competition with the facility that is being improved.

Current-year affected travel is then factored to the future planning year to account for long-term changes in population and vehicle operating cost. Then, the future baseline level of service, travel time, and energy consumption are calculated for the affected trips on the network without the given improvement (the STIP project).

At this point in the process, the impact of the STIP project on the level of service that is provided to affected trips is calculated. By comparing the baseline and "build" travel times and applying the appropriate diversion factors and elasticities, diverted travel and induced travel are computed. However, the change in traffic volume may significantly affect travel time; if so, iteration takes place until travel time and traffic volume reach equilibrium.

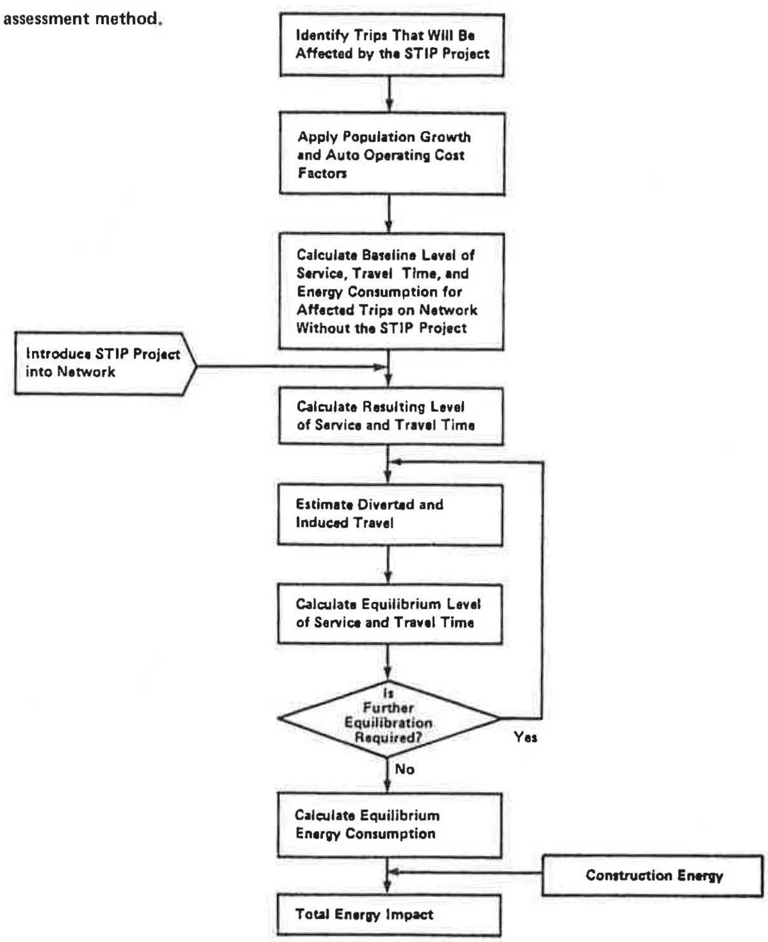
The energy consumed by moving vehicles is then estimated (based on the new traffic volumes, vehicle speeds, and flow characteristics) and combined with construction energy estimates to yield the total energy impact for the project. One early finding of this study was that the energy consumed in the maintenance of a new or improved facility is negligible compared with vehicle and construction energy. For this reason, it has been omitted from the analyses reported here.

MODEL OUTPUT

The new impact estimation procedure forecasts the change in energy consumption in a given target year that results from the construction or implementation of the STIP project. The target year may be any year desired by the analyst (e.g., the year of project construction or 20 years after construction). Two sets of energy estimates are produced. The first is a baseline or no-build forecast of the energy consumed in the target year on the "affected" facilities in the existing network (this is not usually the same as the current-year energy consumption due to changes in population and automobile technology over time). The second is a "build" forecast of energy consumed in the same target year with the added improvement in the transportation infrastructure. Therefore, the two estimates are not before-and-after estimates but rather with-and-without estimates.

Life-cycle energy impacts can also be calculated by using the impact procedures and simply calculating the energy impacts at several time periods in the life span of the project and interpolating for intermediate years. Though the change in energy consumption may be somewhat nonlinear over time, by selecting several time points the total change in energy consumption can be calculated quite accu-

Figure 1. Overview of energy impact assessment method.



rately. Note that, when calculating life-cycle energy impacts, the analyst may want to discount energy flows over time (just as an economist discounts future costs and revenues in evaluating major investments). Discounting of energy flows is appropriate in considering the "value" or economic worth of energy consumed rather than simply the amount of energy used.

Note that, because the model treats individual trips as the behavioral unit of travel, it estimates the total energy consumed by these trips, including those portions of trips that take place both on and off the affected facilities. It does not produce estimates of total energy consumed on the new or improved facility (or facilities) or on specific segments of facilities.

The construction energy impact estimates apply to the complete STIP project. These cannot be directly compared with the vehicle energy impacts because vehicle impacts are calculated for a given year. By dividing total construction energy by the project life, an undiscounted estimate of annual construction energy can be developed and compared with vehicle energy impacts.

VARIABLES ENTERING INTO IMPACT ASSESSMENT PROCEDURES

The impact assessment procedures are sensitive to a wide variety of variables. This section of the paper briefly describes these variables and how they are accounted for in the models. A full discussion of the structure of the models and detailed descriptions of the model equations are given elsewhere (9).

Estimates of fuel consumption are based heavily on previous work by Apostolos, Shoemaker, and Shirley (1); Tardiff, Benham, and Greene (3); and Claffey (4). These estimates are sensitive to the following variables:

1. The vehicle mix on the facility (automobiles, buses, and trucks);
2. Long-term changes in automobile and truck fleet fuel economy;
3. Average vehicle operating speed under both congested and uncongested conditions, both on and off the facility;
4. The incidence and effect of stop-and-go traffic conditions; and
5. Energy consumed during delays at signals and metered ramps.

Estimates of highway capacity and speed are based on methods outlined in the 1965 Highway Capacity Manual (5) and updated in Transportation Research Circular 212 (6). These methods are used heavily by Caltrans in the calculation of various performance indexes (7,8). Highway capacity and speed are a function of the following variables:

1. Facility size and type;
2. Design speed;
3. Grades, geometrics, and sight-distance restrictions (for two-lane roads);
4. Vehicle mix (automobiles versus trucks); and
5. Effects of traffic signals.

The fuel efficiency of vehicles declines dramatically as volume exceeds capacity (i.e., congestion occurs) and average speeds decline precipitously. Fuel efficiency also declines rapidly as vehicle speeds exceed 30 mph for automobiles and diesel trucks and 35 mph for gasoline trucks (see Figure 2). Congestion, however, occurs only during certain times of the day. The impact estimation procedures, using empirical data from the Los Angeles area, calculate the percentage of traffic that experiences congestion on the basis of the relation shown in Figure 3. This allows the separate calculations of travel speeds and fuel economy and consumption during the "congested" and "uncongested" portions of the day, ensuring sensitivity to the markedly different vehicle performance and energy consumption characteristics of these two periods.

Long-term changes in population are accounted for by factoring current-year travel to the baseline year by using county or smaller-area population forecasts. County-by-county data on average trip length are also used. Similarly, the effects of long-term changes in automobile operating cost are included by applying the appropriate direct and cross elasticities of automobile and transit travel with respect to automobile operating cost. (Elasticities used in the initial application of the method in California are given in Table 1, which was developed by Charles River Associates.)

As discussed earlier, the impact estimation procedure incorporates induced and diverted travel. Induced travel is calculated by using travel-time direct and cross elasticities (Table 1), whereas diverted travel is calculated by using travel-time-based proportional assignment. The level of induced travel is, of course, based on the change in total trip travel time rather than on the travel time on some segment of a trip. Trips are divided into on- and off-facility portions. Off-facility speeds are based on existing speeds for urban and rural local traffic. Default values can be used for these speeds with minimal loss of accuracy in the typical case when detailed speed data are not available. Differences between urban and rural areas are also accounted for through the use of larger rural operating-cost and travel-time elasticities (Table 1) and the longer average trip lengths generally observed for rural areas.

Changes in transit travel are sensitive to a variety of variables, including changes in automobile operating cost and travel time. Induced transit travel results from project-related changes in transit travel time and wait time. The energy consumption of the automobile leg of park-and-ride trips is included explicitly (including cold-start factors for automobile fuel economy). In addition, when modal shifts occur between automobile and transit, average automobile occupancy factors are used to equate transit average daily passengers with automobile ADT.

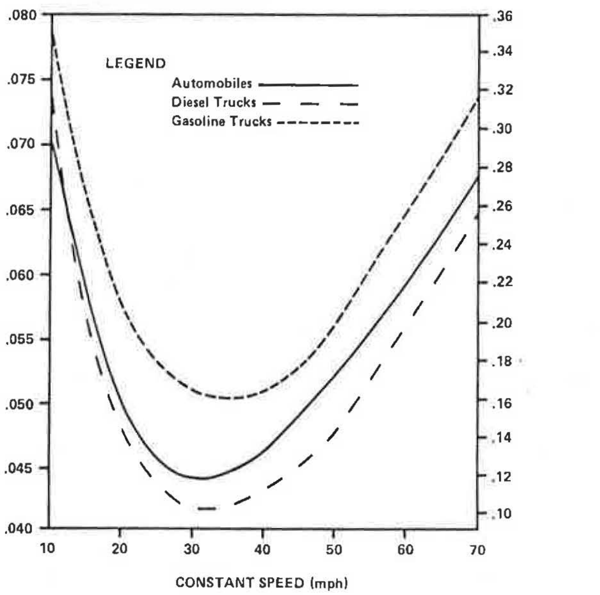
IMPACT ESTIMATION WORKSHEETS

Fifteen different worksheets are available for use in the manual impact estimation procedure. Some of these worksheets (input data, travel time estimation, and project summary sheets) are filled out, at least in part, for all types of projects. Others are used only for specific types of projects. The complete set of available worksheets is described in detail elsewhere (9). The worksheets guide the technician or analyst step by step through the impact estimation process. Intermediate calculations and results are accessible, so that the sources of changes in energy consumption can be identified and discussed. Therefore, the methodology is highly transparent and user oriented. The analyst can also input special knowledge he or she may have concerning the project or its impact area by entering travel speeds, traffic volumes, or other known variables. In addition, the analyst can repeat the impact estimation procedure by using different estimates of selected input parameters to measure the sensitivity of the results.

RESULTS: ENERGY IMPACTS OF SELECTED PROJECTS

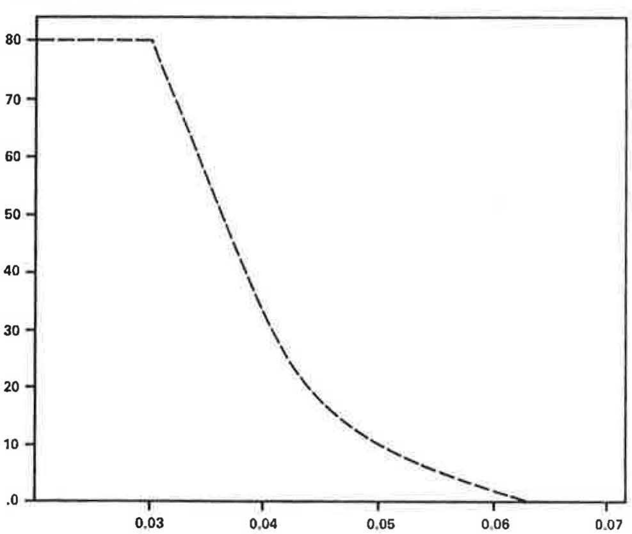
The energy impacts of 20 proposed STIP projects were calculated for the target year of 1999. They included a wide range of project types, including major and minor highway improvements, transit service changes, bicycle zone construction, new freeways, HOV lanes, and ramp metering. This section presents and discusses the results of four representative project analyses.

Figure 2. Fuel consumed at constant speeds by automobiles and tractor-semitrailer trucks.



NOTE: Base Year = 1974

Figure 3. Percentage of ADT experiencing congestion.



US-101, Ventura County

Alternative 1

US-101 in Ventura County is currently a congested four-lane freeway. Under alternative 1, an 18.9-mile segment of the facility is expanded to six lanes, all of which are open to general traffic at all times of the day.

The data given in Table 2 show that a significant decrease (9.2 percent) in vehicle energy consumption results from the proposed project. Because the project reduces congestion, the average trip travel time of affected trips is reduced by 2.2 min (this is the travel time both on and off the freeway for those trips using the improved section). This results in an induced travel of 5.8 percent of the private-vehicle vehicle miles of travel (VMT) in the target year (1999). However, because the travel speed on the currently congested facility is increased to free-flow conditions, average fuel economy improves (Figure 2). Therefore, in spite of significant induced travel, total vehicle energy consumption decreases as a result of this particular project. The construction energy impacts of the project are insignificant compared with the energy consumption of private vehicles.

Alternative 2

Alternative 2 involves the same basic construction as the preceding project, but the six-lane facility will be operated with a reserved with-flow HOV lane and ramp metering during congested periods in both directions. Meters are located at all entrance ramps, and ramp bypasses are provided for HOVs.

The results of the energy impact analysis indicate that a smaller reduction in vehicle energy consumption results from this project alternative (see Table 3). Energy consumed by moving vehicles is reduced by 4.0 percent, and 10.0 percent of the absolute amount of this savings is offset by the energy consumed by vehicles idling at the metered ramps.

The reduction in vehicle fuel consumption results once again from the improved fuel economy of formerly congested traffic that now operates under less congested conditions as a result of ramp metering. Average trip travel times decrease slightly; the increased freeway speed in this case is partly offset by the delays experienced at the metered ramps. Induced travel of 3.3 percent results from this

Table 1. Travel demand elasticities.

Type	Elasticity: Urban Site	Elasticity: Rural Site
ADT direct elasticity with respect to		
Automobile operating cost	-0.35	-0.50
Automobile travel time	-0.40	-0.68
Daily transit passengers direct elasticity with respect to		
Bus travel time	-0.25	NA
Bus wait time[a]		NA
<5 min	-0.13	
≥5 min	-0.20	
Daily transit passengers cross elasticity with respect to		
Automobile operating cost	+0.15	NA
Automobile travel time	+0.08	NA

Note: ADT = average daily traffic.

[a]It is assumed that average wait time is equal to half the headway for transit headways of <10 min. For longer headways, the elasticity value provided here was derived from a bus frequency elasticity of +0.20. It is expressed as a wait-time elasticity only to facilitate the use of the standardized worksheets for all ranges of bus headways.

Table 2. Energy impact summary results: US-101, Ventura County, alternative 1.

Item	Baseline	Post Project	Change (%)
Private-vehicle VMT per day (000 000s)	2.74	2.90	+5.8
Private-vehicle fuel economy (miles/gal)	22.6	26.3	+16.4
Average trip time (min)	16.65	14.45	-13.2
Energy consumed (10^{12}Btu)			
Moving vehicles	5.54	5.03	-9.2
Idling vehicles	0	0	

Note: Total project construction energy = 1.00×10^{12} Btu; annualized project construction energy (undiscounted) = 0.04×10^{12} Btu.

Table 3. Energy impact summary results: US-101, Ventura County, alternative 2.

Item	Baseline	Post Project	Change (%)
Private-vehicle VMT per day (000 000s)	2.74	2.83	+3.3
Private-vehicle fuel economy (miles/gal)	22.6	25.2	+11.5
Average trip time (min)	16.65	15.86	-4.7
Energy consumed (10^{12} Btu)			
Moving vehicles	5.54	5.32	-4.0
Idling vehicles	0	0.02	∞

Note: Total project construction energy = 1.00×10^{12} Btu; annualized project construction energy (undiscounted) = 0.04×10^{12} Btu.

Table 4. Energy impact summary results: CA-39, Los Angeles County.

Item	Baseline	Post Project	Change (%)
Private-vehicle VMT per day (000s)	144.3	147.7	+2.3
Private-vehicle fuel economy (miles/gal)	22.9	30.7	+34.1
Average trip time (min)	21.83	21.05	-3.6
Energy consumed (10^9 Btu)			
Moving vehicles	245.7	213.9	-12.9
Idling vehicles	46.6	6.0	-87.1

Note: Total project construction energy = 5.5×10^9 Btu; annualized project construction energy (undiscounted) = 1.1×10^9 Btu.

project. The new HOV lane by itself increases capacity and results in a small amount of induced VMT. Thus, in this case the effect of the HOV lane is to increase, rather than decrease, energy consumption.

The construction energy impact is essentially identical to alternative 1 of the project. Under the second alternative, the annualized construction energy increase (which in the former project was dominated by the vehicle energy savings) offsets about one-fifth of the vehicle energy savings.

CA-39, Los Angeles County

CA-39 in Los Angeles is a 3.4-mile highway segment that contains 13 signalized intersections. These signals were designed to be interconnected, but the existing control equipment is unreliable. The proposed project is the replacement of existing equipment with new signals and controllers.

In the baseline case, it was assumed that the 13 signals (each with 50 percent green time) functioned essentially independently--i.e., with no interconnection. Therefore, every vehicle had roughly a 50 percent chance of having to stop at each signal. In the "build" case, the signals are assumed to be perfectly interconnected. Therefore, no vehicle stops more than once except under congested conditions when interconnection breaks down and the signals are again conservatively assumed to operate independently.

Significant energy savings result from the project (see Table 4). Idling is reduced substantially so that energy consumed by idling is reduced by more than 85 percent. Equivalent absolute energy savings (though smaller in percentage terms) result from a return to continuous-flow conditions for nearly all uncongested travel, and there is a resulting improvement in fuel economy. These energy savings occur in spite of induced travel of 2.3 percent that results from a 3.6 percent reduction in average trip travel time.

The total construction energy is less than 10 percent of the annual energy savings resulting from this project. This is clearly a project that offers significant energy savings, as well as many other travel-related benefits such as reduced delay.

CA-99, Merced County

CA-99 in Merced County is a four-lane rural expressway running through the city of Livingston, California. Within the 6.1-mile project limits, there are one signalized intersection, five other at-grade intersections, and numerous "T-intersections". Several sections have no shoulders. The existing facility has a very high proportion of heavy truck traffic. The proposed project involves the construction of a four-lane, limited-access bypass near the existing alignment. The existing facility would remain to serve local traffic.

This project was analyzed by treating the existing CA-99 and the new bypass as competing facilities. Traffic was allocated between the two facilities on the basis of relative travel times on the two routes. It was assumed that all heavy-truck traffic would use the bypass (a negligible amount of this traffic is local traffic). Signal delays and idling time were calculated in a manner similar to that used for the CA-39 project in Los Angeles, except that the effects of the signal on cross-street traffic were also considered.

The results of the energy impact analysis given in Table 5 indicate that the combined vehicle energy consumption of affected vehicles on the old and new facilities increases by almost 40 percent as a result of the proposed project. This large increase stems primarily from two sources:

1. High speeds on the bypass result in a net decrease of 7.5 percent in average trip travel time, which in turn generates induced travel of 4.7 percent.
2. For the traffic using the bypass, the average on-facility speed increased from 32.5 mph to nearly 65.0 mph, which results in markedly increased fuel consumption (Figure 2). This effect is even more pronounced because of the high percentage of heavy-truck traffic, whose fuel economy declines even more rapidly at high speeds than that of automobiles.

In addition to the increases in vehicle energy, the construction energy for the new facility is substantial--equivalent, in this case, to the total energy consumed in three years by all vehicles on the existing facility. This is clearly a project that has negative energy impacts associated with the benefits of reduced travel time, increased capacity, and improved safety conditions.

DISCUSSION OF RESULTS

The energy impact estimation techniques presented in this paper were used to analyze a total of 20 California STIP projects and project variations. From

Table 5. Energy impact summary results: CA-99, Merced County.

Item	Baseline	Post Project	Change (%)
Private-vehicle VMT per day[a] (000s)	151.0	158.1	+4.7
Private-vehicle fuel economy[a] (miles/gal)	29.9	22.1	-26.0
Average trip time[a] (min)	19.69	18.22	-7.5
Energy consumed[a] (10^9 Btu)			
Moving vehicles	230.3	326.1	+41.6
Idling vehicles	4.2	1.6	-61.9

Note: Total project construction energy = 917.5×10^9 Btu; annualized project construction energy (undiscounted) = 36.7×10^9 Btu.

[a]Data are based on affected trips made by vehicles on both old and new facilities.

these sample projects, a number of interesting conclusions can be drawn about the typical energy impacts of various classifications of projects. Some of these results are counterintuitive and contrary to commonly accepted conclusions concerning the energy impacts of projects. These results are summarized below:

1. Highway widening or bypass projects can either increase or decrease vehicle energy consumption. Energy is generally saved as long as the improvement is on a congested facility and is small enough just to allow stable traffic conditions. As the capacity improvement allows speeds to exceed about 35 mph, vehicle fuel economy decreases and additional traffic is induced. Both of these factors increase overall energy consumption.
2. STIP projects that are primarily safety related, such as two-way left-turn lanes and shoulder improvements, have negligible energy impacts.
3. Ramp-metering projects yield energy savings when implemented under congested conditions. Above baseline speeds of about 35 mph, ramp metering tends to increase energy consumption. In most cases, ramp delays reduce the amount of induced new travel.
4. Traffic-signal improvements along corridors are effective energy savers, as are all projects that relieve stop-and-go traffic conditions. The effectiveness of signal improvements decreases, however, as the existing level of congestion increases. This is because signal interconnection has decreasing benefits under saturated conditions.

RECOMMENDATIONS FOR FURTHER DEVELOPMENT

With relatively simple modifications, the impact estimation procedures described here could be automated for application on a hand-held calculator or a small minicomputer. This would reduce the length of time needed to evaluate a project from 2-4 h down to less than 15 min. Automating the procedures has five primary benefits:

1. Equilibration of induced and diverted travel could be performed to much stricter tolerances.
2. Faster turnaround time would allow the analyst to make more estimates while varying project and input parameters as a check for sensitivity.
3. The fuel consumption characteristics of a greater number of vehicle types (e.g., small and medium trucks) could be considered.
4. Estimation of life-cycle energy impact would become available without imposing a great time burden on the analyst.
5. The likelihood of human error would be reduced.

As described earlier, most of the components of the quick-response method of assessing energy impacts have been derived from existing complex models or modeling systems. However, the method for deriving the VMT impact of HOV lanes is based on a very limited number of empirical observations. Ongoing work on HOV lane impacts (10,11) is significantly improving the state of the art in modeling these impacts and should be incorporated into the existing set of impact estimation procedures.

Energy consumption data are based on a 1971 report (4) that used road tests of vehicles from model years 1960 through 1968. Overall fuel economy levels have, of course, been factored up so that fleetwide average fuel economy matches current and projected levels. However, the effect of average speed on fuel economy may have changed somewhat in recent years as automobile engines and bodies have been redesigned to be more fuel efficient. This raises the possibility that the curve shown in Figure 2 may not be appropriate for the current vehicle fleet. On the other hand, there is some recent evidence that the basic shape of the curve in Figure 2, including the speed of minimum fuel consumption, is in fact appropriate for newer cars (12). This problem is not specific to the project. Inadequate attention has been paid to this problem in the recent literature, and significant new research in this area is critically needed.

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Transit Use and Energy Crises: Experience and Possibilities

DANIEL K. BOYLE

A representative sample of 66 urbanized areas is used to examine the relation between gasoline supply and transit ridership during the second and third quarters of 1979. An overview of the effect of the 1979 gasoline shortfall on transit ridership indicates that ridership increased by 5.1 percent in the time frame of the study over the corresponding period in 1978. The largest percentage increases in ridership were seen in western U.S. urbanized areas and small urbanized areas. Cross elasticities of transit ridership with respect to gasoline supply are calculated for various categories broken down by region and system size. The measure used for this calculation is arc elasticity. Cross elasticities vary from -0.45 for large systems in the Northeast to -4.99 for small systems in the West, and the cross elasticity for the entire sample is found to be -0.75. The role of transit in alleviating the impact of the 1979 energy crisis is found to be minor: Gasoline savings due to transit patronage increases amounted to less than 5 percent of the decrease in gasoline sales. Methods of calculating ridership increases and gasoline savings attributable to transit for a variety of energy futures are developed. The results indicate that transit cannot be expected to play a major role in a future energy emergency.

As energy efficiency became a newly discovered concern in the wake of the 1973-1974 energy crisis, transit ridership trends rose for the first time in a generation. The 1979 crisis did not catch America completely by surprise: Transit systems around the country were generally in sounder shape than in 1973, thanks in part to an infusion of federal money in the form of operating assistance as well as capital grants. The 1979 energy crisis resulted in a further growth in transit ridership.

This paper is intended to assess the relation between transit ridership and energy supply in the 1979 crisis. The relation is important in both directions. Of direct concern is the effect of a gasoline shortfall on transit ridership, but also investigated is the degree to which transit can soften the impact of a gasoline shortfall by providing an alternative means of transportation and thereby preventing some of the loss of mobility that would otherwise occur. Many studies (1-7) have examined the first part of this problem, but none has focused directly on the second part.

DATA AND PROCEDURES

This study uses a sample of 66 U.S. urbanized areas to examine the relation between gasoline supply and transit ridership during the second and third quarters of 1979. Selection of urbanized areas for the sample was guided primarily by the availability of data for ridership and gasoline supply. Data were also collected for other factors such as population size and density, service and fare levels, gasoline price, region of the country, and transit system size. These other factors were analyzed to determine whether any factor showed a relation with either gasoline supply or transit ridership and whether any factor affected the supply-ridership relation.

A word on the measurement of the key variables involved is in order. Data on ridership and gasoline supply were obtained by month and aggregated both by quarter and by the entire six-month period. Comparison with the corresponding time period in 1978 determined changes in ridership and supply. Ridership data were obtained from the American Public Transit Association (APTA) (8), and monthly gasoline sales by state were available from the Federal Highway Administration (FHWA) (9). These were apportioned to urbanized areas within each state by use of the ratio of daily vehicle miles of travel (DVMT) in a given urbanized area to statewide DVMT (10). This approach assumes that gasoline sales and shortfalls are distributed within each state in the same proportion as DVMT. Sources for other variables may be found in the literature (10-12 and various issues of the Oil and Gas Journal).

Two further notes on data sources should be made. Gasoline prices in neighboring urbanized areas were remarkably similar, and an average of neighboring prices was used where the information was not available for a given urbanized area. In addition, total transit VMT was not available for all urbanized areas, and so system size was measured by peak-hour vehicle requirement. This presents no problem since, where transit VMT was available, its correlation with peak-hour vehicle requirement was very high.

The time frame of the study consists of the second and third quarters of 1979 and comparisons with the corresponding time period of 1978 to determine changes. In larger urbanized areas, all operators are considered part of the same overall transit system.

IMPACT OF 1979 CRISIS ON TRANSIT USE

In the second quarter of 1979, transit ridership rose by 3.3 percent over 1978. In the third quarter, as the impact of the gasoline shortfall hit home, ridership increased by 6.7 percent. The increase in ridership for both the second and third quarters was 5.1 percent.

Data given in Table 1 (8) show that transit ridership grew at a much faster pace on transit systems in the West. As Table 2 (8, 11) indicates, small urbanized areas experienced greater percentage changes in ridership than did large urbanized areas. Table 3 (8, 11) indicates that, when size of transit system replaces population, virtually the same relation holds: Smaller systems show greater percentage increases in ridership. An interesting exception is that the smallest systems rank below moderately small systems in percentage change in ridership. This suggests that there may be a minimum base system size necessary for optimal growth in transit ridership during an energy crisis.

Tables 1-3 indicate that small systems and systems in the West showed the greatest percentage increases in transit ridership during the 1979 energy crisis. Ridership levels are lowest on small systems and on systems in the West (Table 1), and so there is more room for growth. In addition, population growth in the West may have accelerated ridership increases.

Data given in Table 4 (8-10) show no clear relation between percentage changes in gasoline supply and ridership. The trends of percentage changes in ridership with increasing percentage shortfalls are opposite in the second and third quarters. Attempts to find a suppressor variable affecting the supply-ridership relation were unsuccessful, nor did a clear relation emerge when the time frame was expanded to include both quarters. Given the different responses of urbanized areas of different sizes and in different regions, it seemed appropriate to take size and region into account in analyzing the supply-ridership relation. This approach is used in the following section.

Other variables for which data were collected are

Table 1. Percentage change in ridership by region for 1978-1979.

Region	No. of Systems	Change in Ridership (%) Second Quarter	Third Quarter	Mean Monthly Ridership (000s)
Northeast	13	2.4	6.0	11 633
South	24	2.5	6.0	1 725
North Central	16	5.0	6.3	4 180
West	13	13.7	15.8	1 275
Total	66	3.7	6.7	4 183

Table 2. Percentage change in ridership by urbanized-area population.

Urbanized-Area Population	No. of Systems	Change in Ridership (%) Second Quarter	Third Quarter
>1 000 000	12	3.1	6.0
500 000 to 1 000 000	12	7.2	9.6
250 000 to 500 000	11	5.5	10.9
100 000 to 250 000	22	8.4	12.9
<100 000	9	24.1	18.0
Total	66	3.7	6.7

Table 3. Percentage change in ridership by size of system.

Peak Requirement (no. of buses)	No. of Systems	Change in Ridership (%) Second Quarter	Third Quarter
>200 + rail	5	3.2	5.8
>200, bus only	16	4.5	8.5
80 to 200	11	6.1	10.8
40 to 80	18	10.0	12.9
<40	16	6.9	11.7
Total	66	3.7	6.7

Table 4. Percentage change in ridership by percentage change in gasoline supply.

Supply Decrease (%)	Second Quarter No. of Systems	Second Quarter Change in Ridership (%)	Third Quarter No. of Systems	Third Quarter Change in Ridership (%)
>9	4	11.0	15	5.9
7 to 9	13	2.9	12	6.3
5 to 7	13	2.3	17	12.3
3 to 5	21	11.6	11	7.2
<3	15	8.2	11	8.2
Total	66	3.7	66	6.7

not of particular use in this analysis. The range of percentage changes in gasoline price was too narrow to yield significant results. Urbanized areas in the midrange of population density showed the greatest percentage increases in ridership. Ridership changes vary directly with service changes, but it is difficult to determine whether service changes preceded or followed ridership changes in 1979. Fare changes, as might be expected, tend to hold down ridership increases.

In general, size of system and region were salient variables in determining the impact of the 1979 energy crisis on transit use. These two variables are taken into account in the examination of the supply-ridership relation in the next section.

Table 5. Cross elasticities of transit ridership with respect to gasoline supply.

Region	System Size	No. of Systems	Cross Elasticity
Northeast	Large	8	-0.45
	Small	5	-3.40
	Total	13	-0.48
South	Large	10	-0.87
	Small	14	-0.98
	Total	24	-0.90
North Central	Large	5	-0.66
	Small	11	-1.57
	Total	16	-0.69
West	Large	6	-2.55
	Small	7	-4.99
	Total	13	-2.79
All regions	Large	29	-0.68
	Small	37	-2.11
	Total	66	-0.75

CROSS ELASTICITIES OF TRANSIT RIDERSHIP WITH RESPECT TO GASOLINE SUPPLY

Cross elasticity measures the sensitivity of the demand for a particular product to changes in the characteristics of some other product. In this case, what is being measured is the sensitivity of transit ridership to changes in gasoline supply. Transit systems are categorized by system size (large or small, with a peak-hour requirement of 100 vehicles as the dividing line) and by region. Within each category, an aggregate approach is used to measure the changes in ridership and gasoline supply over the six-month period (including both quarters) in 1979 compared with the same time period in 1978. Arc elasticity, which has emerged in the transportation literature as the preferred measure of elasticity (13-15), is used to measure the cross elasticities of transit ridership with respect to gasoline supply. The cross elasticity for the category of system size i and region j is

$$e_{ij} = (\log R_{79ij} - \log R_{78ij})/(\log G_{79ij} - \log G_{78ij}) \quad (1)$$

where R_{xij} is the sum of riders on transit systems of size i in region j in year x and G_{xij} is the sum of gasoline sales in urbanized areas with transit systems of size i in region j in year x.

Table 5 gives the cross elasticities derived from the above calculations. The response of ridership to gasoline supply is much more elastic in western urbanized areas than in other regions of the country. In every region, small systems show greater cross elasticities (in terms of absolute value) than large systems.

The difference in cross elasticity by system size is particularly pronounced in the Northeast. However, a majority of the small transit systems sampled in the Northeast are in Pennsylvania, where an unexplained discrepancy in gasoline data masks the severity of the gasoline shortfall and so exaggerates the calculated cross elasticity. The difference between small and large systems in the Northeast is therefore also exaggerated. In the South, on the other hand, the difference is very small. Many of the small systems in the South actually lost riders in the second and third quarters of 1979; of the 10 systems that lost ridership, 7 were small systems in the South. This was balanced somewhat by the relatively minor gasoline shortfalls in southern urbanized areas in the sample. Nonetheless, the South is the only region in which ridership was relatively inelastic with respect to gasoline supply for small systems.

In general, the relation between transit ridership and gasoline supply is inelastic except in the West: Cross elasticities range from -0.48 in the Northeast to -2.79 in the West. The same pattern holds for large systems: Cross elasticities range from -0.45 in the Northeast to -2.55 in the West. Among small systems, the relation is elastic except in the South: Cross elasticities range from -0.98 in the South to -4.99 in the West. The cross elasticity for the entire sample is -0.75.

It has been suggested that transit systems in the West have excess capacity and so have a greater ability to respond to a crisis situation (16). This might explain the greater cross elasticities in the West. It is possible that small systems have more flexibility than large systems and so are also more able to respond to a crisis. By this line of reasoning, system capacity and flexibility are the important factors affecting the cross elasticity of transit ridership with respect to gasoline supply.

Several other studies have attempted to gauge the effect of a gasoline supply decrease on transit ridership. Sacco and Hajj (4) suggest that a 10-15 percent decrease in supply would result in a short-term transit ridership increase of 5-7 percent, which implies a cross elasticity of approximately -0.5. Carlson (7) reports a 1979 ridership increase of 10 percent matching a peak gasoline shortage of 10 percent, implying a cross elasticity of approximately -1.0. Navin (5) estimates increases in downtown work trips by transit for Minneapolis and north suburban Chicago that correspond to 10 and 25 percent decreases in supply. The implied cross elasticities in Navin's study range from -1.69 to -4.45. An ongoing project at the New York State Department of Transportation (NYSDOT) (17) yields a preliminary cross elasticity of -0.21 for urbanized areas in New York State. Horowitz (6) models responses to various gasoline allocation plans for a 15 percent gasoline shortfall. Transit ridership rises by 20-40 percent, which implies a range of cross elasticities from -1.33 to -2.07. Interestingly, in Horowitz' model the smallest increase in transit ridership occurs in the scenario where gasoline price is highest, and the largest increase occurs in the non-price-based scenario. A National Cooperative Highway Research Program report (1) ties future gasoline supply to future gasoline price, thus making it difficult to extract a ridership-supply cross elasticity from the model. If price is ignored as a factor, in accordance with the assumption that gasoline price has little short-term impact on transit ridership, the implied cross elasticity of ridership with respect to gasoline supply is in the range of -2.26 to -3.05 for the work-trip model and -0.95 to -1.37 overall.

The cross elasticities of Table 5 are within the range found in this review of the literature. This range indicates the likelihood that there is no one firmly established figure and so supports the separate-category approach taken in Table 5.

EFFECT OF INCREASED TRANSIT USE ON 1979 CRISIS

The role of transit in the 1979 energy crisis can be determined by calculating the energy savings resulting from ridership increases and comparing these savings with the gasoline shortfall in each urbanized area. Results are aggregated by region and by size of urbanized area; complete results are given by Boyle (18).

For the purposes of this analysis, it is assumed that all "new" transit riders accounting for the ridership increases are former automobile users and that there is no use of the "car left home". Clearly, these are optimistic assumptions that tend to overestimate the energy-saving role of transit. Given these assumptions, the number of cars left at home due to modal shifts can be obtained by dividing the ridership increase for each urbanized area by an average automobile occupancy of 1.6 persons/automobile. The number of cars left home can then be multiplied by the average trip length to obtain the vehicle miles not traveled, or "saved", by transit. Several sources were consulted to determine average trip length (19-23); the figure finally chosen is 9.0 miles. This is a somewhat liberal estimate. It can be justified by the assumption that the impact of a gasoline crisis is felt most strongly by those who make the longest trips and so the average trip length of those diverted to transit is greater than the overall average trip length.

The formula for computing VMT saved by transit in urbanized areas is as follows:

$$VMT_i = (\Delta R_i/1.6) \cdot 9.0 \quad (2)$$

This can be converted to gallons of gasoline saved by transit by dividing by the average fleet efficiency in miles per gallon. This figure is available by state through the year 1977 (24), and fleet efficiencies for New York State have been calculated by NYSDOT through 1979. An average 1979 fleet efficiency for a given urbanized area can be computed as follows:

$$MPG_{i1979} = MPG_{i1977} \cdot (MPG_{NY1979}/MPG_{NY1977}) \quad (3)$$

The formula for gasoline savings S in urbanized area i is then

$$S_i = VMT_i/MPG_{i1979} = [(\Delta R_i/1.6)/MPG_{i1979}] \cdot 9.0 \quad (4)$$

Note that S_i is gasoline savings due to transit. These savings can be compared with the total reduction in gasoline use in the urbanized area and also to the urbanized-area gasoline consumption in the second and third quarters of 1978.

Tables 6 and 7 (8-11, 24) present mean savings due to transit as a percentage of reduction in gasoline use and of 1978 consumption, aggregated by region and size of urbanized area. Overall, gasoline savings due to transit total only 4.4 percent of the reduction in gasoline use and 0.3 percent of 1978 consumption. It can be seen from Table 6 that increased transit use contributed most to gasoline savings in the West and the Northeast (if the Pennsylvania cases in which there is an unexplained discrepancy in the data on gasoline sales are excluded, the mean percentage savings for the Northeast drops to 5.5 percent). Data given in Table 7 show that the proportion of energy savings due to transit is highest in the largest urbanized areas.

Tables 6 and 7 suggest that transit did not play a major role in the energy conservation effort. Other factors, such as increased fleet efficiency, actual reduction in travel, formation of carpools, or trip chaining, must account for the bulk of energy savings.

The conclusion that the role of transit in alleviating the 1979 energy crisis was minor is reached under the optimistic assumptions that all new transit riders came from automobiles and that cars left at home were not used. Barring unforeseen changes in the operation of transit systems, transit may be expected to play a minor role in any future energy emergency.

FUTURE SCENARIOS: TRANSIT RIDERSHIP AND ENERGY SAVINGS

The methods and results developed and obtained thus

Table 6. Gasoline savings accounted for by transit ridership increases by region.

Region	No. of Systems	Mean Gallons Saved by Transit (000s)	Reduction in Sales: Mean Gallons (000s)	Reduction in Sales: Due to Transit (%)	April-September 1978: Mean Gallons Used (000s)	April-September 1978: Reduction Due to Transit (%)
Northeast	13	1143	17 240	6.6	211 421	0.5
South	24	161	5 709	2.8	127 808	0.1
North Central	16	566	18 587	3.0	248 350	0.2
West	13	392	6 505	6.0	135 399	0.3
Total	66	498	11 320	4.4	174 319	0.3

Table 7. Gasoline savings accounted for by transit ridership increase by size of urbanized area.

Population	No. of Systems	Mean Gallons Saved by Transit (000s)	Reduction in Sales: Mean Gallons (000s)	Reduction in Sales: Due to Transit (%)	April-September 1978: Mean Gallons Used (000s)	April-September 1978: Reduction Due to Transit (%)
>1 000 000	12	2069	40 746	5.1	574 612	0.4
500 000 to 1 000 000	12	369	9 488	3.9	187 407	0.2
250 000 to 500 000	11	158	6 952	2.3	107 297	0.1
100 000 to 250 000	22	65	2 538	2.6	44 068	0.1
<100 000	9	47	1 331	3.5	23 455	0.2
Total	66	498	11 320	4.4	174 319	0.3

far may be used in several ways to address future scenarios. One use is to derive a factor for adjusting ridership forecasts in the event of a future energy shortfall. Another use is to predict ridership response and energy savings due to transit in various energy situations.

A basic problem in forecasting is the emergence of variables considered unimportant or unpredictable at the time of the forecast as significant factors affecting the dependent variable at a later time. Hartgen (25) has shown that the original forecast can be updated in such a situation by use of an adjustment factor that takes the newly important variable into account. This approach can be applied to transit ridership forecasts. A factor for ridership increase in response to a gasoline shortfall can be computed by use of the cross elasticities in Table 5:

$$F_{ij} = 1 + [e_{ij} \cdot (g/100)] \quad (5)$$

where

F_{ij} = a factor to apply to ridership forecasts for an urbanized area in region j and with system size i,
e_{ij} = cross elasticity of ridership with respect to gasoline supply for an urbanized area with system size i and in region j, and
g = percentage change in gasoline supply for the urbanized area.

The original forecast of ridership can be multiplied by this factor to account for the effect of the gasoline shortfall on ridership. Original forecasts for years subsequent to a gasoline shortfall can also be adjusted by use of the factor.

Predicting ridership response and energy savings due to transit in various energy futures is also possible, but it is necessary to know something about the short-term price-ridership relation. Other studies have indicated little short-term relation between gasoline price and transit ridership (2-4, 26, 27). Navin (5) has noted that a 5 percent gasoline shortfall has the same impact on transit ridership as a doubling of gasoline price. Erlbaum and Koeppel (17) estimate the cross elasticity of ridership with respect to gasoline supply as -0.21 and with respect to gasoline price as 0.01 for urbanized areas in New York State. Both studies imply that the cross elasticity with respect to supply is of a magnitude 20 times greater than the cross elasticity with respect to price. A rough estimate of price cross elasticity can be obtained by multiplying the supply cross elasticity by -0.05. This price cross elasticity can then be used to calculate ridership changes for various price increases in a no-shortfall situation.

The supply cross elasticities were calculated in a period when there was a 30 percent price increase. These supply cross elasticities at the 30 percent price-increase level cannot be broken down into supply-only and price-only cross elasticities because the method of estimating price cross elasticity is noniterative. However, the no-shortfall price cross elasticities can be used to obtain the proportion of percentage change in ridership attributable to price at the 30 percent price-increase level. This proportion can then be adjusted to reflect different price increase levels. In mathematical terms,

$$r_{p,s} = r_{30,s} - \{[1 - (p/30)] \cdot (r_{30,0}/r_{30,s})\} \quad (6)$$

where $r_{p,s}$ is the percentage change in ridership corresponding to percentage changes in gasoline price (p) and supply (s).

This formula can be used to estimate the percentage change in ridership for various energy futures. An example is provided in Table 8, which gives percentage ridership increases and gasoline savings due to transit for the scenario involving a 15 percent shortfall and a 30 percent price increase. It is assumed in this example that base transit ridership in 1985 is 6 percent higher than in 1979 (a conservative assumption given post-1973 trends) and the base gasoline consumption in 1985 is 6.5 percent lower than in 1979, in line with predictions for New York State (25).

Table 8 indicates that the role of transit in alleviating a future crisis is likely to be minor, as it was in 1979. A more detailed analysis, including other scenarios, is given elsewhere (18). The detailed analysis reveals that, although price has

Table 8. Effect of 15 percent shortfall and 30 percent price increase in 1985.

Region	System Size	Increase in Transit Ridership (%)	Energy Savings Due to Transit (%)
Northeast	Large	6.8	5.7
	Small	51.0	10.9
South	Large	13.1	3.4
	Small	14.7	0.8
North central	Large	9.9	2.7
	Small	23.6	1.5
West	Large	38.3	5.8
	Small	74.9	8.1

some effect on transit ridership in a no-shortfall situation, the price effect is negligible in a shortfall situation.

SUMMARY AND CONCLUSIONS

Transit ridership for the sample of 66 urbanized areas rose by 5.1 percent in the second and third quarters of 1979 compared with the same time period in 1978. For the second quarter alone, ridership rose by 3.7 percent; the ridership increase for the third quarter was 6.7 percent. Small urbanized areas and urbanized areas in the West showed the largest percentage increases in ridership.

The cross elasticity of transit ridership with respect to gasoline supply ranges from -0.45 for large systems in the Northeast to -4.99 for small systems in the West. The overall cross elasticity for the entire sample is -0.75. The calculated cross elasticities are within the range of those found in or extracted from other studies. Small systems and systems in the West show the most elastic response. In general, however, transit ridership is relatively inelastic with respect to gasoline supply.

Transit played a relatively minor role in alleviating the impact of the 1979 energy crisis. Even with the assumptions that all new riders switched from automobile to transit and left their cars at home unused, the gasoline savings due to increased transit patronage amounted to less than 5 percent of the decrease in gasoline sales. Transit contributes most to energy savings in the Northeast and the West and in very large urbanized areas.

Methods of calculating energy savings and ridership increases for future energy scenarios have been developed. The results indicate that the role of transit in alleviating a future crisis is likely to be minor.

Although it is not the purpose of this paper to examine in detail the reasons for the role of transit in alleviating the 1979 energy crisis, it appears that transit systems do not have the capacity to absorb large numbers of riders in a short-term situation. Even if ridership increases (and, therefore, energy savings due to transit) were doubled, the role of transit would still have been relatively minor, accounting for less than 10 percent of the drop in gasoline sales. Actions to encourage transit use should be part of energy contingency plans, but it must be recognized that other actions will shoulder most of the burden in alleviating a future energy shortfall.

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Indirect Energy Considerations of Park-and-Ride Lots

LAWRENCE C. COOPER

The expenditure of energy to construct and operate a park-and-ride lot is seldom weighed against the motor fuel savings generated by the park-and-ride service. An initial attempt to establish this relation is presented. A procedure is developed to estimate the indirect energy requirements of a prototype park-and-ride lot based on lot size and the fuel savings incurred by various lot usage scenarios. From this, the number of years required for lot fuel savings to account for indirect energy expenditures is determined. The impact on fuel savings of lot operational variables, such as distance to the CBD, bus load factor, and fuel-efficiency rates, is examined. This analysis of energy expenditures and savings is then applied to existing park-and-ride lots in the Dallas-Fort Worth area. It is concluded that indirect energy expenditures are significant enough to warrant consideration in the transportation planning process. It is noted that the indirect energy costs can be accounted for in less than 10 years for most park-and-ride projects. This payback period is significant because it represents the point in time at which energy conservation truly occurs.

The establishment of park-and-ride lots served by express transit operations is generally considered by urban transportation planners and policymakers to be an effective way of conserving energy as well as reducing air pollution and traffic congestion. By leaving their automobiles at specially designated lots and riding transit to the central business district (CBD) or other destinations, commuters, theoretically at least, will use less fuel for transportation.

Spurred by recent petroleum shortfalls, planners and local officials have accelerated the planning and construction of park-and-ride lots as a transportation system management technique. Often not considered in the evaluation of park-and-ride services as energy savers, however, is the fact that the development and construction of these lots and services also entail the expenditure of energy. For instance, fuel is consumed by the vehicles used in lot construction and materials hauling. The materials themselves require energy from mining or manufacturing processes, and the construction of the lot consumes energy. The energy used in these types of activities is termed "indirect" energy (1, p. 5), or energy "implementation costs" (2, p. 5). It has been estimated that indirect transportation energy consumption accounts for more than 40 percent of all transportation-related energy use in the United States. The question that then arises is how long it will take for direct fuel savings from the park-and-ride operations to repay the energy expenditure of costs involved in their establishment. This is important because the point where operational energy savings exceed the energy expended in lot construction is the point at which energy conservation begins.

Because the practice of making estimates of indirect energy use is not well established, such energy costs are seldom considered in the planning of park-and-ride services (as well as other transportation projects). The following discussion is an initial investigation of this energy accounting question that, it is hoped, will lead to more consideration of total energy impacts of transportation projects.

This paper first describes a "typical" park-and-ride lot and its operation as used in this analysis. The indirect and direct energy savings and costs related to this prototype park-and-ride lot are identified and examined. Next, the impact of variations in park-and-ride lot operations and characteristics on energy savings and the payback time of indirect energy expenditures is analyzed through the use of a simple computer program. Finally, this energy savings/cost analysis approach is applied to an examination of existing lots in the Dallas-Fort Worth area.

PARK-AND-RIDE SCENARIO

The assumed characteristics of the prototype park-and-ride lot operations examined here are based largely on data from actual lot operations in the Dallas-Fort Worth area. A recent study (3) of these lots identified and quantified such variables as local bus ridership, lot size, service area, and distance to the CBD for typical park-and-ride operations in the area.

The basic lot itself was considered to consist of an asphalt-covered parking area, a reinforced-concrete bus loading zone, and a simple passenger shelter. Express bus service was assumed to be

Table 1. Indirect energy consumption factors for a park-and-ride lot with 500-car capacity.

Component	Material		Energy Consumption (Btu 000 000s)			
	Type	Amount (tons)	Production	Hauling	Construction	Total
Loading zone	Portland cement	262	1983	20	343	2 346
	Aggregate	130	9	10	23	42
	Lime	16	96	1	8	105
Total			2088	31	374	2 493
Car parking area	Asphalt	1716	837	170	11 119	12 126
	Aggregate	4688	328	352	825	1 505
	Lime	703	4218	53	366	4 637
Total			5383	575	12 310	18 268
Total indirect			7471	606	12 684	20 761[a]

[a]Equivalent to 166 400 gal of gasoline (1 gal = 125 000 Btu).

provided to the CBD or other destination at freeway speeds. Most commuters were assumed to drive their cars to the lot and park them all day at no charge. Kiss-and-riders, those transit users driven to the lot by someone else, were also considered. The scenario here further assumed that the lot would be served by buses because this is the principal form of public transportation in the Dallas-Fort Worth area at this time. These indirect and direct energy assumptions are described in more detail below.

Indirect Energy Considerations

The amount of energy consumed in the construction of a prototype 500-space lot included energy estimates for the production and hauling of materials (aggregate, asphalt, cement, and lime) and the construction of a lot consisting of a reinforced-concrete loading zone and an asphalt parking area. Table 1 (1,4) gives the indirect energy consumption factors used for this lot. All energy consumption was converted into equivalent gallons of gasoline for easy comparison. This table indicates that an estimated 166 400 equivalent gallons of gasoline of indirect energy are consumed by this lot. In addition, the energy cost of a simple passenger shelter was estimated to be 600 equivalent gallons of gasoline (2).

Because the lot considered here was assumed to be of a single, basic design, energy demands for lot improvements, such as fencing, gutters, channelizations, signing, and landscaping, were not included in this analysis. Information on energy costs of such items is available if these are to be included in the lot design (1,2). The indirect energy estimates used should therefore be considered the minimum for a paved lot. It was further assumed that the buses used to provide the park-and-ride service are taken from the existing fleet. If new buses must be purchased, the construction energy cost of these vehicles can be included in the indirect cost estimates. The energy cost of a new bus has been estimated to be 8160 equivalent gallons of gasoline (2), equivalent to about 5 percent of the energy costs of the 500-space lot.

The energy used, even for this simple lot, appears to be considerable, however. The construction of the lot with 500-vehicle capacity and shelter, for example, would expend the equivalent of approximately 167 000 gal of gasoline. In addition, maintenance costs for the lot, including resurfacing estimated at 630 Btu/ft^2/year (2), were considered.

Direct Energy Considerations

The amount of direct energy consumed by the automobiles and buses affected by the park-and-ride lot was determined. The variables used in this estimation process and input into the computer program are described below.

Number of Riders

It was assumed that the size of a park-and-ride lot would be determined directly by use; i.e., a lot will be built at the most efficient size to accommodate users. The size of the lot should be designed so that 80-90 percent of the parking spaces are occupied (5, p. III-9). For example, about 450 automobiles will be parked in a 500-space lot on an average day. By assuming an average automobile occupancy for travel to the lot (1.1 persons/car is used here) and accounting for kiss-and-riders (assumed to be 15 percent of total riders) (6, p. III-5), the total number of one-way riders can be calculated. Because of this approach, no modal-split estimates were necessary.

Lot Distance from Home

Based on surveys of local park-and-ride users (excluding kiss-and-riders) in the Dallas-Fort Worth area, the average distance by automobile from home to a lot was found to be approximately 3.5 miles (6). This distance was input to the model to estimate fuel use between home and the lot.

Lot Distance from Destination

The distance of remote-lot bus service to the destination ranges from 6 to 20 miles in the Dallas-Fort Worth area (7, p. II-4). The model examined distances of 5, 10, 15, and 20 miles from the primary destination point.

Fuel-Efficiency Rates

An average fuel-efficiency rate for automobiles and buses, based on local and national estimates, was assigned to each model run. Because fuel-efficiency rates for cold engines are significantly less than those for warmed-up vehicles, the rate for automobiles was modified by accounting for the cold-start factor (8, p. II-4). The average automobile fuel efficiencies examined ranged from 14.7 miles/gal (the approximate 1979 fleet) to 100 miles/gal (an arbitrary assumed maximum potential). The fuel efficiency of buses was also varied from the assumed average of 6.25 miles/gal. Diesel fuel use was converted into equivalent gallons of gasoline (1 gal of diesel fuel is the energy equivalent of approximately 1.12 gal of gasoline).

Bus Load Factor

Differences in the bus load factor were assumed by varying the number of buses that serve a lot while keeping the number of riders constant. A full bus load was assumed to be 50 persons/vehicle.

Additional Assumptions

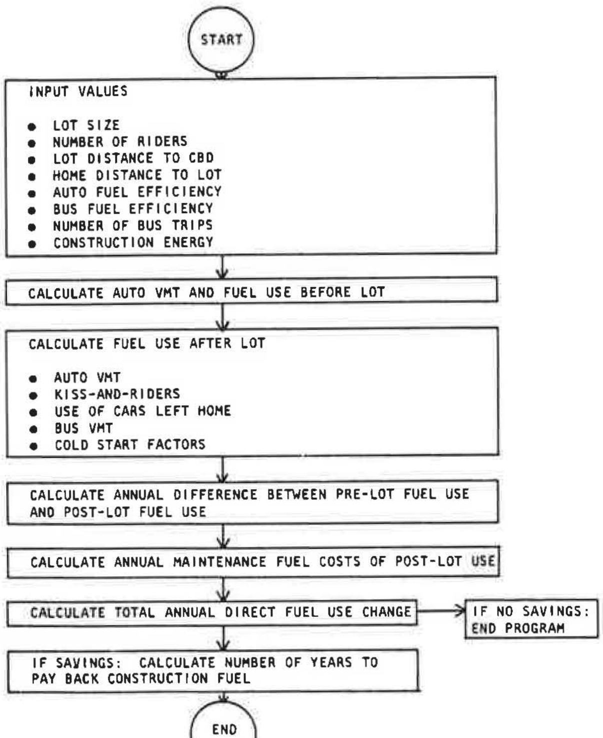
Consideration of use of the cars left home when commuters kiss-and-ride to the lot was also included in this analysis. It has been estimated that 40 percent of the potential savings in vehicle miles of travel (VMT) will be lost during the day by home-based non-work-trip use of automobiles not parked in the lot (9). The resultant VMT saving of kiss-and-ride patrons was adjusted by this factor; i.e., the kiss-and-ride VMT saving equals 60 percent of the normal work-trip VMT.

Energy Use Model

In order to speed the analysis of the numerous park-and-ride lot scenarios examined in this study, the calculations were automated. This simple computer program basically calculated the fuel used by automobiles and buses during the park-and-ride lot operations and then estimated the fuel that park-and-ride patron automobiles would have consumed if the lot did not exist. Other assumptions and factors, such as automobile cold-start factors and energy use for lot maintenance, were also considered. The difference between the vehicle fuel use without the lot and with the lot was then calculated.

If it was determined that the lot saved direct energy, this annual saving was then divided into the total indirect energy cost of the lot. This produced the payback time in years for direct energy savings to equal the indirect energy expenditures. This program is shown graphically in Figure 1.

Figure 1. Flow of park-and-ride energy program.



FINDINGS

Because the characteristics of each individual park-and-ride lot can vary greatly, several lot scenarios rather than a single hypothetical lot were examined. It was hypothesized that variations in lot size, lot distance to destination, number of riders, number of buses in service, and automobile and bus fuel efficiencies possibly had an impact on energy savings and payback time for a park-and-ride lot. To help determine whether these variables had a significant impact on the energy payback time, a sensitivity analysis of the variables was performed. This analysis was performed by altering one variable while the others were held constant. The results of this analysis, shown in Figure 2, indicated that distance to the CBD (or other destination), bus load factor, and automobile fuel-efficiency rates were the most significant variables whereas lot size and bus fuel efficiency were relatively unimportant. The importance of each of these variables is discussed in more detail below.

Distance to Destination

The distance vehicles must travel to their destination, generally the CBD, appears to have a considerable impact on energy savings and energy payback time. Because of the fuel saved by automobiles not going to the CBD, lots farther from the destination would generally result in more energy savings and, therefore, less time for construction energy payback. For the cases examined, all variables (lot size, load factor, etc.) except lot distance were held constant. This analysis indicated, for example, that the energy payback time for a 500-space lot 5 miles from the CBD would be more than three years whereas that for a lot 20 miles away would be less than one year (see Figure 3).

Figure 2. Sensitivity curves for energy analysis variables.

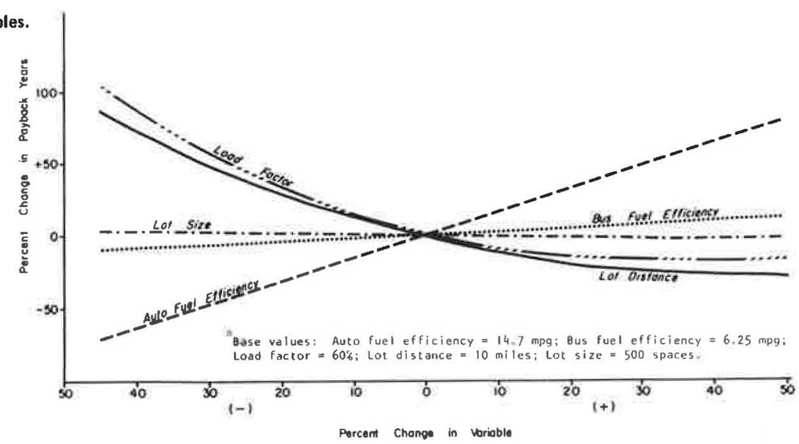


Figure 3. Impact of lot distance from destination.

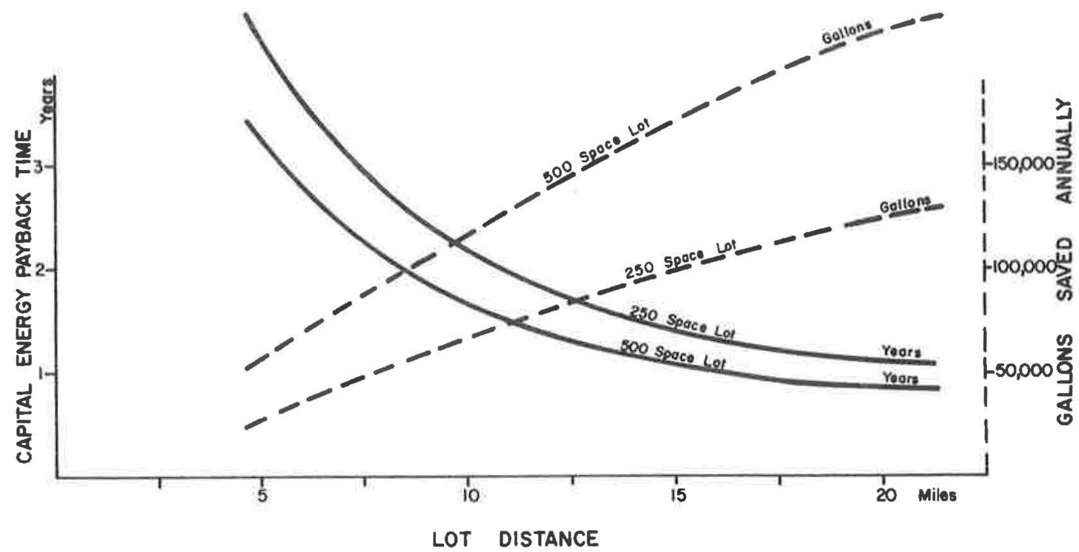


Figure 4. Impact of load factor.

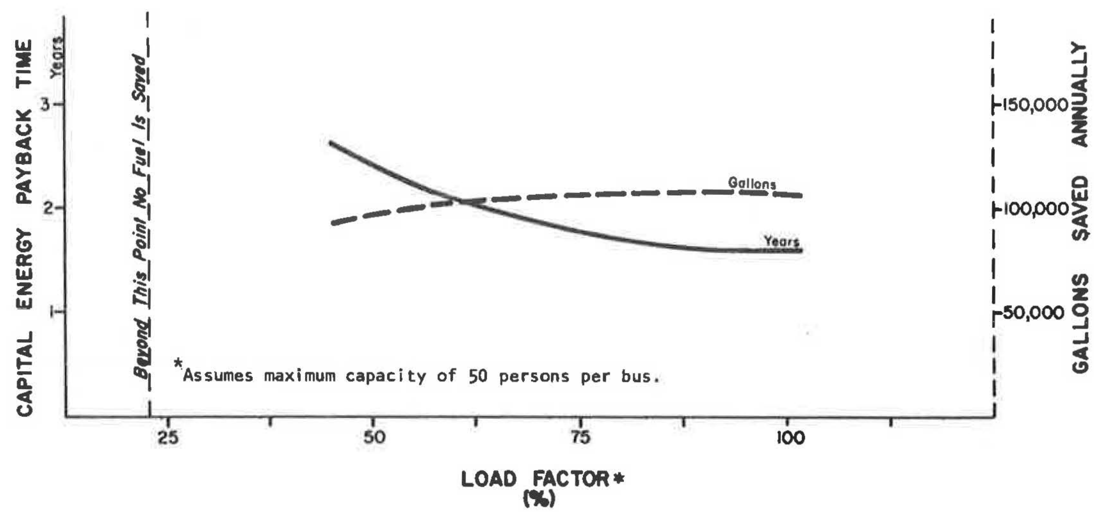


Figure 5. Impact of automobile fuel efficiency.

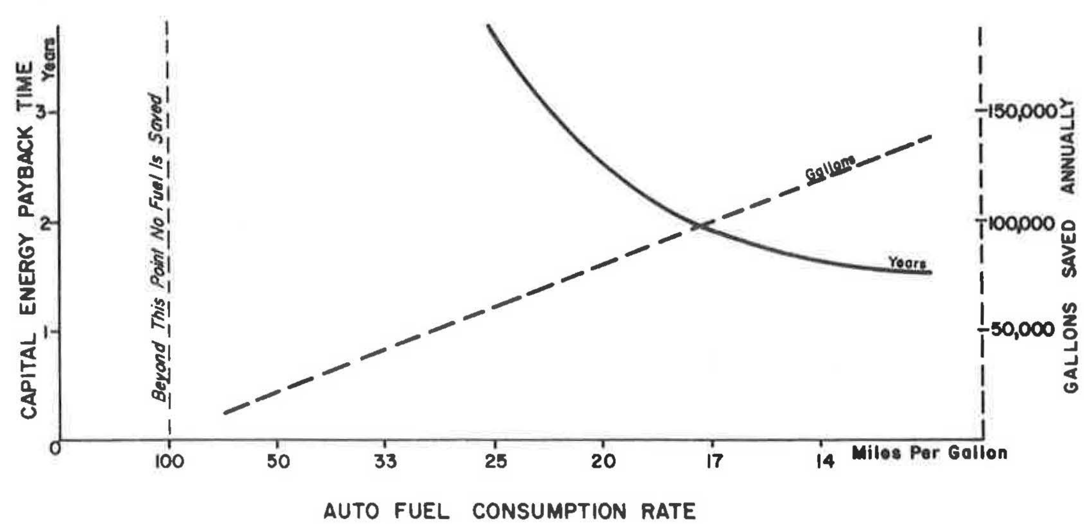


Figure 6. Impact of lot size.

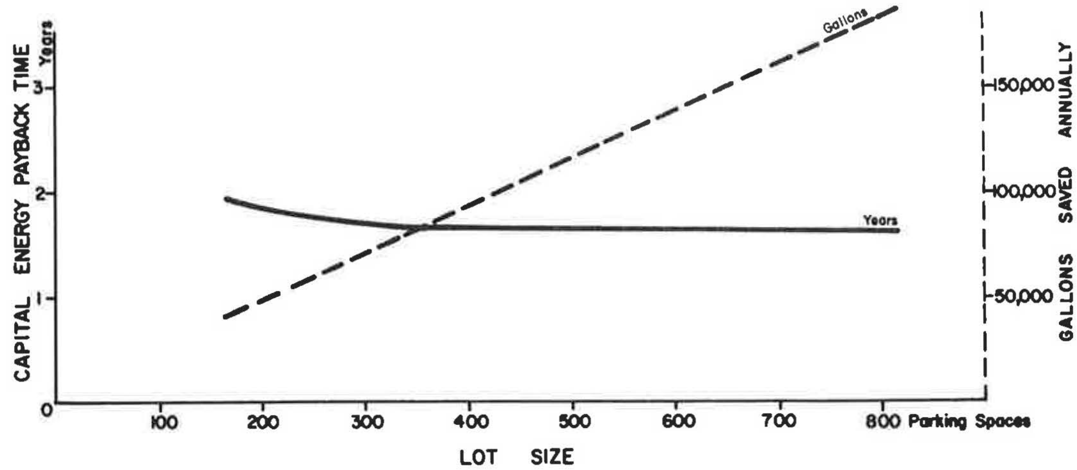


Table 2. Park-and-ride lots in Dallas-Fort Worth area: 1979.

Lot	No. of Spaces	Distance to CBD (miles)	No. of One-Way Person Trips	Direct Energy Saved per Year (gal)	Years to Pay Back Indirect Energy Use
Garland[a]	627	18	710	200 000	1.0
Las Colinas	170	12	75	-3 800	-[b]
North Central	356	11	550	38 000	3.2
Pleasant Grove	710	9	170	700	-[c]
Redbird	100	7	140	6 100	6.6
Ridglea	150	6	85	7 400	-[c]

[a]Combination of two lots.
[b]Payback not included.
[c]Joint-use lots; construction costs not applicable.

Load Factor

To estimate the impact of the bus load factor on total energy use, lot size and number of riders were held constant while the number of buses operating the service varied. Largely due to the relatively small impact of bus fuel use on total direct fuel consumption for the lot, as discussed previously, the impact of load factor on energy savings was not as great as might have been thought. For example, a 100 percent load factor would result in a payback time of 1.6 years, whereas doubling the number of bus trips to reduce the load factor to 50 percent would increase payback time to 2.5 years (see Figure 4). For this case, an average load factor of 22.5 percent was the point at which energy savings would no longer occur.

Fuel Efficiency

Due to federal automobile fuel consumption guidelines and public desire for more fuel-efficient automobiles, the fuel efficiency of the U.S. automobile fleet is expected to continue to improve in the future. The impact of these improved efficiencies on the energy payback time of a park-and-ride lot was therefore investigated.

As might be expected, the analysis indicated that park-and-ride fuel savings appear to be the greatest when automobile fuel efficiencies are lowest. At 14.7 miles/gal for each automobile, an average park-and-ride lot would take 1.6 years in payback time; at a 25-mile/gal rate, this would more than double to 3.7 years (see Figure 5).

This implies, then, that park-and-ride lots in the future will have less potential for saving energy than they do now. Figure 5 also shows that the automobile fuel-efficiency rate would have to increase to about 100 miles/gal before no energy savings would occur.

The sensitivity analysis indicated that the fuel efficiency of buses has a minor impact on indirect energy payback time, probably due to the relatively small proportion of direct energy use attributed to bus use in comparison with automobile use. Because of the relatively small variations in bus fuel efficiency that exist today and improvements expected in the near future, a separate impact analysis of bus fuel efficiency was not considered necessary.

Lot Size

The impact of varying lot sizes, assuming a similar lot use rate, was found to have little impact on energy payback time. Because it was assumed that the size and indirect energy consumption for the bus loading zone would be the same for all lot sizes, a slight efficiency of size was realized (see Figure 6).

It should be noted, however, that the larger the lot the greater is the chance for traffic congestion to occur in and around it. This impact on energy use was not considered here, however. Such considerations should be accounted for in the design of the lot prior to construction (5).

ANALYSIS OF DALLAS-FORT WORTH AREA LOTS

To obtain some idea of the energy efficiency of local park-and-ride lots, the energy consumption model described here was applied to several local lots. The existing operational characteristics of each lot (number of riders, bus trips, distance, etc.) were input to the model. Other variables, such as automobile and bus fuel efficiency, were the same as those used in the model. Construction energy estimates, described earlier in this paper, were made for each of the lots except in the cases of joint-use lots (i.e., the lot was constructed for some other purpose, such as church or shopping-center parking).

Of the six local lots examined, three (Garland, North Central, and Redbird) appear to save sufficient energy to justify their construction. Due largely to low use, the Las Colinas lot does not appear to save energy when total energy costs are considered. A slight increase in ridership of about 15 more users daily would cause the lot to be a fuel-saving venture. In view of the recent trend toward ridership increases, this may have already

occurred. Two other lots, Pleasant Grove and Ridglea, are joint-use lots, so construction costs could not be considered. Table 2 gives these findings.

CONCLUSIONS

This paper has discussed a theoretical examination of the energy use and potential savings of "typical" park-and-ride lot operations and the variables most important in determining these savings. The purpose of this analysis was to determine to what extent park-and-ride operations conserve energy when indirect energy expenditures of the lot are considered. If it can be shown that energy savings from the lot operations can make up in a relatively short time for the energy used to construct the lot, then park-and-ride can be shown to be a truly energy-saving concept.

The findings indicated that, in most cases, the lot operations would save enough fuel to account for the construction energy in a relatively short time--less than 10 years and, in many cases, less than 3 years. It should be noted, however, that under some operational scenarios a lot would not conserve energy, and thus the energy payback would never be realized. An application of the model to operating lots in the Dallas-Fort Worth area indicated that this energy deficit may occur in at least one case locally. In this case, a park-and-ride lot may be provided in order to achieve objectives other than energy conservation.

It should also be remembered that the lots described here are very basic sites. Many lots are improved with landscaping, lighting, sidewalks, and other amenities not considered here. These would naturally entail a somewhat greater indirect energy expenditure and, thus, a longer payback time. These improvements would probably increase the amount of construction energy by approximately 5-10 percent.

The study does not attempt to predict all energy-related implications of a park-and-ride lot. Considerations such as land use changes, traffic diversions, and changes in automobile ownership are beyond the scope of this study and would require far more sophisticated analysis methods than those used here.

Additional study and analysis of this concept appear to be warranted in several areas. For one, a comprehensive examination of the type of energy used or saved is needed. For example, it may be difficult to compare electrical and natural gas energy used to manufacture cement for concrete with gallons of gasoline saved by commuters. If it is determined that it is more important to save one energy type (e.g., petroleum) than others, such factors should be considered.

Energy considerations for the future are also an issue here. Due to uncertain future energy supplies, it may be important to expend energy now, while it is available, in order to develop projects that will save energy in the future. The questions of how much energy to invest and when to invest it are areas that need further investigation.

To summarize, this initial investigation of indirect energy implications of a park-and-ride lot demonstrates that these energy costs are significant enough to warrant consideration by planners and engineers. Of the variables examined, several are, to some extent, within the realm of control by decisionmakers. Lot distance, lot size, and bus load factor are elements that can be altered through the careful planning of park-and-ride lots.

The major study findings appear to be the following:

1. Lot distance, bus load factor, and automobile fuel efficiency are important factors in determining energy savings for park-and-ride lots.
2. Lot size and bus fuel efficiency are relatively unimportant factors in total energy use.
3. Indirect energy expenditures can be accounted for by direct energy savings in less than three years of lot operation in most cases examined.
4. In some cases, park-and-ride lots contribute to increased energy use rather than energy savings.
5. Automobile fuel-efficiency rates must be very high, about 100 miles/gal for the prototype example, before a park-and-ride lot becomes ineffective as an energy-saving measure.

ACKNOWLEDGMENT

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Summary of International Maritime Fuel Conservation Measures

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A project undertaken by the Center for Transportation Research, Argonne National Laboratory, for the U.S. Department of Energy (DOE) to develop a compendium of measures for improving shipboard energy efficiency in the maritime industry is documented. A matrix, or chart, of more than 60 fuel-savings options was developed and then refined with the assistance of representatives of the shipping industry, the academic community, and relevant federal agencies convened at a DOE-sponsored workshop on maritime energy conservation in New York City in April 1981. In addition, 10 measures were judged by workshop consensus to have the greatest fuel-savings potential. Among them were the development of crew motivation for active participation in energy efficiency improvement programs; the revision of operating practices to emphasize and maximize the benefits of slow steaming; the application of self-polishing hull coatings; optimization of ship trim; propeller maintenance and replacement; and dieselization. Later, a list of the 10 most effective measures, the final matrix with an explanatory sheet, and a roster of workshop participants were mailed to more than 1000 ship owners and operators in U.S. foreign trade. An important desired effect of the project is a reduction in the demand for marine fuel at U.S. ports.

The following two hypothetical cases illustrate the two extremes of the international commercial marine operations spectrum:

1. A navigation company operating a fleet of steam-powered bulk transports, tankers, and merchant containerships anticipates a decline in the availability of bunker fuel and a significant increase in fuel cost during the coming decade. It also determines that revenues will not be adversely affected by reducing average port-to-port power if fuel can be conserved by this practice. Because the largest ships in the fleet will be most vulnerable to the expected deterioration in the fuel situation, a program to improve fleet efficiency is introduced that concentrates initially on operations modifications in large vessels. Then, as necessary, capital expenditures are made to improve or replace physical plant. Over time, the smaller, lighter ships in the line are included in the program. Given this program structure, how should the company proceed so that the most cost-effective improvements are implemented first?
2. The owner of two tramp steamers operating between European and North American ports bunkers the vessels whenever possible at U.S. ports to avoid paying the world-market fuel prices demanded elsewhere. Nevertheless, increases in fuel costs are diminishing profit potential to such an extent that total costs will consistently exceed achievable revenues within five years. Cash-flow conditions preclude investing in more efficient vessels in the short term or updating physical plant to get more work from current fuel use. What can this owner do to maintain the profitability of the operation?

How can an appropriate mix of fuel-saving strategies be identified to suit the needs of vessel owners and operators anxious to reduce rapidly rising energy costs of vessels designed and built when oil was $2.00 a barrel? How should an owner or operator be encouraged to reduce fuel use as a means of cutting costs rather than, for example, laying off crew? These are among the difficult questions now facing the marine shipping industry at large.

The marine transportation sector consumes approximately 3 quads (10^{15}) Btu/year (equivalent to about 476 million bbl/year of residual fuel oil), or 15 percent of all transportation energy consumed annually in the United States. Approximately 80 percent of this amount is used in U.S. foreign trade by U.S. and foreign flag vessels. This paper describes a project conducted by the Center for Transportation Research at Argonne National Laboratory (ANL) to encourage energy conservation by the operators of these vessels (both U.S. and foreign). The project involved identifying, evaluating, summarizing, and distributing useful information concerning fuel-savings options to these operators. The information gathered, however, is applicable to most of the maritime industry. The project was sponsored by the Office of Vehicle and Engine Research and Development under the U.S. Department of Energy (DOE).

METHODS

The methods used to conduct this project were as follows (in chronological order):

1. Literature review,
2. Development of a draft matrix,
3. Conduct of a workshop and revision of the matrix,
4. Press release and distribution of the matrix, and
5. Report preparation and distribution.

The first four of these methods are discussed below.

Literature Review

A review of literature on fuel-savings alternatives or options in the international maritime industry was the starting point for this project (the words "option" and "alternative" are used synonymously with the word "measure" throughout this paper because investment funding limitations are likely to force ship owners to choose among measures). Research reports, journal articles, and conference papers were the primary documents reviewed. Proprietary materials concerning specific fuel-saving equipment items were also consulted.

Development of Draft Matrix

The maritime energy efficiency measures matrix was developed primarily by using the review of relevant maritime industry literature to extract and summarize the following information concerning fuel-savings options:

1. Technical descriptions and justifications,
2. Energy savings percentages claimed in demonstration,
3. Estimates of fuel cost savings and payback periods,
4. Estimates of required investment, maintenance, and other costs of implementation, and
5. Advantages, disadvantages, and related information.

Similar information was also obtained from industry operators and consultants in regard to fuel-

savings options that they have implemented. In many cases, this information was used to adjust claimed fuel-savings percentages and to update investment costs and payback periods based on lower investment and fuel costs in the past. These industry sources also provided practical information lacking in the theoretical literature concerning the advantages and disadvantages of options.

The cost-savings estimates for each option were calculated rather than taken directly from data sources. Two early assumptions in the project were that ship operators engage in energy-saving efforts primarily to reduce costs (this assumption was confirmed by consensus during the workshop) and that a range of potential cost savings covering various ship sizes would be useful. Therefore, parametric assumptions were made concerning representative rates of fuel use for small and large vessels. These rates were then combined with the estimated fuel-savings percentage for each option, factored by January 1981 New York Bunker C fuel costs. This procedure enabled an estimated cost-savings range to be included in the matrix for most options. However, for many measures, neither a percentage- nor dollar-based fuel cost savings could be entered on the matrix because those savings, though known to exist, vary by individual ship and route traveled. In those cases, savings were simply identified as ship and route specific (SRS), and it was left to matrix users to evaluate potential savings for their particular circumstances. The same individualized situations apply to the financial payback periods for many options, and the SRS entry was also made in those cases.

Another important assumption made for each fuel-saving measure was to identify its relevant market sector(s). This was done to enable matrix users to focus more easily on alternatives applicable to their ship types.

Conduct of Workshop and Revision of Matrix

An all-day Maritime Energy Conservation Workshop was held on April 24, 1981, at Seamen's Church Institute in New York City. A broad cross section of international maritime industry expertise was represented. The participants included five liner operators, one tanker operator, one bulk ship operator, two university professors, one U.S. Maritime Administration (MARAD) official, two marine engineering consultants, one naval architecture firm representative, and DOE and ANL program managers.

The 66 fuel-savings options in the draft matrix were discussed, some were eliminated, and a few new options were added. The revised matrix has 60 options. All changes to the draft matrix were made by consensus, sometimes after lengthy discussion.

The meeting was taped and notes were taken by ANL representatives so that revisions based on workshop discussions could be made. Following the meeting, these records were carefully reviewed and used to revise the matrix, a copy of which was then sent to each participant for final comments.

Additional purposes of the workshop included obtaining the insights of participants on (a) the level of current energy conservation activities in the industry, (b) the prospects for future efforts to save fuel, (c) recommendations for government actions to facilitate improvements in maritime energy efficiency, and (d) those options in the matrix that have the greatest potential for reducing the consumption of petroleum.

Press Release and Distribution of Matrix

Following the workshop, a press release concerning its results was sent to various maritime industry publications. The following publications printed the release: Journal of Commerce, Traffic World, Maritime Reporter/Engineering News, The Naval Architect, Seaway Review, and The Motor Ship. The release included an ANL address to which requests for matrix copies could be sent. This was done to distribute the matrix as widely as possible and to obtain a further indication of industry interest in energy efficiency.

Copies of the matrix were distributed to a list of 147 American and 920 foreign ship owners and operators compiled from Lloyd's Confidential Index. The principal criterion for including an owner on the list was the indication that one or more of its registered vessels made U.S. port calls. The cover letter stated that the reference list for the matrix was a source of additional information concerning the fuel-savings options and was available on request. The resulting requests provided another low-cost measurement of industry interest. To date, more than 100 requests for the list have been received.

DESCRIPTION OF MATRIX

The final version of the matrix developed during this project is presented in Table 1. The matrix as given is the same as that distributed to ship owners and operators except for minor editorial revisions in format and wording. The following sections describe the information found in each matrix column.

Fuel-Savings Measures

The energy conservation measures listed in the first column of the matrix are categorized into seven different types:

1. Operations,
2. Engine improvements and fuel changes,
3. Ship design and operating-strategy planning,
4. Propeller and hull modifications,
5. Potential engines and fuel still under development,
6. Potential hull and propeller changes still under development, and
7. Reintroduction of previously discarded technologies.

For many fuel-savings options, several suboptions are presented. For example, many different measures to improve ship power plant operation are delineated. The list of measures in the matrix, although comprehensive, should not be considered all-inclusive.

Claimed Fuel Savings

Unless accompanied by footnote "d", which indicates adjustment by workshop consensus, fuel-savings percentages in the second column are those claimed in the references cited. The word "claimed" is used in the column heading because, for many measures, claims of savings varied, depending on the sources cited. In addition, because each vessel and trade route is different, workshop participants agreed that every user of the matrix should not expect exactly the same result. Even so, for many options, fuel-savings estimates of workshop participants and in references were close enough to warrant a single number. The SRS entry was made where not even an estimated range of savings was found or where workshop participants could not agree with the reference claims and yet conceded that some savings potential was likely.

Table 1. Maritime energy efficiency measures matrix.

Fuel-Savings Measure	Claimed Fuel Savings[a] (%)	Assumed Fuel Use[b] (000 bbl/ year)	Claimed 1981 Fuel Cost Savings[c] ($000s/ year)	Additional 1981 Costs, If Available ($000s): Investment	Additional 1981 Costs, If Available ($000s): Maintenance and Repair	Claimed Payback Period (if available)	Assumed Market Sectors (ship types)	Reference and Workshop Remarks
Operations								
1. Development of crew understanding, motivation, cooperation, and participation (preferably through a management program)	SRS	SRS	SRS	-	-	-	All ships	Workshop participants unanimously agreed (a) this is the single most important element in an effective fuel-savings program and (b) strong front-office support is needed (e.g., a specific, top-management-supported manager responsible for energy conservation, reassurances to crew concerning legality and safety of new operating procedures, positive or negative internal publicity based on performance, etc.). If crew cooperation is not achieved, any measure affected by crew performance will not achieve its potential. It was agreed that crews affect plant tuning more than any other fuel-savings options.
2. Slow steaming								
a. General speed reduction	1.0-30.0[d]	120 240	40-1200[d] 80-2400[d]	See remarks	-	NA	All ships	Effect on fleet's ability to meet cargo volume requirements must be considered to avoid uneconomic use of less efficient ships. Requires balancing of fuel cost savings, other cost increases (capital, crew), marketing considerations (weekly sailings, etc.), and revenue losses. May require major port facility improvements.
b. Slow initial speed on voyages, with speedup later only when necessary	SRS	SRS	SRS	0	-	NA	All ships	Use minimum speed that will achieve schedule early in voyage. Requires close coordination with ship masters and convincing them of fuel- and cost-savings potentials. May not apply to time-chartered ships.
3. Increased or reduced speeds to gain favorable tides while arriving at port	SRS	SRS	SRS	0	-	NA	All ships	Same as 2b. Speed reduction when berthing space is not available is a similar strategy.
4. Increased use of electric in-port feed pumps	15[d] (in port only)	SRS (in port)	SRS	0	-	NA	All steam ships	One operator claims use of these pumps as intended can save $114 000/year in fuel for a six-ship fleet but that operator confidence in reliability and safety often must be strengthened by correcting minor problems (e.g., poor plunger packing, valve assemblies). Large, main-feed pumps are inefficient in port due to mechanical losses and wasted (dumped) steam; electric pumps have superior mechanical efficiency, which makes possible cycle gains and shutdown of one boiler in port (avoids wasted steam).
5. Cargo pooling	SRS	SRS	SRS	0	-	NA	Liners	FMC has allowed several of these agreements (and is considering others) for U.S. foreign commerce operators; no approval is needed for strictly non-U.S. movements. Justifications include energy savings, improved vessel use, and savings in crew costs. Senate Bill 125 would expand maritime antitrust immunity in this area.
6. Use of smaller vessels for pickup and delivery to eliminate port calls	SRS	SRS	SRS	SRS	-	SRS	Liners	Application by many firms has usually been based on other reasons (e.g., economic); fuel savings are an incidental benefit. As a related strategy, it was suggested that the U.S. government consider reducing port-call requirements for subsidies.
7. Improvement of steering efficiency	SRS	-	SRS	-	-	SRS	All ships	Significant fuel savings can be gained by tuning steering engine, installing adaptive autopilot, etc., to reduce drag on rudder.
8. Weather routing (preferably with satellite communications)	-3 to 3[d] (see remarks)	120 240	SRS SRS	SRS SRS	- -	NA NA	All ships	Prevention of cargo and hull damage due to storms is often primary motive for use. Can improve ship use besides saving fuel. Requires timely communications before and during voyage about ship schedule, speed trim, load, and weather. Coordination with ship captain critical to success. Claimed fuel-savings range is workshop consensus; negative savings could result from altering ship course for storms that do not occur, for example. Weather routing firms have documented up to 10% fuel savings on some voyages. Annual fuel savings were agreed to be a more meaningful measure than voyage savings.
9. Satellite navigation	0.5	120 240	20 40	10-15 10-15	- -	1 year 1 year	All ships	Improves navigation accuracy and shortens voyage length (miles). Price of satellite signal receiving equipment is <$5000 (>17 000 sets in use).
10. Satellite communication	SRS	120 240	SRS SRS	65 (including installation)	- -	SRS SRS	All ships	Maritime satellite terminals have several communications uses—e.g., weather routing reports, engine room data, medical emergencies, payroll requirements, ship requisition data, cargo documents, and navigational aids. Satellite communications involving first three of these can save fuel. Recent international agreement ensures satellite availability through 1980s.
11. Optimization of ship trims	2.0-4.0	120 240	80-160 160-320	0 0	- -	NA NA	Containerships	Savings are greater than 2-4% where trim is 1-10 ft at bow, but in one case structural limitations allowed only even-keel operation. At least one operator is using

Table 1. Continued.

Fuel-Savings Measure	Claimed Fuel Savings[a] (%)	Assumed Fuel Use[b] (000 bbl/ year)	Claimed 1981 Fuel Cost Savings[c] ($000s/ year)	Additional 1981 Costs, If Available ($000s): Investment	Additional 1981 Costs, If Available ($000s): Maintenance and Repair	Claimed Payback Period (if available)	Assumed Market Sectors (ship types)	Reference and Workshop Remarks
Operations (continued)	10.0-25.0	120	400-1000	250	-	SRS	RO/RO ships	computers to determine optimum trim. Costs shown are for dense ballast material. Extensive tests using actual vessels at varying ship speeds or at least ship model simulations are recommended prior to fleetwide implementation.
		240	SRS	SRS	-	SRS		
	SRS	120	SRS	SRS	-	SRS	Tankers, dry bulk ships (ballast trip legs only)	
		240	SRS	SRS	-	SRS		
12. Following ocean currents	SRS		SRS	-	-		All ships	Self-explanatory.
13. Improved power plant operation with continuous monitoring of								
a. CO flue gas and combustion air trim control (automatic)	1.5-5.0	120	56-200	80/boiler	-	1 year	All steam ships	Automatic trim (optimizing of fuel-air ratio) is key system feature; adjustments are made 7 times faster than by hand. CO monitoring system has many advantages over oxygen monitoring systems: It reduces measurement problems due to flue gas stratification by using light for measuring over entire width of uptake, has less nuisance failures and lower response times, and can use dedicated computer. CO can also be more effectively measured because it varies most dramatically at point of optimum combustion and only occurs in nature as product of combustion. Savings can be increased with variable-speed forced-draft fan motor controllers.
		240	112-400	80/boiler	-	1 year		
b. Oxygen flue gas and combustion air trim control (automatic)	1.0-3.0[d]	120	40-120[d]	8/boiler	-	1 year	All steam ships	Oxygen monitoring systems (including automatic) improve control of excess air to furnace, thereby improving combustion, and are less expensive than CO systems. Both a and b address the problem of excess combustion air, but register modification may be advisable to reduce excess air to around 5% if ship boilers operate at 15% excess air.
		240	80-240[d]	8/boiler	-	1 year		
c. New, improved burner register systems	0-3.0	120	60	40	-	1 year	All ships	Tests show that new burner register systems (designs) considerably reduce excess air to boilers in some applications.
		240	120	40	-	Unknown		
d. Use of condensate for lube oil cooling or for ship's evaporator (at reduced ship speeds)	0.2-0.5	120	8-20	SRS	-	<1 year (new ship), 1-2 years (retrofit)	All steam ships	Cooler is expensive and must be supplemented by parallel seawater-cooled unit. Heat recovery with condensate cooling slightly reduces low-pressure bleed steam required for feed heating, thereby increasing amount of steam exhausting to condenser. Most effective with vacuum pump instead of air ejector. Caution: Care must be taken so that no leaks occur in cooler.
		240	16-40	SRS	-			
e. Use of vacuum pumps to replace air ejectors (at reduced power)	0.2	120	8	SRS	-	SRS	All steam ships	None.
		240	16	SRS	-	SRS		
f. Improved plant tuning, heat balance and fuel consumption information, and instrumentation	2-10[d]	120	80-400[d]	SRS	-	SRS	All steam ships	Especially important during slow steaming. Fuel savings achieved by at-sea analyses to discover immediately needed operational modifications and dockside repairs. Efficient fuel oil, SHP, and steamflow meters recommended. Tune-up costs are virtually nil and some useful instruments are very low priced (e.g., hand-held instruments for performance checks).
		240	160-800[d]	SRS	-	SRS		
g. Use of viscosity controllers	SRS	SRS	SRS	SRS	-	-	All oil-driven ships	Important due to variances in fuel being supplied. Enables close control of bunker viscosity, which is single most important factor for good fuel atomization. Critical for enabling other fuel-savings measures (e.g., economizers) to be effective.
h. Use of shore-produced fresh water (potable and feed)	SRS	SRS	SRS	SRS	-	-	All ships	Replaces shipboard evaporator operations. May be implemented by converting some ship tanks for water storage. Has high cost-savings potential.
Engine improvements and fuel changes								
1. Use of slow-speed diesel ships								
a. Retrofitted	25[d]	120	1000[d]	13 000 to 18 000	-	Unknown	Tanker-liner	Investment costs are very rough estimates based on following cost approxima-

Table 1. Continued.

Fuel-Savings Measure	Claimed Fuel Savings[a] (%)	Assumed Fuel Use[b] (000 bbl/year)	Claimed 1981 Fuel Cost Savings[c] ($000s/year)	Additional 1981 Costs, If Available ($000s): Investment	Maintenance and Repair	Claimed Payback Period (if available)	Assumed Market Sectors (ship types)	Reference and Workshop Remarks
Engine improvements and fuel changes (continued)								
				(installed U.S. engine, 17 000 SHP)				tions: engines @ $270/SHP (foreign built), $460/SHP (U.S. built); installation @ $10 million (liners), $5 million (tankers—steam plant need not be ripped out). Retrofit is only recommended for relatively new ships because of long payback periods. U.S. engine-room labor pool with experience is limited; work emphasis at sea and in port would change from operation to maintenance; good quality, high-priced fuel would be required; and future fuel availability is uncertain. Main diesel engines do not provide ship hotel power
				10 000 to 15 000 (installed foreign engine, 17 000 SHP)	-	Unknown		
		240	2000[d]	21 000 to 26 000 (installed U.S. engine, 34 000 SHP)	-	Unknown		
				14 000 to 20 000 (installed foreign engine, 34 000 SHP)	-	Unknown		
b. Newly built	25[d]	120	1000[d]	0	-	NA	All ships	Same as 1a. Also, installation costs of slow-speed diesel engines (see 1a) are roughly equal to those of alternative steam turbines; therefore, no additional investment costs.
		240	2000[d]	0	-	NA		
2. Use of medium-speed diesel ships								
a. Retrofitted	25[d]	120	1000[d]	12 000 U.S.	150	SRS	Tanker	Same as 1a except that better-quality fuel is required and installed engine costs (including gearbox) are about 10% less. See 1a for explanation of investment costs. One major oil company has recently ordered 7 conversions (5 completed so far).
				9000 foreign	150	SRS		
		240	2000[d]	19 000 U.S.	150	SRS		
				13 000 foreign	150	SRS		
b. Newly built	25[d]	120	1000[d]	0	150	NA	All ships	Same as 1b.
		240	2000[d]	0	150	NA		
3. Improvement of steam use with								
a. Dual economizer steam air heater (retrofit)	1.5-3.5[d]	120	60-140[d]	400[d]	-	3 years[d]	All steam turbine ships	Shorter installation time than 3b—generally 2 to 6 weeks. Cycle and component modifications are not complex. Percentage fuel savings increase as power requirements decrease. Portions of retrofit can be done during voyage port calls. Rotary regenerative air heater using stacked plate heat exchanger can achieve similar savings at about 30% higher system cost.
		240	120-280[d]	SRS	-	SRS		
b. Fluid regenerative air heater	1.5-3.5[d]	120	60-140[d]	540 (2 heaters installed)	-	5 years	All steam turbine ships	Longer installation time than 3a, but usually no more than 6 weeks. More complex cycle modifications. One economic analysis estimates rates of return significantly lower than 3a.
		240	120-280[d]	180 (2 economizers)	-	5 years		
c. Maintained and improved superheat	0.5-1.5	120	20-60	150 (est.)	-	SRS	All steam turbine ships	Achieved through increased superheater surfaces or use of attemperator (steam temperature controller). Increasing temperature of steam increases its volume and thermal efficiency and reduces its moisture and resultant turbine blade erosion.
		240	40-120	SRS	-	SRS		
d. Alternative main feed pump for reduced power operations	0.7-1.8	120	28-72	175	-	SRS	All steam turbine ships	Smaller, steam-driven pump (installed in addition to main feed pump and in port feed pump); usually are mechanical feed pumps directly from the turbine-generator set to take advantage of increased blade heights or arc of steam admission and greater number of stages. One study found a 5-year investment payback for this kind of pump. Electric feed pumps are also viable in most cases.
		240	56-144	250	-	SRS		
e. Single-boiler operation during slow steaming and in port	0-3.0	120	0-120	0	-	NA	All steam turbine ships	At greatly reduced plant loads of slow steaming, using only one boiler out of two enables that one to operate close to its normal full rating and save fuel through higher superheater steam temperatures. Should be implemented as a company policy; crew must often be convinced that such operation is safe and approved by regulatory agencies, e.g., U.S. Coast Guard. Caution: Use proper procedures in layup of boiler so that no air gets in water. Follow manufacturer's instructions.
		240	0-240	0	-	NA		
f. Increased numbers of active feed-water heaters	1.0-3.0	120	40-120	SRS	-	SRS	All steam turbine ships	One author recommends 5 heaters if space is sufficient. However, workshop participants agree that each new heater saves progressively less (diminishing marginal returns) and that adding these heaters is a major cycle modification.
		240	80-240	SRS	-	SRS		
g. Cascaded turbine-bleed system	1.0-5.0[d]	120	40-200[d]	0	-	0 (new ship)	All steam turbine ships	For new ship, installation costs are approximately equal to those of other high- and low-pressure base arrangements. Retrofits can be readily made when turbine is opened for other reasons. System is applicable only for operating consistently
		240	80-400[d]	0	-			
		120	40-200[d]	SRS	-	4-7 years (retro-	All steam	

Table 1. Continued.

Fuel-Savings Measure	Claimed Fuel Savings[a] (%)	Assumed Fuel Use[b] (000 bbl/year)	Claimed 1981 Fuel Cost Savings[c] ($000s/year)	Additional 1981 Costs, If Available ($000s): Investment	Maintenance and Repair	Claimed Payback Period (if available)	Assumed Market Sectors (ship types)	Reference and Workshop Remarks
Engine improvements and fuel changes (continued)								
		240	80-400[d]	SRS	-	fit, 350-200 days at half-power)	turbine ships	between 20 and 60% of design power. For retrofit installation, payback period shortens as days per year at half-power increase.
h. Additional turbine-bleeds for feed-water heating	0.6	120	24	SRS	-	SRS	Steam turbine ships	If operating at less than full power during most of voyage, retrofit of turbine incorporating steam bypass and optimizing for lower superheat temperature and pressure achieves similar result.
		240	28	SRS	-	SRS		
i. Reduced condensate subcooling	0-1.2[d]	120	0-48[d]	2	-	<2 months	All steam ships	Overcooling of main engine exhaust can be reduced by fitting copper-nickel orifice to reduce main circulating flow by up to 25%. Most appropriate for ships with scoop injection because scoop is usually oversized. Caution: Special care required during use with axial or mixed-flow circulating water pumps.
		240	0-96[d]	SRS	-	Unknown		
4. Use of coal-fired boilers	95 (oil only)	120	NA	3000 (see remarks)	-	3 years (small ship)	All new ships	Net potential operating cost savings of up to 28% (after deductions for capital costs, increased maintenance, and labor costs). Retrofit difficult, but can be done during hull conversion layup, for example. Requires 200-300% more boiler volume and fuel storage and handling space. Eight new bulk carriers using these boilers have been ordered (two were later canceled due to resale value concerns of insurance companies). Fuel availability at ports is a major concern, since most ports would have to retrofit for coal bunkering. Pollution regulations may restrict coal firing to out-of-port operations. Investment costs shown are additional costs beyond those for an oil-fired plant.
		240	NA	8000 (see remarks)	-	2 years (small ship)		
		120	NA	Unknown (retrofit)	-	Unknown	All ships	
		240	NA	Unknown (retrofit)	-	Unknown		
5. Use of coal-oil (or petroleum coke) slurry for steam boilers	15-40[d] (oil only)	120	Unknown	SRS	-	SRS	All ships	Most retrofitable alternative for using coal or petroleum by-product as a substitute for oil; slurries are pumpable, bunkerable, relatively stable (except at high temperatures) during storage. Combustion approximates that of oil. Still under development.
		240	Unknown	SRS	-	SRS		
6. Use of fuel-oil modifications (emulsions, additives)	0-5.0[d]	120	0-200[d]	Unknown	-	2 years	All ships	MARAD-funded study found that heavy corrosion of fuel pumps and injectors did not occur with use of water-oil emulsions. Water-to-oil ratios of up to 12% did not adversely affect integral engine-mounted components. Savings are often inversely proportional to operating efficiency of crew and equipment. Caution: Carefully evaluate fuel-oil modification system and its performance prior to full-scale use.
		240	0-400[d]	Unknown	-	2 years		
7. Use of waste heat recovery on diesel engines	7.0	120	280	Unknown	-	Unknown	Ships with diesel engines	MARAD-funded study on applicability to other power plants found economic merit (percent discounted cash flow) of diesels to be double that of steam turbines.
		240	560	Unknown	-	Unknown		
8. On-board continuous blending of heavy and diesel fuel oil	NA	NA	NA	80-250	-	1[d]-2 years	All ships	Primarily a cost-saving measure but reduces consumption of high-grade diesel fuel. One company experienced investment payback in less than one year. Widely used.
9. Use of wind-assisted (primarily sail) vessels	15-25	120	600-1000	SRS	-	SRS	All ships <40 000 deadweight tons	Currently being used by 1600-ton Japanese tanker. Computer coordinates engine and sail power. Reduced rolling results in 2-3% additional fuel saving. Weather routing is important to maximizing savings. Some analysts think sails will be used only in interisland service, not in international trade due to limitations of sail material (weight, height, and strength), bridges, and interference with cargo handling (nontankers). MARAD study found that inverse economies of scale exist (i.e., percentage savings are greater for smaller ships), passage time variance is only a problem for very high-speed liner trades (>20 knots), and retrofitting appears feasible. Detailed MARAD economic analysis planned.
		240	1200-2000	SRS	-	SRS		
Ship design and operating strategy planning								
1. Optimization of design speed and block coefficient	Unknown	Unknown	Unknown	Unknown	-	-	All new ships	Design speeds and block coefficients should be analyzed and balanced with anticipated fuel and inventory costs. Past analyses have used minimization of required freight rates as basis for optimization.
2. Operating strategies maximizing use of most-fuel-efficient existing ships	Unknown	Unknown	Unknown	Unknown	-	-	All ships	These strategies can minimize fuel use (during fuel shortages) and/or maximize profits (during normal times). May entail nonuse of some ships. Fuel-efficient ships should be used at optimum speeds.

Table 1. Continued.

Fuel-Savings Measure	Claimed Fuel Savings[a] (%)	Assumed Fuel Use[b] (000 bbl/ year)	Claimed 1981 Fuel Cost Savings[c] ($000s/ year)	Additional 1981 Costs, If Available ($000s): Investment	Additional 1981 Costs, If Available ($000s): Maintenance and Repair	Claimed Payback Period (if available)	Assumed Market Sectors (ship types)	Reference and Workshop Remarks
Propeller and hull modifications								
1. Hull improvements								
a. Dry-dock cleaning and conventional painting	See remarks	- -	- -	65-150 65-150	- -	- -	All ships	Fouling begins as soon as vessel enters water, requiring progressively more power (fuel). Underwater hull scrubbing has some short-term benefits but accelerates fouling in the long term.
b. Use of self-polishing, anti-fouling coatings	2-7	120	80-280[d]	Less than 1a to $200 more than 1a	-	2-2.5 years (1 application); 1 year (2 applications)	All ships	Useful if ship operates in warm waters and/or has extended periods (up to 2.5 years) between dry-dockings. Preparatory blast-cleaning down to white metal accounts for much of savings. Fuel savings are higher for large and low-speed ships and increase with time as self-polishing action causes hull to become smoother. Widely used.
		240	160-560[d]	75-100 (SRS) for blasting, 175-250 (SRS) for coating	-	2 years		
c. Use of self-polishing coatings on first quarter of ship length	0.8-2.8	120 240	32-112 64-224	SRS SRS	- -	SRS SRS	All ships	Research has found that cleaning and application of antifouling coatings are most effective for this part of ship length (>40% of total potential savings can be gained here). Partial cleanings can thus be cost effective when scheduling or other factors inhibit total cleaning. Some operators apply coatings only to vertical sides, which foul more than flat bottom of ship.
d. Use of copper-nickel sheathing on hull	SRS	120 240	SRS SRS	SRS SRS	- -	SRS SRS	All ships	Copper-nickel is highly resistant to fouling and saltwater corrosion, but current technology is expensive. Can be used as primary underwater hull material or as cladding over ordinary steel.
e. Repair of underwater hull plating damage	SRS	SRS	SRS	SRS	-	SRS	All ships	Exterior plating deformation (shell indentations, bilge, keel distortions, etc.) should be evaluated for fuel savings as well as structural integrity requirements. Even moderate underwater structural deformation increases hull resistance appreciably, although there are no published guidelines. Ship owners should emphasize this to maintenance personnel to ensure effective and timely hull repairs.
2. Fuel-efficient propellers for new ships								
a. Large, slow-turning propellers	0-10[d]	120 240	0-400[d] 0-800[d]	SRS SRS	- -	1.5-2.5 years	All ships	Optimal design should seek low revolutions and blade area ratio (requires appropriate pitch of propeller). One major propeller manufacturer considers that maximizing propeller diameter (consistent with draught conditions) and optimizing shaft RPM accordingly is the best propeller propulsion savings strategy.
b. Ducted or nozzle propellers	0-8[d]	120 240	0-320[d] 0-640[d]	500-1000 SRS	- -	1.5-2.5 years	Low-speed ships	Propeller design must be adapted and integrated with duct design to produce optimum combination of thrust from propeller and duct for a given power. Structural security of duct in adverse conditions is of vital importance. Can be retrofitted.
c. Controllable pitch (CP) propellers	-3 to 10[d]	120 240	0-400[d] 0-800[d]	SRS SRS	- -	SRS SRS	New geared diesel ships	Close to maximum efficiency can be maintained regardless of ship's loading condition. Maneuverability is improved (especially where high thrust is required at low speed), reducing overall power requirement, but initial cost and maintenance costs are high and reliability is low. Widely used. Shaft-driven generators can be added. Caution: A major propeller manufacturer notes that, at designed pitch setting, these propellers are no more efficient than fixed-pitch propellers. At off-design pitch, CP propeller loses efficiency because diameter and pitch distribution are no longer optimal. More importantly, in all conditions, high hub diameter ratio with a CP propeller can reduce efficiency by 2-3%. Fixed-pitch propellers can also be used with geared diesel engines.
3. Propeller changes for ships already in service								
a. Redesigned or repitched propeller to adjust for hull roughening, slow steaming, deteriorated engine performance, and/or	0-10[d]	120 240	0-400[d] 0-800[d]	SRS SRS	- -	SRS SRS	All ships	Hull fouling increases mean wake encountered by propeller, which, when combined with reduced engine torque due to aging, increases power needed to maintain speed. By reducing propeller diameter (it should still be as large as possible, consistent with draft and aperture) or adjusting its pitch by adjusting the angles of its trailing edges, less power is lost than would be lost if these adjustments were not made and ship had to run at less than optimum. Increasing propeller diameter by 7% can reduce power requirements even further than the 25-35% reduction due to slow-speed running, resulting in 9-10% additional fuel savings. Caution: Must integrate into total ship propulsion system. Large drop in ship speed due to propeller change requires new analysis of turbine efficiency.

Table 1. Continued.

Fuel-Savings Measure	Claimed Fuel Savings[a] (%)	Assumed Fuel Use[b] (000 bbl/ year)	Claimed 1981 Fuel Cost Savings[c] ($000s/ year)	Additional 1981 Costs, If Available ($000s): Investment	Additional 1981 Costs, If Available ($000s): Maintenance and Repair	Claimed Payback Period (if available)	Assumed Market Sectors (ship types)	Reference and Workshop Remarks
Propeller and hull modifications (continued) new engine gearing arrangement or stern design								
b. Regular repair and repolishing of propellers								Prevents loss of efficiency; blade roughness increases fuel consumption. Careful grinding and polishing very important during dry-dockings. If polishing of entire propeller is not possible, regular polishing of as much as can be accessed in port by trimming the ship still achieves good fuel savings. Low-cost measure (under $3000). Savings are short-term but prevent cumulative roughening of propeller. Caution: High-quality control required during polishing to avoid damage to propeller surfaces.
1. Entire propeller (during dry-docking)	0.25-0.50	120 240	10-20 20-40	3 3	- -	1 week 1 week	All ships	
2. Outer part of propeller (midway between dry-dockings)	0.25-0.50	120 240	10-20 20-40	3 3	- -	1 week 1 week	All ships	
Potential engines and fuel still under development								
1. Adiabatic engines	25	120 240	1000 2000	Unknown Unknown	Unknown Unknown	Unknown Unknown	Ships with medium-speed diesel engines	Adiabatic (constant heat) compression of fuel-air mixture enables operation at cylinder temperature of 1500°F. Must use exhaust heat recovery to maximize savings.
2. Liquefied coal and oil shale	Unknown (residual oil only)	120 240	Unknown Unknown	Unknown Unknown	Unknown Unknown	Unknown Unknown	All ships	More expensive than residual oil but may have to be used if residual oil is in short supply in future.
Potential hull and propeller changes still under development								
1. Tunnel stern	Unknown	-	-	0	-	Unknown	All ships	Formed by bringing afterbody down around propeller. Propulsion system efficiency may increase, but tunnel stern resistance is higher than that of conventional open stern due to increased surface area and frictional drag. Interrelationship among these factors and their net effect on fuel consumption are unknown. Primary use being considered is new naval construction.
2. Other hull design improvements	-	-	-	-	-	-	All ships	Bulbous bows are a widely accepted design feature intended to reduce wavemaking resistance. Though most effective in new ship designs, they have been successfully applied to existing ships. They are not, however, universally applicable even when carefully designed. Recent U.S. Navy studies found at least one case where fuel use was less without a bulb.
3. Reaction fin (retrofit device)	Unknown	-	-	-	-	-	VLCCs	Obtains forward thrust from rotating water inflow to propeller in reverse direction of propeller rotation. Preliminary research found that reaction fins improve propulsion performance more effectively than nozzle propellers and consistently reduce power requirements. However, the quantity of savings is affected by ship hull hydrodynamic characteristics; more study is needed.
4. Contrarotating propellers	0-13[d]	120 240	0-520[d] 0-1040[d]	SRS SRS	- -	Unknown Unknown	New liners	Advantageous on fast ships where propeller diameters are usually limited by draft structural design and high RPM. Sharing load between two propellers also reduces cavitation and therefore erosion, vibration, and noise. Reliability is still unproved due largely to mechanical shafting complications.
Reintroduction of previously discarded technologies								
1. Contraguide rudders	Unknown	-	-	-	-	-	All ships	Relatively inexpensive; saved up to 0.5% fuel in U.S. Liberty ships in World War II. Government-supported research appears warranted.

Note: SRS = ship and/or route specific (used where not even an estimated range of potential fuel savings and/or payback period was found), FMC = Federal Maritime Commission, RO/RO = roll-on/roll-off ships, SHP = ship horsepower, MARAD = U.S. Maritime Administration, and VLCC = very large crude carriers.

[a] Fuel savings of options are not directly additive since each new savings will diminish the base annual fuel consumption that can be further reduced.
[b] Fuel use rates of 120 000 and 240 000 bbl/year were selected as representative of small and large ships, respectively. These two rates were used in calculating information in other columns.
[c] Based on assumed annual baseline fuel use and January 1981 Bunker C cost in New York (approximately $33/bbl). No attempt has been made to predict probable fuel cost escalations over time.
[d] Reference estimates have been adjusted by workshop consensus.

Assumed Fuel Use

The third column of the matrix provides a simplified parametric basis for estimating the annual dollar fuel-cost savings implied by the claimed fuel-savings percentages in the second column. After discussions with workshop participants, annual fuel consumption rates of 120 000 and 240 000 bbl/year were selected as representative of small- and large-ship fuel use rates, respectively. Although these rates exclude tramp ships on the low end of the spectrum and ultralarge crude carriers (ULCCs) on the high end, they cover most liners and tankers.

Claimed 1981 Fuel-Cost Savings

The savings estimates given in column 4 of the matrix were derived by multiplying the claimed fuel-savings percentages in the second column by the estimated annual fuel consumption values in the third column and the January 1981 Bunker C fuel cost in New York City of $33/bbl.

The cost savings estimated in column 4 are gross, rather than net, savings. They do not take into account the allocations of investment costs necessary to realize the savings or the higher maintenance or other operating costs required by some fuel-savings options (e.g., retrofitted medium-speed diesel engines). Nevertheless, they do translate energy savings into gross dollar savings, which relate more closely to the primary business profit motive.

Additional 1981 Costs

Two columns are included under the heading, "Additional 1981 Costs": (a) investment costs and (b) maintenance and repair costs. Information proved difficult to obtain for these columns, and so there are many blank spaces in them. The lack of information resulted mostly from a primary emphasis in the literature on the energy and cost savings of the conservation measures and not on added costs. In addition, these costs varied so widely in some cases that an SRS entry was made to cover the wide range. Nevertheless, users of the matrix should realize that added costs do accompany many of these measures. These costs must be determined for individual ships in order to calculate the payback periods on which investment decisions are usually based.

Claimed Payback Period

The payback periods in column 7 are labeled "claimed" because they are based on claimed fuel savings, which often vary by ship and trade route. Similarly, investment, maintenance and repair, and other additional costs required by fuel-savings measures also vary by ship and sometimes by trade route as well. Nevertheless, the payback periods given, especially when less than a year or two, should provide ship operators with useful decision-making information. Cases in which estimates from the literature were modified by workshop consensus are identified in the matrix by footnote "d".

Calculations of payback period were not attempted for the matrix primarily because, even where annual fuel savings could be estimated, there were insufficient data on additional costs required by the conservation measures. In addition, such calculations would be unwieldy and inappropriate for a summary matrix because reviews of relevant confidential payback analyses revealed the need for highly individualized (ship-specific) and detailed data, in addition to projections of a wide range of petroleum price escalations.

Assumed Market Sectors

Many of the energy conservation measures are applicable to all ships, but others are designed for certain ship types (e.g., liners and tankers), ages, sizes (e.g., less than 40 000 deadweight tons), speeds, or engine types (e.g., steam turbine and slow-speed diesel). Column 8 was added to help ship operators using the matrix to focus more easily on the measures appropriate for their vessels.

Remarks

Important information concerning operator experiences and the functions, advantages, disadvantages, and risks of the fuel-savings options is presented in the last column of the matrix. Many changes made in the draft matrix during the workshop are contained in this column. The column provides qualitative, and in some cases quantitative, information vital to proper evaluation of the measures.

CONCLUSIONS AND RECOMMENDATIONS OF WORKSHOP

Status of Industry Fuel-Savings Efforts

Workshop participants agreed that significant progress is being made in the development of energy efficiency improvement programs in segments of the maritime industry but that this trend is far from universal. Although it was recognized that all companies desire to save fuel in this era of rising bunker costs, many operators have operating and financial constraints that severely limit or prevent efforts to save fuel. Difficulty in developing the support of ship crews for operational and equipment modifications to save fuel was identified as a particularly important constraint.

Nevertheless, the workshop consensus was that economic considerations (i.e., high bunker costs) are providing a major incentive to conserve fuel and that the maritime research community and many firms other than those represented at the workshop are taking steps to do so. One example cited was the Ships Operating Efficiency Panel of the Ships Technical Operations Committee, Society of Naval Architects and Marine Engineers (SNAME). Panel Chairman James Sweeney, who was a participant in the workshop, noted that 90 percent of the panel's activities involves the evaluation of fuel-savings measures. He also said that the panel, composed primarily of ship owners, has a growing list of members, some of whom have as few as two ships.

Another example of growing industry interest in improving shipboard energy efficiency is the recent establishment by SNAME of an ad hoc Committee on Maritime Energy Research and Development. Committee functions include consolidating the energy conservation results of other SNAME panels, monitoring and evaluating research on energy efficiency, and making recommendations for needed future research. Committee Chairman David O'Neil, also a workshop participant, is circulating the matrix developed during this project to committee members. He indicates that the committee will likely adopt the matrix as a useful document that summarizes recent research results concerning maritime energy conservation alternatives.

The workshop consensus was that distribution of the matrix to participants in U.S. foreign trade will help to spread knowledge of the wide range of alternatives available for saving marine fuel to a broader segment of the industry than is currently active in energy conservation.

Table 2. Ten fuel-savings measures with highest potential.

Measure	Fuel-Savings Potential
Development of crew motivation, cooperation, and participation (preferably with management program)	Ship and route specific
Slower ship speeds, as allowed by trade-offs with other operating costs and service requirements	≤30%
Maintenance of hull surfaces, including use of self-polishing coatings	≤7%
Repair, adjustment, or replacement of propellers	≤10%
Finer engine tuning, including improvements in combustion and instrumentation	≤10%
Conversion from steam to diesel engines	≤25%
Use of coal or coal slurries as fuel	Can replace petroleum at large cost savings
Improvements in ship trim	≤25%
Improvements in steam cycle or diesel engine	≤7%
Improvements in steering efficiency	Ship and route specific

Note: First measure listed is considered to have the highest potential of all. Other measures are not listed in order of importance.

Fuel-Savings Measures with Greatest Potential

After the matrix was reviewed and refined, the workshop participants assigned priorities to the fuel-savings measures according to their potential. It was decided that a list of the 10 measures considered to have the greatest potential would provide ship owners with a useful starting point. This list, which was agreed on by consensus, is presented in Table 2.

The alternative unanimously agreed on as the most important ingredient of any successful fuel-savings program is the development of crew understanding, motivation, cooperation, and participation. The other nine measures could not be individually ranked, however, despite demonstrable differences in estimated fuel savings, because of interdependencies and other interrelations among these measures and because of differences in investment costs and planning horizons. Ship owners are therefore advised to evaluate each item on this list in terms of its appropriateness for their operations.

Opportunities for Government Facilitation of Maritime Fuel Conservation

Workshop participants were asked at the outset of the meeting to be prepared during discussions of the fuel-savings measures to identify opportunities for government facilitation of energy efficiency improvements. As a result, four types of regulations were identified as warranting analysis by the federal government to determine (a) the nature of their impacts on maritime energy efficiency and (b) ways of improving the regulatory climate for fuel-savings measures. The areas of investigation identified were suggested by individual workshop participants and not by consensus because it was decided not to request extension of workshop consensus to matters involving complex and sensitive economic and political issues. Nevertheless, it appears that the following should be subject to balanced assessment to identify (a) potential opportunities for government facilitation of improved maritime energy efficiency and (b) possible related negative effects:

1. Cargo pooling,
2. Reduced port-call requirements under ship subsidy agreements,
3. Increasing allowable time periods between dry-dockings, and
4. Eliminating fuel surcharges.

Cargo pooling is not a problem for strictly foreign operations, but any such agreements involving U.S. operators must receive the approval of the FMC under the Shipping Act of 1916. However, seven shipping companies have operated between 1977 and 1981 under the Atlantic Steamship Energy Conservation Agreement approved by the FMC: Atlantic Container Line GIE; Dart Containerline, Inc.; Farrell Lines, Inc.; Hapag-Lloyd AG; Sea-Land Service, Inc.; Seatrain International, S.A.; and United States Lines, Inc. In addition to saving fuel, cargo-pooling agreements may make possible reductions in crew costs, improvements in vessel utilization, and trade route expansion for vessel operators. Balanced assessment requires that antitrust considerations be investigated prior to any regulatory revision.

Reducing port-call requirements under U.S. ship subsidy agreements would be a policy change that U.S. operators might or might not take advantage of, depending on whether such reductions would make sense economically. Such reductions are already being accomplished with a system of smaller "feeder" ships operated by nonsubsidized Sea-Land Service, Inc. However, such systems can only be justified if the cargo is insufficient for larger ships and there is adequate capital to support the smaller ships.

Several workshop participants questioned the U.S. Coast Guard requirement for dry-dockings of ocean-going U.S. vessels every two years. One suggestion was that DOE request the Coast Guard to lengthen the standard period, given the impact of new technology. The use of self-polishing, antifouling coatings on hulls and mechanical seals on new ship shafts, both of which reduce major maintenance needs and obviate a two-year cycle, was cited as a major reason for pressing the Coast Guard to lengthen the time between required dry-dockings.

The allowance of surcharges on freight rates that enable fuel price increases to be passed along to shippers was also identified as a regulatory practice that inhibits efforts to conserve fuel, since it eliminates the need to save fuel in order to maintain revenues after fuel costs. However, workshop participants acknowledge the plight of firms whose pressing operating problems and financial constraints impair their ability to develop energy efficiency improvement programs. It was also noted that firms that conserve fuel can either assess fuel surcharges and keep the additional profits as a reward for their efficiency or not assess the entire surcharge and thus set rates below their competitors' in an effort to generate new business.

FINAL OBSERVATIONS

This project illustrates how commonness of purpose can be used to develop a good working relationship among government, the research community, and industry. The major cost savings available to ship operators through improved energy efficiency, which is also a national goal, provided the impetus for pooling knowledge, insights, and resources. This experience has proved that government-sponsored research can provide a valuable information development function for business and that knowledgeable maritime industry representatives can provide government with an invaluable, experience-based information evaluation function.

ACKNOWLEDGMENT

An expanded version of this paper is available from the authors. That version includes an additional section in which it is shown how the measures pre-

sented in the matrix can be combined by operators into a comprehensive, fleetwide energy conservation program. A list of references for the matrix is also included.

Limited Trucktrain: A Concept for Energy Conservation and Truck Productivity

ROBERT K. WHITFORD

The widespread use of turnpike double and western triple trucks constrained to operate only on the Interstate system offers the potential not only for a reduction in U.S. diesel fuel consumption but also for a major increase in trucking productivity. This option is based on two 40- or 45-ft trailers (doubles) or two 27- to 30-ft trailers (triples) with axle weights maintained at the present 20 000-lb single/34 000-lb tandem level. Under this approach, the Interstate would be modified to provide for adequate access to truck stops and to provide parking areas or "corrals" where doubles and triples would be made up for intercity movement and disassembled for city delivery. Two scenarios are evaluated for their potential in fuel savings. Fuel improvements are estimated to be about 22 percent. A turnpike double offers nearly the same energy intensity as conventional trailer-on-flatcar unit trains traveling at similar speeds. Potential productivity improvements in trucking are so substantial that the industry may have to consider changes in its mode of operation. Under this scheme, about 500 trucks can do the job of 900, resulting in a reduction of drivers and capital equipment. The road stress as expressed in terms of equivalent axle load is slightly below that for single trucks moving the same freight. For the investment in road alterations and tractor upgrading, fuel savings equivalent to $15 000 to $40 000/bbl/day are realized (oil shale plants require an investment of about $35 000/bbl/day). Considering the reduced number of drivers and tractors, dollar savings much greater than the fuel cost are achieved. The overall benefit/cost ratio exceeds 10 for a nominal road rehabilitation cost factor, which makes trucktrain a very attractive option. Negative factors concern highway safety and the potentially severe impact on the railroads.

Liquid fuel limitations make it imperative to explore all avenues to conserve petroleum. Although intercity trucking consumes only about 8 percent of the petroleum used in transportation, it needs to be considered. The trucking community has been engaged in near-term and longer-term efforts to improve fuel economy (1,2). Substantial increase of truck size and weight offers a significant opportunity for fuel economy. The concern, of course, is to prevent any measure from becoming counterproductive by making trucking seem more attractive than its more energy-efficient competitors, the railroads and barges.

The approach suggested here, which expands the concept presented by Michael and others (3), is to open the Interstate highway system to trucks whose weight is close to the "bridge-formula" load limit and whose lengths are commensurate with that limit. Weight limitations of 20 000 lb for a single axle and 34 000 lb for tandem axles would be retained. A maximum gross vehicle weight of 125 000 lb has been suggested. Commensurate lengths would be equivalent to about 85 ft of cargo-carrying capacity.

The federal Interstate system would be revised to provide numerous "trailer parking lots" or corrals. These corrals, like those provided on the Massachusetts Turnpike or the New York Thruway, would be convenient to most urban centers and major freight depots. They would be the only locations where doubles and triples could be made up for intercity movement and disassembled for delivery. No doubles or triples would be allowed to leave the Interstate. They would be disassembled as they passed through the corrals, and, if desired, trailer weights could be determined and user fees assessed at these points.

The Interstate would also be altered to provide ingress and egress to truck stops. These areas, similar to the service areas on toll roads, would be special for trucks; therefore, in the trucktrain configuration, trucks would not use the regular interchange ramps and local highways.

Walton and Burke (4) looked at similar truck configurations (although they used 102-in width) on all Texas highways, computing costs, energy saving, and commodities carried. In general, their results for energy saving are consistent with those presented here. This study should be viewed as a "first-cut" evaluation aimed at reviewing one option for saving liquid petroleum versus investment to provide the savings. Productivity gains in freight movement offer further very significant benefits. Potential disbenefits are considered qualitatively.

SCENARIOS

In the present political climate, wholesale permission to operate 40-ft doubles and 27-ft triples on the Interstate would not be granted. A major, but not emergency, petroleum shortfall will see truckers pressing hard for the system proposed here (because it improves labor and capital productivity at the same time that it reduces fuel consumption). Perhaps the 14 western states might become the first to allow the double or triple (100-ft-rig) approach. For purposes of calculation of the medium scenario, it has been assumed that 10-15 contiguous states in the West would open their limits in weight and size. Currently, the 14 continental states west of the Mississippi account for about 31 percent of heavy-combination truck miles.

Only under an extreme emergency would the federal government require the Interstate highway system to accommodate 100-ft rigs with maximum gross vehicle weight (GVW) of 125 000 lb. If this were to happen, it is likely that this carriage would be sufficiently attractive to general freight and specialized carriers that (except for movement of hazardous materials) they would make a maximum effort to use it. Private carriers, especially industries that have their own fleets, would also find ways to use the system. However, exempt haulers, under their contractual arrangements, might not be free enough or have the incentive to use such a system. Thus, for this short analysis, the following assumptions have been used:

1. Scenario A--No additional savings will occur beyond those already occurring with turnpike doubles and the present western doubles and triples.
2. Scenario B--With an additional 10 states per-

mitting doubles and triples, it has been assumed that about 50 percent, or an additional 15-18 percent, of truck ton miles will benefit from the savings.

3. Scenario C--A federal mandate that allows 40-ft doubles and 27-ft triples on the Interstate will mean that this type of traffic will be preferred when compared with limits on other roads. It is estimated for the purpose of this analysis that at least 80 percent of freight could be subject to the benefits of the Interstate. Since there will undoubtedly be some circuity to take advantage of the increased productivity offered by doubles and triples, it appears reasonable to estimate that about 65 percent of the total traffic would shift to movement by doubles and triples.

Using the forecast from the National Transportation Policy Study Commission (5), Table 1 provides two growth levels for the freight traffic in each of the study scenarios B and C. Scenario A is assumed as zero and is therefore not included in the table. The freight growth of level 2 is an average of the medium and high forecast levels (5, Appendix Table 37), whereas level 1 is slightly more optimistic than the low forecast.

Table 1. Forecast of ton miles subject to carriage in limited-trucktrain concept under two scenarios.

Year	Level of Growth in Freight Traffic	Forecast (billion ton miles): Total U.S.	Subject to Improvement Scenario: B (15-18%)	C (65%)
1980		580	90	380
1985	1	735	110	480
	2	840	140	550
1990	1	800	130	520
	2	1000	160	650
1995	1	875	140	570
	2	1250	200	800
2000	1	950	160	620
	2	1540	250	1000

FUEL SAVINGS

The truck size and weight study at Purdue University (3) provided, from currently available data, the fuel used and the road stress caused [equivalent 18 000-lb axle loadings (EALs)] by an average fleet carrying 14 300 tons of freight per day. Table 2 (3) identifies fleet characteristics for the present 80 000-lb GVW limit moving 14 300 tons. [Purdue University (3) used the 1974 Interstate Commerce Commission (ICC) "empty/loaded" data (6) to derive the traffic weight model. The movement of 14 300 tons in 1000 trucks with 26 percent empty was considered the median. Table 2 reflects the more recent change from 73 280- to 80 000-lb GVW in all states.] Table 3 results from loading the same amount of freight into double and triple bottoms and calculating both gallons per mile and EAL for the new fleet. It can be seen from Table 3 that total GVW is considerably reduced because only 484 trucks are needed to move 14 300 tons in the limited-trucktrain concept compared with the 906 trucks in Table 2. This reduction results in an anticipated amount of road damage for this amount of freight movement that is actually less than that for the traffic considered in the base case (Table 2).

The fuel used by this fleet of doubles and triples is reduced by 22 percent. The tables illustrate that the gasoline saved is 165.5-129.3 gal/movement of 14 300 tons of freight for 1 mile. [Walton (4) gives a fuel-saving improvement on In-

Table 2. Baseline of average truck fleet with weight limits at 80 000 lb.

GVW (lb 000s)	Avg Weight Used (lb 000s)	Percentage of Fleet	EAL per Truck	Freight per Truck (tons)	Avg Fuel Economy per Truck (miles/gal)	906-Vehicle Fleet: Vehicles	Freight (tons)	EALs	Gross Weight (lb 000 000s)	Fuel Consumption (gal/mile)
20-35	29	28.7	0.2	0-3	8.0	260	89	52	7.54	32.5
35-50	45	15.5	0.5	8.5	6.2	140	1 190	70	6.31	22.6
50-65	60	7.1	2.3	17.0	5.0	64	1 086	1473	3.84	12.8
65-75	75	16.7	2.9	24.5	4.5	151	3 700	438	11.33	33.6
75-80	80	27.4	4.1	28.0	4.1	248	6 944	1017	19.84	60.5
80-85	85	4.7	5.1	30.0	3.9	43	1 290	219	3.65	3.5
Total						906	14 300	1943	52.50	165.5

Table 3. Increase in weight limits to 125 000 lb GVW, 20 000 lb single axle, and 34 000 lb double axle to move 14 300 tons.

GVW (lb 000s)	Avg Weight Used (lb 000s)	Truck Type	EAL: Rigid Pavement	EAL: Flexible Pavement	Freight per Truck (tons)	Fuel Economy (miles/gal)	To Move 14 300 Tons: No. of Trucks in Fleet	Freight (tons)	EAL: Rigid Pavement	EAL: Flexible Pavement	GVW (lb 000 000s)	Fuel Consumption (gal/mile)
20-35	33		0.2	0.2	0.3	7.6	82	86	16.4	16.4	2.71	10.8
35-50	45		0.5	0.8	8.5	6.2	24	204	12.0	12.0	1.08	3.9
50-65	60		2.6	2.0	17.0	5.0	24	408	62.4	48.0	1.44	4.8
65-85	80	Semi	3.7	2.2	28.0	4.1	42	2 352	155.4	92.4	6.726	20.5
		27-ft double	2.0	2.2	28.0		42		84.0	92.4		
85-110	105	27-ft triple	4.1	4.4	36.0	3.5	100	3 600	410.0	440.0	10.5	28.6
110-125	125	27-ft triple	7.0	7.6	45.0	2.8	50	7 650	350.0	380.0	21.25	60.7
		40-ft double	4.5	2.9	45.0		120		540.0	348.0		
Total							484	14 300	1630.2	1429.2	43.7	129.3

Note: Maximum single-axle and double-axle load = 20 000 and 34 000 lb, respectively.

Table 4. Fuel saved by using trucktrain.

Year	Level of Growth in Freight Traffic	Fuel Saved (bbl 000 000s/day)	
		Scenario B	Scenario C
1980		15 000	62 000
1985	1	18 300	79 000
	2	23 300	90 000
1990	1	21 700	84 000
	2	26 500	100 000
1995	1	23 300	92 000
	2	32 600	130 000
2000	1	26 500	97 000
	2	41 700	163 000

terstate highways of 0.82 over 20 years. The ratio for this model (129.3/165.5), suggestive of average U.S. truck movement on the Interstate, is 0.78.] This saving amounts to about 0.0025 gal/ton mile. Projected fuel savings in barrels per day, using the ton miles subjected to this system (Table 1), are given in Table 4.

CAPITAL COSTS

The capital costs required for the limited-trucktrain option fall into four categories.

Truck Upgrading

The first area of capital costs is the upgrading of the truck to handle the extra loads. Some tractors already have the capability to pull the extra load. Heavy-duty axles, larger engines, improved brakes, etc., will be required to upgrade others. The improved productivity resulting from upgrading will more than offset these costs. In 1990, for an estimated 50 000 miles/year/tractor, 50 000 heavy-duty tractors would be needed for scenario B, and about 250 000 to 380 000 tractors for scenario C. The heavy-duty cab is estimated to cost about $10 000 to $15 000/tractor. Under these assumptions, the investment would amount to about $750 million for scenario B and $3.5 billion for scenario C.

The investment costs for truck improvement are related to the amount of freight subjected to the higher loads and to the operating principles. For example, do you keep the upgraded trucks (probably less fuel efficient than their nonupgraded equivalents) on the Interstate and meet most traffic at the corral, or do you simply unhook the trailer(s) at the corral and take the single trailer for further delivery?

Interstate Upgrading

The second area of capital costs is in upgrading the Interstate to provide for truck stops. This analysis assumes that a truck stop is needed about every 40 miles and that about 600 are required. The investment cost considered is to provide access roads to the stops, each of which requires the equivalent of 1-2 miles of two-lane Interstate-type construction. At $1.5 million/mile for good freeway construction, Yoder of Purdue University estimates that $1.4 billion would be required.

Provision of Corrals and Access

The corrals used for the make-up and disassembly of the doubles and triples must be paved and freeway access provided. Upgrading the non-Interstate access to some corrals may also be required. Corrals closer together than 50-75 miles would not be appropriate and, for most areas of the country, 200 miles is a more reasonable distance between corrals. These calculations assume that corrals near intersections of two Interstates can serve both. Two corrals will be needed in some areas where one corral cannot serve both directions. Two-hundred corrals for the entire country would be a conservative estimate. The cost components of each corral break down as follows:

1. An access road to the Interstate is assumed to represent 3 miles of two-lane road, for a cost of $4.5 million/corral.
2. The corral itself needs to accommodate about 100 trailers at one time and will need room for maneuverability. This will require approximately 4 acres of high-grade parking lot plus the land; at $10/yd² of Interstate-type concrete and $150 000 for the land, this means that it will take $2 million to construct each corral.
3. Local roads leading to the corral may need upgrading. For many cases, it can be assumed that the truck will enter the corral by taking the normal entrance to the Interstate and move to the closest corral over the Interstate. A conservative estimate suggests that perhaps about 80 corrals will need about 5 miles of additional high-grade, two-lane highway to provide new or upgraded access routes. This will increase the cost by about $600 million, or an average of $2 million/corral.

The total investment cost is approximately $8.5 million/corral.

Road Upgrading

The fourth element of potential cost is the upgrading of roads. The EAL (measure of road damage) will actually be somewhat less for the same freight carried without the trucktrain (3). Therefore, the only reason for added cost to upgrade will be increased traffic. If traffic grows by 10 percent, the increased traffic will require an increase in road rehabilitation costs somewhere in the range of 0.1-0.5 ¢/total ton-mile of trucktrain carriage. (Estimates of rehabilitation costs vary. The whole area is being evaluated by the U.S. Department of Transportation in their studies of user charges and truck size and weight. This paper uses a rough computation by assigning the total Interstate costs to trucks.)

Investment Cost for Two Scenarios

For scenario B, some minor upgrading of the road and truck-stop egress will be needed. Twenty corrals are anticipated at $10 million each and 100 truck stops at $4.5 million, which makes a maximum investment of $900 million ($650 million for road and corrals plus $250 million for tractors). Implementation of scenario C will require a minimum of $6 billion total investment.

Each investment cost for the roadway and the corrals is independent of the year, except for inflationary updating. It will probably take five years to implement all the road changes, but it is reasonable to assume that the system can be put into effect on a makeshift basis very quickly if necessary.

PRODUCTIVITY INCREASES

Implementation of the limited-trucktrain concept will greatly improve the productivity of the line-haul portion of trucking. Several important measures are estimated:

1. Ton-miles per dollar (up 32 percent)--The

cost of line-haul is a function of distance and percentage loaded return (backhaul). Based on data given by Suckanec (7), the costs per mile range from about $1.20 with a 50 percent backhaul to about $0.90 with a 100 percent backhaul for a trip of 300-600 miles. The table below gives an estimate by line item of the line-haul costs, which decrease from about 7.5 to 5.67 ¢/ton-mile for trucktrain:

	Truck Cost ($/mile)	
Item	Without Trucktrain	With Trucktrain
Labor	0.45	0.62
Depreciation	0.35	0.44
Fuel	0.24	0.35
Maintenance	0.36	0.08
User costs	0.10	0.20
Total	1.20	1.70

2. Ton-miles per gallon (up 26 percent)--Based on the traffic models of Tables 2 and 3, the energy productivity increases by about 26 percent, from 87 to 110 ton miles, for each gallon of fuel.

3. Ton-miles per labor hour (about 40 percent increase)--The productivity for labor includes an allocation of stem time for assembly and disassembly in the corrals and strictly enforced speed limits. Strictly enforced driving times may also increase labor hours over minimum. For example, a 400-mile run for a single truck might take about 9 h (710 truck miles/h) whereas for a double with two drivers it could take 13 h (1000 truck miles/h) split between the two drivers, which is an increase of 40 percent. Even allocating 8 h for the two drivers with the double gives an improvement of about 16 percent.

4. Annual ton-miles per tractor (up 56 percent)--Based on the fleet model of Tables 2 and 3, it takes only 486 tractors to do the job formerly done by 906. With corral time and more stringent inspection and maintenance, tractor availability will likely be reduced. A 20 percent increase in tractors, which has been granted for the trucktrain, is assumed in the productivity computation.

BENEFITS AND COSTS

Trucktrain produces significant benefits for the highway system, trucking, and, potentially, the general public:

1. The highway system will be better preserved if weight limits are enforced and travel over secondary and local rural highways is reduced. The trucks will, of course, develop a different travel pattern. If the suggested approach generates increased use of 27-ft trailers over the large number of 40-ft trailers now involved, congestion resulting from city pickup and delivery might be reduced.

2. Trucking, of course, benefits by achieving a significant increase in productivity. A number of industrial and operational adjustments will occur, probably including the development of some special over-the-road long-haul companies. Many more drivers will be able to spend more time at home, a benefit they often request (8).

3. Road conditions should improve if new mechanisms are provided to enforce weight and to collect costs. In addition to the inherently better safety suggested by some of the western carriers, the new mechanisms will make it possible to maintain control of drivers who are allowed access and require them to have extra training, insurance, and special licenses. Safety should also improve if new travel patterns emerge that decrease or limit travel of combination trucks on non-Interstate highways.

Note should also be taken of the following potential problems if a maximum shift to the suggested system occurs:

1. Because of a reduction in the use of tractors, there will be a corresponding decrease in the number of drivers. At the present time, there are about 2 million truck drivers in the United States (9). Installation of scenario C could create unemployment for about 30 percent, or 600 000 drivers.

2. The excessive number of unused tractors would cause problems in the used-tractor market and could result in the failure of companies that depend on that market. Changing systems affects both the sales and service industries and the large companies that turn over their fleets every two or three years. The productivity gains probably outweigh this concern.

3. Truck size and weight are factors in certain types of highway accidents. Increased disparity of size and weight between trucks and other vehicles could result in greater damage to the smaller vehicles. The heavier trucks will have poorer acceleration-deceleration capabilities (10), cause more splash and spray (11), and require longer passing distance and longer stopping distance. Added brake wear will result from increased weight (12). In addition, even though the total number of vehicles will be less, the impact of large numbers of double trailers may be psychologically forbidding to the motoring public. If the average motorist feels too unsafe, an alternative, potentially less safe, non-Interstate road would be chosen.

4. There will be a minimal impact on the manufacturers of tractors, who will experience an increased demand for more substantial tractors and for heavy-duty parts for retrofit. Increased maintenance, particularly for brakes, will be required.

5. Perhaps the most significant effect will be on the railroads. If the costs of truck transportation and the service offered by this new use of the Interstate become very attractive, then some percentage of the traffic (13) will move from the more energy-efficient rail mode to trucks. The transition from rail to truck was not quantified because of insufficient data and the difficulty in adequately estimating the traffic that will move from rail to truck. Hymsom (13) begins to identify some of the possible effects of the new system but, for a good forecast, factors such as spatial distribution of markets, fleet mix, equipment, utilization and availability, reduction in circuity, rate structure, empty truck/haul ratios, intermodal coordination [trailer on flatcar (TOFC)] potential, and average revenue yields must be analyzed on a region-by-region basis.

Energy intensity calculations that compare truck and rail, especially TOFC, are quite variable. In examining a number of results (14-16), a 40-ft average truck seems to vary from about 1600 to about 2200 Btu/ton-mile on line-haul. For example, where 32 loaded (16.6 tons/trailer) and 4 empty trailers are hauled and fuel use is 4 miles/gal full and 8 miles/gal empty, an energy intensity of 2200 Btu/ton-mile results.

For the double 40, the extra weight reduces fuel efficiency by about 25 percent to 3 miles/gal, resulting in 1400 Btu/ton-mile for the example of 16 loaded double bottoms and 2 empty doubles. The double-bottom fleet of Table 3 shows about 22 percent reduction over that of Table 2.

The standard TOFC depends on operating conditions, loaded versus empty trailers, percentage use, grade, wind, and speed. Based on a 20-car dedicated standard flatcar (TTX) train carrying 36 trailers (32 loaded and 4 empty) and the use of Sprint data

Figure 1. Estimated Btu per ton mile for TOFC versus truck.

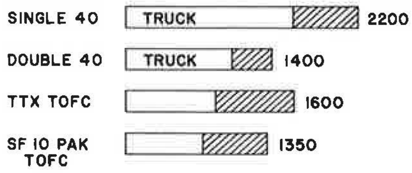
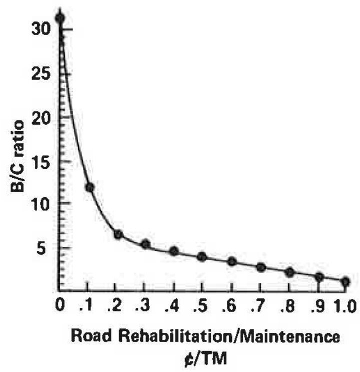


Figure 2. B/C ratio versus road rehabilitation costs.



(14) of 3.88 gal/1000 gross ton-miles, an energy intensity of 1600 Btu/ton-mile results. Other references show results as low as 800 Btu/ton mile (15). Even for the consist fully loaded with 20 tons of cargo in each trailer and 3.5 gal/1000 gross ton-miles, the energy intensity is 1130 Btu/ton-mile. The Santa Fe "Fuel Foiler" (10-PAK) provides an improvement in energy intensity of 15 to 20 percent.

It is probably safe to say that TOFC thus is about twice as energy efficient as conventional truck and about equivalent to the double 40 concept. Figure 1 shows the comparison.

The benefits of this approach considerably outweigh the costs, as shown below:

Discount Rate (%)	Billions of Dollars Benefits	Costs	B/C Ratio
0	220	14	15.4
10	74	6.2	12
20	33	3.6	9.3

Three discount rates are identified, and 0.1 ¢/total ton-mile is assumed in the simulation for road rehabilitation. Figure 2 shows how the B/C ratio (using a 10 percent discount rate) varies as a higher assessment is made for road rehabilitation.

CONCLUSIONS

There is no question that a trucking system such as that described in this paper would save diesel fuel, improve productivity, and ultimately save consumer costs. Implementing such a system nationwide would save more than 100 000 bbl/day, which is equivalent to an investment of about $6 billion for synthetic fuel plants.

Enhanced productivity for truck and better use of tractors mean that truckers would see some or all of the cost as being advantageous to them. The amount can easily be raised by increasing the user charge. Any increase in the user charge will be more than offset by the reduction of costs per ton-mile that will occur with reduced labor (25-40 percent) and equipment (20-40 percent). Insurance and special pay to drivers of doubles will rise. Stem time will increase as will benefits to the unemployed.

Obviously, a number of questions remain. Two in particular are highest priority:

1. What, in fact, will be the modal shift from rail to truck if such a configuration is considered?
2. Can the motorist's safety concerns be overcome?

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Potential Fuel Savings of General-Freight Carriers Operating Under Bridge Formula B Gross Vehicle Weight Limits

ROGER W. KOLINS

The number of gallons of diesel fuel that could be saved if 65-ft twin-trailer operations were permitted to operate under state weight limits designated on the basis of Bridge Formula B is estimated. This formula, developed by the American Association of State Transportation and Highway Officials, would only be applied to 65-ft twin-trailer operations and would permit them to operate at up to 85 500-lb gross vehicle weight as opposed to the arbitrary ceiling of 80 000 lb now established as the federal limit. The analysis indicates that application of Bridge Formula B to define the gross vehicle weight limit of 65-ft twin-trailer operations would save the United States 229 927 000 gal of diesel fuel annually.

This paper presents an estimate of the fuel savings that could result if Bridge Formula B, developed by the American Association of State Highway and Transportation Officials, were applied to define the gross vehicle weight (GVW) limits of five-axle trucks, as is the case in many states today (1). Bridge Formula B would not affect the permissible GVWs of all five-axle tractor-semitrailer combinations traveling under the formula's single- and tandem-axle weight limits of 20 000 and 34 000 lb, respectively. Five-axle tractor-semitrailers would still be restricted to 78 500 lb as under current federal vehicle weight limits. But without the arbitrary ceiling of 80 000 lb, now imposed by many states, 65-ft twin-trailer combinations operating under an uncapped Bridge Formula B would be permitted to reach a GVW of 85 500 lb. Twin-trailer combinations would still be restricted to single- and tandem-axle weights less than or equal to 20 000 and 34 000 lb, respectively.

If 65-ft twin trailers were permitted to operate in all states, it is conservatively estimated that 16.34 percent of intercity truck tonnage would be transported in twin-trailer vehicles. This figure is derived under the assumption that, at minimum, the proportion of less-than-truckload (LTL) motor freight tonnage traveling under "cube-out" conditions (in which motor carriers reach their cubic load capacity prior to reaching the allowable GVW) is potential twin-trailer traffic. LTL freight tonnage has been estimated to constitute 34.4 percent of all intercity motor freight tonnage (2), and A.T. Kearney has estimated that 47.5 percent of LTL motor-carrier trips travel under cube-out conditions (3, p. iv-i). The 16.34 percent potential twin-trailer freight estimate is the product of 0.344 and 0.475.

In the analysis presented in this paper, data on carrier line-haul operations are used to develop a probability function that, in turn, is used to predict the average payload weights a general-freight carrier will experience under given size and weight limits. The method used was first developed for presentation at the 1977 Transportation Research Forum (4).

The logic or model underlying this research is as follows: The impact of liberalized size and/or weight limits on truck payloads is, predominantly, a function of three factors: (a) the practical (or loadable) trailer cubic capacity, (b) increases in payload weight capacity, and (c) the availability of freight sufficiently dense to exploit payload weight capacities.

TRUCK-WEIGHT-LIMIT IMPACT MODEL

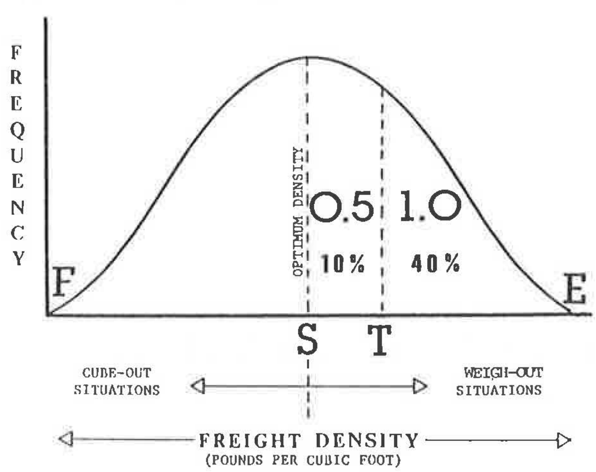
At any given truck size and weight limit, there is a freight density at which both size and weight capacities are fully used--the "optimal density". To the extent that the freight hauled is less or more than this optimum density, cubing- or weighing-out situations occur; that is, either cubic size or weight capacity is reached before the alternative capacity can be fully used.

To predict the average payload change in response to an altered weight limit, the probability of weighing-out must be estimated. If it is assumed, for illustration, that freight densities hauled by common carriers of general freight are normally distributed, with the optimal density for a representative truck equaling the mean, the probability of cubing- or weighing-out by assumption would be 50 percent, as reflected by the FE curve in Figure 1.

An increase in weight limits would produce an increase in payload capacity and cause the optimal density to shift in favor of denser, less frequently encountered freight. The shift from optimal density decreases the frequency of weighing-out by 10 percent. Only when densities T to E are hauled (40 percent of the time) can the full potential of the added capacity be exploited. When those densities that lie between the old and new optima, S and T, are hauled, cubing-out situations will occur but with heavier freight.

The impact of an increased weight limit over the range from S to T, which decreases the rate of weighing-out, may be approximated by reducing by half the frequency with which the freight densities occur. A factor of 0.5 appears appropriate since tonnage lost, due to the cubic constraint, approaches zero as the density of the freight ap-

Figure 1. Truck-weight-limit impact model.



proaches T and, conversely, the tonnage loss factor approaches 1.0 as the density of freight approaches S. The median effect between zero and 1.0 is 0.5.

The range of densities, F to S, bounded by cubic limitations prior to the change in weight-limit policy, would still be bounded after weight increases are permitted. Consequently, any added payload capacity would have no impact whatever on the cube-out rate, hence payload consisting of densities less than S.

For general-freight common carriers then, facing a market where their shipments are of an LTL nature and occur with a random frequency of densities, the probable average payload increase, stemming from an increase in the weight limit, will not have a one-to-one correspondence with the increase in the limits. In the illustration, the impact of the weight limit increase would be, on average, only 45 percent of the maximum potential weight increase.

To review the calculation procedures, the impact factor of 1.0 times the probability of experiencing a density between T and E is 40 percent (1.0 x 40), the impact factor of 0.5 times the probability of experiencing a density between S and T is 5 percent (0.5 x 10), and the impact factor of zero times the probability of experiencing the densities between F and S, 50 percent, is zero. In sum, the average maximum potential weight increase would be 40 percent plus 5 percent, or 45 percent.

DATA DEVELOPMENT: DISTRIBUTION OF GENERAL FREIGHT DENSITIES

Estimation of the distribution of general-freight densities is the first step in estimating the probable payload increases general-freight common carriers will experience for single-trailer (a tractor-semitrailer combination, 55-ft long with a 45-ft trailer) and double-trailer (twin-trailer combination, 65-ft long with two 27-ft trailers) operations, given an increased GVW limit. The distribution of freight densities can be derived from carrier outbound dispatch records, where the carrier records the following data: trailer length, weight, and cubic capacity use and traffic-leg origin and destination. From these data, trailer cargo density can be computed as follows:

$$\text{Trailer cargo density} = P/(L)(H)(W)(U) \qquad (1)$$

where

P = cargo weight (lb),
L = trailer inside length,
H = loaded trailer inside height,
W = trailer inside width, and
U = cubic capacity use.

Note that the estimates of trailer cargo density pertain to the average density of trailer cargos rather than individual bills of lading. This averaging should give the derived density distribution a very slight leptokurtic bias.

In June 1980, 19 carriers were contacted to obtain terminal outbound dispatch records for the first week of July 1980. The previous study by Kolins (4) indicated no seasonal variation in the distribution of freight densities experienced by general-freight common carriers. Seven carriers provided the required data in usable form. Each of the seven carriers had broad regional or nationwide authority.

The seven carrier data sets comprised nearly 200 000 trailer movements. To reduce this number to a more manageable size, a 3 percent sample of all dispatch records was taken for each carrier according to its origin terminal. A computerized random number generator program produced 6561 records, of which 2227 were 27-ft trailer movements and 4334 were 45-ft trailer movements. The number of trailer-movement records used from each carrier ranged from 567 to 1719. To facilitate ease of data manipulation and consistency among the seven data sets, each carrier's terminals were assigned to Census production areas (as defined by the U.S. Bureau of the Census) nearest them.

For the seven carriers as a group, there appeared to be no effort on the part of carriers to favor one trailer length over another to receive light or dense freight. Both the T-test and Kolmogorov-Smirnov two-sample tests were used to test the hypotheses of dissimilar means and dissimilar distributions. Both hypotheses were rejected at the 0.05 level.

Trailer cargo densities were then computed for the 6561 trailer loads and arrayed according to their movements between Census production areas. Since a 45-ft trailer represents 1.67 times the cubic capacity of a 27-ft trailer (45 ÷ 27 = 1.666), the equipment capacities were adjusted to reflect equivalent units. Thus, an appropriate conversion was made to the 45-ft-trailer records so that each density observation within the sampled freight-movement data would represent an equivalent unit of cargo. The sample program from the Statistical Package for the Social Sciences (5) was used to randomly sample approximately 67 percent of the 4334 freight-density observations for 45-ft trailers, or 2882 observations. This sampled set was then added to the original 6561 observations to create a freight-density data base of 9443 equivalent unit observations for 27-ft trailers.

STUDY REGIONS

The following Census production areas were chosen to represent three study regions: areas 26-35, omitting 32, for the Southeast; areas 3-21 for the Northeast; and areas 37-49, omitting 44 and 45, for the Southwest. Census production areas 24, 25, and 32 (Baltimore, Washington, D.C., and Louisville, respectively) were omitted in order to provide clearly defined borders between the regions. The sample sizes for the three regions were 2262, 3546, and 2135, respectively.

The shape of the freight-density distribution curve, as well as line-haul operating conditions, will vary from region to region. Hence, the impact of a given weight-limit change can be expected to differ between regions. As a consequence, two modifications were made to the survey data to construct freight-density distribution (probability) curves that reflect regional variations in general-freight traffic. First, the production-area sample sizes were normalized so that each production area contributed the same weight or influence to the derivation of the regional freight-density distribution curve. Second, the normalized production-area samples were weighted to reflect their relative output contribution to the region under examination. The relative production-area output levels were derived from estimates of the outbound tonnage originating in the production areas for the weeks ending August 16, 1980, and September 13, 1980, as derived from data of American Trucking Associations, Inc. (6).

IMPACT OF WEIGHT LIMITS ON TRUCK PAYLOADS

The survey freight-density data indicated that, as a rule, LTL general-freight carriers do not frequently experience sufficiently dense freight to make full

use of GVW limit increases from 73 280 to 80 000 lb or 80 000 to 90 000 lb. Table 1 gives the marginal increases in average five-axle payload weights, by truck type and region, derived by the truck-weight-limit impact model, for increases in the GVW limit from 73 280 to 80 000 lb and from 80 000 to 90 000 lb, calculated from the following formula:

$$\text{Marginal payload weight increase} = M_r U_r (Max_n - Max_o) \quad (2)$$

where

M_r = regional weight-limit increase impact factor derived from freight-density distribution data,
U_r = regional average trailer cubic capacity utilization rate,
Max_n = new maximum payload weight (GVW limit - tare weight), and
Max_o = old maximum payload weight.

Table 1 also presents the maximum payloads, optimal densities, and impact factors (M_r) used. Tare weight can be derived from the data in Table 1. The typical percentages of trailer cubic capacity used (U_r) in over-the-road LTL operations for the southeastern, northeastern, and southwestern regions are 84, 79, and 80 percent, respectively, as found from the survey data (1).

From the survey data, initial average payload weights by vehicle type were also developed for general-freight carriers operating under the 73 280-lb weight limits in each region (4). To develop the expected average general-freight payload and GVWs reported in Table 2, the marginal payload increases of Table 1 are added to the 73 280-lb weight limit base payload estimate and then tare-weight estimates are added to these. This provides the data necessary to calculate the impact of increased truck weight limits on LTL fuel productivity for general-freight carriers.

IMPACT OF INCREASED TRUCK SIZE AND WEIGHT LIMITS ON CARRIER FUEL PRODUCTIVITY

The fuel consumption formulas reported below indicate the 1981 relation between fuel consumption rates and vehicle gross weight at a maximum speed of 55 mph for single-trailer and twin-trailer combinations, respectively (7):

$$GPM = 0.000\,93(K) + 0.137\,88 \quad (3)$$

$$GPM = 0.000\,90(K) + 0.135\,20 \quad (4)$$

where GPM is gallons per mile and K is GVW in thousands of pounds.

The fuel formulas provide estimates of the fuel consumption rates of individual trucks, but for this analysis a systemwide average fuel consumption rate is required that incorporates an assumed ratio of empty to loaded miles, as follows:

$$\text{BTU/ton mile} = [S(GVW) + C] + \phi[S(T)]\,[BTU/(1/2)P] \quad (5)$$

where

S = slope of the appropriate fuel consumption curve;
GVW = tractor-trailer combination GVW (lb 000s);
C = constant of the appropriate fuel consumption formula;
ϕ = empty to loaded miles allocation ratio, expressed as percentage of empty miles over percentage of loaded miles [general-freight carriers average an empty mileage rate of 10 percent (8, p. 6; 9); therefore, ϕ = 0.10/0.90 = 0.1111];
T = tractor-trailer combination tare (empty) weight (lb 000s); and
(1/2)P = payload weight, expressed in thousand-pound units converted to tons.

The expected average Btu per ton mile energy consumption rates, by region and vehicle type, under GVW limits of 73 280, 80 000, and 90 000 lb are given in Table 3.

BRIDGE FORMULA B ANALYSIS

To estimate the state-by-state potential fuel

Table 1. Derivation of marginal payload weight increases.

		Maximum Payload[a] by GVW (lb)			Optimal Density[b] by GVW Limit (lb/ft²)			Impact Factor by GVW Limit			Marginal-Payload Weight Increase by GVW Limit (lb)	
Vehicle Size	Region	73 280 lb	80 000 lb	90 000 lb	73 280 lb	80 000 lb	90 000 lb	73 280 lb	80 000 lb	90 000 lb	73 280 to 80 000 lb	80 000 to 90 000 lb
Single, 55 ft	Northeast	43 980	50 250	NA	15.17	17.33	NA		0.2021	NA	1001	NA
	Southeast	43 980	50 250	NA	15.17	17.33	NA	Base	0.1617	NA	852	NA
	Southwest	43 980	50 250	NA	15.17	17.33	NA		0.1518	NA	1154	NA
Double, 65 ft	Northeast	42 180	48 300	56 800	11.72	13.42	15.78		0.4559	0.2972	2204	1996
	Southeast	42 180	48 300	56 800	11.72	13.42	15.78	Base	0.3997	0.2565	2055	1831
	Southwest	42 180	48 300	56 800	11.72	13.42	15.78		0.4339	0.3081	2124	2095

[a]Tare weight may be derived by subtracting maximum payload from maximum vehicle weight limit. Tare weight included fuel (1400 lb) and driver (200 lb) weight.
[b]Optimum density calculations based on 2900-, 3600-, and 5400-ft³ dry freight capacities.

Table 2. General-freight average payload and GVW estimates.

		Estimated Payload by GVW Limit (lb)			Estimated Gross Weight by GVW Limit (lb)		
Vehicle Size	Region	73 280 lb	80 000 lb	90 000 lb	73 280 lb	80 000 lb	90 000 lb
Single, 55 ft	Northeast	27 236	28 237	NA	56 536	57 987	NA
	Southeast	28 600	29 452	NA	57 900	59 202	NA
	Southwest	29 105	30 259	NA	58 405	60 009	NA
Double, 65 ft	Northeast	32 683	34 887	36 883	63 783	66 587	70 085
	Southeast	34 320	36 375	38 406	65 420	68 075	71 405
	Southwest	34 187	36 311	38 406	65 287	68 011	71 605

Table 3. Energy consumption rates for single- and double-trailer operations under various weight limits.

		Energy Consumption by GVW Limit (Btu/ton mile)		
Vehicle Size	Region	73 280 lb	80 000 lb	90 000 lb
Double	Northeast	1754	1663	1597
	Southeast	1682	1605	1551
	Southwest	1687	1608	1544
Single	Northeast	2085	2025	NA
	Southeast	1998	1952	NA
	Southwest	1968	1906	NA

savings resulting from permitting twin-trailer combinations to operate nationwide under 85 500-lb Bridge Formula B weight limits, it must be recognized that current state truck size and weight limits fall into five categories:

1. States where 65-ft twin trailers are permitted to operate under GVW limits of 80 000 lb,
2. States where 65-ft twin trailers are permitted to operate under GVW limits of 73 280 lb,
3. States with GVW limits of 80 000 lb where 65-ft twin-trailer operations are not permitted,
4. States with GVW limits of 73 280 lb where 65-ft twin-trailer operations are not permitted, and
5. States where 65-ft twin trailers are permitted to operate under "grandfathered" GVW limits of 85 500 lb or more.

The states and the District of Columbia are categorized below with respect to these five conditions as of August 1981:

1. Category 1--Arizona, California, Delaware, Florida, Iowa, Kentucky, Maryland, Michigan, Minnesota, Nebraska, Ohio, Texas, and Wisconsin;
2. Category 2--Arkansas, Illinois, Indiana, and Missouri;
3. Category 3--Alabama, Connecticut, District of Columbia, Georgia, Maine, Massachusetts, New Hampshire, New Jersey, New York, North Carolina, Pennsylvania, Rhode Island, South Carolina, Vermont, Virginia, and West Virginia;
4. Category 4--Mississippi and Tennessee; and
5. Category 5--Alaska, Colorado, Hawaii, Idaho, Kansas, Louisiana, Montana, New Mexico, Nevada, North Dakota, Oklahoma, Oregon, South Dakota, Utah, Washington, and Wyoming.

In Louisiana weight limits are 83 400 lb on Interstates and 88 000 lb on other highways.

The estimation procedures for each category are similar in that they assume a potential twin-trailer use rate of 16.34 percent and they interpolate from the regional productivity analysis the increase in fuel productivity brought about by moving from the base truck size and weight conditions to conditions in which twin trailers are permitted to operate under Bridge Formula B 85 500-lb weight limits.

Category 1 and 2 States

The computations in this section are composed of three steps. Step 1 estimates the fuel productivity increases (per state) derived from an increase in the use of 65-ft twin-trailer combinations from current levels to the 16.34 percent use rate. Table 4 presents the stepwise calculation results. A weighted average of percentage of twin-trailer traffic over the period 1975-1979 was developed for each state, from the Federal Highway Administration's Rural Interstate Station Truck Count data base (column 3). The expected increase in twin-trailer traffic (column 4) was determined by subtracting actual use from the potential use level of 16.3 percent. The increase in fuel productivity that accrues from moving freight in twin trailers as opposed to tractor-semitrailers (assuming no change in the current weight limit) is calculated from Table 3 and reported in column 5, Table 4. The net productivity increase resulting from the expected increased use of twins (column 6) is the product of columns 4 and 5.

Step 2 estimates the energy consumption savings derived from 65-ft twin-trailer combinations operating under 85 500-lb weight limits as opposed to 80 000- or 73 280-lb GVW weight limits. The data for step 2 are presented in Table 3. To estimate the energy consumption rates (Btu per ton mile), by region, of twin-trailer operations operating under 85 500-lb weight limits from the energy consumption rates at 80 000 and 90 000 lb, the data presented in Table 3 are interpolated. Five substeps are required.

The first substep is to calculate the strength of the nonlinear relation between the energy consumption ratio and GVW limits. The actual deviation in

Table 4. Fuel productivity increase deriving from an increase in trailer use rate.

Category	State	Analysis Region	Current Twin-Trailer Traffic[a] (%)	Expected Increase in Twin-Trailer Traffic[b] (%)	Fuel Productivity Increase (%)	Fuel Productivity Net Increase (%)
1	Arizona	Southwest	16.3	0	15.6	0
	California	Southwest	41.9	0	15.6	0
	Delaware	Northeast	0	16.3	17.9	2.92
	Florida	Southeast	0	16.3	17.8	2.90
	Iowa	Northeast	1.4	14.9	17.9	2.67
	Kentucky	Southeast	0	16.3	17.8	2.90
	Maryland	Northeast	0	16.3	17.9	2.92
	Michigan	Northeast	2.0	14.3	17.9	2.55
	Minnesota	Northeast	0.7	15.6	17.9	2.79
	Nebraska	Northeast	7.8	8.5	17.9	1.52
	Ohio	Northeast	1.5	14.8	17.9	2.65
	Texas	Southwest	3.8	12.5	15.6	1.95
	Wisconsin	Northeast	1.3	15.0	17.9	2.69
2	Arizona	Southeast	0	16.3	15.8	2.58
	Illinois	Northeast	3.9	12.4	15.9	1.97
	Indiana	Southeast	2.0	14.3	15.9	2.27
	Missouri	Northeast	6.2	10.1	15.9	1.61

[a]Taken from FHWA Rural Interstate Station truck counts, weighted average of 1975-1979 period.
[b]Column 4 = 16.3 - column 3, if the answer is positive.

Table 5. Fuel productivity gains of permitting twin-trailer combinations to operate under 85 500-lb gross vehicle weight limits versus 80 000-lb and 73 280-lb limits and its impact.

Category	Region	Fuel Productivity: Calculation of Increase (Btu/ton mile)	Fuel Productivity: Increase (%)	Expected Percentage of Twin Trailers	Productivity Impact of Weight Limit Change (%)
1	Northeast	(1663 - 1610)/1663	3.19	16.34	0.52
	Southeast	(1605 - 1560)/1605	2.80	16.34	0.46
	Southwest	(1608 - 1557)/1608	3.17	16.34	0.52
2	Southeast	(1682 - 1560)/1682	7.25	16.34	1.18
	Northeast	(1754 - 1610)/1754	8.21	16.34	1.34

Table 6. Estimation of potential fuel savings for category 1 and 2 states.

State	Productivity Change (%): Increased Size	Productivity Change (%): Increased Weight	Productivity Change (%): Total Impact	Diesel Fuel (gal 000s)	Fuel Savings (gal 000s)
Arizona	0	0.52	0.52	154 709	804
California	0	0.52	0.52	799 682	4 158
Delaware	2.92	0.52	3.44	18 410	633
Florida	2.90	0.46	3.36	312 637	10 505
Iowa	2.67	0.52	3.19	195 467	6 235
Kentucky	2.90	0.46	3.36	155 097	5 211
Maryland	2.92	0.52	3.44	103 811	3 571
Michigan	2.55	0.52	3.07	246 481	7 567
Minnesota	2.79	0.52	3.31	202 032	6 687
Nebraska	1.52	0.52	2.04	100 542	2 051
Ohio	2.65	0.52	3.17	526 281	16 683
Texas	1.95	0.52	2.47	838 280	20 706
Wisconsin	2.69	0.52	2.21	213 208	4 712
Arkansas	2.58	1.18	3.76	143 633	5 401
Illinois	1.97	1.34	3.31	471 900	15 620
Indiana	2.27	1.34	3.61	376 108	13 577
Missouri	1.61	1.34	2.95	264 616	7 806

Note: Based on Table MF-25 of FHWA Highway Statistics, adjusted to represent diesel fuel used by trucks with five or more axles; derivation technique from Kolins and Selva (10).

Btu per ton mile from the mean value is approximately 1 percent, since a minor curvilinear relation is observed between the range of GVW values. This relation holds true up to 10 000-lb differences. If one uses the Northeast as an example, the calculation of bias of straight-line interpolation is as follows:

$$1597/[(1/2)(1663 + 1566)] = 0.989 \approx 0.99 \qquad (6)$$

This factor remains at 0.99 for all regions.

The next three substeps are as follows:

1. Calculate the difference between the Btu per ton mile consumption rates for twins operating under 80 000-lb versus 90 000-lb GVW limits:

Region	Calculation
Northeast	1663 - 1597 = 66
Southeast	1605 - 1551 = 54
Southwest	1608 - 1544 - 64

2. Calculate the portion that would account for the 5500-lb increase in GVW limit, if weight limits defined by Bridge Formula B were adopted (55 percent of the difference calculated in item 1):

Region	Calculation
Northeast	66x0.55 = 36.3
Southeast	54x0.55 = 29.7
Southwest	64x0.55 = 35.2

3. Estimate the energy consumption rate of twin-trailer combinations operating under an 85 500-lb GVW limit by subtracting the Btu per ton mile range from the 80 000-lb energy consumption rate estimate, and multiply the net Btu per ton mile estimate by 0.99:

Region	Calculation
Northeast	(1663 - 36.3) 0.99 ≈ 1610
Southeast	(1605 - 29.7) 0.99 ≈ 1560
Southwest	(1608 - 35.2) 0.99 ≈ 1557

The final substep of step 2 is to calculate the fuel productivity impact on interstate motor-carrier traffic that would result from twin-trailer weight limits being increased from 73 280 to 85 500 lb. These estimates, for the relevant analysis regions are presented in Table 5.

Step 3 (Table 6) combines the estimated fuel productivity benefits calculated in steps 1 and 2 and applies the percentage productivity increases, by state, to their diesel fuel consumption for the year 1979 in order to estimate the potential fuel savings in gallons.

Category 3 States

For the states that fall in category 3, the productivity gains of a simultaneous increase in size and weight limits must be considered. Table 3 reports the estimated average energy consumption rates for single-tractor-trailer combinations operated by general-freight carriers under 80 000-lb GVW limits in the Southeast and the Northeast to be 1952 and 2025 Btu/ton mile, respectively. In the category 1 states, the expected energy consumption rates of 65-ft twin-trailer combinations operating under 85 500-lb GVW limits for the Southeast and the Northeast were estimated to be 1560 and 1610 Btu/ton mile, respectively.

Therefore, it can be expected that, for those general-freight carriers that take advantage of twin-trailer combinations under 85 500-lb GVW limits in the category 3 states, the increase in carrier fuel use productivity will be 20.08 percent (1952 - 1560) ÷ 1952 in the Southeast and 20.49 percent (2025 - 1610) ÷ 2025 in the Northeast. Assuming that 16.34 percent of motor-carrier tonnage will be moved in twin-trailer combinations, the expected productivity impact of increased weight limits and removed restrictions on the use of twin-trailer combinations for the category 3 states with respect to total truck fuel use is 3.28 percent for the southeastern states and 3.35 percent for the northeastern states.

Table 7 presents estimates of the fuel savings that would result if twin-trailer combinations were permitted to operate nationwide under Bridge Formula B weight limits for those states in category 3.

Category 4 States

The computations for category 4 states are identical to those for category 3 states except that the base GVW limit is 73 280 lb. The energy consumption rate for single-tractor-trailer combinations operating in the Southeast under 73 280-lb GVW limits has been estimated at 1998 Btu/ton mile. This increases the fuel productivity gains to be enjoyed by carriers that convert their present operations to twin-trailer operations under 85 500-lb GVW limits for

Table 7. Estimation of potential fuel savings for category 3 and 4 states.

Category	State	Analysis Region	Productivity Impact of Increased Weight Limits and Removed Restrictions on Operation of Twin-Trailer Combinations (%)	State Diesel Fuel Consumption (gal 000s)	Fuel Savings (gal 000s)
3	Alabama	Southeast	3.28	199 385	6 540
	Connecticut	Northeast	3.35	72 803	2 439
	District of Columbia	Northeast	3.35	18 410	617
	Georgia	Southeast	3.28	311 367	10 213
	Maine	Northeast	3.35	38 732	1 298
	Massachusetts	Northeast	3.35	123 965	4 153
	New Hampshire	Northeast	3.35	18 048	604
	New Jersey	Northeast	3.35	231 577	7 758
	New York	Northeast	3.35	232 739	7 797
	North Carolina	Southeast	3.28	271 429	8 903
	Pennsylvania	Northeast	3.35	514 810	17 246
	Rhode Island	Northeast	3.35	16 184	542
	South Carolina	Southeast	3.28	162 649	5 335
	Vermont	Northeast	3.35	21 461	719
	Virginia	Southeast	3.28	225 961	7 412
	West Virginia	Northeast	3.35	67 420	2 259
4	Mississippi	Southeast	3.58	125 780	4 506
	Tennessee	Southeast	3.58	269 816	9 659

the Southeast to 21.92 percent (1998 - 1560) ÷ 1998. With 16.34 percent expected twin-trailer use, if Mississippi and Tennessee were to adopt the Bridge Formula B twin-trailer GVW limits and permit twin-trailer operations, their anticipated fuel savings would be 3.58 percent of the fuel currently consumed by trucks with five or more axles within their borders. Table 7 summarizes the calculations to derive the estimated fuel savings for the two category 4 states. No estimation procedures are necessary for the fifth category.

SUMMARY

If 65-ft twin trailers were permitted to operate nationwide under the Bridge Formula B GVW limits of 85 500 lb at 60-ft axle spacing, diesel fuel savings totaling 229 927 000 gal would be expected in 34 states and the District of Columbia, based on 1979 diesel fuel consumption rates.

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Economic Impacts of Petroleum Shortages and Implications for the Freight Transportation Industry

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The major economic impacts that result from petroleum supply interruptions and the subsequent effects on the demand for freight transportation are described. The analysis involved a simulation of the effects of three different levels of fuel supply shortfall on intercity freight transportation. The research included the use of three economic and transportation models to simulate the economic impacts of oil shortfalls and the resulting change in freight transportation demand as expressed in tons shipped, ton miles of travel, and fuel use. Economic effects are discussed for a base case and then for 7, 14, and 23 percent petroleum shortfalls. The demand for freight transportation is determined by the output of various commodity sectors that generate traffic for the truck, rail, water, air, and pipeline modes. The effects of various diesel fuel price levels are also examined. The analysis suggests that at low, or controlled, fuel prices the more significant impacts for freight movements will be the reduction in output in the bulk commodity sectors, which are dominated by the waterway and rail modes. At high fuel prices (i.e., equilibrium levels), shipping is significantly decreased in all commodity sectors, but modal shifts are likely to occur from truck to rail and even from rail to water in some corridors.

The United States has experienced significant economic problems associated with two of the three major interruptions in the world supply of petroleum--the Arab oil embargo in 1973-1974 and the Iranian revolution in 1979. Less difficulty was encountered with the loss of crude oil due to the Iran-Iraq war. High inventories coupled with reduced demand have made the loss of those supplies barely noticeable. Saudi Arabia increased its oil production to partially compensate for a reduction in the oil spot-market price in order to eventually produce a unified Organization of Petroleum Exporting Countries (OPEC) price. Competing economic and political goals in the Middle East cause this region to remain volatile, which suggests that future disruptions in petroleum supply are highly probable, if not inevitable.

Petroleum supply shortages produce economic shocks that have a direct effect on the demand for freight transportation. However, the changes in economic activity are not uniform. Some sectors show a dramatic decline in production and sales that goes far beyond the level of the oil shortage, whereas others show no adverse impact or even some moderate gain. To quantify these economic changes, an econometric model and two freight transportation models were used to simulate the effects of three different shortage situations. This section provides a brief discussion of the modeling process. A description of the control forecast and three hypothetical oil shortfall cases simulated by the models is included in the following section.

The Data Resources, Inc. (DRI), Quarterly Model of the U.S. Economy has been used in this study to analyze the impacts of petroleum shortfalls at the national level. The DRI model is a simultaneous-equations model that includes a circular flow of income and expenditure in the economy.

The DRI model provided macroeconomic indicators for the Argonne National Laboratory Freight Responsive Accounting for Transportation Energy (FRATE) model to estimate the change in commodities shipped by mode before any contingency actions are initiated. The FRATE model calculates annual ton miles of travel (TMT) for commodities, accounts for modal activity, and computes the transportation energy consumed based on economic-sector output levels.

The base-year ton-mile estimates for the economic sectors in FRATE are derived from the U.S. Bureau of the Census Commodity Transportation Survey (1). The FRATE economic activity sectors are paired with similar sectors in the DRI econometric model in order to apply the projected output growth rates to the base-year ton-mile estimates (2). The model assumes, for lack of a better indicator, that ton-mile growth is directly related to output growth rates. Traffic estimates for truck, railroad, marine, air, and pipeline modes are calculated based on historic modal-split distributions (1,3-5).

Energy intensity values associated with each economic sector are based on the freight mode and the type of service provided by that mode (3,4,6). The FRATE economic-sector ton-mile estimates are applied to the energy intensity values for projected energy consumption values. FRATE then aggregates the energy demand of all sectors by type of mode.

The third model used in this analysis was the National Freight Demand Model (NAFDEM), developed for Argonne National Laboratory by the Massachusetts Institute of Technology. NAFDEM provides a means to determine shipper response to rate and level-of-service alterations imposed by carriers during fuel shortfall situations. This response could involve a change in the freight mode selected for shipment, a change in the size of shipment, or both. The logic governing the degree and direction of change arises from a utility logit model of freight mode and shipment size developed and calibrated to observed shipper behavior by Chiang and others (7). NAFDEM does not include the pipeline mode since it is not applicable for most commodity sectors.

A basic premise of NAFDEM is that shippers in any commodity group seek to move more freight by the mode or modes that maximize their total utility. This utility is computed from the mode-specific rate and level-of-service relations to commodity characteristics developed by Chiang. NAFDEM constructs a utility function for a simulated firm that is defined by, or synthesized from, the characteristics of and demand for the commodity it ships. In order to construct the initial utility function, baseline annual commodity use rates by receiving firms; shipping distances; shipment sizes; commodity densities, perishability, and value per unit weight; and travel times, rates, and reliabilities by mode must all be defined for the shipper and commodity (these variables largely define the firm). In the modeling process, values for most of these variables are randomly selected by using a Monte Carlo procedure from a set of commodity-group-specific ranges (probability density functions), each bounded within a sampling confidence interval centered on the mean value. The baseline modal probabilities estimated by this procedure are assumed to result in the "observed" distribution input to the model from a run of FRATE for the appropriate fuel shortfall conditions.

NAFDEM calculates the perturbations in modal choice and shipment sizes brought about by each synthesized shipper's attempt to continue to maximize its total utility after a change in carrier rates and level of service is defined. Computed values of the rate and level-of-service equations developed by Chiang and others (7) are modified by changes in

fuel cost and/or service parameters (see below). These new values will in turn change the computed "perception" of each firm within a commodity group as to which mode best suits the firm's overall needs. Therefore, the distribution of choice probabilities is recalculated from the utility function for each shipper considered, according to the revised rates and service levels, and the total change in each predicted probability over the respective baseline value determines the redistribution of mode and shipment size.

ECONOMIC IMPACTS

Numerous policy variable assumptions are required in the DRI model before a solution is realized. This section summarizes the major forecast assumptions and results for the base case from the DRI simulation (8) prior to the shortfalls and the results of the petroleum shortfall simulations.

Base-Case Forecast

The energy-related cost assumptions associated with Table 1 considered that there would be no appreciable shortfall due to the Iran-Iraq conflict. The refiners' acquisition cost increases were based on increases in imported crude oil according to Saudi Arabia's proposed long-term pricing strategy. This resulted in an average imported crude oil price of $54/barrel in 1983 (the DRI base-case simulation has subsequently been revised to reflect a price of $39/barrel in 1983) compared with $34 in 1980. Domestic crude oil prices, which were deregulated under the Reagan Administration in January 1981, result in an average domestic crude oil price of $55/barrel in 1983 compared with $24 in 1980.

A mild recession was forecast in the first half of 1981. The recession was prompted by a decline in real disposable income and high interest rates. The lower consumption led to a decline in investment and inventories. The anticipated tax cuts were forecast to lead to recovery in the economy later in the year. The 1982 economy was forecast to have a strong growth with a gain of 3.3 percent in real gross national product (GNP).

Assumptions Underlying Shortfall Scenarios

The three petroleum shortage scenarios analyzed in this study are a 1.2 million-bbl/day shortage directed entirely at the United States and worldwide shortages of 5 million and 10 million bbl/day; the latter two result in U.S. shortfalls of 2.3 million and 3.9 million bbl/day, respectively. The first scenario, a 7 percent shortage, would probably have impacts slightly more severe than the U.S. experienced because of the Iranian revolution. The second scenario, a 14 percent shortfall, would correspond roughly to a 20 percent cutoff in oil production by all of the OPEC members. The last scenario, a 23 percent shortfall, might result from an interruption of petroleum flow through the straits of Hormuz or a major upheaval in the Middle East causing a cutoff of all Saudi Arabian oil supplies.

Table 2 gives the key assumptions that underlie the various shortfall scenarios. [This study used existing scenarios for the basic parameters. A 7 percent, one-year shortage was the basis for the U.S. Department of Energy (DOE) regulatory analysis of the Standby Federal Conservation Plan; the 14 percent, six-month interruption was examined by the DOE Economic Regulatory Administration; and a 23 percent, one-year shortfall was the scenario for a DOE Conservation and Solar Energy Study. At the time of this study, analyses of those shortage levels were in draft form and had not been distributed.] Although the supply interruptions were assumed to commence on July 1, 1981, the impact on the United States is cushioned by the two-month lag in transporting oil from the Persian Gulf. As a result, the level of imports reaching the United States gradually decreases from July 1 to September 1. Similarly, the availability of crude returns to normal over a two-month period at the end of the crisis.

The deregulation of oil has dramatically changed the environment in which the petroleum industry operates. As a consequence, future shortfalls will be materially different from those the United States experienced in 1973-1974 and in 1979 for two reasons:

1. Higher prices for imported crude oil have previously been offset by controlled domestic prices. Under decontrol, domestic prices are expected to rise proportionate to imported prices.
2. The impact of the rising world oil price would have been delayed by the two-month transportation lag. Under decontrol, the price of crude oil to domestic refiners may well rise in anticipation of the arrival of higher-priced imported crude.

The net effect is that the price that domestic refiners pay for crude oil may adjust fully and immediately to the rise in the world oil price.

Impacts of Shortfall Scenarios

The economic consequences of petroleum shortfalls are assessed by examining key indicators in comparison with the base-case forecast. These indicators fall into four broad categories: macroeconomic, financial, price, and energy. Macroeconomic indi-

Table 1. Energy-related assumptions for DRI base-case forecast.

Item	1980	1981	1982	1983
Refiners' acquisition costs				
Foreign crude ($/bbl)	34.04	40.55	46.51	54.46
Domestic crude ($/bbl)	24.34	40.25	47.00	55.02
Gross "windfall profits" taxes ($000 000 000s)	13.40	34.30	46.00	52.40
Gasoline taxes (¢/gal)				
Federal	4.00	4.00	4.00	4.00
State	8.98	9.51	11.73	13.30

Table 2. Key assumptions in oil shortage scenarios.

Shortage Level[a] (%)	Magnitude (bbl 000 000s/day) U.S.	World	Duration (no. of months)	Transportation Lag (no. of months)	Beginning Date	IEA Sharing Invoked
7	1.2	1.2	12	2	7/1/81	No
14	2.3	5.0	6	2	7/1/81	Yes
23	3.9	10.0	12	2	7/1/81	Yes

Note: IEA = International Energy Agency.

[a]Percentage of total U.S. petroleum demand.

cators include real GNP, housing starts, automobile sales, and unemployment. Financial indicators include the federal deficit, the federal funds rate, and the prime rate. Price indicators include the producer price index, the consumer price index, and core inflation. Energy indicators include the prices of gasoline and home heating oil and total gasoline consumption. These indicators were examined as to their immediate and long-run behavior due to future petroleum shortfalls compared with the base case and 1979 shortfall. Real GNP, gasoline prices, and total gasoline consumption effects during the petroleum shortfalls are discussed here in further detail.

Real GNP

The base case for GNP forecast shows a mild recession in the first half of 1981 followed by a moderate recovery through the balance of the forecast period. The impact of a 7 percent oil shortage on GNP is expected to be relatively minor. GNP is off about 1 percent; by the end of 1983, the economy is about one-quarter behind the base-case forecast. Despite its short 6-month duration, the 14 percent shortfall scenario could be expected to deprive the economy of 12 months of growth. Real GNP recovers from the third quarter of 1982, although it would continue to lag about a year behind the base case, so that GNP would be down nearly 3 percent by the end of 1983. The greater magnitude and duration of the 23 percent shortfall leads to four quarters of declining real GNP followed by a very weak to moderate recovery in 1983. It should be noted that by the last quarter of 1983 the economy would have lost almost two years of growth and be more than 5 percent behind the base case.

The impacts of a severe petroleum shortfall are twofold:

1. The economy loses one to two years of real growth.
2. Output that is lost during several years of weaker economic growth will not be recovered. Future economic growth starts from a lower base and continues to lag behind the control forecast.

Price of Gasoline

The price of gasoline over the past decade has increased gradually with the exception of two rapid upward movements (1973-1974 and 1979), both caused by imported petroleum supply interruptions. Depending on storage supplies and the state of the economy, future interruptions could cause a similar price spurt. In fact, the absence of price regulations could cause the price adjustment to be quicker and more severe than in previous crises. In contrast, though, current high inventories of petroleum and refined products, as well as the fuel switching capability (from oil to gas) in some industries, provide a cushion against the upward price pressures caused by an oil shortage.

The control forecast is predicated on the absence of further oil price shocks during the forecast period and gasoline prices drifting upward at 1-2 ¢/month, breaking the $2 level in the last half of 1983 (this reflects price increases of 15-20 percent/year over the forecast period).

The shortfall prices, referenced here and based on the DRI model, are not equilibrium prices but rather retail prices that reflect the higher crude oil acquisition costs and production and distribution costs. More will be said later in this paper about equilibrium prices, but the general trend of the curves is likely to be the same. In the 7 percent case, the major adjustment occurs by mid-1982, when the price of gasoline exceeds $2/gal. In the following quarters, the price of gasoline resumes a steady upward climb. In the 14 percent scenario, prices would adjust over a four-quarter period to reflect the new, higher crude prices: After reaching $2.63 in the second quarter of 1982, prices drift downward through the end of the year before rising again in 1983. In the 23 percent scenario, prices would adjust over a six-quarter period, breaking the $4 level in the last half of 1982. However, this price level is not sustainable, and a downward correction of more than 15 percent is forecast for 1983.

A doubling of gasoline prices over the course of a single year would be significant. However, more significant is the fact that a crisis-induced gasoline price level, after a relatively minor adjustment, sets the floor for future gasoline prices. Following the 1979 crisis, the price of gasoline nearly doubled; in the ensuing glut of gasoline inventories, however, the price has displayed remarkable resiliency. The shortfall scenarios suggest that, once again, the market would adjust to a permanently higher gasoline price level.

Beyond the aggregate economic impacts discussed above, a major, permanent increase in petroleum product prices has implications for key sectors and a number of regions. The automobile and housing industries are severely affected. Production in the steel industry, which supplies both, would be off 10 percent during 1982 and 1983 in the 23 percent shortage case compared with the base case. Chemicals, nonferrous metals, stone, clay, and glass all suffer 10-15 percent losses in output.

On a regional level, a shortage would most directly affect the industrial Midwest and Northeast, where a large fraction of heavy industry is located. In the short run, tourist regions and industries would be benefited by gasoline availability; in the long run, they would be hurt by its continued higher price. This long-run effect reflects a shift in consumer buying patterns from energy-intensive goods and activities.

Total Gasoline Consumption

Total gasoline consumption is a broad indicator of the price sensitivity of gasoline demand. The control forecast predicts a slow downward drift in consumption over the 1981-1983 period. This trend is accelerated by a petroleum shortfall. The decline in gasoline consumption is disproportionately large in comparison with the crude oil shortfall during the shortage. This reflects attempts to meet distillate demands at the expense of discretionary uses of gasoline such as pleasure driving.

Summary

The base-case forecast period presumes an economic recovery in this analysis. For that reason, the shortage impacts are tempered by the existing expansionary forces in the economy. The 7 percent, and even the 14 percent, shortages still allow for overall economic growth in spite of severe effects in some sectors. The 23 percent shortage produces a recession. The major short-run impacts of any of the oil shortage scenarios include a reduction in GNP, increases in prices and interest rates, and a reduction in petroleum product supply, which drives prices up. Automobile sales and housing construction are the two sectors most severely affected.

The longer-term consequences of petroleum supply interruptions include GNP growth from a lower base, inflation at a higher rate, and higher petroleum

product prices long after the shortage has ended.

SHORTFALL-INDUCED CHANGES IN FREIGHT TRANSPORTATION

The effects of interruptions in the petroleum supply on freight transportation demand are manifested in two distinct ways:

1. The resulting decline in economic activity will mean less demand for freight to be transported and therefore less fuel consumed. These changes in economic activity are not uniform across all sectors; thus, the various transportation modes are affected differently.
2. Apart from the shortfall-induced economic decline, a rapid increase in the price of fuel can be expected in the absence of price controls; this would result in a further decline in the demand for freight transportation and produce shifts in the modal choice of shippers. (An area for further analysis is the cyclic effect of increasing transportation prices on economic activity in the various commodity sectors, which is beyond the scope of this study.) Furthermore, the extent of the decline in total economic activity is not the same as the magnitude of a petroleum shortfall, since each industry varies as to its dependence on petroleum. As a consequence, transportation firms face the prospect of a relatively high demand for their services forcing them to seek new sources of fuel supply, increase their conservation efforts, or most likely a combination of both.

Transportation Activity in Base Case

Forecast changes in the economic activity of some individual sectors have significant influence on several of the freight modes. Mining and construction industries are good examples of changing TMT activity as calculated by FRATE. In the base case, the coal-mining sector was forecast to have declining output in 1981 due to an anticipated miners' strike. In 1982 and 1983, the industry was forecast to recover and grow at a rate double the GNP rate. This is of special significance to the railroads, some of which depend on coal as their chief revenue source. The construction industry is expected to gear up for new housing starts by 1983. It is at this point that the industry would be experiencing the most rapid growth rate since 1977. Since the trucking industry dominates transportation in the construction sector, it is expected to benefit considerably from this growth.

The TMT projection for oil and gas shows growth at 1.6 percent annually, only half the rate of GNP. Movements of petroleum products are expected to gradually decline due to the continued conservation. This decreased demand will particularly affect pipeline and waterway operators.

Increases in industrial products are prompted by a strong recovery in business investments in 1982 and 1983. This suggests that the ton miles for high-valued, time-sensitive manufactured goods that travel by truck and air will increase.

Overall, the base-case growth areas are those that are dominated by truck travel. By 1983, nearly all of the manufacturing sectors are growing faster than GNP. Primary products that are carried by rail show a steady but slower growth rate.

Transportation Activity in Shortfall Scenarios

The freight transportation industry is affected in several distinct ways during an interruption in the petroleum supply. First, shippers make transportation decisions due to changes in output as a result of the shortfall and fuel price increases. In addition, carriers may initiate operational changes to save fuel. Only the influence of shipper decisions is examined here; evaluations of operational changes that carriers can use to reduce their demand for fuel were not available at the time this paper was written.

Effects of Changes in Economic Activity on Freight Transportation

The relation between economic indicators and freight transportation during an energy shortfall may be different from the historical association of GNP and intercity TMT, since freight movement tends to be a lagging indicator of economic activity. When less petroleum is supplied to a national economy than is anticipated, a decline in economic activity will occur regardless of whether the prices of crude oil and refined petroleum products are controlled or not. The change in economic activity, which will vary widely by industry sector, will then directly affect freight transportation in that fewer goods will be transported. To the extent that the demand for freight transportation declines, the demand for transportation fuel will also decline, assuming no shift to energy-intensive modes for the remaining traffic.

To illustrate the effects of a petroleum shortfall in some detail, the analysis focuses on a particular quarter during the supply interruption rather than presenting an overview of the quarter-to-quarter changes. The first quarter of 1982 has been selected, since it embodies the cumulative results of nearly two quarters of the effects of the various petroleum shortfall scenarios (assumed to begin July 1, 1981, although the effect on the United States is cushioned by the two-month lag in transporting oil from the Persian Gulf). By using the DRI changes in sectoral growth rates with the corresponding FRATE sectors, the change in freight transportation demand due to the change in goods output can be isolated. This would be the effect if fuel prices were frozen at the outset of the shortfall. The constrained fuel supply, though, indicates that this demand situation is far from equilibrium.

One of the most significant results shown is that the demand for freight transportation has been reduced by only a small fraction of the extent of the shortfalls. Even in the 23 percent shortfall case, the demand for freight transportation declines only 3.2 percent. The resulting decrease in the demand for fuel is even less--1.6 percent--as given in Table 3.

The combination of several factors produces these changes. The primary goods sectors, which account for about 40 percent of all TMT, experience mixed effects. The mining sectors, due to their highly energy-intensive operations, decline during a petroleum shortfall. This adversely affects the modes handling these bulk commodities--principally the railroads and marine transportation. Movements of domestic crude oil and natural gas are increased slightly as the result of increased oil and gas production in response to refiners' higher crude oil acquisition cost during a shortfall. Pipelines benefit from this, although the total TMT for this mode would be down due to decreased volume of refined petroleum products. Energy use for pipelines would be increased slightly due to the high energy intensity for natural gas pipelines.

In the manufacturing industries, which require primary goods as input, production is not shown to change as substantially as in the primary sectors,

Table 3. Change in freight transportation intercity TMT and energy demand due to decline in economic activity: first quarter of 1982.

	Change by Shortfall Level (%)					
	TMT			Energy Use		
Mode	7 Percent	14 Percent	23 Percent	7 Percent	14 Percent	23 Percent
Truck	-1.2	-1.6	-2.0	-1.2	-1.6	-2.0
Rail	-1.6	-2.0	-2.4	-1.8	-2.3	-2.6
Water	-1.9	-3.0	-4.7	-1.6	-2.5	-4.0
Air	-0.6	-0.8	-1.0	-2.0	-2.4	-2.8
Pipeline	-1.2	-1.9	-3.4	+0.1	+0.4	+0.7
Avg	-1.5	-2.2	-3.2	-1.0	-1.2	-1.6

especially in the initial periods of an energy shortfall. Stockpiling of production inputs is common among manufacturers. Inventories above normal operational requirements ensure that production goals can be met, even in the face of extended transportation difficulties, such as prolonged transportation worker strikes or adverse weather conditions. A major exception to this generalization about manufacturing industries is the motor-vehicle sector, which is the sector most seriously affected during an interruption in petroleum supply. Generally, the relatively mild effects for much of the manufacturing sectors would keep the demand for the truck mode relatively high.

This change in the demand for freight transportation as influenced by declining economic activity could only be expected to occur if the price of transportation fuels were frozen at the preshortfall levels. Although this would not be expected to happen, the isolation of this component of freight transportation demand provides a useful basis for examining, in perspective, the fuel price effects on the freight transportation industry.

Fuel Price Effects on Freight Transportation

As shown in the previous section, the decline in economic activity is not nearly as large as the decline in the availability of transportation fuels during a petroleum shortfall. The purpose of that section was to illustrate the economic activity component of the change in freight transportation demand. Since shipping decisions are significantly influenced by freight rates, fuel prices could be expected to have a considerable impact on the amount and modal distribution of goods movement.

By again using the first quarter of 1982 as the analysis period, the NAFDEM model was used to iterate to an equilibrium fuel price--one that produces changes in shipment size, mode shifts, or reductions in the volumes shipped to the extent that fuel demand approximates that available during the shortfall.

Estimates in this study of the fuel available to the freight transportation industry explicitly considered two factors. First, the historical precedents of the two previous shortfalls indicate that refineries would be expected to increase the production of distillate fuels at the expense of gasoline. This flexibility to change the gasoline/distillate (G/D) ratio is greater now than it was during the 1970s because of the decline in the demand for home heating oil as prices have risen. This flexibility has been used in the past since the discretionary nature of much gasoline use makes its demand more elastic than that of diesel fuel. As given in Table 4, this analysis assumes that 1-3 percent of the diesel fuel shortfall (depending on

Table 4. Factors affecting extent of freight transportation fuel shortfalls.

Crude Oil Shortfall Level (%)	Shortfall Eliminated by Changing G/D Ratio (%)	Remaining Distillate Shortfall (%)	Shortfall Met by Economic Decline[a] (%)	Shortfall Met by Fuel-Price Effect (%)
7	1	6	1	5
14	2	12	1	11
23	3	20	1.5	18.5

[a]From Table 3.

Table 5. Diesel fuel prices and effects during oil shortfalls.

Shortfall Level (%)	Necessary Reduction in Demand for Freight Fuel[a] (%)	Fuel Price ($)		Reduction in Demand for Freight Fuel with Cost-of-Production Price (%)
		Equilibrium	Cost of Production	
7	5	2.65	1.80	1.3
14	11	4.25	2.40	4
23	18.5	7.05	3.20	7.2

Note: Base-case fuel price = $1.50/gal.
[a]From Table 4.

the scenario) could be eliminated through increasing its production by varying the G/D ratio. Such an estimate is relatively conservative; greater changes would, of course, further reduce the primary effects of a shortfall on freight transportation.

The remaining distillate shortfall can be met in two basic ways. One, which has been examined, is due to the decline in economic activity, which in turn reduces the amount of transportation demanded. The second way is to allow the price to rise in order to further reduce demand. As Table 4 indicates, the price effect would have to be responsible for the largest portion of the reduction in fuel demand and, consequently, significant increases in the price of fuel could be expected.

Table 5 gives the effects of two different types of fuel prices. An equilibrium fuel price occurs if the price is uncontrolled and allowed to rise to a market-clearing level. In this case, the reduction in the demand for fuel will equal the level to which the availability of fuel has been reduced. The equilibrium fuel prices were derived by setting the reduced level of fuel availability in NAFDEM and letting the model iterate to a fuel price that would achieve a comparable fuel reduction. An alternative that has been used in the past is to control the price of fuel below market-clearing levels but to allow oil producers, refiners, distributors, and retailers to pass along the increase in costs of crude oil and associated production costs in each step until it reaches the consumer. In this analysis, this is referred to as the cost-of-production fuel price. These fuel prices were derived by using the DRI fuel prices for each shortfall level. Although the cost-of-production fuel price is markedly lower than an equilibrium price, the level to which the demand for fuel is reduced is also considerably less.

The effects of equilibrium fuel prices on the demand for freight transportation in each shortfall scenario are given in Table 6. The high fuel prices that could be expected during a petroleum shortfall adversely affect every sector except crude oil and natural gas. Compared with the effects of just the decline in economic activity, the fuel price impacts have both similarities and differences. The most

Table 6. Change in freight transportation TMT and energy demand due to equilibrium fuel prices: first quarter of 1982.

	Change by Shortfall Level (%)					
	TMT			Energy Use		
Mode	7 Percent	14 Percent	23 Percent	7 Percent	14 Percent	23 Percent
Truck	-6.0	-12.8	-21.8	-6.9	-13.6	-22.6
Rail	-4.5	-10.7	-18.5	-5.4	-11.5	-19.4
Water	-0.6	-1.0	-1.5	-0.8	-1.5	-2.2
Air	-2.7	-8.2	-15.6	-3.8	-9.2	-16.7
Avg[a]	-3.5	-7.8	-13.3	-5.4	-11.2	-18.9

[a]Excludes pipeline.

Table 7. Modal shares of tons and ton miles of freight transportation during oil shortfalls: first quarter of 1982.

	Modal Share by Shortfall Level (%)							
	Tons				Ton Miles			
Mode	0 Percent[a]	7 Percent	14 Percent	23 Percent	0 Percent	7 Percent	14 Percent	23 Percent
Truck	35.1	34.5	33.7	32.7	26.2	25.7	25.0	24.0
Rail	49.4	49.8	50.3	51.0	37.3	36.8	36.1	35.2
Water	12.8	13.0	13.2	13.5	36.3	37.3	38.7	40.6
Air	2.7	2.7	2.8	2.8	0.2	0.2	0.2	0.2
Total[b]	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

[a]Base case. [b]Excludes pipelines.

obvious difference is the degree of influence on the demand for freight transportation. It is within the commodity sectors, though, that some important observations can be made. The primary goods industries that dominate bulk goods shipments continue to show significant reductions in freight transportation demand. The manufacturing sectors, which previously had indicated a relatively small decline in economic activity, are now shown to be sensitive to shipping costs. As a result, the truck mode begins to reflect a greater share in the loss of freight shipping demand because of the loss of traffic in those sectors in which it is the predominant carrier. In contrast to the economic activity component of freight transportation demand, increases in fuel prices produce modal shifts in favor of the rail and water modes.

Changes in freight transportation demand in response to a partially controlled fuel price, such as the cost-of-production price, are in the same direction as shown for the equilibrium price, but the magnitude, as expected, is less.

Changes in Modal Preference

The total tons to be shipped declines, as expected, during an oil shortfall. In the case of equilibrium fuel prices, total tons shipped are forecast to decline 5.6, 12, and 20.5 percent for the 7, 14, and 23 percent shortfalls, respectively. Since fuel prices are an important component of operating costs for the carriers, freight rates would change as fuel prices increase. This, in turn, would cause shippers to modify their total shipments or choice of mode in order to minimize transportation costs. Table 7 gives the changes in the mode share of tons shipped and ton miles as a result of the change in fuel price (equilibrium level) along with the decline in economic activity. Although it is not shown in the table, tons shipped and ton miles of travel decline not only in the aggregate but also for each mode. Therefore, even though dramatic mode shifts do not appear, freight traffic within mode will decrease.

Pipelines were excluded from this analysis since they carry only crude oil, natural gas, and refined petroleum products. As mentioned earlier, the domestic movements in the first two sectors increase slightly during an interruption in the oil supply. Pipelines, generally recognized as the most efficient freight mode, would be the beneficiary. As the principal mover of refined petroleum products, pipelines would show a decline in traffic in this sector. Overall, the specialized nature of pipelines would mean that this mode is excluded from the decisions of shippers in most commodity sectors. Thus, the analysis was directed to the remaining four modes.

Air

The air freight mode is the most energy intensive of the competitive modes. It provides a service for those shippers whose commodities are time sensitive. Even without petroleum supply problems, shippers pay a premium price to use this mode. Consequently, it is not unexpected that the demand for this mode is relatively inelastic. The tons shipped by air decline, though to a lesser extent than for the other modes; as a result, its market share of freight transportation demand remains relatively constant, whether expressed in tons shipped or ton miles of travel. Some shift to the truck mode, which generally has the next-highest service characteristics, would be expected. Even with a constant or slightly increasing market share, air freight would still account for a very small percentage of total freight transportation energy demand.

Truck

The truck mode, under equilibrium fuel-price conditions, was forecast to have the largest decline in freight traffic. In terms of tons shipped, the truck share declines from 35.1 percent in the base case to 32.7 percent in the 23 percent shortfall case. Given the $7/gal fuel price that was forecast, a greater shift away from this mode might be anticipated. Several factors, though, limit the potential shift from truck to other modes. First, the truck (highway) network is considerably more extensive than the networks for the competing modes, which restricts the opportunity for modal choice for many origin-destination routes. Many of the shorter intercity trips would continue to use trucks. Less-than-truckload (LTL) shipments would probably be consolidated into truckload shipments before a modal shift would occur. In addition, the fraction of operating expenses for the truck mode that fuel represents is not vastly different than it is for the truck mode's chief competitor, the rail mode. As a result, the changes in freight rates are not likely to be substantial. In fact, for LTL operations, the percentage of operating costs attributed to fuel is about half of what it is for truckload operations. But some shift of truck traffic to the rail mode would be expected.

Rail

Although rail freight traffic does decline just as with the other modes, the market share increases. This situation, which occurs with an equilibrium fuel price, is in contrast to the change due only to the decline in economic activity without any in-

crease in fuel prices. In that situation, the decrease in the demand for freight transportation is greater for rail than for truck. With an equilibrium fuel price, rail improves its market share. The shift to increased shipment size favors the railroad, and it is likely that rail will increase its share of intermodal traffic for longer-haul trips in those corridors where rail can provide dedicated service. Equipment availability may become a limiting factor. Even though railroads may gain traffic at the expense of the truck mode, rail may lose some traffic to water transportation where that mode is available.

Water

The total demand for marine transportation is also down during a petroleum shortfall, although its relative energy efficiency makes it extremely competitive for bulk shipments during a time of rising fuel prices. This is true even though fuel is a very high percentage of operating costs for this mode. The model showed that the water modal share of both tons shipped and TMT would increase during any of the shortfalls tested. In corridors where this mode is competitive, it could be anticipated that some rail traffic will shift to marine transportation.

CONCLUSIONS

A pattern has begun to emerge from the effects of various fuel price levels. If prices are frozen at preshortfall levels, the changes in economic activity will affect the primary goods sectors the most. Rail and water transportation would see the greatest decline in the demand for their services. The demand for fuel, however, will continue to exceed by far the available supply. If fuel prices are allowed to rise to an equilibrium level, then the demand for fuel will be balanced with the reduced supplies. Total traffic will be decreased, and shifts in modal preference will generally be in the direction of air to truck, truck to rail, and rail to water.

From a policy perspective, there is often discussion of allocating fuel to those modes considered more energy efficient than others. This analysis shows that shifts in modal preference would tend to occur in the direction that an allocation program would probably try to achieve. In addition, allowing fuel prices to rise to an equilibrium level provides incentives for carriers and shippers to conserve energy by minimizing costs.

As noted in the analysis, a fuel price that is controlled below an equilibrium level will result in a gap between the demand for and the supply of fuel. In the past, this has introduced considerable uncertainty into the marketplace. In contrast to fuel supplies actually being available (although at high prices in an equilibrium case), fuel was perceived to be available when it was not. This was most evident at the retail level of the truckstops, which tended to be the weakest link in the distillate fuel distribution chain. For the truck mode, in particular, this perception by carriers could result in a significant decrease in the reliability of delivery schedules. Spot shortages also were reported for the other modes, especially marine transportation. However, the problems were generally less severe for the bulk fuel purchasers. Although fuel distribution problems could be expected in the initial stage of an oil shortfall even under equilibrium pricing conditions, the adjustment period would probably be much shorter than it would with controlled prices.

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Simulation for Estimating the Impact of Supply Restriction Policies on Gasoline Consumption

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A simulation model is developed to measure the impacts of several supply restriction policies on gasoline consumption during energy shortfalls. The model, which uses FORTRAN programming language and the next-critical-event approach, takes a microscopic view of travel in a typical urban area in Virginia. The model is built to assess the impacts of the following supply restriction policies: odd-even rationing, weekend closure of stations, upper and lower limits on fuel purchase, and elimination of one day's driving per week. The primary entities in the model are households, automobiles, and service stations. During the simulation period, a real-life situation is simulated in which automobile drivers make work, shopping, recreation, and other trips determined from specified distribution functions. Each trip has its own characteristics, such as trip purpose, length, average speed, and the time at which it is made. During the course of the day, drivers visit gasoline stations when the fuel in their vehicles is low, wait in lines when stations are busy, and park their vehicles at home when gasoline is unavailable. The results of this simulation reveal that only elimination of one day's driving per week has some notable effect on fuel consumption when the level of a gasoline shortage is low (around 5 percent). However, when the shortage level is up to about 15 percent, none of the policies tested has an important effect on the reduction of fuel consumption. The most significant impact on travel behavior and fuel consumption stems from the shortage itself.

Since 1950, transportation has accounted for a relatively constant share of the total petroleum demand (about 52-55 percent) and total energy demand (about 25-26 percent) (1). Whereas the percentage share of transportation stays constant, transportation energy demand has grown considerably in absolute terms over the past 30 years. Between 1950 and 1977, petroleum demand for transportation increased 190 percent; between 1970 and 1977, it increased 25 percent (1). In 1979, 18.6 million bbl/day were consumed in the United States, of which 7.9 million bbl were imported (2). Excluding a dramatic technological breakthrough, it appears that this dependence on petroleum by the transportation sector will continue into the 1980s (3). The United States has experienced severe shortages of gasoline in the past, and a recurrence of these conditions seems inevitable due to our continuing dependency on foreign petroleum supplies. For these reasons, it is necessary for state and local governments to evaluate potential contingency measures beforehand.

Within the framework of contingency planning, numerous alternatives are available (rationing programs, promotion of ridesharing and transit, adjustment of peak-hour demand, etc.). This paper only addresses the impacts of the following supply restriction policies on fuel consumption: (a) elimination of one day's driving per week, (b) weekend closure of stations, (c) odd-even rationing, and (d) upper and lower limits on fuel purchase.

A computer simulation model is developed to estimate travel behaviors in response to shortage situations and consequent rationing policies. Numerous models have been developed for this purpose. These models fall into the basic categories of aggregate (4,5) and disaggregate (6,7). The disaggregate models permit a broader range of travel and policy options than the aggregate approach. However, both modeling techniques have important limitations. All of the models to date are demand based and lack a component for limiting the supply of gasoline.

The model developed for this analysis adds a supply component to the estimation of consumption. This addition makes the model more realistic for simulating shortfalls.

Under free-market conditions, the price of gasoline will increase during supply shortfalls. However, since the model was built before the deregulation of gasoline prices, the price of gasoline is assumed to be fixed in the model during supply shortfalls. This fixed price, which is below the equilibrium price, makes demand higher than supply. Queues are therefore formed in gasoline stations. The model incorporates the feedback between queue length and demand to reflect the dynamic interrelations present in the real world.

The modeling technique adopted for this analysis represents a departure from the conventional econometric modeling approach. A stochastic simulation model was developed for this study because of some of its inherent advantages over the econometric approach. The true validity of the econometric model lies in its ability to transfer historical relations into the future. Econometric models cannot adequately deal with new technology for different futures from the historic past. Very few data exist concerning the way drivers reacted to either the 1973-1974 or the subsequent gasoline crisis. However, in order to predict the effects of different supply restrictions on fuel consumption, one cannot effectively project past trends into the future (as in the econometric model) simply because sufficient data on past trends do not exist. In addition, Louviere and others (8), in their recent work comparing econometric with stochastic simulation models, found that the stochastic model is equal to the conventional model in terms of predictive ability. Furthermore, the parameter estimates of the stochastic model were found to be temporally and spatially stable and consistent with the estimates of the econometric model.

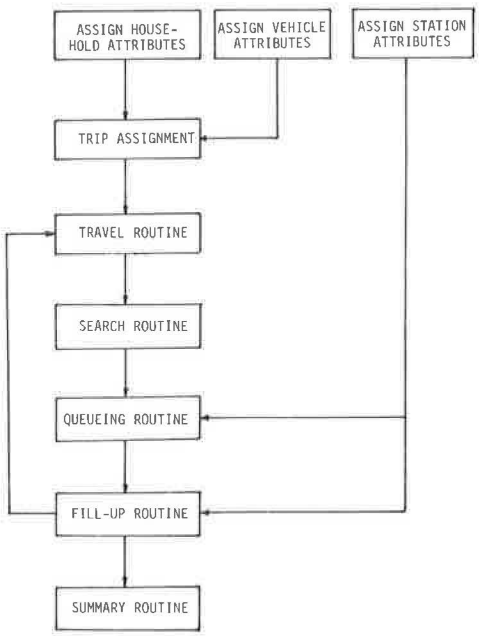
METHODOLOGY

The model simulates the travel activities of passenger vehicles for a typical urban area in Virginia. Statistics for the model are based on data from the City of Richmond, which exhibits characteristics (population density, area size, automobile fleet, etc.) typical of urban areas in Virginia. According to the passenger vehicle-to-station ratio, 2500 passenger vehicles and three service stations are created for the hypothetical urban area. They exhibit operating and capacity characteristics similar to those of their real-life counterparts.

Model Formulation

The model, shown in Figure 1, consists of nine major components: household attributes, vehicle attributes, station attributes, trip assignments, travel routine, search routine, queuing routine, fill-up routine, and summary routine. First, the attributes of the household, vehicles, and service stations are initialized. Actual travel activities are then simulated in the travel routine according to their assigned trips, household attributes, and vehicle attributes. As soon as the level of gasoline in a vehicle reaches the point where fuel is needed, a service station is searched. The queuing routine is then activated, the fill-up routine is called, and

Figure 1. Major components of model.



the vehicle is filled with a certain amount of gasoline. It then leaves the station and reenters the travel routine. Gasoline in the service station is reduced by the fill-up amount. If the level of gasoline in a service station is below a certain point, a distributor is asked to refill the station.

The model uses the next-event approach to update activities in the system. The simulated "clock" is advanced by the amount necessary to cause the most imminent event to take place in a day and continues until the end of the simulation period. The basic concept underlying the next-event approach is that there is no need to view the system at points in time other than those at which critical events occurred. The critical events defined in the model are start of a trip, end of a trip, search for a service station, enter a service station, leave a service station, call to refill a service station, end of a day, and end of the simulation period.

After the base model is formulated, it is calibrated to replicate the actual unconstrained condition of travel and fuel consumption in Virginia. Supply constraints and restriction policies are then imposed on the model to examine their effects on travel and fuel consumption.

Assignment of Household Attributes

Three attributes are assigned to each household in the model: household income, vehicle ownership, and household size. Since, according to the 1977 Nationwide Personal Transportation Study (NPTS), the average number of vehicles per household is 1.52, approximately 1645 households are generated in the model to own the 2500 vehicles. These attributes are assigned to households by certain probability distributions through the Monte Carlo approach. Unlike most other previously developed models in which the attributes of vehicle ownership, household income, and household size are just assigned randomly to each household through their marginal probability distributions, this model makes use of their joint probability distributions to assign these attributes. The joint probability distributions are calculated from Federal Highway Administration 1977 NPTS Public Use Tape.

Assignment of Vehicle Attributes

Six attributes are assigned to each vehicle in the model: license plate number, size, tank capacity, average fuel consumption rate, an initial amount of gasoline, and a regular refilling point.

Assignment of Station Attributes

Six attributes are assigned to each service station: station hours, station capacity, number of pumps in the station, average service time, an initial amount of fuel, and the day and amount of replenishment. The initial amount of fuel is randomly assigned between one-fifth and the full capacity of the tank. All other attributes are obtained through a random sampling of three service stations in the Richmond area.

Trip Assignment

Vehicles in the model are assigned to perform four types of trips: work, shopping, recreation, and other. Work trips include travel for earning a living. Shopping trips in the model represent travel for purchasing commodities. Recreation trips include travel for social and recreational purposes. Other trips in the model stand for the remaining trip purposes, such as civic, educational, religious, and personal business. The percentage of vehicle trips and average trip length by trip type are first assigned to each vehicle by its household income and then modified by its vehicle ownership, household size, and day of the week the trip is made. These percentages are then used as probability distributions to assign trips to each vehicle by using the Monte Carlo technique. Trip starting time is also assigned to each trip according to the distribution of daily traffic and its purpose (9). An idle period is assigned to each trip at its destination according to its purpose. These idle periods are assumed to be uniformly distributed in the ranges given below:

Trip Type	Idle Period (h)
Work	6-9
Shopping	1-4
Recreation	2-8
Other	1-3

The work trips are performed mostly on the weekdays. For weekend travel, shopping and recreation trips are the dominant ones. However, the average vehicle miles of travel (VMT) for recreation trips is much more than that for shopping trips during weekend days (10).

In the event of gasoline shortages, it is likely that people will cut their trips according to the discretionary level of each trip. Work trips in the model are regarded as nondiscretionary, unlike recreation trips, which are considered the most discretionary. Shopping trips are considered important, but their lengths are reduced according to gasoline shortage levels (11). The discretionary level of other trips in the model is assumed to be between that of work and shopping trips.

Travel Routine

Once all relevant attributes are assigned to the vehicles, the travel routine is performed. The model is simulated by the next-event approach. By comparing the starting time of all trips, the earliest one is selected and the simulated "clock" is moved forward in time to that point. The selected vehicle is then assigned a trip length according to

its household attributes and trip purpose. The average travel speed is assumed to be a function of trip length and the level of fuel supply constraints. The longer the trip length, the higher is the average travel speed expected. Speeds will be lowered slightly during gasoline shortages in an effort to conserve energy (12). The fuel consumed on the trip is calculated from vehicle characteristics and travel speed. The travel time is also computed from trip length and average speed. The recorded time of the vehicle is then advanced by the time it spent on the trip. Once a vehicle arrives at its destination, an idle period is assigned to it according to its trip purpose. The simulation model searches again through the time of occurrence of each event, selects the next-earliest one, moves forward in time to that point, and updates the status of the system, and so on. This process continues until the clock is advanced to a value greater than 24, and the simulation process starts all over for the next day.

Search Routine

When the fuel in a vehicle is below its refilling point, the driver under normal conditions searches for a service station with the shortest waiting line. When a vehicle arrives at a service station, the driver must decide whether it is worth the time to wait in the queue or to seek another station. This decision is based on two factors: the level of gasoline shortfalls and the length of the queue. A driver will be more inclined to join a long queue when he or she realizes that queues at competing stations are likely to be long because of a limited-supply condition. On the other hand, a driver will be more inclined to seek shorter queues during the period of energy abundance.

Queuing Routine

Once the vehicle enters a service station, a queuing system is activated. The service facility in this model is specified as a multiserver system with infinite storage capacity. The service time is assumed to be exponentially distributed. The queuing discipline is in a first-come-first-served order.

Fill-Up Routine

As soon as the clock moves forward to the time that a vehicle is going to be served, the fill-up routine is entered. At this point, the status of the system has the following changes:

1. The amount of fuel in the vehicle is increased by the quantity with which the vehicle is filled.
2. The number of vehicles in that service line is reduced by one.
3. The amount of fuel in the station is subtracted by the quantity with which the vehicle is filled.
4. The time attached to the vehicle is advanced by the time consumed at fill-up.

If the level of gasoline in a service station drops below its refilling point and the next day is not a scheduled refilling day, a special request for replenishment is sent to the distributor. When the amount of gasoline in the station is depleted, the station is closed.

The refueled vehicle returns to the travel routine and continues its travel activities.

Summary Routine

Some of the variables in the model are summarized at the end of each day and at the end of the simulation period. The most pertinent ones are

1. Amount of gasoline consumed during the simulation period,
2. Amount of gasoline consumed annually by automobiles in Virginia,
3. Total VMT for automobiles in the model during the simulation period,
4. Annual VMT for automobiles in Virginia,
5. Total VMT for automobiles in each household income category, and
6. Total VMT for automobiles in each household vehicle ownership category.

Model Calibration and Validation

Several experimental runs are first executed for the base model. The outputs show that the model is functioning in the manner intended. The base model is then calibrated by comparing the following model outputs with the Virginia data: annual VMT, annual vehicle gasoline consumption, and annual VMT per vehicle (13). The percentages of VMT by work trip, shopping trip, recreation trip, and other trip are compared with the nationwide data (9).

Adjustments of various trip lengths and fuel consumption rates are made to reduce the differences between the model outputs and the actual data until they are acceptable. Various random number seeds are used to run the model to make a sensitivity analysis of the system. Both the means and standard deviations of the outputs are found acceptable.

In order to validate the base model, some of the results generated by the model are compared with nationwide data (9). The table below illustrates the model output for distribution of VMT by household income and vehicle ownership (income in 1977 dollars):

Item	VMT (%)	Households (%)
Household income		
<$5000	15	21
$5000 to $9999	21	22
$10 000 to $14 999	23	21
$15 000 to $24 999	26	24
≥$25 000	15	12
Vehicles owned by household		
1	24	41
2	43	40
≥3	33	19

It appears that these results are quite consistent with the actual travel pattern in the United States.

Introducing Gasoline Shortages into the Base Model

The base model is formulated under the condition of ample supplies of gasoline. For the purpose of reflecting the degree of hardship in obtaining gasoline, an indicator called HARD is introduced into the model. The value of HARD, which is a nonnegative real number, is determined by two factors.

The first factor is the percentage of a vehicle being rejected by service stations (PREJ). When a vehicle needs to be refilled but cannot get gasoline from service stations, it is defined as being rejected by service stations. This can occur when (a) a station is closed because its fuel is depleted and (b) the vehicle is not allowed to be refilled due to certain restriction policies. Thus, the value of PREJ contributed by condition a can somewhat reflect the level of gasoline supply shortages and that

contributed by condition b can disclose the hardship in obtaining gasoline imposed by restriction policies. The value of HARD is assumed to increase proportionally with the value of PREJ.

The second factor is the average queue length at service stations (QUEUE). As the waiting lines get longer, the hardship of refill increases. The value of HARD is assumed to be increased by the amount of QUEUE/6.

The value of HARD varies between 0 and 6. The previous factors can be regarded as a kind of inconvenience cost that, as jointly represented by HARD, will have certain impacts on travel demand. On the other hand, changes in travel demand affect fuel consumption and, consequently, the value of HARD. For example, increases in queue lengths will raise the value of HARD and thus reduce the demand for travel and consequently decrease the fuel consumption. This results in less frequent visits to gasoline stations and hence reduces queue length, lowers the value of HARD, and so on. In this way, the model incorporates some feedback between these factors and travel demand.

The following behaviors in the model are assumed to be influenced by HARD:

1. Trip assignment--It is assumed that, when the difficulty of obtaining fuel increases, trips will be cut according to their discretionary level. In the event of a 20 percent shortfall, discretionary travel can be cut by as much as 25 percent (12). The specific type of discretionary trip that best lends itself to being reduced is the recreation trip. In response to a 20 percent shortfall, New York State survey respondents generally agreed that they will vacation closer to home, change modes for vacation, and be more likely to cancel vacation trips altogether (12). The frequency of shopping trips is reduced only slightly, but trip lengths are decreased during shortage conditions. The frequency of other trips is reduced by a small amount, but trip lengths remain unchanged. Work trips, on the other hand, are reduced only slightly by diverting some trips to other modes (i.e., transit, carpool, etc.).

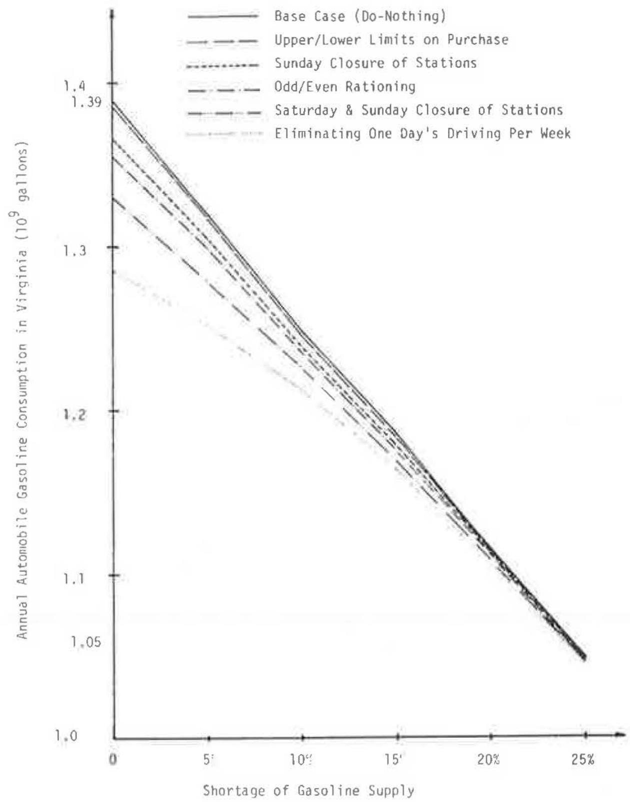
2. Trip chaining--It is assumed that trip chaining will be increased during gasoline shortfalls. Instead of separate round trips to work, to shop, and to visit, travel activities can be scheduled to permit visiting many destinations on a single trip. In the model, trip chaining is made by eliminating one trip and increasing the length of another by a certain amount.

3. Refilling point and fuel purchase--It is assumed that, when the difficulty of obtaining fuel increases, automobile users will increase the frequency with which they refill. This in turn will result in more frequent visits to gasoline stations and hence longer wait lines. An even higher value of HARD will result in this case, which will further worsen the situation. It is also assumed that drivers will be more inclined to refill more fuel during any one stop at service stations.

SCENARIOS AND RESULTS

The model is developed to measure the impacts of several supply restriction policies on gasoline consumption during energy shortfalls. These policies are first evaluated under a normal (no-shortage) condition. The fuel consumption of the base case (do-nothing) scenario is used as a reference point for evaluating the results of other scenarios. Shortages up to 25 percent of normal supply are then simulated in the model.

Figure 2. Automobile gasoline consumption versus supply shortage under various restriction policies.



Base Case Scenario

In the base case, no restriction policies are adopted. As can be seen in Figure 2, fuel consumption declined proportionately with reduced supply. The fuel consumption under the no-shortage condition (1.39 billion gal, the result of the calibrated base model) is the actual automobile fuel consumption in Virginia for 1979 (13). The slightly fluctuating results under various levels of supply shortage are caused by the randomness of the random numbers generated in the model.

Upper and Lower Limits on Fuel Purchase

The upper limit on fuel purchase restrains the maximum quantity of gasoline with which a vehicle can be refilled. The purpose is to prevent chaos among gasoline buyers within a short period of time. However, on the other hand, it causes more frequent visits to gasoline stations. The lower limit requires the purchase of gasoline to be at least a specified amount. It tries to prevent frequent refillings and thus reduces gasoline queues. These two restriction policies are in fact two different ones. However, since some gasoline stations used both of them at the same time during the past energy crisis, the two policies are used together in the model as one single policy.

The upper and lower limits on fuel purchase are assumed to be 10 and 6 gal, respectively, in this scenario. The result of this scenario indicates that the reduction in fuel consumption is almost negligible, as shown in Figure 2. The primary impact of this policy is on gasoline queues; there is little impact on fuel consumption.

Odd-Even Rationing

The policy of odd-even rationing excludes vehicles with unmatched odd-even plate numbers from being refilled at the gasoline station during even-odd days. Although this policy reduces gasoline queues at stations, the inconvenience of refilling it imposes on automobile users will cause a reduction in travel. The fuel consumed under this condition (1.355 billion gal) is only about 2.5 percent less than that in the base case. The ineffectiveness of this policy in reducing fuel consumption is due to the fact that most of the vehicles are usually refilled every four to five days under normal conditions. Thus, this policy does not disrupt their refilling actions to a significant extent. Moreover, most automobile users can adjust their refilling days to get along with this policy. However, those who do need to obtain gasoline daily will be affected by this policy.

Weekend Closure of Service Stations

Under the policy that assumes closure of all service stations on weekends, two scenarios are examined: (a) closing all stations on Sundays only and (b) closing them on both Saturdays and Sundays.

For the scenario of Sunday closure, most consumers can adjust their refilling days away from Sunday except those who need to travel long distance on that day. This scenario results in a 1.7 percent reduction in fuel consumption from the normal condition.

For the scenario of both Saturday and Sunday closure, the reduction of fuel consumption is about 2.5 times that of the previous scenario (about 4.3 percent below the normal condition).

Elimination of One Day's Driving

The scenario that eliminates one day's driving prohibits vehicles from operating on one weekday per week. The day of prohibition is assigned according to the vehicle's license plate number, as follows:

Last Digit of Plate Number	No-Driving Day
1 and 6	Monday
2 and 7	Tuesday
3 and 8	Wednesday
4 and 9	Thursday
5 and 0	Friday

The elimination process is executed at the very beginning of the travel routine once this scenario is initiated. In the event that travel is prohibited for a vehicle on a given day, other vehicles in the household, if any, with proper plate numbers are first searched out as substitutes. Trips that are supposed to be taken on the prohibited day, except work trips, are scheduled for trip chaining on the following day. The reduction of fuel consumption under this policy is about 7.5 percent below the normal condition, as shown in Figure 2.

As with most of the other policies, when the level of fuel supply shortages increases, fuel consumption under this policy tends to be closer to that of the do-nothing case. Under a 15 percent shortage, the fuel consumption for this policy is only 1.86 percent lower than that of the do-nothing case, since at higher shortage levels the excess travel demand has already been curtailed and the remaining travel demand is hard to suppress.

CONCLUSIONS AND DISCUSSION

Since the model was originally developed for the Virginia Division of Motor Vehicles (DMV) to estimate the impact of several restriction policies on the collection of state gasoline tax revenues, reduction of gasoline consumption was used as a criterion for evaluating these policies. Therefore, in terms of reducing fuel consumption, these policies were ranked in descending order as follows:

1. Elimination of one day's driving per week,
2. Saturday and Sunday closure of stations,
3. Odd-even rationing,
4. Sunday closure of stations,
5. Upper and lower limits on fuel purchase, and
6. Do nothing.

The results of the model show that only the elimination of one day's driving per week has some notable impact on fuel consumption, if the level of shortfalls is low. When the shortfall level is increased to around 15 percent, all policies have little or no significant impact on the reduction of fuel consumption. The most important impact on travel and fuel consumption comes from the shortage itself.

The reduction of fuel consumption should not be the only criterion for evaluating alternative restriction policies. Those policies that reduce fuel consumption the most, on the other hand, may impose the most hardship in obtaining gasoline on the automobile users. Thus, these policies are also ranked, as in the table below, by the HARD value (for all levels of gasoline shortage) to reflect the hardship in obtaining gasoline that each policy imposes on automobile users:

Rank	Restriction Policy	Comparative Avg HARD Value
1	Saturday and Sunday closure of stations	3.05
2	Odd-even rationing	2.71
3	Sunday closure of stations	2.49
4	Upper and lower limits on fuel purchase	2.20
5	Do nothing	2.15
6	Elimination of one day's driving per week	2.07

The average HARD value is used only as a reference for comparative purposes. However, the inconvenience costs should include not only the hardship in obtaining gasoline but also the disruption in travel caused by the restriction policies and by the unavailability of fuel.

The model is currently being revised to include two major refinements: the fluctuation of the price of gasoline under decontrol status for various shortage conditions and a comprehensive determination of inconvenience costs for travelers under alternative policies.

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Assessment of State Emergency Energy Conservation Planning

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Since the enactment of a federal law providing a framework for a coordinated national response to energy supply interruptions, there have been many developments that have tended to hinder this objective. The current oil glut and stabilizing prices, the lack of sufficient planning funds, and the redirection of federal regulatory policy are some of the factors that are affecting the progress of transportation emergency energy conservation planning. A survey was conducted by the New York State Department of Transportation to determine the status of state emergency conservation plans as required by the Emergency Energy Conservation Act of 1979 and to assess each state's plan development process with particular emphasis on the format of the plan, the extent of local plan coordination, impact assessments of specific measures, and measurement of specific implementation details. The results of this survey suggest several shortcomings of emergency conservation planning as conducted by state transportation and energy agencies throughout the country: lack of money for plan development and implementation, inadequate cost estimates of the plan, lack of good coordination with local plans, lack of evaluations regarding energy savings, and no assessment of economic impacts.

The possibility of energy supply interruptions has been a constant threat to oil-importing nations over the past few years. The past two "crises" (1973-1974 and summer 1979) evoke memories of long lines at gasoline stations, reduced travel mobility, and general frustration.

Prompted by these events, Congress in November 1979 enacted the Emergency Energy Conservation Act (EECA). One of its many purposes was to encourage the development of statewide plans to deal with energy shortages prior to their occurrence. The philosophy behind the EECA was to have in place state plans that could respond to a shortage in a rational, coherent manner--that is, to help maintain essential mobility, reduce gasoline lines, and prevent panic buying at service stations.

Several organizations, including the National Conference of State Legislatures, the National Governors' Association, and the U.S. Congress (1,2), have followed the progress of EECA plan development. These surveys primarily reviewed statewide efforts rather than evaluating the extensiveness of the planning effort. In October 1980, the New York State Department of Transportation (NYSDOT) sent a questionnaire to all state energy offices and transportation departments throughout the country, not only to inquire about the status of these plans but also to learn what actions other states are including in their plans, to assess their planning processes, and to record their experiences so that energy planning in New York State may have the benefit of other work.

Although the responsibility for developing EECA plans has fallen on state energy offices, many state transportation departments have been actively involved in energy conservation, contingency, and long-range planning. Since we were interested in the extent of transportation department involvement in the EECA plan development process, the same survey was therefore distributed to all state transportation departments as well as energy offices. Responses to the survey numbered 27 from energy offices and 22 from transportation departments. Of these, 9 responses were received that were not entirely usable. Even though both types of responses were received from only 11 states, the transportation department responses provide insight into EECA planning for those states in which the energy offices did not respond.

STATUS AND DEVELOPMENT

The development of transportation plans for gasoline and diesel emergencies has been initiated in part by federal directives. The Federal Highway Administration and Urban Mass Transportation Administration encourage the preparation of energy contingency plans by the state transportation departments and the local metropolitan planning organizations (MPOs), and encourage each state highway agency to work cooperatively with state energy officials in preparing the transportation elements of emergency

energy conservation plans or EECA plans (3,4).

With the passage of the EECA in November 1979, Congress directed the establishment of a Federal Gasoline Rationing Plan and standby Federal Emergency Energy Conservation Plan. States are required to prepare and submit an emergency conservation plan to the U.S. Department of Energy (DOE) within 45 days of the establishment of a mandatory energy conservation target by the President. If a state does not submit a plan, or if a plan does not attain the target, a federal standby plan consisting of mandatory measures may be imposed on the state (5). So far, only voluntary gasoline reduction targets have been issued.

The requirements for state emergency energy conservation plans under the legislation are fairly broad. A plan must demonstrate the capability of meeting the target, equity, and consistency with state and federal law and must include appropriate public participation. State plans may contain measures suggested by the federal standby plan, coupled with other proven measures or measures uniquely appropriate to the state or local area.

Under the EECA, if a state failed to submit a plan to DOE within 45 days of a presidential declaration of an energy emergency, a federal standby plan would become operable in that state. Initially, eight transportation measures were considered as components of this plan:

1. Public information program,
2. Minimum fuel purchase restrictions,
3. Odd-even fuel purchase restrictions,
4. Employer-based commuter and travel measures,
5. Speed-limit enforcement,
6. Compressed work week,
7. Vehicle use sticker, and
8. Recreational watercraft restriction.

However, DOE has since withdrawn the measures that were proposed for inclusion in the federal plan--the compressed work week, vehicle use sticker, recreational watercraft restrictions, and one section of the employer-based commuter and travel measure--and is removing certain of the interim final measures--the odd-even fuel purchase, the rest of the employer-based commuter and travel measure, and speed-limit enforcement--as well as the only nontransportation measure--the mandatory building temperature restrictions. The public information and minimum automobile fuel purchase measures remain in the federal plan as interim final rules (6).

Two other significant events have recently affected the original intent of energy emergency planning--to provide for a coordinated national response: decontrol of petroleum and the Reagan Administration's budget policies.

On January 28, 1981, President Reagan issued an executive order decontrolling crude oil and other petroleum products, effective immediately rather than September 30, 1981, the expected date for termination of federal controls. This order eliminated not only price controls on gasoline and diesel fuel but also allocation rules that assured transit systems of a guaranteed supply of petroleum products in the event of shortages. The latter aspect of this order is of particular concern to energy planners. Special Rule 9 of the Emergency Petroleum Allocation Act assured transit systems of 100 percent of their current requirements for diesel fuel. This was terminated March 31, 1981, along with the federal authorization of a state set-aside of middle distillates, which previously allocated 4 percent of the state supply based on local hardships, regional problems, and statewide priorities. This latter mechanism was relied on during the last shortage by public transportation operators that were unable to receive their full 100 percent requirements from their prime suppliers.

DOE made available to the states planning grants of up to $29 000 for assistance in developing emergency energy conservation plans. The grants were the first installment of financial assistance provided to the states during the 1981 fiscal year for emergency planning. This money was to result in development of a management plan that described the steps the state would take to develop, maintain, and implement its fuel emergency plans. Phase 2 money could then be used to support full development of state EECA plans. However, at this time no funds

Table 1. Status of EECA plans according to state energy departments.

		In Development				
State	Not Yet Begun or Just Starting	Public Hearings	Task Force	Working Papers	Draft Form	Submitted to DOE[a]
Alabama	X					
Arizona					X	
Arkansas					X	
California					X	
Delaware						
Florida						X
Hawaii				X		
Idaho	X					
Indiana	X					
Iowa						X
Kansas				X		
Louisiana	X					
Maryland						
Massachusetts						
Minnesota				X		
Missouri						X
Montana					X	
Nebraska						X
Nevada		X				
New Hampshire					X	
New Mexico					X	
North Carolina					X	
North Dakota				X		
Ohio					X	
South Carolina				X		
Tennessee					X	
Washington	X					

[a]None returned by DOE.

for phase 2 have been appropriated by Congress for FY 1981/82.

Other recent developments at DOE suggest that the focus on emergency energy planning has diminished (7). Technical assistance for developing emergency plans has not progressed. Initially, the regional offices of DOE were planning to conduct workshops for energy planners and to publish guidelines. However, the FY 1981 budget for these activities was rescinded and work was never completed on the planning guidelines.

Given these factors, it is incumbent on the states to take the initiative for planning for energy shortfalls. Although the current glut in the world oil market has diminished any urgency, it is likely that this surplus will subside and possibly leave many states ill-prepared.

Tables 1 and 2 give the status of EECA plans as indicated by state energy and transportation officials in the survey. As can be seen from these tables, the status of EECA planning has varied extensively from state to state. Four states--Florida, Iowa, Missouri, and Nebraska--have submitted their plans to DOE for review and approval. The majority of responses indicate that plans are circulating in draft form for comment within the respective states. However, quite a few states either have not yet started or are just beginning the planning process since federal funding of up to $29 000 has become available for this purpose.

Developing an EECA plan entails a great deal more effort than preparing a list of conservation measures to ensure an effective response to energy shortfalls. Basic steps to initiate this planning process include the designation of a lead organization, assurance of funding, and manpower availability.

The lead organization for development and coordination of the EECA plan is usually the state energy office. However, since the implementation of a plan might require the services of many other agencies, a cooperative effort is noted by many of the respondents to the survey.

The cost and manpower needed to develop a plan were concerns of every state that responded to the survey. Most states indicated that they did not have the resources available, exclusive of federal assistance, to develop a plan. Estimates of the costs ranged as low as $25 000 to $400 000. With receipt of federal funds, many states expect to proceed further in the development of their plans.

Table 2. Status of EECA plans according to state transportation departments.

		In Development				
State	Not Yet Begun or Just Starting	Public Hearings	Task Force	Working Papers	Draft Form	Submitted to DOE[a]
Alabama	X					
Alaska	X					
Arkansas				X		
California				X		
Connecticut					X	
Florida						X
Georgia	X					
Idaho						
Illinois	X					
Iowa					X	
Louisiana	X					
Maine	X					
Massachusetts				X		
Minnesota				X		
Nebraska						
New York					X	
Oregon					X	
South Carolina						
Texas	X					
Utah	X					
Wisconsin					X	
Wyoming	X					

[a]None returned by DOE.

Table 3. Measures for inclusion in state EECA plans according to state energy offices.

Action	AL	AZ	AR	CA	DE	FL	HI	ID	IN	IA	KS	LA	MD	MA	MN
Public information	X	X	X	X		X	X	X		X	X				X
Compressed work week		X	X	X			X	X		X	X				X
55-mph enforcement	X	X	X	X		X	X	X		X	X				X
Vehicle use sticker plan	X	X	X	X		X	X	X		X	X				X
Restriction on recreation vehicles	X	X													X
Employer commuter plan	X	X	X	X		X	X			X	X				X
Odd-even or minimum purchase	X	X	X	X		X	X	X		X					X
Permit standees on buses	X		X												
Use of spare buses	X		X				X								
Stockpiling of buses			X				X								
Use of school buses	X		X				X								
Nonwork bus travel			X				X								
Government employee plan	X	X	X			X	X	X		X					X
Staggered hours	X	X	X	X		X	X	X		X					X
Shared-ride taxi	X			X		X	X								
Parking fees			X	X		X	X			X					
Bicycle incentives	X	X		X			X	X							
Other		X		X		X	X			X					

FORMAT OF PLAN

Existing state and local contingency plans contain a sufficient base of suitable emergency measures that can be drawn on for inclusion in a state's EECA plan. Of course, further refining and screening of these measures are necessary to evaluate and select those measures that are most appropriate for that particular state and energy situation.

Tables 3 and 4 give the measures that are or might be included in state EECA plans. Table 3 contains the responses of energy offices, and Table 4 contains the responses of transportation departments. In scanning these tables, one notes that many states relied on the federal standby plan elements, although not exclusively, as major components of their plans. All of the plans include some type of public information program. In some states, very extensive and costly programs are currently used for ongoing conservation activities. Examples include Florida's "Save It" campaign, estimated to cost $500 000; Ohio intends to operate a 24-h public information program; and Arkansas will rely on the U.S. Department of Transportation (DOT) "Featherfoot" program.

Notably absent from the federal standby plan were transit measures. However, many states indicated that they would include at least one of the five transit choices in the survey: permitting standees on buses, spare bus use, stockpiling of buses, use of school buses, and promotion of transit for nonwork travel.

The most unpopular measure was the restriction of recreational vehicles and boats. This proposed measure for the federal standby plan has since been dropped due to overwhelming public opposition.

COORDINATION WITH LOCAL PLANS

One particular aspect of EECA planning that led to the shift of responsibility from federal to state government was that differences exist between areas of the country with respect to their susceptibility to energy shortages, types of travel profiles, and ability to conserve. Just as likely to occur are regional, modal, and demographic differences within states. Thus, blanket state-level implementation of measures may not always be appropriate and in fact may prove detrimental. How the states deal with these possible intrastate differences will affect the effectiveness of the state plan.

Most states proposed to tackle this problem by integration of local contingency activities into the development and implementation of the state EECA plan. The majority of states indicated that local plans are available and will be coordinated with the state plan. Coordination would occur via the regional planning commissions or MPOs in most states or with local participation on task forces or steering committees.

However, a survey by the General Accounting Office (GAO) concludes that regional contingency planning has progressed slowly due to lack of specific guidance, confusion about how these plans will interface with state EECA plans, and uncertainties about what actions the federal and state governments might implement.

The California Department of Transportation has developed guidelines for local plan coordination (9). The guidelines, called local energy emergency operation plans, specify the role of each level of government. The state provides assistance to the local areas in the form of workshops and other technical assistance. The cities and counties are required to identify the specific measures to be implemented within their jurisdiction. The MPOs and regional planning agencies allocate planning funds and provide technical assistance when requested. These guidelines also specify the roles and tasks for transportation providers and major employers.

While the California effort does serve as a catalyst for local plan coordination, other states rely on county coordinators or actually review the local plans for compatibility and integration. Regardless of the mechanism used, it is important that local plan coordination become an integral part of emergency energy planning. Overlapping responsibilities and distinct emergency planning activities initiated by different agencies have created a need for better definition of roles, responsibilities, and coordination prior to a shortage. How well a state responds to this need will determine its effectiveness in implementation of its emergency measures.

IMPLEMENTATION

General procedures for plan implementation as well as measure-specific details must be clear, prearranged, and agreed on by the actors involved. As mentioned previously, it is usually the energy office within each state that has been delegated the lead responsibility for administering and implementing emergency energy plans. Examination of the plans received showed that provisions were included for cooperation with other state agencies, especially transportation departments. For example, in Florida a memorandum of understanding between energy and transportation departments specifies their respective roles. Any EECA plan will require many agencies to implement, maintain, monitor, or enforce

MO	MT	NE	NV	NH	NM	NC	ND	OH	SC	TN	WA
X	X	X	X	X	X	X	X	X	X	X	X
	X				X	X	X				X
X	X	X	X	X	X	X	X	X	X	X	X
X		X	X	X	X	X	X		X	X	X
							X				
X	X		X	X	X	X	X	X	X	X	X
X	X	X		X			X	X	X	X	X
				X							
			X	X	X			X	X		
								X			
X	X	X	X	X	X	X	X	X	X	X	X
	X			X	X	X	X	X	X		X
					X	X					
X						X	X	X			X
X	X			X			X				
X			X				X				

Table 4. Measures for inclusion in state EECA plans according to state transportation departments.

Action	AL	AK	AR	CA	CT	FL	GA	ID	IL	IA	LA	ME	MA	MN	NE	NY	OR	SC	TX	UT	WI	WY
Public information			X	X	X	X			X	X		X	X	X		X	X				X	X
Compressed work week			X	X		X			X	X		X		X			X				X	
55-mph enforcement			X	X		X			X	X		X	X	X		X	X				X	X
Vehicle use sticker plan			X			X			X	X			X	X			X				X	
Restriction on recreational vehicles			X									X		X			X					
Employer commuter plan			X	X		X				X		X	X	X		X	X				X	X
Odd-even or minimum purchase			X	X	X	X				X		X		X		X	X				X	X
Permit standees on buses			X		X	X										X	X					
Use of spare buses				X	X	X			X							X	X					
Stockpiling of buses			X	X	X	X										X	X				X	
Use of school buses			X	X	X				X			X										X
Nonwork bus travel			X	X		X			X							X	X					
Government employee plan				X		X			X			X	X	X		X	X					X
Staggered hours			X	X		X			X	X		X	X	X			X				X	X
Shared-ride taxi			X	X		X			X			X	X			X						
Parking fees				X						X							X				X	
Bicycle incentives				X		X			X			X					X				X	
Other				X					X	X			X			X	X				X	

Table 5. Possible monitoring and measuring techniques for energy emergencies.

Key Emergency Variable	Monitoring Technique	Measuring Technique
Fuel availability	Oil company data	Anticipated gasoline delivery data demonstrate that an area will experience a reduction in gasoline supplies during any month that is at least 5% below expected demand
	Weekly reports by city and county energy coordinators	Variations in number, type, amount, and location of hardship requests for state fuel set-aside program
Gasoline lines	Local-area survey conducted by city/county energy coordinator or MPO	At least 50 percent of all retail gasoline stations in an area experienced a significant gasoline line at least once during 75 percent of days included in a recent sample period of at least 4 days; at least 50 percent of all retail outlets in an area sold gasoline for 5.5 h/day or less during at least 75 percent of days included in a recent sample period of at least 4 days[a]
Violence at gasoline stations	Weekly police department report	No. of reported incidents
Automobile and truck traffic volumes and patterns	Weekly report by operators of key transportation facilities (e.g., bridges, tunnels, thruway, parkway)	Changes in daily and weekend vehicle traffic
Automobile occupancy	Same as above; special survey or spot counts by MPOs	Changes in peak, off-peak, and weekend automobile occupancies
Public transit ridership	Daily monitoring of individual routes by transit operators; weekly summary of ridership changes reported to state by telephone	Changes in transit ridership and in peak-hour load factors
Public- and private-sector perception of emergency, actions taken, and compliance	Weekly telephone surveys of households in affected areas; monitor state and local area hotline requests for information; reports from private interest groups (e.g., automobile clubs); media reports and surveys	Quantitative and qualitative judgments of public perceptions and actions taken
Changes in fuel price	Monthly or weekly metropolitan area fuel price surveys of retail gasoline stations	Rate and/or amount of increase or decrease for a specified area
Fleet turnover		Rate of new-car purchases and amount of fuel savings from change in average fleet fuel efficiency

[a]Monitoring and measuring techniques presented in the Department of Energy Interim Decision and Order on the District of Columbia petition for special fuel allocations during an emergency period, January 2, 1980.

various aspects of a plan. This involvement will require actions that are both costly and timely. Similar agreements will allow their roles to be defined when a shortage actually occurs.

Of course, the provision of new funds or the shifting of funds from other programs--federal or state--to implement emergency measures is an important issue. Almost half the states responding were either uncertain of the implementation costs or did not answer this question, even though their plans were already in draft form. Nearly every state appears to rely on federal or state funds not yet available to implement its plans. If a shortage occurred, most states would probably not be in a position to immediately implement many of their proposed measures.

Cost is a variable that can change according to the severity of a shortage. The Missouri Division of Energy estimated the implementation costs of its plan as anywhere from $1000 to $2.6 million for the first year. The Illinois DOT estimated the cost of its plan at a minimum of $9.7 million, $7 million for its carless sticker plan alone. To refine this estimation, the plan needs to define at what level of shortage certain measures will be added or intensified. Trigger mechanisms can play an important role.

A trigger mechanism can be an event or an action that signals the need for implementing or disengaging certain measures. Most states are using a numerical percentage of fuel shortages as well as a qualitative indicator to move through response phases. To fully understand emergency conditions, data on fuel availability should be considered together with information on travel demand changes, public perception of the shortage, and other important indicators. Table 5 suggests a range of key energy emergency variables that could be monitored and measured at the statewide and local-area levels (10).

On the national level, numerical indicators of projected fuel shortages will initiate the process set up by EECA--that is, the issuance of mandatory fuel reduction targets that trigger implementation of state emergency energy conservation plans or the federal standby plan.

Table 6. Compliance with federal gasoline consumption targets: 1980.

State	Gallons (000s) Consumption	Gallons (000s) Target	Difference Between Consumption and Target (%)	Difference Between 1980 and 1979 Consumption (%)
Alabama	1 962 046	2 023 268	-3.0	-6.3
Alaska	201 373	188 082	+7.1	-2.5
Arizona	1 328 722	1 374 846	-3.3	-6.0
Arkansas	1 178 800	1 225 409	-3.8	-7.2
California	10 992 050	11 324 244	-2.9	-3.3
Colorado	1 503 288	1 525 537	-1.5	-3.4
Connecticut	1 327 582	1 312 612	+1.1	-3.3
Delaware	293 851	285 542	+2.9	-4.1
D.C.	171 451	197 051	-13.0	-15.7
Florida	4 810 520	4 727 816	+1.7	-1.9
Georgia	2 874 923	2 884 955	-0.3	-4.9
Hawaii	354 529	312 488	+13.5	+6.6
Idaho	488 333	536 626	-9.0	-9.4
Illinois	4 816 780	5 178 087	-7.0	-7.1
Indiana	2 686 146	2 813 475	-4.5	-7.2
Iowa	1 561 192	1 633 340	-4.4	-9.2
Kansas	1 310 568	1 390 549	-5.8	-6.8
Kentucky	1 755 397	1 798 091	-2.4	-6.0
Louisiana	2 081 328	2 028 165	+2.6	-3.6
Maine	517 014	532 509	-2.9	-4.6
Maryland	1 941 209	1 865 491	+4.1	-0.5
Massachusetts	2 301 675	2 254 034	+2.1	-4.6
Michigan	4 274 036	4 547 529	-6.0	-10.1
Minnesota	2 045 270	2 145 552	-4.7	-7.9
Mississippi	1 194 845	1 221 127	-2.2	-7.5
Missouri	2 602 627	2 686 115	-3.1	-6.6
Montana	459 950	491 197	-6.4	-7.9
Nebraska	816 426	875 403	-6.7	-10.0
Nevada	500 286	510 594	-2.0	-0.1
New Hampshire	413 214	427 935	-3.9	-5.2
New Jersey	3 260 992	3 200 617	+1.9	-3.9
New Mexico	746 655	787 160	-5.1	-5.9
New York	5 672 549	5 614 538	+1.0	-4.7
North Carolina	2 932 274	3 006 470	-2.5	-6.3
North Dakota	407 250	431 445	-5.6	-8.2
Ohio	4 982 574	5 025 549	-0.8	-7.0
Oklahoma	1 845 259	1 862 067	-0.9	-2.8
Oregon	1 330 612	1 363 613	-2.4	-3.8
Pennsylvania	4 700 328	4 720 187	-0.4	-6.8
Rhode Island	381 826	375 618	+1.6	-3.3
South Carolina	1 554 787	1 601 891	-2.9	-6.2
South Dakota	423 517	460 279	-8.0	-10.3
Tennessee	2 417 939	2 440 716	-0.9	-4.4
Texas	8 106 499	8 311 174	-2.5	-6.9
Utah	734 992	736 217	-0.2	+0.6
Vermont	238 842	247 599	-3.5	-8.5
Virginia	2 599 199	2 633 762	-1.3	-5.1
Washington	1 882 513	1 962 400	-4.1	-5.7
West Virginia	845 242	840 486	+0.5	-4.9
Wisconsin	2 177 363	2 260 026	-3.7	-7.4
Wyoming	373 723	389 916	-4.2	-2.1
Total	106 378 366	108 515 417	-2.0	-5.5

FUEL TARGETS

The President is empowered to impose mandatory gasoline conservation targets for each state on a finding of an imminent shortage. The state would be required to meet these targets, which are the product of gasoline use during a three-year period. Currently, DOE has established voluntary targets as a way to encourage states to conserve and to facilitate the EECA planning process. A state is in compliance with the target if its cumulative consumption is within 2 percent/year of the target. At the time of this report, 39 states, including the District of Columbia, are meeting the targets for 1980, and only 6 states--Alaska, Hawaii, Delaware, Louisiana, Massachusetts, and Maryland--are above the allowable percentage error of 2 percent.

While it should be understood that the present voluntary targets may well be quite different from any mandatory target, they do serve a useful purpose. The target program familiarizes the states with the procedures used by DOE and also emphasizes the urgency of energy conservation. However, these targets have come under fire. In testimony before a congressional subcommittee (2), it has been suggested that the national quarterly targets were higher than the national gasoline consumption projected by DOE.

An analysis of Table 6 shows another side of the coin. In a comparison of 1980 and 1979 state gasoline consumption, all but Hawaii and Utah have reduced their consumption. This suggests that most states can meet the targets but are consuming considerably less gasoline compared with the same period in the previous year. The targets are within reach, but they represent a real savings. The total state consumption was 5.5 percent less in 1980 than in 1979 and met the target by 2 percent.

BENEFITS OF PLAN

Basically, there are four responses to energy emergencies, the first three of which reduce fuel consumption without loss of mobility:

1. Public response--Consumers will make changes in travel patterns to replace lost mobility implied by a shortage even if government takes no action. For example, by switching to transit, carpooling, and organizing trips better, consumers can maintain mobility while reducing vehicle travel and thus fuel consumption.
2. Government actions--Government agencies can implement measures in cooperation with private business to help maintain mobility by providing new or expanded services or by helping consumers to use existing services and other measures to maintain order, to reduce negative economic impacts, and to distribute negative impacts equitably.
3. Improvements in fleet fuel efficiency--The improvements in average automobile fuel efficiency as new cars are purchased and older cars are retired over the years continue to preserve mobility with less fuel. Vehicle miles of travel are constrained by the shortage level and the fuel efficiency of the fleet.
4. Reduction in mobility--Reduction in mobility is the amount of reduction in fuel use to be made up by reducing mobility. Mobility is defined as the ability of a person to travel for different purposes by whatever mode and circumstance he or she would choose.

How effective the first three responses are to a fuel shortage will determine the extent of reductions in mobility necessary to balance supply and demand of fuel. Since the businesses and residents of a state face potential hardships and losses, assessing the impacts of each measure, individually and in total, is an essential component of emergency energy planning. Specifically, each measure should be evaluated for expected energy savings and for social and economic impacts.

The survey asked questions concerning the extent of such an assessment by the states. More than half the states that responded did not determine the amount of energy to be saved, expressed as a percentage of annual state gasoline use, due to their EECA plan. Typical answers were that it varied, it depended on the severity of the shortage, or it would save as much as necessary. Very few of the plans examined contained an analysis of the energy savings expected.

The other area that the plans do not generally address involves economic impacts such as (a) loss of income from fuel price increases, (b) economic value of lost mobility, (c) losses due to waiting in

gasoline lines, (d) revenue losses to government (fuel taxes and tolls), and (e) losses to travel and recreation industries.

Such an assessment in advance of a shortage can minimize opposition by those directly affected and can help identify those steps that can relieve some of the hardships created by the emergency measures.

SUMMARY AND CONCLUSIONS

While emergency energy conservation planning is certainly not progressing uniformly throughout the country, the survey noted that a considerable amount of activity is (or at least was) under way. The conflict in the Persian Gulf region, the escalation of prices by the Organization of Petroleum Exporting Countries, and the DOE Emergency Planning Grants have served as the impetus for further planning. However, as conditions change in the demand, supply, and price of fuel, the plans need to be refined to ensure their responsiveness.

Some of the more specific shortcomings of emergency planning to date include the following:

1. Lack of money for plan development and implementation,
2. Inadequate cost estimates of measures,
3. Lack of good coordination with local plans,
4. Lack of evaluations regarding energy savings due to the plans, and
5. No assessment of economic impacts of the measures.

The current redirection of federal policy appears to be toward reliance on an unregulated market to ensure an orderly adjustment to any future interruption in energy supply. States cannot rely on the Federal Gasoline Rationing Plan, the federal standby plan, or EECA regulations for the next shortage. Funding for developing state plans or implementing them may not be forthcoming. Thus, the onus is on the state to ensure that appropriate measures are evaluated and included in its planning efforts.

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Efficacy of Urban-Area Transportation Contingency Plans: A Study of Completed Plans

ARTHUR POLITANO

As of October 1981, approximately 93 percent of all urban areas had begun transportation energy contingency plans and 37 percent of all urban areas had completed them. An exploratory study of a sample of completed plans was undertaken in order to understand their ability to be implemented and to suggest improvements that would increase the efficacy of those plans not yet completed. The study relied on the Federal Highway Administration's field resources to collect completed plans. A total of 20 completed plans were studied by the headquarter's staff of the Federal Highway Administration and the Urban Mass Transportation Administration. The sample was chosen randomly, and the population of the corresponding cities ranged from 25 000 to 1 180 000, covering all regions of the country. The summer 1979 energy shortage showed that some plans were implemented well and others were not. Based on these experiences, four elements of completed plans were examined: scope, organization, timing, and efficacy of measures. As a result of the study, it was possible to identify those aspects of a plan that could make it more implementable and effective. The plan would (a) cover an entire urbanized area and all modes, (b) include intergovernmental and interagency agreements concerning responsibility for implementation, (c) identify preimplementation tasks and a mechanism to phase in tasks, and (d) contain provisions to evaluate the potential and appropriateness of a measure and its attendant barriers. It is hoped that these observations will help local areas to improve the quality of transportation energy contingency plans.

On January 28, 1981, President Reagan removed price and allocation controls on U.S. crude oil and refined petroleum products by issuing Executive Order 12287. By eliminating restrictive price and allocation controls, the President sought to encourage conservation of energy through the increase of domestic oil prices.

Consistent with the President's direction, the U.S. Department of Energy (DOE) issued its latest National Energy Policy Plan (1). The policy plan relies on (a) market forces, (b) growth in the Strategic Petroleum Reserve, (c) dual-fuel capability for manufacturers and utilities, (d) increased domestic output, and (e) international coordination in order to ensure emergency preparedness on a national level. These actions will reduce the pressure on local areas to take drastic actions in the event of future energy emergencies. In order to assist local areas to help themselves, a reexami-

nation of urban area experiences with energy contingency planning may prove helpful.

Although the energy shortages of 1973 and 1974 dissipated quickly, they left the federal government and the Congress with a resolve to avoid future hardships resulting from shortages. The first major effort was begun by Congress with the passage of the Energy Policy and Conservation Act of 1975. In it, Congress required the President to submit an energy conservation contingency plan to apply to all states.

The next major effort of Congress was the passage of the Power Plants and Industrial Fuel Act of 1978. In responding to the growing dependence of the U.S. economy on foreign oil and its implications for national security, Congress required the President to issue an executive order that would promote energy conservation among federal agencies and their respective federal-aid programs. The last major effort of Congress was the passage of the Emergency Energy Conservation Act of 1979. This act (a) allowed the President to establish energy conservation targets for federal and state governments, (b) required state governors to submit emergency conservation plans within 45 days of the publication of conservation targets, and (c) directed the President to prepare a Standby Federal Energy Conservation Plan for states whose plans fail to meet conservation targets.

Subsequently, the above actions have undergone some modification. As per the Energy Conservation Act of 1979, the standby federal plan would be implemented in each state if the state were to fail to meet conservation targets set by the President in the time of a shortage. Congress approved a standby rationing plan in December 1979.

Almost independently of the congressional efforts, the Federal Highway Administration (FHWA) and the Urban Mass Transportation Administration (UMTA) on March 29, 1979, issued a joint memorandum to their field staffs, advising that they stress energy contingency planning as a priority planning activity. This memorandum was issued prior to any formal regulation after an examination of oil stocks and consumption demand indicated a potential shortage. In support of the accelerated planning activity, the U.S. Department of Transportation (DOT) amended a DOE contract with the Massachusetts Institute of Technology, requesting the development of appropriate technical information. This resulted in the familiar trilogy of reports entitled Transportation Energy Contingency Strategies (2).

On August 29, 1980, DOT formally issued regulations (Petroleum and Natural Gas Conservation: Federal Transportation Assistance Programs) responding to the requirements of Executive Order 12185. The approach of FHWA and UMTA to this effort was to modify existing regulations. Under Section 450.120(a)(8)(ii)(c) of the regulations, metropolitan planning organizations (MPOs) were asked to include, as necessary, efforts to "respond to short-term disruptions in their energy supply" as part of their planning activities. The role of DOT has been primarily to provide nonprescriptive technical assistance. In order to determine the status of urban energy contingency plans and to suggest improvements that would increase their local effectiveness, FHWA and UMTA embarked on a short-term study of 20 completed contingency plans.

APPROACH

The study approach consisted of four tasks. The first task was to identify a universe of states whose urban areas had completed transportation energy contingency plans. This information was readily available from the December 31, 1980, Program Emphasis Area reports of FHWA. For each region, the reports included a state-by-state summary of the number of local contingency plans initiated and completed.

The second task was to select urban areas and to solicit contingency plans. In order to ensure national representation, the sample of urban areas had to be drawn from as many regions as possible and had to reflect a variety of sizes. Of the 21 states that reported completed urban area contingency plans, 10 were randomly selected and supplemented with 4 other states to enlarge regional representation. The states and respective urban areas studied were as follows:

State	Urban Area
Colorado	Denver, Pueblo
Connecticut	Westport, Norwalk
Florida	Gainesville, Miami
Idaho	Boise
Indiana	Indianapolis, Anderson
Louisiana	New Orleans
Minnesota	Minneapolis-St. Paul
Mississippi	Jackson
Missouri	Kansas City, St. Louis
North Carolina	Asheville, Charlotte
Pennsylvania	Allentown
Tennessee	Nashville
Texas	San Antonio
West Virginia	Parkersburg

For each state, two completed plans were selected, when available. The first was selected from a small metropolitan area and the second from a large one. From the combined 14 states, a total of 20 urban areas were selected for the sample.

Once the sample was selected, the next step was to acquire the plans. For this step, the FHWA regional and division offices were most helpful. As necessary, these offices obtained the plans from either the state or the urbanized area.

The fourth and last step in the analysis was to identify the criteria according to which the completed plans would be studied. Experience with energy contingency plans has indicated that most areas made efforts to prepare effective plans. The great majority of plans followed a list of activities suggested in part 1 of the March 1980 report, Transportation Energy Contingency Strategies. This report, prepared by the Massachusetts Institute of Technology, listed activities for urban areas to pursue. Encouraged by the report, most areas undertook a comprehensive planning effort.

Still, areas experienced difficulties in implementing their contingency plans. Consequently, it was decided to concentrate the study on plan implementability, since this was the more pressing concern. The basis for this focus comes from several sources (3;4;5, p. 28), all of which pointed to the need for implementable plans.

The criteria used in the study are listed below:

1. Organization--(a) Identification of agencies responsible for planning and implementing conservation measures and their respective and specific tasks (3,4), (b) interagency agreement specifying implementation responsibilities, measures to be applied, and a single coordinating agency (3,4), (c) intergovernmental agreement among elected officials specifying the nature of support for implementing the contingency plan (3,4), and (d) mechanism to coordinate plans with the state energy office and state transportation agency (5);
2. Process--(a) Inclusion of a mechanism that can phase in measures in order to avoid a crisis (4,5), (b) availability of local funds and resources to

support implementation of contingency measures (4,5), and (c) existence of a process to periodically update plans and suitability of measures (4,5);

3. Scope--Coverage of entire metropolitan area and all modes (4,5); and

4. Measures--(a) Evaluation of a measure's ability to conserve fuel and maintain mobility (3,5), (b) identification and completion of preimplementation tasks for each measure (3-5), (c) measures specifically tailored to the urban area (3,4), and (d) identification and resolution of barriers to the implementation of measures (3-5).

The criteria were combined to form common review materials, which were applied to each of the 20 urban contingency plans. Both UMTA and FHWA headquarters staff participated in the reviews.

RESULTS

As of October 1981, 93 percent of all metropolitan areas had initiated plans. Fifty-five plans have been completed, which represents about 37 percent of all metropolitan areas. The 20 plans used in this analysis, 90 percent of which were prepared after the spring of 1979, were completed between February 1978 and January 1981.

The 20 plans cover a range of cities, from Westport, Connecticut, with a population of 25 000 to New Orleans with a population of 1 180 000. Of all plans used in this study, more than 70 percent came from cities with less than 500 000 population.

The agency that most often prepared the energy contingency plan was the MPO. MPOs completed 55 percent of all plans, transit agencies 20 percent, and cities 15 percent.

The four elements of contingency plans listed earlier--scope of plans, organization, timeliness of measures, and efficacy of measures--are discussed below.

Scope

The plans in the study sample cover the range of modes and areas. Nevertheless, most of the plans cover a single mode, mostly transit-related measures (40 percent), and other modes (15 percent). The remainder (45 percent) cover all modes. Furthermore, most actions cover the public sector (65 percent). The remainder cover both the public and private sectors. In addition, most plans (65 percent) cover all areas; the remainder cover only the central city.

Organization

Of the 20 plans in the study sample, 55 percent indicate neither the agency responsible for coordinating plan implementation nor which agencies are to implement which measures, leaving a doubt about how these plans would be applied.

Most plans that indicate a coordinated implementation approach do it through a metropolitanwide council or commission (20 percent of the entire sample). Other means include a transit authority, an emergency energy coordinator, or a sharing of responsibility based on each agency's expertise.

The existence of formal agreements would eliminate confusion between agencies and speed a coordinated implementation. Yet 90 percent of all plans reviewed have no formal agreements among implementing agencies, 85 percent have no agreements among government agencies, and 75 percent show no coordination between the state transportation and energy offices.

Timeliness of Measures

Of the 20 plans in the study sample, 45 percent explicitly identify preimplementation tasks for energy contingency measures. Description of preimplementation tasks ranges from a brief sentence to a more expanded description. Thirty percent of the plans give some attention to phasing in contingency measures.

Moreover, of the 20 plans studied, only 20 percent have provisions for updating. These facts suggest difficulty with the timely implementation of measures.

Efficacy

Of the 20 plans studied, only 45 percent consider financing in one fashion or another. Two plans provide specific information on the costs to implement measures. The remaining areas plan on seeking funds from metropolitan councils or state or federal governments. Of the 20 plans studied, 40 percent identify sources of funds to implement contingency measures.

It is appropriate to select contingency measures based on specific local and statewide contexts rather than on expected common conditions. To do otherwise would severely limit the public acceptability of a measure and its efficacy. Still, a review of 20 contingency plans shows that only 25 percent of all plans specifically select measures based on local needs. In the remaining cases (75 percent of all plans), areas identify candidate measures for implementation but leave it to others to make a selection. This latter case is a potentially confusing situation.

Of the 20 plans studied, 50 percent consider the energy conservation potential of a measure and 35 percent consider, in general fashion, the ability of a measure to maintain mobility. The approach has been to identify the increase in transit ridership or demand for carpooling and to develop measures to meet increases in demand. The sole emphasis on conservation seems to miss the concern for maintaining mobility. Above all, the concern for people, and thereby mobility, is paramount.

Last, 35 percent of the plans identify barriers to implementation, and 10 percent of the plans discuss ways of overcoming them. This suggests that only a few cities will not face delays in implementing contingency measures.

RECOMMENDATIONS

In 1979, the fuel shortage dissipated so quickly that contingency plans were not fully implemented and in some cases were never implemented (4). Implementation of contingency plans requires preparatory work and coordination. Many competing interests have to be brought together and made to operate cooperatively. In addition, if contingency measures are to be effective locally, they should be evaluated and ready for implementation in advance of a shortage. Only in this way can the impacts of a shortage be abated.

Scope

For contingency plans to be truly comprehensive and evenhanded, it would seem desirable to develop contingency plans that cover a broad range of locations and modes. Intrasuburban travel, private-sector participation, and automobile-related measures are more often neglected. These are lost opportunities for addressing emergency circumstances at the local level.

An example of comprehensive energy contingency plans covering the entire region can typically be found in plans prepared by MPOs (approximately 55 percent of sample plans). A good example of a comprehensive plan is the one developed for the Kansas City Metropolitan Region by the Mid-American Regional Council (MARC), the MPO (6). MARC covers eight counties and three cities in the Kansas City area.

With few exceptions, the focus of most plans is on the work trip, ostensibly because it is identifiable and repetitive. Yet some measure could be applied to nonwork trips. Non-work-oriented measures, taken from the Miami contingency plan (7), have included (a) voluntary driveless days, (b) reducing travel through telecommunication, (c) reducing or combining discretionary trips, and (d) bicycle transportation incentives. Some thought regarding the use of measures, focusing on nonwork trips and intrasuburban trips, appears necessary.

Organization

Unless institutional roles are decided and organizational planning is completed in advance of an emergency, local areas will lose valuable time that could be better used to phase in measures. Appropriately, then, a major task of contingency planning could be to identify the jurisdiction or the agency that should act in a crisis and to get it to acknowledge responsibility. To do this, key elected officials should be made aware of the important and potential benefit of contingency planning and should agree to provide appropriate action in an emergency.

With the help of interagency agreements between implementing agencies and intergovernmental agreements between local jurisdictions, the structure and context for implementing measures are set. Rather than being a stumbling block, interaction between agencies and governments could be used to develop complementary responses to a shortage.

To be effective at the local level, interagency agreements may have to identify (a) the lead coordinating agency, (b) participating agencies, (c) responsibility for implementing measures, (d) responsibility for coordinating implementation, and (e) measures to be applied. Similarly, intergovernmental agreements may include (a) support for implementing designated measures in a jurisdiction and (b) commitment to implement measures as required or indicated by the lead coordinating agency or in some other manner. However, many elements in an agreement will depend on the complexity of transportation issues in each local area.

Timing of Measures

During the 1979 shortage, calls for assistance flooded the ridesharing agencies and, because of insufficient staff, agencies were slow in responding. Similarly, calls for transit information were overloading existing lines. Agencies were often too late to react and with too little effort (4).

For all energy contingency measures, a need exists to identify and accomplish preimplementation tasks if the measures are to be implemented smoothly and if the implementation is to abate the shortage. In addition, once contingency measures have been identified, they should be periodically reviewed to ensure that the plans are consistent with current circumstances. The events of the 1979 energy shortage showed that those areas that implemented energy contingency measures in advance of the shortage could cope better. In the Dallas-Fort Worth area, local energy coordinators were already in place prior to the fuel shortage and were very effective in keeping the general public and local governments informed (4).

Timeliness is a plan's relevancy to current conditions. Alternatively, we might ask, How current is it? The justification for updating plans periodically is understandable. The external assumptions with which contingency plans are prepared change. Unless the plan and the measures reflect the change, implementation, at best, will not benefit the area and, at worst, will be a waste of time. From the plans studied, an update may be indicated every third year or on an as-needed basis.

Efficacy

A U.S. General Accounting Office report (5) found that the issue of funding is likely to be a constraint on the effectiveness of local response to an energy shortage. Judging by the austerity of the national economy, cities can best meet the expenses by exploring local sources of financing in advance of a shortage. Some options have included preprogramming of funds, as in Kansas City, Missouri, or establishing a contingency fund, as in Norwalk, Connecticut. In any case, local areas could identify needed funds and budget an equivalent amount for use in the event of an emergency. Expenses may include hiring additional staff and extra overtime costs.

A study from the Office of the Secretary of Transportation (4) found that several transit properties could not meet the surge in demand in spite of the fact that they had prepared for a shortage by rehabilitating and placing old buses in service. In other cases, a shortage of vans and personnel existed. Consequently, the surge in demand could not be met by the contingency measure taken. These difficulties raise a question as to whether measures are evaluated for their ability to maintain mobility in addition to their ability to conserve energy. Moreover, one could question whether measures were specifically chosen to meet the area's needs.

The purpose of a contingency plan is to provide for basic mobility and public safety during an emergency situation. Therefore, the ability of each selected measure to maintain mobility should be known. In this way, a local area can determine whether a measure can alleviate the situation by itself or whether other measures are needed. Furthermore, it is important to know at what intensity a measure will be implemented. Only by knowing the potential of a measure to maintain mobility can an area determine how intensively a measure should be applied.

In some cases, even though appropriate measures were selected and implemented, barriers reduced the effectiveness of a measure. In 1979, for example, the use of school buses was hampered by constraints on vehicle design, the fact that school hours coincided with the peak morning travel period, etc. Common sense suggests that ways of overcoming barriers to the implementation of any measure should be considered and acted on before a shortage occurs.

CONCLUSIONS

Since the March 29, 1979, memorandum on energy contingency planning, the U.S. oil picture has changed. In 1979, gasoline consumption exceeded production. Since December 1980, the opposite has been true (8). As recently as June 1981, the Lundberg Letter reported that "high gasoline stocks are still with us" (9).

On the international level, any interruption in supply, deliberate or otherwise, could change this situation suddenly and radically. It is unclear

whether world petroleum supplies will tighten with other Middle Eastern conflicts. If so, supplies could be tight and the familiar shortages, lines, and price increases could recur. On the national level, any number of possible scenarios may affect the availability of fuels and consequently may disrupt transportation. These scenarios may include severe winter weather, natural disaster, transit strikes or work stoppages, increased consumer demand, changes in the price of crude oil, and others. Since the demand-supply balance is tenuous and since both international and national events cannot be predicted with certainty, local self-interest would suggest a review of the implementability of an urban plan with respect to maintaining mobility under any of the above scenarios.

The most recent federal action to avoid shortages was taken on January 28, 1981, with the decontrol of crude oil and petroleum products. In this case, the market is the allocation mechanism, since the price is allowed to rise to the market-clearing level. The price reduces the demand for gasoline to the level of the supply available; very simply, as prices increase the gallons consumed decrease. Some research indicates that a 1 percent shortage in gasoline will result in a 5 percent increase in price (10).

Since the marketplace allocates gasoline according to what the buyer will bear, there are other issues of equity and costs that may have to be considered. Certain segments of the population may be affected more than others. A contingency plan may begin to consider these issues also.

Although decontrol of oil and petroleum products may lead to less concern about gasoline consumption in urban areas, the implementability of their plans may still be a concern because of the possible emergencies listed in this paper. The one that has been occurring with increasing frequency is the transit strike. A noteworthy example is the New York strike of April 1980, in which all bus and subway services stopped for 11 days. Since a contingency plan had been prepared in advance of the strike, public agencies were able to coordinate their efforts and maintain mobility and public safety. Thus, a contingency plan was able to alleviate the adverse effects of the strike.

Based on this study of 20 contingency plans, more emphasis on plan implementation appears necessary to make the plans effective in meeting local mobility needs. The following tasks seem particularly useful:

1. Increase the scope of plans to include all modes on a regional basis, including, where appropriate, the private as well as the public sector.
2. Develop interagency agreements or memoranda of understanding that specify each jurisdiction's commitment and cooperation in implementing the regional contingency plan.
3. Develop a monitoring mechanism that can be used to signal an energy shortage in an area.
4. Identify and complete preimplementation tasks.
5. Update energy contingency plans and measures to reflect the existing situation, perhaps every 3 years or as necessary.
6. Identify and commit local sources of funds to support implementation of the plan.
7. Evaluate each measure for its appropriateness to each area, its potential effectiveness in bringing about the desired mobility and conservation levels, and its potential impact.
8. Identify obstacles to implementing measures and develop appropriate solutions.

If these tasks are completed, it is likely that urbanized areas will be prepared for dealing with an energy shortage. The eight tasks listed above require considerable effort. It appears appropriate for local governments to take the lead in preparing, implementing, and financing local contingency plans. Since local governments would be closest to the effects of a shortage, they are in the best position to prepare specific measures for abating the effects of a shortage. By taking the lead, they will also have the flexibility to prepare a plan that is sensitive to their own needs. To supplement local efforts, the federal role will likely be one of providing nonprescriptive technical assistance on an as-needed basis.

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National Methanol Fuel Systems: A Transportation Fuel Pathway

DANIEL SPERLING

One set of opportunities for decreasing the transportation sector's dependence on petroleum is the substitution of methanol for gasoline. The potential for implementing the transition is investigated within the context of a development path. Elsewhere, the feasibility of methanol has been studied mostly from either a production or an end-use perspective. Here, a systems perspective is used to integrate methanol production, distribution, and end-use activities into a staged development path. The path chosen is one designed to simulate a rapid and large production buildup. The choice of a high-growth path accentuates future conflicts and therefore sets the framework for pursuing the two purposes of the paper: (a) to highlight the critical factors that affect the expansion of methanol fuel activities and (b) to identify key opportunities for hastening the transition to methanol fuels. A set of market penetration strategies is devised that best responds to constraints and opportunities, and specific government and industry actions are proposed to support these strategies. It is shown that technical, economic, and institutional barriers to efficient distribution and rapid market penetration may be overcome with a moderate amount of government support. That support depends, however, on the formation of a national consensus to support methanol as an alternative fuel. The implementability of a high-growth methanol path is addressed. The major concerns are examined in order to give policymakers and others an understanding of the costs and responsibilities government would have to assume in order to promote a rapid transition to methanol fuel use.

The three principal challenges facing the introduction of alcohol fuels are (a) establishment of a producing industry, (b) penetration of traditional petroleum markets, and (c) development of an efficient distribution system. These challenges must be addressed in concert, for action taken with regard to one problem area may severely affect the feasibility of options in another area. The structure that has been used to investigate these challenges is a development path.

This paper focuses on one methanol development path. The chosen path is one designed to simulate a rapid and large production buildup that would reach 1.5 million bbl/day of methanol in the mid to late 1990s. It represents the upper limit of opportunities for introducing methanol fuel to this country. The choice of this high-growth scenario is intentional. It accentuates future conflicts and therefore sets the framework for pursuing the two purposes of this paper: (a) to highlight the critical factors affecting the expansion of methanol fuel activities and (b) to identify key opportunities for hastening the transition to methanol fuels.

The problem of introducing methanol fuels into the transportation sector is of more than passing interest. Methanol may prove to be the most attractive replacement for gasoline in motor vehicles. Recent cost estimates indicate that methanol from coal (if available) would probably already be price competitive with gasoline and less expensive than any other available fuel, especially when one considers the higher quality and energy efficiency provided by methanol (1-3).

The paper is organized to focus on the three challenges cited earlier. First, to set the stage, the general characteristics and attributes of the chosen path are presented. Then the supply component is specified for this high-growth development path. Financial risk and its impact on plant investment are the main concerns here. The most attractive end-use markets for methanol are also identified and quantified. The supply industry and end-use markets are then compared. The resulting disequilibrium between supply and demand serves as an input to the subsequent analysis of fuel distribution needs. Next, the major components of the development path having been examined, a set of market penetration strategies is devised. Finally, the major constraints and uncertainties facing the introduction of methanol fuels are summarized within the context of the three challenges cited earlier. Where precise policy opportunities exist to solve or mitigate constraints and uncertainties, they are presented. Where obvious answers do not exist, more general approaches are suggested.

INTRODUCTION TO DEVELOPMENT PATH

The opportunity for producing the most alcohol in the shortest time frame at the lowest cost comes from the indirect liquefaction of coal into methanol. (Other important feedstocks might be "remote" natural gas, which is now flared or left undisturbed, and cellulosic biomass, such as wood. These secondary sources could not, however, be diverted to methanol production in as large quantities, or as inexpensively, as coal in the next 20-30 years or so.) The development path is therefore based on the construction of coal-to-methanol processing plants. It will be shown how a large coal-to-methanol industry leads to the deployment and use of systems and activities that are national in scope. A salient feature of the development path, and one that influences the evaluation of many other path activities, is the large size of individual plants.

Economies of scale will dictate that individual plants be very large in size, at capacities of 40 000 bbl/day or more, costing more than $2 billion (1). Two important implications of large plant size are that (a) each plant will constitute a significant increment to the supply base and (b) large amounts of capital will be concentrated in relatively few coal-to-methanol projects.

The concentration of investments in only a few projects and the need to manage large units of methanol output create situations that favor the participation of large economic units in this path. The large processing plants must be matched with similarly large distribution systems and massive modification or production of end-use technologies. Thus, this path requires investment in pipelines to transport the large quantities of methanol and large production runs of methanol vehicles by major automobile makers to provide the end-use technology. The diversion of investments to a new industry and new activities is risky, however. To achieve rapid production increases and market penetration would require the participation of large firms that can use their market power and resources to reduce uncertainty and risk.

Uncertainty comes about in two ways. First, it comes from the unpredictability of petroleum prices. Methanol is a substitute for petroleum products, mostly gasoline; the market price of methanol will therefore be determined by the price of gasoline. This uncertainty is beyond the influence of producers, yet it directly affects their rate of return on investment. The second source of uncertainty is the virtual absence of methanol markets. Prospective plant owners are called on to invest

substantial sums of money in projects that require a lead time for construction of 5-10 years. It is difficult to forecast markets, especially in these early years of the path, and even more difficult for producers to procure sales contracts for methanol so far in advance of actual plant operation.

Risk is based in part on these uncertainties of price and market and in part on the construction and operation of the physical plant itself. Although the indirect liquefaction technologies to be used for methanol production have been successfully demonstrated, there are always engineering problems in upsizing demonstration plants and putting together old technologies in new combinations. Unexpected problems are often expensive to resolve and may also lead to costly construction delays. Susceptibility to disruptions, such as natural disasters or strikes by coal miners or rail workers, is another source of risk.

The high degree of uncertainty and risk is a major impediment to the implementation of an ambitious methanol development path. If it is determined that such an effort is in the nation's interest, then it may be necessary for the public sector to reduce price and market uncertainty for producers and to encourage intraindustry and interindustry coordination by easing antitrust rules. The rapid-growth path presented in this paper would only come about as the result of coordinated and concerted efforts by key actors in the public and private sectors. These efforts would recognize and build on the interdependencies between and among producers, shippers, and users. Intentional and structured systems would have to be established to promote the production, distribution, and use of large volumes of methanol. Smooth and successful implementation of methanol-serving systems would require the blessing and support of government. Public policy therefore plays a key role in the emergence of a high-growth methanol development path.

PATH SPECIFICATION

Supply Industry

The predominant production sequences in this path are conversion of coal to methanol and, secondarily, remote natural gas to methanol. In both cases, processing plants are large and expensive--generally \$2-4 billion/plant for coal conversion and somewhat less for gas conversion--and are generally owned by large energy companies.

Natural gas is the current feedstock for production of industrial methanol; the conversion processes are well established. Remote gas will be converted by those same processes. The first and second generations of coal-to-methanol plants, at least through 1995, would use exclusively the indirect liquefaction processes, where coal is gasified into a synthetic gas that in turn is processed into methanol. Some processes are already commercialized, and others are near commercialization. The newer and more efficient processes are less proven and carry some risk. A key factor in gas conversion and most indirect liquefaction processes is that methanol is the only important output (although some coal-to-methanol processes could also produce significant amounts of synthetic natural gas). This inflexibility makes producers more vulnerable to price and market shifts.

The supply components for the hypothesized development path are drawn from surveys of actual proposed coal-to-synfuel projects. Most of the proposed plants were identified from applications for financial assistance to the federally sponsored U.S. Synthetic Fuels Corporation. The plants in most cases were proposed to begin operations generally by 1993 (in most cases, conditioned on some form of financial support by the U.S. government). Proposed plant capacities are mostly between 10 000 and 50 000 bbl/day. Full-sized commercial coal-to-methanol plants are expected to be somewhat larger, however--typically 50 000 bbl/day or more (4).

Table 1. Proposed coal synfuel plants.

State	No. of Plants	State	No. of Plants
Alaska	1	North Dakota	3
Alabama	1	Pennsylvania	2
California	1	Tennessee	2
Colorado	3	Texas	1
Illinois	2	Utah	2
Kentucky	2	Virginia	1
Louisiana	1	Washington	1
Montana	4	West Virginia	1
New Mexico	2	Wyoming	2
North Carolina	1		

Note: Data based on surveys prepared for the National Alcohol Fuel Commission (5) and applications to the U.S. Synthetic Fuels Corporation (6).

Table 1 lists 33 plants identified in the surveys. They are hypothesized to constitute the mid-term supply component of the high-growth methanol development path, for the period 1995-2000. Average plant output is assumed to be 50 000 bbl/day, which sets industry capacity at 1.65 million bbl/day (25 billion gal/year). This production level is ambitious; although it is compatible with the lofty goals established by the Energy Security Act of 1980, it would satisfy only about 15 percent of 1980 gasoline energy demand. The 33 plants would consume 120 million tons of coal annually, about 5-10 percent of projected 1995 coal production (7).

The precise plants identified in the surveys will not be the ones finally constructed as coal-to-methanol plants, but they do provide a good indication of where future plants might locate. The apparent preference for western sites is in large part due to the lower cost of western coal and its suitability for the first generation of indirect liquefaction processes used to produce methanol. Other preferred feedstocks are lignite in Texas and Montana and peat in North Carolina and Minnesota.

The major risks perceived by prospective coal-to-methanol producers are due to large market and price uncertainties; methanol markets are uncertain because they do not yet exist, and methanol prices are uncertain because they are mostly determined by oil prices, which in turn are mostly determined in the unpredictable political arena. These uncertainties could be significantly reduced by government price and purchase guarantees, similar to those currently proposed for the federally sponsored U.S. Synthetic Fuel Corporation.

The second source of risk perceived by coal-to-methanol producers is associated with the costs and reliability of the processing plant. This risk, though substantial, is less critical than price and market uncertainty for two reasons:

1. The plants will be based on existing technology or at least evolutionary improvements on it (4).
2. Prospective plant operators and owners have considerable experience with other industrial projects of similar size and the normal problems associated with them: construction delays, start-up and operating troubles, and unknown inflation rates of equipment and construction costs.

Given these conditions, it is anticipated that the coal-methanol industry will evolve like other

capital-intensive industries, such as petroleum refining; that is, a successive stream of technical process improvements will be made. [If the reported experience of the chemical methanol industry holds, cost reductions of 15-20 percent will be achieved over the first five years of operation (8).] Changes of the spectacular discontinuity variety will not be made, and therefore associated risks will also not be spectacular.

Potential Markets

Methanol is a high-quality fuel and a useful chemical. Methanol is currently used mostly in the chemical industries. In late 1979, a methanol derivative, MBTE, began to be used as an octane-boosting gasoline additive, replacing other traditional additives that were being restricted by the U.S. Environmental Protection Agency. By late 1980, almost 10 percent of total methanol production, equivalent to an annual rate of about 100 million gal, was being diverted to the MBTE additive (3).

The chemical market for methanol is projected to grow steadily in the foreseeable future but, generally, traditional natural gas feedstock sources will be retained (3). The chemical industry is not considered a significant near-term market for a new coal-to-methanol industry.

The greatest potential application for methanol is as a gasoline substitute, although it is an attractive fuel in other applications as well. Its attractiveness is based on technical, economic, and environmental criteria. Methanol is a high-quality (octane) fuel that potentially provides greater engine efficiency than any conventional petroleum products. Methanol also burns more cleanly than petroleum fuels, since it has no particulate or sulfur oxide emissions and greatly reduced nitrogen oxide emissions. Because methanol is a fairly expensive fuel, it is competitive only with the most expensive hydrocarbon fuels, such as gasoline and light distillates, and, of course, it is most competitive in areas where air pollution is a problem. Because the gasoline market is many magnitudes greater than any other potential end-use market, the focus of this paper is on the use of methanol as a gasoline substitute in the transportation sector.

An important qualifier applies here. The advantages of methanol, particularly its greater efficiency, are captured by redesigning an engine to take advantage of the different combustion characteristics of methanol. The use of methanol-gasoline blends in an unchanged (or slightly modified) gasoline engine will provide few or none of the potential efficiency benefits of methanol.

Other much smaller markets would also arise during the remainder of this century if large price-competitive methanol supplies became available. Principal secondary applications would be gasoline engines in nontransportation uses (e.g., agriculture and construction applications) and diesel engines in both transportation and industrial uses. Diesel engines are not a primary market because major retrofits and/or engineering advances need to be made before methanol can be used. Methanol can be used as a blend with both gasoline and diesel engines, but, again, the opportunities are more limited with diesels.

MATCHING SUPPLY WITH MARKETS: IMPLICATIONS FOR A DISTRIBUTION SYSTEM

Spatial Disequilibrium

The implementation of the high-growth development path quickly leads to spatial disequilibrium between demand and supply. The output of a single coal-to-methanol plant is greater than total gasoline consumption in some states. It would provide enough fuel for about 1 million automobiles.

Figure 1 shows that in the late 1990s, when total production would have surpassed the targeted 1.5 million bbl/day, six contiguous states in the Rocky Mountain and Great Plains areas would be producing a tremendous excess of methanol. Those six states, which contain 3 percent of the nation's population, would produce one-half of the methanol. Even if all six states converted all their vehicles and electric-generating gas turbines to methanol, they could consume only about one-third of the methanol they produced. The excess in the area would be truly enormous when one considers that actual market penetration in any given area is unlikely to exceed 10 percent of the potential market for at least several years after methanol sales begin. Market penetration is limited by the rate at which new vehicles are purchased. The adaptation of end-use technologies (especially motor vehicles) to methanol takes many years. Instantaneous markets do not become available for methanol when a new plant begins operations.

Methanol plants in the Rocky Mountain area, almost from the inception of the industry, will be as

Figure 1. Hypothesized methanol supply compared with 1980 gasoline fuel demand on energy-equivalent basis.

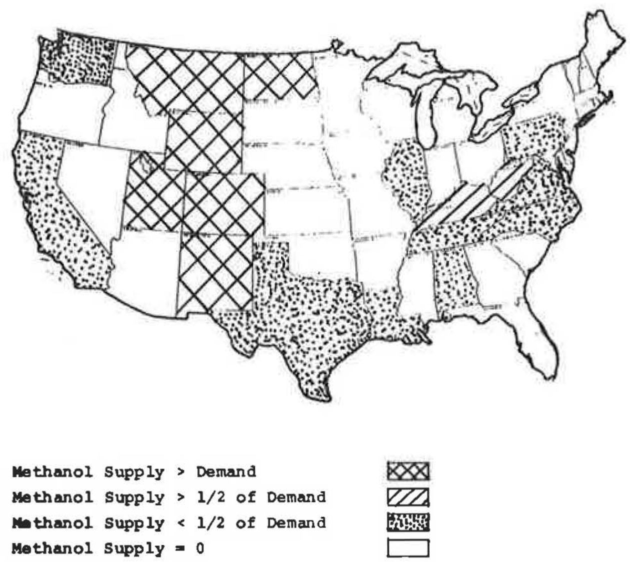
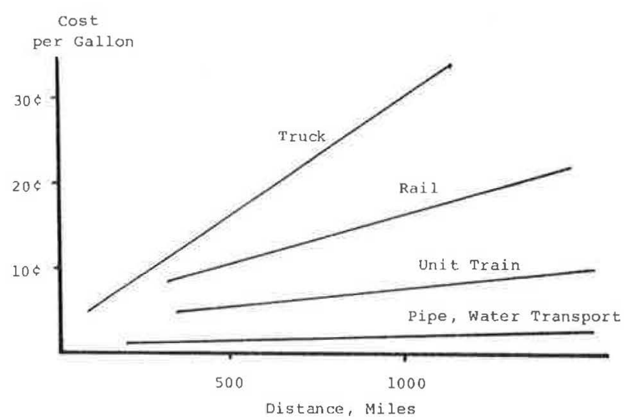


Figure 2. Liquid commodity freight rates: 1981.



far as 1000-2000 miles away from their principal markets. Plants located in Illinois and the Appalachian area will be closer to possible markets. With aggressive marketing of methanol as a transportation fuel, markets in Appalachia and nearby regions may be able to absorb locally produced methanol output as it becomes available.

Pipelines as Key to National Distribution

The movement of large volumes of methanol becomes feasible on one condition: inexpensive transportation services. Figure 2 illustrates the superiority of pipeline over rail and truck. The cost functions are intended only to be representative; actual rates vary considerably. With this caveat in mind, a rough estimate for the cost of a 1000-mile shipment of 1 gal of fuel would be as follows:

Mode	Cost (¢)
Truck	30
Rail	17
Unit train	8
Pipe	2

Because about 2 gal of methanol replace 1 gal of gasoline, the difference in transportation costs between pipe and truck would be 56¢ per gasoline-equivalent gallon and between unit train and pipe, 12¢/gal.

Long-distance methanol shipments generally are feasible only by pipe. (The costs of water transportation are similar to those of pipeline, but most coal conversion plants would not be located near waterways. Where water transportation is available, it is an attractive alternative.) Even for trips as short as 100 miles, pipe is the preferred mode if sufficient volume exists. Pipeline transportation is therefore essential to path development because of spatial disequilibrium between supply and demand.

As a rule of thumb, a minimum volume of about 10 000 bbl/day is required to justify a pipeline. Coal conversion plants will produce on the order of 50 000 bbl/day. So, even accounting for local use and diverse destinations, most plants, especially those in the Rocky Mountain and Great Plains areas, will depend on pipelines to decrease their distribution costs.

There are two obstacles to methanol distribution by pipeline: the large initial investment and the incompatibility of methanol with existing pipelines. Pipeline investment costs are large but not overwhelming. The cost of building a 1000-mile pipe to carry 50 000 bbl/day (which requires a 10-in-diameter pipe) would add about $150 million (9) to the initial $2 billion plant investment. The pipeline in this case adds 8 percent to the total investment.

The 8 percent pipeline cost covers only the first link in the trip to the final delivery point. Once fuel reaches the first terminal, it is often transshipped to other local terminals, where it is delivered locally by truck. Economies of scale exist all along the line. It is therefore in the interest of shippers to consolidate. The highest level of consolidation is complete integration of methanol into the existing petroleum product distribution system, where average distribution (transportation and storage) costs have hovered around 5¢/gal until recently (10).

Integrating methanol into the existing pipeline network, as an alternative to constructing new pipelines, presents difficulties (11). Product pipeline operators are generally hostile to alcohol, partly because it may strip away corrosion inhibitors but more importantly because the alcohol, especially methanol, may corrode and shorten the lives of pipelines, their major asset. Further testing is required but, if corrosion is a problem, pipes could be coated with special materials, although with some disruption and, according to industry sources, at some undetermined but probably large cost.

Methanol Blends in Distribution System

The use of methanol-gasoline blends requires some modifications in the existing distribution system but not because of the physical blending process. Blending could take place at oil refineries, bulk storage terminals, or in blending pumps at service stations; blending pumps are already widely used in some areas for gasoline, and blending at refineries and storage terminals presents no critical barriers. Some cost may be incurred by the logistics of blending, possibly more and longer transshipments, but it should not be too great (11). A more important drawback to blending is the need to deter water intrusion into the storage and transportation vessels of the distribution system.

The "wet" characteristics of the petroleum product distribution system may be a major barrier to the use of methanol-gasoline blends. Currently, water is allowed to intrude into storage tanks, pipelines, and other tank vessels. If methanol is used straight, water is not a problem. It is a problem, however, if methanol is blended with gasoline; even the presence of 0.1 percent water may cause the liquids to separate (12). Technically speaking, the petroleum distribution system could be easily dehydrated (it would require new valves, fixed roofs on storage tanks, and generally tighter operational controls), but the disruption and cost would be significant. No single major change would be required, but many small modifications would. Exxon data (updated and inflated to 1981 dollars) suggest that the cost for dehydrating the distribution system would be about 3-5¢/gal of methanol for a large methanol industry (13).

In terms of the distribution system, the disadvantages of methanol blending are not onerous. Already alcohol blending is occurring: In 1980, 135 million gal of ethanol and almost 100 million gal of methanol-based additives were blended with gasoline (3). The ethanol was blended in storage terminals in a 10/90 proportion with gasoline, and the methanol-based additives were blended at refineries.

MARKET PENETRATION STRATEGIES AND OPPORTUNITIES

Fuel prices are not explicitly treated in developing this ambitious nationally oriented path and in analyzing market penetration strategies. Petroleum products are the fuels against which methanol will compete for market share. Oil and gas will dominate those markets into the foreseeable future and will therefore determine fuel market value. To a large extent, however, oil and gas prices are set in the political arena and not in the market place, which creates great uncertainty over future price trends. Even if methanol production costs were precisely known, it would be difficult to predict specific prices and times when methanol could penetrate traditional oil and gas end-use markets.

Methanol offers advantages over other fuels, including presumably greater security of supply and cleaner burning qualities, which attract it to certain market segments even when it is not competitive on a price basis. Earlier in this paper, penetrable markets were identified. In this section, some credible penetration strategies are devised for marketing the methanol outputs of the development path's ambitious production schedule. Emphasis is

placed on the timing and matching of production, distribution, and marketing activities.

Transportation Sector

Methanol can be used as a fuel additive, as a component in a fuel blend, or straight. Each type of use has a role to play in the penetration of gasoline markets.

In the first stage of market penetration, methanol is used as a gasoline additive ("additive" is defined here as a liquid constituting up to 5 percent of fuel volume). It is highly attractive in that role because it boosts the octane rating of the gasoline fuel and requires no vehicle modification. The use of methanol additives saves energy and extends gasoline supplies by significantly easing the severe energy-intensive refinery processing otherwise required to obtain gasoline's premium octane rating; one estimate is that approximately 2 gal of oil are replaced by each gallon of methanol (or methanol-based) additives (14). As noted earlier, by late 1980 a methanol-based additive was already being used at the rate of about 100 million gal/year.

The potential market for methanol as an additive is limited, however. In view of the difficulties and cost in distributing methanol from the remote and rural regions where methanol plants would locate, an average market penetration of 2 percent is about the maximum that would be feasible and likely. Two percent of the market represents about 2 billion gal, the output of only 2-3 typical coal-to-methanol plants. The additive option is best regarded as an initial market for smaller methanol plants using biomass or remote natural gas as feedstocks and as a small "guaranteed" market (to the extent that long-term supply contracts could be secured with oil refineries) for the first few coal-to-methanol plants.

Greater market opportunities are presented by the use of methanol as a blend component. This second option, blending, is fraught with difficulties and burdensome costs, however. The first concern is inaccessibility to the existing gasoline distribution system. Pipeline owners would be hesitant to handle methanol; this hesitance may be overcome only after years of researching, testing, and corrosion-proofing of the pipes. Another distribution obstacle is the problem of water intrusion; it would be solved only by building a parallel distribution system, at great cost because of missing economies of scale, or by dehydrating major parts of the existing gasoline distribution system, again at great cost. From a distribution perspective, blending is unattractive.

Blending is also unattractive from an end-use perspective. First of all, fuel intake components of vehicles must be redesigned; second, certain materials in the engine and fuel lines must be replaced; and third, dramatically increased evaporative emissions would have to be controlled. Possibly the greatest end-use disadvantage, however, is the foregone efficiency benefit. The use of straight methanol in appropriately designed vehicles should provide efficiency improvements of about 30 percent [estimates generally range from 15 to 40 percent, depending mostly on the extent of engine and power-train redesign (2)]. This efficiency gain is not realized in conventional gasoline vehicles that are modified only to be compatible with methanol, as would be the case when blends are marketed.

The preferable strategy for marketing large volumes of methanol is as a straight fuel. The water contamination problem disappears in this case, and vehicles can be designed to capture fully the efficiency and clean-burning benefits of methanol. Unfortunately, market conditions and the timing of supply availability preclude moving directly from the additive stage to the straight methanol stage. Market conditions dictate that a secure and widely dispersed methanol fuel supply be available before consumers are called on to switch; they must be assured that fuel supplies are available not only in their own neighborhood and region but elsewhere as well. However, the gradual buildup of production capacity precludes the possibility of establishing a prominent and widespread retail market in a brief period of time. It would take many years to provide such an extensive network of retail outlets with adequate fuel supply.

The marketing of methanol blends is therefore a necessary but not fully attractive transition strategy. Even though a transitional period with blends is probably necessary, its duration and dimension can be abbreviated. This is accomplished by developing other smaller, specialized methanol markets during the additive marketing stage. Methanol production capacity could be built up and general marketing in the transportation sector restricted to additives only as long as possible. Meanwhile a retail infrastructure could be established and greater experience with fuel methanol gained. When production capacity begins to accelerate, the new output would be diverted to straight methanol use as quickly as possible.

The most prominent of the small, specialized markets referred to above are vehicle fleets, the gas turbines of electric utilities, and self-contained regional fuel markets. Vehicle fleet markets are examined in the following section. Electric utilities and self-contained regional markets such as California and possibly the Rocky Mountain area are not addressed further in this paper.

Corresponding to the fuel marketing strategies must be vehicle production strategies. Vehicle production strategies can be devised to ease the risk and cost burden to automobile makers. Transitional vehicle strategies that match the fuel marketing strategies have already been hinted at but are addressed more explicitly here.

Before any methanol fuel is consumed, in a >5 percent blend proportion, engines and vehicles must be modified. Current production models can be retrofitted for methanol, but the cost ranges up to $2000/vehicle (15). To capture completely the benefits of methanol, the entire engine, drive train, and fuel system should be redesigned. This redesign is now taking place in Brazil for ethanol fuels. A transitional strategy is simply to make a vehicle methanol compatible and not methanol efficient. The cost is much less: The inner coating of the fuel tank must be replaced, the sensor-controlled fuel intake system must be modified (generally for blends with more than 10-15 percent methanol), and certain noncompatible materials must be replaced (2).

Thus, the cost burden and the risk to automobile makers would be softened by a gradual transition to true for-methanol vehicles. The first step is conversion of one or more models to methanol-compatible status. The extra development and production costs would be small. Large fleets could convert their methanol-compatible vehicles to methanol-efficient status if the economics were justified. Several years later, after the first large coal conversion plants come on line and more experience has been gained with methanol fuel, automobile makers could begin production runs of efficient for-methanol vehicles. Ford and Volkswagen already have mounted major research and development programs to build methanol vehicles, so these suggested production strategies should be reasonable.

Vehicle Fleets

An early and key methanol market is vehicle fleets. Fleets are ideal initial markets because vehicles are fueled and maintained in a few centralized locations. Fuel distribution and availability problems are simplified. By themselves, fleets constitute a substantial market, but just as important is their function as a test market for the general vehicle market.

Until distribution becomes widespread, fleet operators will be the primary users of methanol fuel. The early use of alcohol fuel by several large fleet operators may be the key to stimulating large production runs of alcohol vehicles by automobile makers. Early and important markets are government fleets. Government fleets account for about 12 percent (about 1 million vehicles) of all fleet vehicles and 1 percent of total U.S. gasoline vehicles (16,17). They consume about 1.5 billion gal of gasoline per year, which represents 1.5 percent of annual gasoline sales.

The conversion of business fleets to alcohol may be more important not only because it opens up a large market but also because it sends a signal that alcohol is a viable competitor in the marketplace. This may be the key development that convinces automobile makers to initiate on-line production runs of alcohol vehicles.

The Bank of America is the first business to convert a major part of its large fleet to methanol. The Bank's objective in converting to methanol use is to establish a secure fuel supply so that Bank operations are not threatened by fuel shortages such as those of 1979. The program has been so successful that, in addition to the initial group of 146 converted vehicles, the Bank has ordered 100 more and is seriously considering eventually converting its entire fleet of 2000 vehicles to methanol (15). The Bank's enthusiasm stems from the unexpectedly efficient and relatively trouble-free performance of the methanol vehicles, which comes as a bonus to their primary objective of fuel security. The vehicle conversion costs (15) incurred by the Bank of America represented about 15 percent of vehicle life-cycle costs; additional costs of about $5000 for modifying a fuel station are minor when amortized over the station life.

If rapid market penetration is to occur, a number of large institutions, such as the Bank of America, must decide that the objective of long-term fuel security is important enough to justify making a major and early commitment to methanol. One could imagine that a large number of large business fleets would consider justifiable the extra 15 percent or so in transportation costs, particularly where transportation costs are a small percentage of a firm's annual expenses.

An impediment to converting early fleets to methanol may be the absence of a used-car market. Fleet operators may be reluctant to risk foregoing revenues that they would otherwise receive from vehicle resale. A 1977 survey indicates that resale value as a criterion of vehicle purchase is very important for rental fleets, fairly important for business fleets, and a minor consideration for utility, taxi, and police fleets (16). Survey responses regarding time of resale suggest that resale value is large for rental fleets, negligible for taxi fleets, and somewhere in between for other fleets. The survey results are averages, however, and do not signify that fleet operators in each sector behave identically. One concludes from this evidence that, although vehicle resale may be an important barrier to methanol market penetration in some cases, significant numbers of fleets would consider it a minor consideration.

One response to uncertainty over vehicle resale is to guarantee vehicle repurchase. Car dealers, associations of car dealers, or the government could assume this responsibility. The firm that converts Bank of America vehicles already provides such a guarantee.

Table 2. Sequence and timing of path activities.

Year	Activity
1980	Methanol and a methanol derivative, MBTE, gain use as octane-enhancing gasoline additives
1984	Barge-borne methanol plants begin operation offshore of United States; methanol from remote gas may also be produced in Canada, Alaska, and elsewhere
1985	Production runs of methanol-compatible vehicles; some fleets, especially government, start converting to methanol
1987	Methanol-from-coal (including peat and lignite) plants begin operation; electric utilities in southern California and other smog-prone areas begin using methanol; many large fleets (government and private) begin switching to methanol
1989	Methanol blended with gasoline for use as transportation fuel; parts of petroleum product distribution system are dehydrated
1990	Production runs of methanol-efficient vehicles by major automobile makers
1994	Blending mostly eliminated and methanol used as a straight fuel; methanol completely integrated into liquid fuel distribution system
1997	Total methanol production reaches 1.5 million bbl/day

RECOMMENDATIONS FOR PATH IMPLEMENTATION

The previous sections outlined the development of activities that contribute to an accelerated and large-scale introduction of methanol fuels. Presented below is a summary of important activities. Dates are assigned to suggest the earlier plausible or necessary occurrence of that activity or event, given the production target of 1.5 million bbl/day by 1995-2000. Table 2 summarizes the sequence and timing of path activities.

In this accelerated development path, coal conversion would be the major supply source and motor vehicles the major market. But during the initial stages, the indivisibilities, long lead times, and remote rural locations of production facilities would not match well with the dispersed, urbanized location of vehicles and their demand for stable and widely available fuel supplies.

The challenge is to stimulate production in a way that matches the timing of developing markets while not overwhelming the capabilities of the distribution infrastructure. The public sector is called on to provide incentives and remove barriers so that each of the three major activities may proceed. Key private-sector participants would have to coordinate their efforts to mitigate mismatches of demand and supply and to ensure efficient deployment of resources. They must also assure the automobile-buying public that methanol fuel is an attractive alternative and will be widely available.

A program of actions to support the timetable is suggested below. The actions are grouped according to the three challenges identified at the beginning of this paper. The focus is on the public sector, but industry actions are also included.

Establishment of a Producing Industry

The major barriers to coal-to-methanol investments are uncertainties of market and price. Government responses to reduce uncertainty and risk, in order of effectiveness, might be (a) price guarantees, (b) purchase guarantees, and (c) tax incentives. Government programs should attempt to create stable

market environments. Reducing the cost of capital (for instance, through loan guarantees) is a secondary concern because market risk appears to be significantly greater than technological risk for large-scale methanol producers.

Penetration of Traditional Petroleum Markets

Methanol is a replacement for petroleum, a fuel that has dominated the transportation market and other markets for many decades. The challenge is to reduce market barriers and exploit opportunities where appropriate so as to ensure the growth of reliable and stable markets for methanol as it becomes available. The first step is to overcome barriers to the use of methanol. The second step is to encourage the establishment of diverse and stable markets as methanol becomes available. Some specific proposals for creating such conditions are as follows:

1. Modification of national fuel and vehicle (emission) certification procedures;
2. Government purchase of methanol fleet vehicles;
3. Imposition of the requirement that some percentage of vehicle production be methanol compatible by 1985 and methanol efficient by 1990, or three years after the first large methanol plants come on line (the requirement should be put into law now so as to reduce market uncertainty);
4. Tax incentives to automobile makers for producing methanol vehicles;
5. Temporary removal of excise tax on methanol fuel;
6. Government or dealer guarantees to repurchase methanol fleet vehicles;
7. Automobile industry guarantees to supply fuel for methanol vehicles (one option would be establishment of methanol stations in key locations);
8. Tax credits to large methanol users (e.g., vehicle fleets and electric utilities); and
9. A workshop to disseminate information to vehicle fleet operators.

Development of an Efficient Distribution System

The key strategies for timely and efficient provision of distribution services are, first, integration of methanol shipments into the existing petroleum product distribution system and, second, coordination of new investments, principally pipelines. The public sector traditionally has not played a strong or prominent role in fuel distribution activities and probably has few opportunities to promote these strategies. Its principal role may be of a passive nature in promoting coordination: to relax competition requirements on pipeline owners and encourage coordination in deploying methanol pipelines. This coordination may lead to clustering of plants to reduce the proliferation of methanol pipelines and to achieve economies of scale in pipeline use--a promising trend from the perspective of distribution cost, especially in the Rocky Mountain and Great Plains areas where local markets are sparse anyway.

Because the public sector plays a small role in meeting the distribution challenge and because most specific actions will be a result of coordinated planning, the following proposals are general in nature:

1. Supportive Federal Energy Regulatory Commission policies to encourage coordinated planning and deployment of pipelines;
2. Clustering of plants, especially in remote western coal regions, to establish a more concentrated pipeline network;
3. Immediate establishment of research and development programs and testing programs to determine opportunities for integrating methanol into the existing petroleum pipeline network;
4. Coordinated planning among shippers, pipeline owners, and storage tank owners to selectively and efficiently dehydrate a distribution network that permits fuel blending.

CONCLUSIONS

The methanol development path formulated in this paper presents one set of opportunities for making the transition from petroleum to alcohol fuels. It is a path that leads to the greatest use of alcohol fuel in the shortest time frame. But rapid expansion of the new methanol industry will not proceed unless aid is forthcoming. The new industry is rife with risk and uncertainty. Start-up costs are formidable. Implementation of the high-growth path within such a short period would require considerable public-sector support. Government support is forthcoming, however, only if a national consensus coalesces to promote alternative fuels.

Consensus formation must survive the scrutiny of many interest groups. A national methanol path will be judged as to its environmental, economic, political, and social implications. If the national objective of fuel security is strong enough and the adverse impacts of the path are not too unpalatable, then government support will materialize and the high-growth methanol development path will become reality. Lack of a strong national consensus will probably not mean abandonment of methanol as an alternative fuel, however. Enough special market niches and favorable production situations exist to elicit at least some methanol investments in the near future.

ACKNOWLEDGMENT

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Motor-Vehicle Fuel Economy: Estimated Cost and Benefits from 1980 to 2020

R.K. WHITFORD AND M.J. DOHERTY

Results of an analysis of motor-vehicle fuel economy performed by Purdue University as part of an ongoing analysis of the costs, benefits, and effects of various energy options are discussed. The analysis is presented in three sections: (a) automobiles, (b) light trucks, and (c) combined results and sensitivities. Three scenarios are studied in the automobile and light-truck sections. In the third section, automobile and light-truck scenarios are combined.

About 70 percent of the petroleum consumed in transportation is used by passenger automobiles and light trucks. Obviously, improvements in these vehicles or in their use could pay large dividends in reduced fuel consumption. However, unless domestic automobile makers can meet the demand for fuel-efficient automobiles, the United States may be simply substituting one import, automobiles, for another, oil. Congress passed legislation in 1975 that required a corporate average fuel economy for new cars of 27.5 miles/gal by 1985. Should more be done beyond 1985? If so, how much?

Purdue University is performing an analysis for the U.S. Department of Transportation (DOT) to determine the benefits, costs, institutional and environmental impacts, distributional equity effects, and technology mobilization for various energy options, including oil from shale, coal liquefaction, biomass liquids, freight movement, and automobile fuel economy. This analysis is called transition path analysis. This paper reports the work done to date, primarily in the development of nationwide costs and benefits for the passenger car and light-duty truck. All benefits are measured in terms of oil saved.

The discussion of the results is divided into three parts: automobiles, light trucks, and combined results and sensitivity.

AUTOMOBILES

Sales Forecast

The sales forecast was based on a relatively mature market. The forecast is based on an average increase in sales of about 0.33 percent each year, which would cause the total fleet to grow from 106 million cars in 1980 to 122 million in 2020 (1). Past sales cycles seem to correlate with gross national product, and the length of the cycles reflects the average life span of cars. If this average age stays relatively fixed, we can expect six-year cycles in the future. Figure 1 shows the Purdue sales estimate and also indicates the reference low and high sales estimates from DOT (2) and the Mellon Institute (3) for comparison.

Baseline

Whereas other studies have used a baseline of 27.5 miles/gal for new cars in 1985 and later, this study instead assumes that no investments are made solely to improve fuel efficiency after 1985 and that some improvement will occur with normal replacement of worn-out plants and obsolete tools. More specifically, it is assumed that the industry will spend no more than $2 billion/year (after 1982) and that consumers will continue to demand improved fuel efficiency. The timing of line changeover will slow from the present replacement schedule of every 10-12 years to every 15-17 years. New models will be introduced much less frequently than at present.

This baseline is very different from that used by other studies, since fuel economy continues to improve over time. This means that future investments over the baseline achieve lower fuel savings with the moving baseline used here than would be achieved with a static baseline.

Scenarios

Meeting the 1985 standards will not be a severe technological problem. The standards will be met by the implementation of downsizing, front-wheel drive, limited material substitution, and less powerful engines. Although the scenarios predict large increases in fuel economy, this is not unrealistic in light of existing technological developments. According to a June 1980 news release, General Motors is predicting a corporate average fuel economy of more than 32 miles/gal in 1985.

The scenarios for this study are as follows:

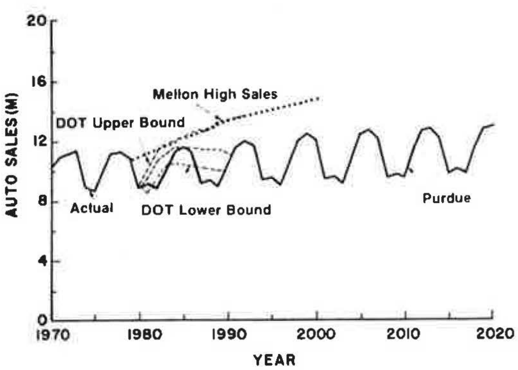
1. Scenario A--Production line changeovers will occur every 10-12 years and one new model will be introduced by the industry each year. Diesels will achieve 25 percent of the market. New-car fuel economy will reach 32.4 miles/gal in 1985, about 40 miles/gal in 2000, and 43.3 miles/gal in 2020.
2. Scenario B--Weight will be reduced significantly after 1990, and diesel penetration will be 50 percent by the year 2000. Fuel economy will reach about 32.5 miles/gal in 1985, 50 miles/gal in 2000, and 55 miles/gal in 2020.
3. Scenario C--Weight will be reduced even further and an 80-mile/gal sub-subcompact (commuter car) will account for 15 percent of the market by 2020. Diesels will penetrate 100 percent of the intermediate and large-car markets. Fuel economy will reach almost 59 miles/gal in 2000 and 64 miles/gal in 2020.

These scenarios, though not perfect, are illustrative of likely happenings under the definitions. The composite new-car fuel economy for the various scenarios is shown in Figure 2.

Technology Improvements

The primary areas of effort are downsizing, redesign for front-wheel drive, material substitution, and change to higher percentage of diesels. Other technology improvements incorporated include such items as aerodynamic design, improvements in accessory efficiency, improved transmission, turbochargers, and engine design parameters. However, no allowance has been made to incorporate either a Stirling or Brayton cycle engine.

Figure 1. Automobile sales forecast.



Downsizing to 1985

The 1985 fleet will be composed of four sizes of automobiles: subcompact, compact, intermediate, and large. The principal way in which the weight reduction will be realized is through downsizing and front-wheel drive on many models. Only limited changes in materials are anticipated, mostly to higher-strength steel and some aluminum castings.

After 1985

The improvements proposed in the fleets after 1985 are assumed to occur in five principal areas:

1. Materials substitution will account for a decrease in weight of about 750 lb for the large car and 450 lb for the subcompact.
2. A sub-subcompact will be introduced in the highest-rate scenario in about the year 2000 for two-passenger commuting.
3. Continued improvements in drive train, aerodynamics, and rolling resistance will account for about a 2.5- to 4-mile/gal improvement over this period.
4. Improvements in engine control coupled with an overall reduction in acceleration performance will provide an improvement of about 3-4 miles/gal.
5. Increased penetration of diesel in the year 2000, from 25 percent in scenario A to more than 75 percent in scenario C, represents a significant opportunity to improve fuel economy.

Investment Costs

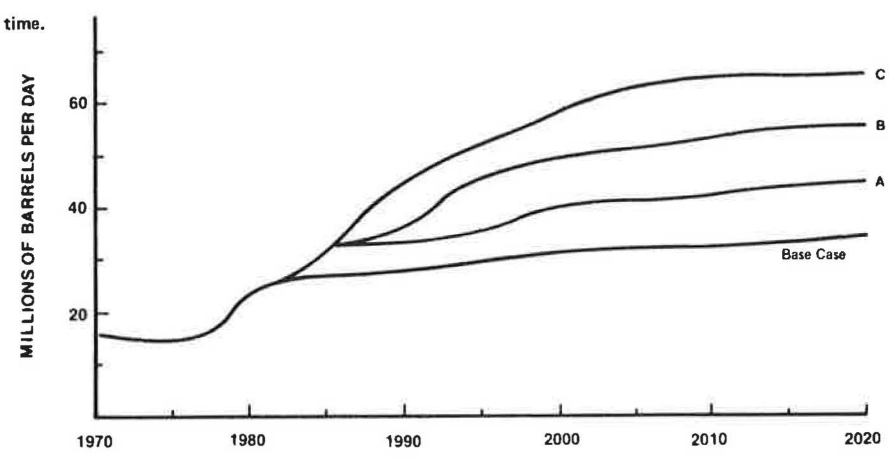
Data on investments were drawn from the report by Shackson and Leach (3) as well as assembly-line and production-facility changes outlined in the 1981 report by DOT (2).

The number and timing of the engine, transmission, and assembly lines that would be changed over were approximated based on a 10- to 12-year life for an engine plant and a slightly longer life for an assembly plant. Each engine plant turnover cost $300 million, and an assembly plant change for a major redesign like front-wheel drive or major material substitution was $1 billion. Only costs that involve a change for fuel economy are included. Table 1 indicates the total differential investment in 1980 dollars between the baseline and the various scenarios.

Variable Costs

The variable cost per car in 2020 ranges from an

Figure 2. New-car fuel economy over time.



additional $580 for the base case to $980 for scenario A, $1445 for scenario B, and $1750 for scenario C. Table 1 gives the variable cost for each scenario expressed in costs over the baseline car for that year. The major costs result from the switch to diesels ($400/car), turbocharger, transmission, and other improvements ($80-$170/car) and the substitution of materials, as given in Table 2. Substitution with more costly plastics occurs as the car gets lighter and plastic parts more complex (4).

Fuel Savings

Fuel consumption for the scenarios, in millions of barrels per day, is shown in Figure 3. It is interesting to note that for all scenarios, including the baseline, there is an overall drop over the long term. Since only a very minor increase in automobile use and fleet size is predicted, the curves do not bend upward near the end of the period. It is also worthy to note that even scenario A shows a reduction from the 1980 use of 4.8 million bbl/day to 1.9 million bbl/day.

This is much less than the 3 million to 3.5 million bbl/day postulated by several studies (3,5,6). The differences appear to be attributable to three major factors:

1. Others assumed that the baseline fleet would reach 27.5 miles/gal in 1985 and stay at that level. Our baseline shows an improving fleet fuel economy; this represents about a third of the difference.
2. This section is for automobiles alone. About one-third of the difference is due to truck fuel economy alone.
3. The conservative sales forecast means that there are fewer automobiles in the scenarios. Others contemplate a fleet of 160 million cars in 2000. This accounts for the remainder of the difference.

Economic Efficiency

By using a fuel escalation of 3 percent/year, the results of the efficiency model presented in Table 3 show that scenario A is by far the best scenario for the passenger car. The internal rate of return is more than 20 percent, and the resource cost is substantially less than the cost of oil on the market today.

LIGHT TRUCKS

The approach to determining fleet mix and future capability for light trucks is somewhat different than that for automobiles. Whereas automobiles are purchased primarily for personal transportation, light trucks usually serve more than one transportation need. Most light trucks (roughly 60 percent) are purchased for personal use. However, this use frequently includes such duties as hauling, recreation, and outdoor activities as well as personal transportation.

Sales Forecast

The sales forecast for light trucks uses the same assumptions as that for automobiles. Thus, it is assumed that truck sales will vary with automobile sales and will be about 20 percent of total vehicle sales for all scenarios. This results in an annual growth rate of 1.5 percent/year in the light-truck fleet to the year 2000 and approximately 0.4 percent thereafter. Truck sales are projected to vary from 2.2 million in 1980 to a high of 3.2 million in 2020.

Baseline

The baseline for the light-truck model is much like the baseline in the automobile model. Thus, it shows some fuel-economy improvement over time. The major technological thrust is a program of gradual weight reduction to occur at the time of production line rollover. This results in an average weight reduction of 800 lb by 2020. Diesels will account for 10 percent of the market in 2020. A slight shift in fleet mix is also expected to improve fuel economy as existing minitrucks are substituted for conventional pickups. The baseline investment is held to a maximum of $0.5 billion after 1987, when a

Table 1. Investment and variable costs for automobile scenarios.

Year	Differential Investment by Scenario ($000 000 000s)			Differential Variable Cost Above Baseline by Scenario ($/car)		
	A	B	C	A	B	C
1985	9.5	12.3	12.5	190	240	250
1990	9.2	26.8	34.4	250	450	680
1995	7.3	34.5	55	250	550	930
2000	5	41	70	250	535	1170
2010	13	44	77	345	774	1200
2020	16	43	66	400	865	1170

Note: Amounts in 1980 dollars.

Figure 3. Fuel use for various scenarios: automobiles.

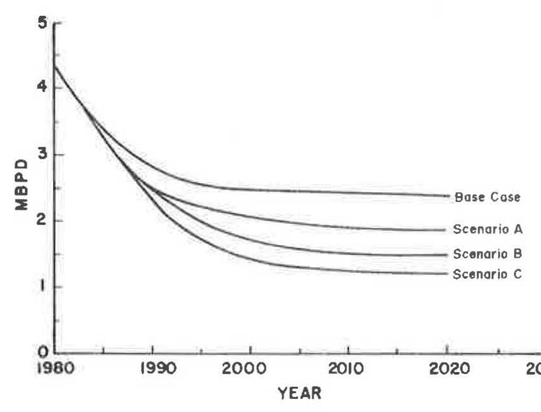


Table 2. Weight-reduction data by time period for scenario C.

Year	Weight Removal (lb)				Cost per Replacement Pound ($)	Steel Weight to Weight of Substitute Material	Cost of Substitute Material to Steel Cost
	Subcompact	Compact	Intermediate	Large Car			
1985-1990	200	200	200	300	1	2:1	2:1
1991-1995	200	200	200	200	1.50	2.25:1	3.4:1
1996-2000	50	200	300	250	2	2.5:1	5:1

Table 3. Economic results of fuel-economy scenarios for passenger cars.

Scenario	Item	Total Dollars	Ten Percent Discount Rate	Internal Rate of Return (%)
A	Benefits ($ billion)	495	58	22.3
	Costs ($ billion)	135	26	
	B/C ratio	3.7	2.0	
		3.7	2.0	
	Resource cost ($/bbl)	22.4	32.7	
B	Benefits ($ billion)	864	80	16.6
	Costs ($ billion)	301	55	
	B/C ratio	2.9	1.45	
	Resource cost ($/bbl)	29.1	45.4	
C	Benefits ($ billion)	1122	107	15.4
	Costs ($ billion)	479	83	
	B/C ratio	2.3	1.3	
	Resource cost ($/bbl)	35.3	51.1	

Table 4. Investment and variable costs for light-truck scenarios.

Year	Total Investment for Fuel Economy over Baseline ($)			Differential Variable Cost ($/truck)		
	A	B	C	A	B	C
1985	3.8	4.2	4.2	142	142	142
1990	4.6	11.2	12.1	165	500	645
1995	6.0	14.8	19.5	256	709	1363
2000	6.4	17.1	18.8	355	1026	1332
2010	7.9	15.6	16.1	570	1021	1169
2020	11.7	14.3	14.3	797	1027	1027

Note: Amounts in 1980 dollars.

20-mile/gal fleet average is attained. The baseline will reach the suggested 1985 light-truck fuel efficiency of 21 miles/gal in 1990.

Scenarios

All scenarios and the baseline begin in 1980 with an average inertia weight of 3775 lb, 17.9-mile/gal new-truck fuel economy, and 2 percent diesel penetration.

1. Scenario A--Lighter components and a mix shift result in a 1165-lb reduction from the current average weight, which will be spread over the entire 40 years of the model. A 50 percent diesel penetration will be achieved by the year 2020.
2. Scenario B--The weight reduction is the same as in scenario A but will be achieved by the year 2000 with 65 percent diesel penetration. The fleet will be 100 percent dieselized by 2020.
3. Scenario C--The same average weight and percentage of diesel penetration will be achieved as in scenario B except that the goals will be met on a vastly accelerated schedule. In this scenario, all technological changes will be complete by 1995.

Investment Costs

The same investment cost models as in the automobile fuel economy were used. Each engine plant turnover was estimated to cost $300 million, and the estimated incremental downsizing and material substitution cost was $340 million/line. Major redesign, such as the van redesign to accommodate a turbocharged diesel, was estimated at $600 million. The difference among the scenarios in total investment is due to differences in the time required for change. These results are presented in Table 4.

Variable Costs

The variable cost per truck in the year 2020 ranges from an additional $679 for the baseline to $1472 for scenario A and $1702 for scenarios B and C (Table 4). The major costs result from the switch to diesels ($400/truck) and the material substitution costs (as explained in the previous discussion of automobiles). The cost schedule for the average 1165-lb weight reduction program in the three scenarios is $0.50/lb for the first 580 lb, $1.00 for the next 350 lb, $1.50 for the next 260 lb, and $2.00 for the final 60 lb.

Fuel Savings

Fuel consumption for light trucks in 1980 (see Figure 4) is approximately 1.35 million bbl/day. For the baseline, this consumption is reduced to 0.9 million in the year 2020. Fuel consumption for the scenarios ranges from 0.64 million bbl/day for scenario A to roughly 0.5 million for scenarios B and C. The bulk of the fuel savings results from the shift to diesel. For example, a 2600-lb minipickup in 1980 achieves 25.2 miles/gal and a 2700-lb achieves 31 miles/gal in 2020. The same truck as a diesel achieves 47 miles/gal.

Economic Efficiency

The internal rate of return for the three scenarios ranges from 24.17 to 21.72 percent; scenario A has a very slight edge over the others. It is interesting to note that, although scenarios B and C are virtually identical with respect to the type of light-truck fleet that will result in 2020, the investment schedule for scenario B seems to yield a slightly higher rate of return. These results are presented in Table 5.

COMBINED RESULTS AND SENSITIVITIES

All of the studies to date treat automobile fuel economy and light-truck fuel economy as a single package. For these results, passenger-car scenario A has been combined with light-truck scenario A, and so on.

Fleet Fuel Use and Savings

Fleet fuel use based on past vehicle miles of travel (VMT) performance is shown in Figure 5. The automobile/light-truck fleet will exhibit a decrease in fuel use from 6.3 million to 3.3 million bbl/day just due to the normal turnover of plant and equipment. The small investment of scenario A adds another 0.8 million bbl/day to that. Scenarios B and C get a lower return for a much higher investment.

Economic Results

As presented in Table 6, the net benefits are increased somewhat in the combined approach largely due to the higher benefits from the light-truck scenarios. The internal rate of return is likewise a small amount higher.

Sensitivity to Discount Rates

Each of the scenarios was evaluated at 5, 10, and 15 percent discount rates and at a 3 percent oil price increase. In Figure 6, B/C ratio is plotted versus discount rate for the three scenarios.

Different Base Data

The B/C ratio and the internal rate of return are

Figure 4. Fuel saved over baseline: light trucks.

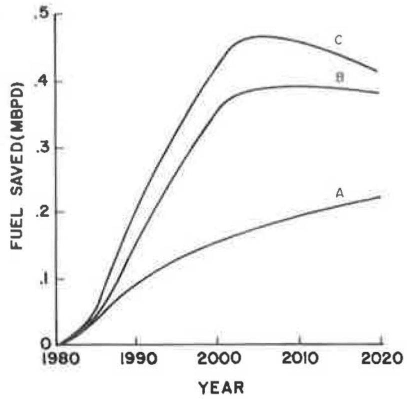
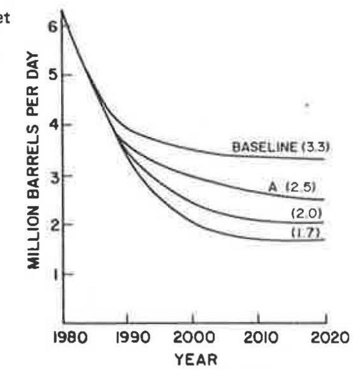


Table 5. Economic results of fuel-economy scenarios for light-trucks.

Scenario	Item	Total Dollars	Ten Percent Discount Rate	Internal Rate of Return (%)
A	Benefits ($ billion)	202	19.1	24.17
	Costs ($ billion)	52	8.6	
	B/C ratio	3.87	2.22	
	Resource cost ($/bbl)	21.62	28.93	
B	Benefits ($ billion)	371	36.1	23.57
	Costs ($ billion)	99	18.1	
	B/C ratio	3.76	1.99	
	Resource cost ($/bbl)	21.89	32.8	
C	Benefits ($ billion)	426	41.3	21.72
	Costs ($ billion)	120	23.0	
	B/C ratio	3.54	1.79	
	Resource cost ($/bbl)	23.16	36.7	

Figure 5. Motor-vehicle fleet use over time.



based on the particular assumptions made concerning the stream of costs for the scenarios in comparison with the baseline. Concern for the adequacy of this baseline suggested that two other baselines be used to test sensitivity. These are the static baseline and the Environmental Policy and Control Act (EPCA) baseline.

The static baseline in effect freezes fuel economy at 1980 levels (22.5 miles/gal for automobiles and 17.9 miles/gal for trucks). Thus, there are no investment costs and no increase in variable cost per vehicle. This baseline is very similar in principle to the baseline used in the Mellon report (3).

In the EPCA, baseline investments and costs are included only until 1985, when the mandated fuel-economy standards are in effect. After 1985, the baseline becomes a straight line and effectively parallels the static baseline. Costs included through 1985 are $26.4 billion for investment and variable cost of $413/automobile [these figures are comparable to those reported in other studies (3,7)].

The effects of these baselines on economic efficiency in scenario B are given in Table 7. As noted in the table, in addition to the differing baselines, the results of the scenario are very similar to results presented in the Mellon report (3).

Surprisingly, the results seem to be very similar no matter what baseline is used. However, absolute

Table 6. Economic results of fuel-economy scenarios for combined motor-vehicle categories.

Scenario	Item	Total Dollars	Ten Percent Discount Rate	Internal Rate of Return (%)
A	Benefits ($ billion)	697	70	22.8
	Costs ($ billion)	187	35	
	B/C ratio	3.72	2.00	
	Resource cost ($/bbl)	22.3	31.7	
B	Benefits ($ billion)	1235	116	18.34
	Costs ($ billion)	400	73	
	B/C ratio	3.1	1.6	
	Resource cost ($/bbl)	26.9	41.5	
C	Benefits ($ billion)	1547	148	16.94
	Costs ($ billion)	599	106	
	B/C ratio	2.60	1.40	
	Resource cost ($/bbl)	31.9	47.1	

Figure 6. B/C ratio versus discount rate at 3 percent increase in fuel price.

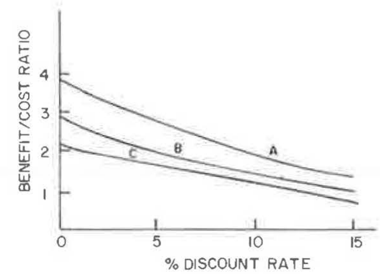


Table 7. Sensitivity of economic results to other data sources and differing baselines through year 2000.

Scenario	Item	Total Dollars	Ten Percent Discount Rate	Internal Rate of Return (%)
Mellon data[a] (5)	Benefits ($ billion)	413	113	16.88
	Costs ($ billion)	187	84	
	B/C ratio	2.20	1.35	
	Resource cost ($/bbl)	26.15	40.17	
Mellon data (5), our baseline	Benefits ($ billion)	145	38	18.20
	Costs ($ billion)	80	30	
	B/C ratio	1.81	1.29	
	Resource cost ($/bbl)	32.10	42.73	
Scenario B, static baseline	Benefits ($ billion)	522	139	16.58
	Costs ($ billion)	254	106	
	B/C ratio	2.05	1.31	
	Resource cost ($/bbl)	28.31	41.76	
Scenario B, EPCA baseline	Benefits ($ billion)	334	83	17.86
	Costs ($ billion)	168	61.9	
	B/C ratio	1.99	1.34	
	Resource cost ($/bbl)	29.73	41.98	

[a]Data similar to Mellon case of low sales and no mix shift: investment = $84.9 billion, automobile fuel economy = 45 miles/gal, light-truck fuel economy = 23 miles/gal.

cost values may be more meaningful when taken in conjunction with a "moving" baseline, which means assuming that some advances in motor-vehicle fuel economy will occur simply as a result of continuing demand for more efficient transportation.

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Forecasts of Intercity Passenger Demand and Energy Use Through 2000

MARC P. KAPLAN, ANANT D. VYAS, MARIANNE MILLAR, AND YEHUDA GUR

The development of forecasts of national travel demand and energy use for automobile and common-carrier intercity travel through the year 2000 is reported. The forecasts are driven by the Passenger Oriented Intercity Network Travel Simulation (POINTS) model, a modified direct-demand model that accounts for competition among modes and destinations. Developed and used to model SMSA-to-SMSA business and nonbusiness travel, POINTS is an improvement over earlier direct-demand models because it includes an explicit representation of the relative accessibilities of cities and a utility-maximizing behavioral multimodal travel function. Within POINTS, path-building algorithms are used to determine city-pair travel times and costs by mode, including intramodal transfer times. Other input data include projections of SMSA population, public- and private-sector employment, and hotel and other retail receipts. Outputs include forecasts of SMSA-to-SMSA person trips and person miles of travel by mode. For the national forecasts, these are expanded to represent all intercity travel (trips longer than 100 miles one way) for two fuel price cases. In both cases, rising fuel prices, accompanied by substantial reductions in modal energy intensities, result in moderate growth in total intercity passenger travel. Total intercity passenger travel is predicted to grow at approximately 1 percent/year, slightly faster than population growth. Automobile travel is forecast to increase slightly more slowly than population and air travel to grow almost twice as fast as population. The net effect of moderate travel growth and substantial reduction in modal energy intensities is a reduction of approximately 50 percent in fuel consumption by the intercity passenger travel market.

This paper describes the methods used by Argonne National Laboratory (ANL) in projecting future intercity passenger travel and associated fuel consumption through the year 2000. These projections were developed for the Office of Vehicle and Engine Research and Development of the U.S. Department of Energy (DOE) and are documented in an Argonne National Laboratory report (_1_).

Intercity passenger travel accounts for approximately 16 percent of domestic passenger miles of travel and 13 percent of domestic passenger-related fuel consumption. Generally regarded as highly discretionary, this travel sector is perhaps best modeled via behavioral, policy-sensitive methods. The following steps provide an overview of the methods used by ANL:

1. Detailed city pair modeling to estimate person miles of travel (PMT) from standard metropolitan statistical area (SMSA) to SMSA by trip purpose and mode,
2. Computation of growth rates from a 1977 base year for SMSA-to-SMSA PMT by mode,
3. Application of the above growth rates to 1977 estimates of intercity PMT (intercity travel is defined as all trips of 100 miles or more one way) to estimate future-year intercity PMT by mode,
4. Application of vehicle load factors to convert automobile and light-truck PMT into vehicle miles of travel (VMT), and
5. Application of VMT- or PMT-based energy intensities to convert PMT and VMT to British thermal units by mode.

MODELING SMSA-TO-SMSA PMT

SMSA-to-SMSA travel for the base year and all future years was modeled by using the Passenger Oriented Intercity Network Travel Simulation (POINTS) model. POINTS estimates passenger demand for the four major modes (automobile/light truck, air, bus, and rail) that compete for this market. Like most recent approaches to intercity travel demand modeling, POINTS is a direct demand model. It simultaneously estimates (a) the total number of trips and the geographic distribution of their origins (trip generation), (b) the joint probability distribution of trip origins and destinations (trip distribution), and (c) the mode by which the travel occurs (mode split). All of these aspects of SMSA-to-SMSA travel are modeled as a function of (and are therefore sensitive to) the amount of activity (population, employment, sales, etc.) at the origin and destination cities and the transportation level of service that connects them. Although POINTS shares these attributes with other direct-demand models, two significant improvements have been incorporated into

POINTS that distinguish it from most other models of the type. These improvements have been included in an effort to overcome certain theoretical deficiencies in the traditional direct-demand formulation (2). These improvements, which are similar to those reported by Gantzer (3), include

1. An explicit representation of origin and destination accessibility and
2. The inclusion of an internally consistent multimodal travel function based on utility-maximizing (hedonic) principles, and an explicit specification of the most probable distribution of value of time.

A direct-demand model can be written in the simplest terms as follows:

$$V_{ijm} = K P_i F_{ijm} A_j \quad (1)$$

where

V_{ijm} = volume of trips by mode m between origin i and destination j;
K = constant of proportionality;
P_i = function of trip-producing activity at origin i;
F_{ijm} = function of travel impedances, usually time (T) and cost (C) by mode m between i and j; and
A_j = function of trip-attracting activity at destination j.

In the traditional direct-demand model, the multiplicative factors in Equation 1 are usually represented as power products:

$$V_{ijm} = K P_i^{a_1} A_j^{a_2} T_{ijm}^{a_3} C_{ijm}^{a_4} \quad (2)$$

Although this is a very simple representation of the many alternative direct-demand models that have been formulated (2), all have preserved this basic form.

One consequence of the above formulation is that the number of trips generated by each origin is directly proportional to the access of the origin to all destinations (4):

$$V_{im} = K P_i \sum_j F_{ijm} A_j = K P_i I_{im} \quad (3)$$

where $I_{im} = \sum_j F_{ijm} A_j$ is the accessibility of zone i to the activity at all zones j.

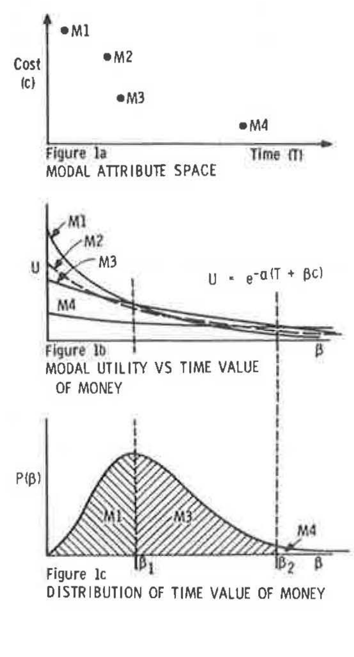
This is not a desirable trait, since the implication is that there is no competition between destinations. An increase in the attractiveness of one destination (with all others held constant) will induce a proportional gain in travel between it and all other places, while the interchanges between all other places will remain unchanged. Since it is reasonable to believe that some "new" travel will be induced and some "old" travel will be redirected, access is included in POINTS as an explicit variable with a coefficient less than zero but greater than minus one. Thus, the trip-generation implications of improved access are mitigated but not totally eliminated.

Similar problems exist with most of the functional relations of the travel impedance measures. In the simplest of formulations, Equation 2, competition between modes is completely ignored. In the commonly used logit formulation, the inclusion of new modes does not alter the relative split among previously existing modes (5). Several other formulations that avoid such logical inconsistencies rely on separate equations for trip distribution and modal split, thus sacrificing some of the theoretical attractiveness of the simultaneous nature of direct-demand models (2). One approach that avoids these inconsistencies while preserving simultaneity is Blackburn's behavioral utility-maximizing approach (6). In that approach, it is assumed that the mode selected for each trip is that which maximizes the trip's utility and that each tripmaker has a constant trade-off rate between the attributes of the modes. If only two attributes (say, time and cost) are of interest, Schneider (4) has developed a formulation based on utility-maximizing principles in which the most probable distribution of trade-off rates (value of time) across travelers is specified by the entropy-maximizing principles popularized by Wilson (7).

The development of Schneider's formulation is presented graphically in Figure 1. Assume that four alternative modes are available for a given origin-destination (O-D) pair and that they are arranged in attribute space (time and cost), as in Figure 1a. Then the disutilities of travel by each mode for travelers with varying time values of money (β) are defined according to entropy maximization as the four negative exponential curves displayed in Figure 1b. In the example, interchange mode M1 is the fastest and most expensive mode. Therefore, for travelers with the lowest time value of money (the highest value of time), $\beta = 0$ and the utility derived from traveling is highest by mode M1. The utility of travel by this mode drops rapidly as travelers who value money more highly are considered. At the opposite extreme, M4 is the slowest and cheapest mode. Since cost is a much smaller relative contribution to the total disutility of travel for M4, the curve decays at a much slower rate as β increases in value. Consequently, travelers with very high values of β (i.e., low values of time) will maximize the utility of their travel by choosing M4. In this example, travelers with values of β greater than zero but less than β_1 will prefer M1, those with a time value of money between β_1 and β_2 will prefer to travel by M3, and those whose value of β is greater than β_2 will choose M4.

According to this paradigm, in this example M2 will not be considered attractive by any traveler. It can be shown that only modes that form a convex surface when arrayed in attribute space are compet-

Figure 1. Multimodal utility maximization with distributed population for four-mode case.



itive (i.e., attractive to some portion of the population).

The aggregate modal split for the interchange is defined by the proportion of travelers in each range of β. If the population of travelers is distributed with respect to β according to the probability density function $P(\beta)$, as shown in Figure 1c, the proportion of travelers traveling by each mode is determined by the integral of $P(\beta)$ over the range of β that maximizes U.

A consistent aggregate measure of the relative utility of travel for the interchange that considers also the distributed value of α is defined by

$$F_{ij} = {}_0\int^{\infty} {}_0\int^{\beta_1} \exp[-\alpha(T_1 + \beta C_1)]\, P(\beta)\, d\beta d\alpha + {}_0\int^{\infty} {}_{\beta_1}\int^{\beta_2} \exp[-\alpha(T_3 + \beta C_3)]\, P(\beta)\, d\beta d\alpha + {}_0\int^{\infty} {}_{\beta_2}\int^{\infty} \exp[-\alpha(T_4 + \beta C_4)]\, P(\beta)\, d\beta d\alpha \quad (4)$$

The principal difficulty in applying this approach lies in determining the appropriate probability density function for β. Some researchers have postulated a log-normal distribution; others have assumed it to be empirically defined by the distribution of a surrogate variable like income (8). Schneider has deduced a "most probable" distribution of β according to entropy-maximizing principles as (9):

$$P(\beta) = \left({}_0\int^{\infty} \exp\{-\alpha[(T^{-1} + bC^{-1})/(T^{-1} + \beta C^{-1})]\}\, d\alpha\right) \div \left({}_0\int^{\infty} {}_0\int^{\infty} \exp\{-\alpha[(T^{-1} + bC^{-1})/(T^{-1} + \beta C^{-1})]\}\, d\alpha d\beta\right) \quad (5)$$

A major advantage of incorporating this probability density function is that the integrals are solvable in closed form and do not require time-consuming numerical integration to valuate.

With the travel function defined by the above logic and an explicit representation of accessibility, two direct-demand models (one for business travel and one for nonbusiness travel) have been included in POINTS. These are described by Equations 6 and 7. The choice-of-activity variables (GVPOP and HTPOP) were adopted from earlier intercity demand modeling efforts at the New York State Department of Transportation (10).

$$V_{ijm}^{BIZ} = [K^{BIZ}(GVPOP_i * GVPOP_j)\exp(\gamma^{BIZ})\, F_{ijm}^{BIZ}] \div (I_i^{BIZ}\, I_j^{BIZ})\exp(\delta^{BIZ}) \quad (6)$$

$$V_{ijm}^{NBIZ} = [K^{NBIZ}(HTPOP_i * HTPOP_j)\exp(\gamma^{NBIZ})\, F_{ijm}^{NBIZ}] \div (I_i^{NBIZ}\, I_j^{NBIZ})\exp(\delta^{NBIZ}) \quad (7)$$

where

V_{ijm}^{BIZ} = volume of business trips between origin SMSA i and destination SMSA j by mode m;
V_{ijm}^{NBIZ} = volume of nonbusiness trips between origin SMSA i and destination SMSA j by mode m;
GVPOP = SMSA population weighted by percentage of government employment;
HTPOP = SMSA population weighted by percentage of total services receipts generated by the hotel sector;
I_i^{BIZ} = access of SMSA i to the business travel attraction variable GVPOP $[I_i^{BIZ} = \sum_j \sum_m F_{ijm}\, GVPOP_j \exp(\gamma^{BIZ})]$;
I_i^{NBIZ} = access of SMSA i to the nonbusiness travel attraction variable HTPOP $[I_i^{NBIZ} = \sum_j \sum_m F_{ijm}\, HTPOP_j \exp(\gamma^{NBIZ})]$; and
F_{ijm} = solution to Equation 4, where $P(\beta)$ is defined as in Equation 5:

$$F_{ij1} = \left(\{K_2[2\sqrt{a(T_1 + bC_1)}]\}/[a(T_1 + bC_1)]\right)\{1 - [1/(1 - R_1 S_{12})]\}$$

$$F_{ij2} = \left(\{K_2[2\sqrt{a(T_2 + bC_2)}]\}/[a(T_2 + bC_2)]\right) \cdot \{[1/(1 + R_2 S_{12})] - [1/(1 + U_2 S_{23})]\}$$

.
.
.

$$F_{ijn} = \left(\{K_2[2\sqrt{a(T_n + bC_n)}]\}/[a(T_n + bC_n)]\right)[1/(1 + R_n S_{n-1,n})] \quad (8)$$

where

K_2 ( ) = modified Bessel function of the second order;
T_m = travel time between SMSAs i and j by mode m;
C_m = travel cost between SMSAs i and j by mode m;
$S_{m,m+1}$ = $(T_{m+1} - T_m)/(C_m - C_{m+1})$ when the modes are ranked by ascending travel time;
R_m = C_m/T_m;
a and b = calibration constants that specify the average sensitivity of trips to the impedance measure $(T + \beta C)$ and the average value of β, respectively;
γ^P and δ^P = calibration parameters that determine the utility curves of activity and accessibility for trip purpose P, respectively; and
K^P = constant of proportionality for purpose P.

Despite the theoretical advantage of the POINTS travel demand model, at least two disadvantages are associated with it. First, the utility-maximizing logic precludes the choice of "inferior" modes. An inferior mode, in the context of the paradigm, is any mode that lies above the convex surface formed by the line segments that connect the competitive modes (e.g., M2 in Figure 1a). In reality, many such modes do attract some (though most often few) trips. Such behavior can be explained either by including additional dimensions in the attribute space or by explicitly defining a random error term to account for travelers' imprecise perceptions. Pragmatically, however, difficulties of measurement and mathematical tractability preclude such extensions.

An even more pragmatic problem associated with the POINTS demand model is its highly nonlinear form. It is difficult, if not impossible, to transform Equations 6 and 7 into linear forms. Thus, standard algorithms to estimate the model parameters based on goodness of fit to observed data cannot be used. In consequence, a heuristic process must be used for parameter estimation.

DEVELOPMENT OF POINTS MODEL INPUT DATA

To model intercity travel, two data bases were required: One provided projection-year information to be input to the POINTS model, and the other provided base-year information necessary to calibrate the model. Both contained demographic and transportation system data. The base-year data base provided additional information on actual travel demand.

The Bureau of Economic Analysis (BEA) 1980 cycle

of regional economic projections provided the required population and employment data (11). The BEA projections are compiled by SMSA for three scenarios. Scenario 1 assumes that within a state each SMSA will maintain its 1969 share of the state's economic activities; scenario 2 assumes that the SMSA share will change as a result of 1969 to 1978 shifts, moderated by a set of decay factors; and scenario 3 assumes that the SMSA share will change as a result of the 1969-1978 trend and that there will be still greater moderation from decay factors (12). In each scenario, national totals remain constant. For this project, scenario 2 was selected and data were aggregated from the 266 SMSAs to 142 urban areas.

Four transportation networks (highway, air, bus, and rail) were coded. Each of the 142 urban areas was coded as an O-D node. Eleven Canadian cities were also coded as nodes to allow for alternative travel routes available through Canada. Several nodes were coded for the rail network to represent nonurban route intersections. Travel times, distances, tolls, and fares were obtained for each network. Four network files were created. Frequencies for the air network were included on each link record; frequencies of rail routes were coded as a separate file to be input directly to the path builder. Rail route numbers were coded on each link to permit the path builder to identify transfer between routes.

A minimum-impedance path-building algorithm that can estimate layover times at transfer points for the air and rail networks was used. The highway and bus networks were assumed to have no layover times. For long trips on highway and bus networks, additional time and cost penalties were input exogenously to the POINTS model.

Layover times were computed by using the frequency of service on connecting links. It was assumed that frequencies cover a 12-h period, which represents a typical travel interval. Airline and rail services normally cover such a period. This period may be longer for very heavily traveled routes and considerably shorter for small urban areas. Layover times are dependent on interarrival times on one link and interdeparture times on possible connecting links. These interarrival-interdeparture times in turn are dependent on frequencies. Two methods are used in computing layover times, one based on uniform probabilities and the other based on random service. For each transfer point, layover times were computed by using both random and uniform probability methods. An average of the two values was taken for miniminum-impedance path building.

The minimum-impedance paths were traced and urban-area-to-urban-area matrices were developed for time, distance, toll, and fare. Within the POINTS model, highway costs were computed as a function of distance. For highway and bus modes, time and cost penalties for overnight stays were added.

The observed calibration trip tables were constructed from detailed information on each trip, including origin, destination, purpose, and mode, as obtained from the 1977 National Travel Survey (NTS) (13), in which O-D information is provided in the form of state or county codes for all intercity trips and SMSA codes for trips involving certain selected urban areas. Origin information is provided for 30 SMSAs, and destination information is provided for 52 SMSAs, including the above-noted 30 origin SMSAs. After consolidating all the nearby SMSAs, the 30 origin SMSAs were reduced to 26 urban areas for the POINTS model. Though an additional 22 destination SMSAs were available on the file, their usefulness for calibration purposes was limited since the POINTS model deals with both productions and attractions. Data on attractions alone were not sufficient.

The NTS file was searched for trips between the 26 urban areas. These trips were disaggregated by purpose and mode. Two purposes, business and nonbusiness, were assigned. Four mode categories (highway, air, bus, and rail) were developed from the modes on the data file. Eight trip matrices, one for each purpose-mode combination, were developed. Base-year population and employment data were obtained from the BEA regional economic projections file for the selected 26 urban areas. The 1980 modal network files were assumed to represent the 1977 transportation system with respect to travel times and distances. Travel costs were deflated back to 1977 values.

CALIBRATION OF INTERCITY PASSENGER MODEL

The calibration of the POINTS travel demand model attempts to replicate multimodal intercity travel between 26 U.S. cities. The 26 cities were chosen because they are the only cities coded explicitly for both trip origin and destination in the 1977 NTS. However, because the POINTS model considers destination competition (through the access term), the modeling of travel between the 26 city pairs was performed in the context of all U.S. SMSAs. The POINTS calibration process is shown in Figure 2.

Data on intercity travel times and costs by mode and trip end were input for 142 consolidated SMSAs. Trip-end data included one-way access-egress times and costs by mode, population, government employment, total employment, hotel receipts, and total retail receipts. The four calibration coefficients (a, b, γ, and δ) were systematically varied in successive applications of the POINTS model. After each model run, the trip interchanges (by mode) between the 26 city pairs were extracted from the trip tables produced by POINTS for the 142 SMSAs. The synthetic 26-city trip tables were compared with the observed 26-city trip tables constructed from the NTS data. Coefficients of determination (R^2), trip length distributions by mode, and modal-split estimates by distance of travel were compared. The process continued until the "best" fit was obtained. The word "best" is used here quite loosely to mean the best under the circumstances as opposed to a truly global optimum fit. Because the calibration process was one of trial and error, it is entirely possible that a better fit could have been obtained (though it is not likely to have been much better). The final calibration coefficients and the R^2 between observed and synthetic trip inter-

Figure 2. POINTS calibration process.

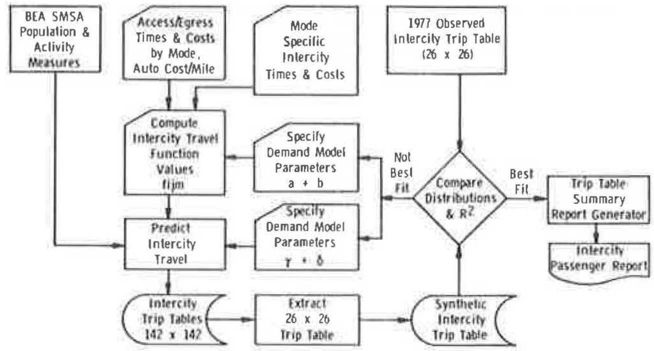


Table 1. Fuel prices for low and medium price cases.

Case	Type of Fuel Price	Amount ($) 1980	1985	1990	2000	Avg Annual Change (%)
Low price	Crude oil price per barrel	27.9	43.6	52.8	75.8	5.1
	Fuel price per gallon					
	Gasoline	1.23	1.61	1.85	2.45	3.5
	Diesel	1.03	1.50	1.75	2.39	4.3
	Jet	0.97	1.32	1.58	2.23	4.3
Medium price	Crude oil price per barrel	27.9	37.9	46.3	64.3	4.3
	Fuel price per gallon					
	Gasoline	1.23	1.42	1.68	2.24	3.0
	Diesel	1.03	1.31	1.58	2.18	3.8
	Jet	0.97	1.14	1.41	2.08	3.8

Note: Prices in 1980 dollars.

changes are given below [b in minutes per cent (1977 dollars)]:

Coefficient	Business	Nonbusiness	All
a	0.000 28	0.000 018	
b	0.017	0.05	
γ	1.30	1.35	
δ	0.35	0.40	
R^2			
All modes	0.756	0.923	0.910
Automobile	0.761	0.966	0.960
Air	0.604	0.595	0.645
Bus	0.0	0.056	0.278
Rail	0.979	0.133	0.833

PREDICTING SMSA-TO-SMSA TRAVEL

The calibrated POINTS model was used to predict SMSA-to-SMSA PMT of travel by automobile, air, bus, and rail for three forecast years (1985, 1990, and 2000). Forecasts were made for two fuel price cases: low (moderate economic growth) and medium (constrained economic growth), as given in Table 1. BEA projections of SMSA population and employment for each of the forecast years were input to the model. Inter-SMSA travel times, access-egress times and costs, and percentage of hotel receipts remained unchanged in all forecasts. Automobile operating cost per mile and common carrier fares were modified to account for the effects of changing fuel prices and vehicle fuel efficiencies. These cost factors are given in Table 2.

Table 2. Modal cost factors.

Year	BIZ, Automobile	NBIZ Automobile	Air	Bus	Rail
1977	1.00	1.00	1.00	1.00	1.00
1985					
Low	1.12	1.25	0.98	1.06	1.11
Medium	1.21	1.35	1.03	1.08	1.12
1990					
Low	1.18	1.30	1.05	1.08	1.21
Medium	1.25	1.37	1.09	1.09	1.24
2000					
Low	1.35	1.47	1.09	1.12	1.45
Medium	1.42	1.54	1.13	1.14	1.51

Initial POINTS forecasts indicated rather large increases in bus PMT. The model predicted an increase in the bus share of PMT from approximately 2 percent to almost 9 percent in the medium fuel price case. This was considered to be unreasonable, and the POINTS estimate was adjusted. The adjustment process made the simple assumption that the combined share of surface common carriers (bus and rail) would remain constant over time. The excess PMT was reapportioned between the automobile and air modes in proportion to their originally modeled shares.

Predicting Intercity Travel

Comparison of the 1977 POINTS estimate of SMSA-to-SMSA PMT (206.242 billion PMT) with the NTS reported intercity PMT (381.860 billion) demonstrated the necessity to account for non-SMSA-to-SMSA travel. Total intercity PMT was estimated by computing percentage changes in SMSA PMT (by mode) between the base-year estimate and each POINTS forecast. These "growth factors" were applied to base-year modal PMTs. The resulting intercity PMTs are given in Table 3. The population forecast is given below:

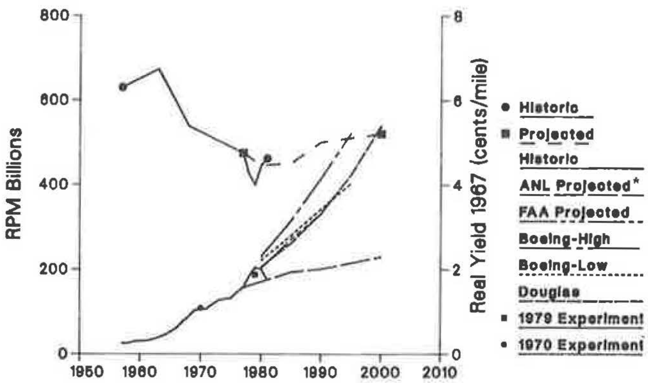
Year	Level	Population (000 000s)	Growth (%)
1977		217	
1985	Low	232.5	7.1
1990	Medium	243.5	12.2
2000	Medium	260.4	20.0

According to the adjusted POINTS estimates in Table 3, total intercity PMT grows at roughly the same rate as population. From 1977 to 1985, PMT grows at a rate slightly lower than population (6.1 versus 7.1 percent); from 1985 to 1990 and from 1990

Table 3. Forecast intercity PMT.

Mode	1977 (000 000s)	1985 Amount (000 000s) Low	1985 Medium	1985 Growth (%)	1990 Amount (000 000s) Low	1990 Medium	1990 Growth (%)	2000 Amount (000 000s) Low	2000 Medium	2000 Growth (%)
Automobile	237 056	240 263	232 988	0	261 591	256 715	8.8	278 470	274 056	16.4
Air	129 587	152 884	141 981	17.3	158 450	157 246	31.9	181 813	180 477	39.7
Bus	9 147	10 424	9 885	8.2	11 317	11 068	21.4	13 222	13 091	43.2
Rail	3 977	3 953	4 601	5.6	3 607	3 764	-7.0	2 910	2 862	-27.0
Other	2 093	2 327	2 292	0	2 457	2 426	0	2 741	2 713	0
Total	381 860	409 851	401 747	6.1	437 422	431 221	13.7	479 156	473 199	24.3

Figure 3. Forecasts of airline revenue passenger miles and yield.



to 2000, PMT grows at a slightly faster rate than population (13.7 versus 12.2 percent and 24.3 versus 20.0 percent, respectively). However, when the data are reviewed by mode, significant differences become apparent: Automobile travel grows significantly slower than population whereas air travel grows significantly faster.

When the POINTS forecast of commercial aviation revenue passenger miles (RPMs) is compared with historical trends and other forecasts (14-17), such as those illustrated in Figure 3, a fundamental difference becomes evident. All other major forecasts show RPMs growing at an accelerated rate through the year 2000, a rate comparable to observed growth between 1960 and the late 1970s. RPMs also increase under the POINTS forecast, but they do so at a much decelerated rate. Moreover, most forecasts imply a 150 percent increase in RPMs per capita between 1980 and 2000. By contrast, the POINTS forecast estimates an increase of only 14 percent.

A view of the historical trend in yield (revenue per revenue passenger mile) helps to explain some of these differences. Yield, measured in constant 1967 dollars, is a reasonably good index of the change in the real cost of air travel to the air traveler. In the early 1960s, following the introduction and diffusion of turbofan jet technology, yield dropped dramatically. Beginning in the late 1960s, the rate of decline slowed somewhat until 1978, when a combination of events, including deregulation, resulted in strong competition and a sharp reduction in yield. This latter trend continued through 1979 despite higher operating costs brought on by a rapid increase in jet fuel prices. A widespread discount campaign by major airlines fostered the 1979 decline in yield. Although yield was down, RPMs reached record levels, partly as a result of discount fares and coupons and partly as a result of travelers shifting from automobile to air travel because of the unavailability of gasoline. In 1980, and again in the first quarter of 1981, yield registered its first significant real dollar gains since the early 1960s. This increase is consistent with the future cost factors presented in Table 2. The POINTS input assumed that real yield would increase at a rate consistent with rising fuel costs while accounting for improved aircraft energy efficiencies. This reversal in the yield trend helps account for the shape of the POINTS forecast curve.

Although the POINTS model was calibrated with cross-sectional data at only one point in time (1977), the POINTS forecast implies that the future demand for aviation travel will respond like a typical technology substitution curve, taking its familiar S-shape. The high RPMs recorded for 1978, 1979, and 1980 (in relation to the POINTS forecast) represent an artificial technological "improvement" (intense marketing and price competition) that could not be sustained in the long run because of low associated profit. Therefore, from the point of view of the POINTS forecasts, these data points are aberrant. Nevertheless, a simple experiment was devised to test the ability of POINTS to simulate some of the unusual conditions that resulted in these demands. In an effort to replicate the peak demand of 1979, a 15 percent reduction in the real cost of air travel (from 1977 values) and a 50 percent increase in out-of-pocket automobile costs were input to the model. The automobile cost increase is based solely on the rate of growth in retail gasoline price. It does not include the opportunity costs associated with waiting in gasoline lines or the intangible "cost" of uncertain fuel availability. The result was a 17.7 percent increase in air RPMs (over 1977 levels) as compared with the 23.8 percent observed increase. This shortfall can be attributed to the 1979 fuel shortage, which was not simulated in the test run. Nonetheless, the POINTS estimate is in the range of the other forecasts of 1979 demand shown in Figure 3. This indicates that POINTS is capable of responding reasonably well to a range of input specifications.

A further test of the validity of POINTS as a predictive model involved backcasting to 1970. SMSA population and employment were universally factored back to 1970 levels. The real cost of travel was adjusted for each mode, and automobile travel times were reduced to represent the 70-mph versus 55-mph speed limit. The POINTS backcasted air RPM was 112 billion miles versus the 109 billion miles reported by the Transportation Association of America (18). Applying the POINTS per capita automobile PMT backcast to 1972 population resulted in 267 billion miles versus the 277.5 billion miles reported by the 1972 NTS. Thus, POINTS replicated fairly well both the past higher automobile PMT (-3.7 percent error) and the lower air RPM (+2.76 percent error).

INTERCITY ENERGY INTENSITIES

Estimates of intercity passenger-mode energy intensities are given by year in Table 4.

The major assumptions underlying these estimates are discussed by mode below:

1. The bus energy intensity estimates are based on information provided by the American Bus Association. Improvements in fleet average miles per gallon of 5 percent by 1985 and 10 percent by 1990 are assumed. No improvements are assumed beyond 1990. These estimates are based on technological efficiency changes, primarily downweighting and a shift to turbocharged V-6 engines by major bus operators.
2. Intercity rail energy intensity has been dropping slightly over time, at an average rate of -1.4 percent/year from 1975 to 1978 (19). As the National Rail Passenger Corporation (Amtrak) attempts to improve the efficiency of its operations and to increase load factors, this trend should continue. Therefore, an average annual change of -1.0 percent has been assumed through 1990. Beyond 1990, energy intensity is assumed to remain constant.
3. Intercity automobile energy intensities were derived from projected vehicle stocks. Highway miles per gallon (MPG) was calculated for each vehicle type by using the following equations:

$$\text{Combined MPG} = 1.18 \text{ city MPG} \quad (9)$$

$$\text{Highway MPG} = (\text{combined MPG} - 0.55 \text{ city MPG})/0.45 \quad (10)$$

The result was then degraded to an on-the-road fuel

Table 4. Intercity energy intensities by mode: 1977-2000.

Mode	Measure	1977	1980	1985	1990	2000
Bus	Passenger miles per gallon	141.5	144.0	151.2	158.4	158.4
	Vehicle miles per gallon	6.1	5.9	6.2	6.5	6.5
	Btu per passenger mile	980	963	917	876	876
	Change from base (%)	-	Base	5.0	10.0	10.0
Rail	Btu per passenger mile	3410	3308	3137	2967	2967
	Change from base (%)	-	Base	5.0	10.0	10.0
Automobile	Passenger miles per gallon	34.5	41.3	52.9	64.0	82.4
	Vehicle miles per gallon	15.2	18.2	23.3	28.2	36.3
	Btu per vehicle mile	8239.9	6996.5	5275.5	4462.6	3495.1
	Change from base (%)	-	-	24.5	36.0	50.0
Air	Passenger miles per gallon	19.9	26.4	31.0	37.0	48.8
	Btu per passenger mile	8224	5114	4352	3653	2764
	Change from base (%)	-	Base	17.5	40.0	85.0

economy estimate by using historical trends and limited survey data (20,21). The degradation accounts for driving conditions, vehicle maintenance, climate, etc., and corresponds to the difference between the on-road fuel economy of new vehicles under relatively favorable conditions and the on-road fuel economy of the entire fleet across a range of conditions. The degradations were as follows: in 1980, 12 percent for all vehicles; in 1985-2000, 20 percent for gasoline vehicles, 10 percent for diesel vehicles, and 0 percent for electric vehicles. Finally, a weighted average was computed from the estimates of automobile, van, and light-truck highway miles per gallon. The results show a rapid and significant improvement from 1977 to 2000.

4. Improvements in future air efficiencies are expected to come as a result of both airline operational changes and new aircraft technologies. Aircraft technologies should undergo rapid changes throughout the 1980s and 1990s as the advances developed in the Aircraft Energy Efficiency (ACEE) program of the National Aeronautics and Space Administration (NASA) reach technological readiness (22). The ACEE program began in 1976 and was originally scheduled for completion in 1985. The goal of the program was to achieve a 50 percent improvement in aircraft fuel efficiency through the acceleration of certain key technologies. Six specific projects were chosen for research and development: (a) engine component improvement; (b) energy-efficient engine; (c) advanced turboprop; (d) energy-efficient transport; (e) laminar flow control; and (f) composite primary aircraft structures.

When the anticipated effects of operational and technological improvements are combined, total fuel efficiency can be expected to improve as follows:

Period	Improvement Over Base (%)
1980-1985	17.5
1985-1990	22.5
1990-1995	30
1995-2000	15
Total	85

The increase from 1990 to 1995 is due to the expected influx of NASA ACEE project improvements. The rate drops from 1995 to 2000 as the operational and technological improvements considered in the baseline scenario achieve full market penetration.

The PMT values in Table 3 multiplied by the corresponding energy intensities from Table 4 result in estimates of base-year (1977) and future energy use. An automobile occupancy factor of 1.9 person miles/vehicle mile was assumed for converting Btu per VMT to Btu per PMT. The final estimates of fuel consumed in intercity passenger transportation are shown in Table 5. Despite significant increases in PMT, projected increases in vehicle fuel efficiencies reduce fuel consumption by almost 50 percent.

Table 5. Forecast fuel use for intercity travel.

Year	Fuel (10^{15} Btu) Automobile[a]	Air	Bus	Rail	Total
1977	1.028	0.8786	0.0090	0.0136	1.9292
1985					
Low	0.6671	0.6654	0.0096	0.0124	1.2538
Medium	0.6470	0.6614	0.0091	0.0144	1.3319
1990					
Low	0.6144	0.5788	0.0099	0.0107	1.1940
Medium	0.6029	0.5744	0.0098	0.0117	1.1988
2000					
Low	0.5123	0.5025	0.0159	0.0086	1.0393
Medium	0.5042	0.4988	0.0158	0.0085	1.0246

[a] An automobile occupancy rate of 1.9 person miles/vehicle was assumed across all forecast years.

CONCLUSIONS

For two cases of relatively high fuel prices (3-4 percent/year rate of increase), with steady but relatively less dramatic improvements in modal energy intensities, the price of intercity passenger travel will increase. Despite these price increases, structural changes in the population (size and distribution) may be expected to result in an increase in per capita intercity travel; total intercity passenger miles of travel will increase slightly faster than population. With the average value of time for intercity travel held constant over time (business at $35/h and nonbusiness at $12/h, in 1977 dollars) and slower price increases for air travel versus automobile travel, air travel grows at a rate almost twice that of population while automobile travel increases at a rate slightly less than population. The net effect of moderate travel growth and substantial reductions in modal energy intensities is a reduction of approximately 50 percent in fuel consumption by the intercity passenger travel market.

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Trends in Energy Use and Fuel Efficiency in the U.S. Commercial Airline Industry

JOEL B. SMITH

The relative contributions of four components of fuel-efficiency gain to total efficiency improvement in the U.S. commercial airline industry since the 1973 oil embargo are identified, and a determination is made as to whether the efficiency improvements after 1973 represent a change in behavior from past trends. Civil Aeronautics Board data are used. Total efficiency increases since 1973 are divided into four components of efficiency gain/load factor, mix, seating capacity, and technical and operating efficiency. The contribution of each component to the improvement of fuel efficiency is measured by estimating how much fuel would have been needed to deliver actual services in a particular year had the component under study been held at its 1973 level while the other components varied. The rise in load factors accounts for one-third of the efficiency gain from 1973 to 1980. The increase is due in part to deregulation of the industry. Seating capacity made the second largest contribution, followed by mix and technical and operating efficiency. To compare pre- and post-embargo trends, a trend of yearly seat miles per gallon for the pre-embargo period was derived and extrapolated into the post-1973 period. Actual seat miles per gallon does not rise above the historic trend until 1979. Industry behavior did not change its historic patterns until 1979. Apparently, that was the first time that fuel costs became a significant financial burden to the airlines. The industry response to the fuel price rise was hampered by the time lag involved in introducing new-model aircraft into the fleet.

The U.S. government is reducing its role in encouraging energy conservation to lessen America's dependence on imported oil. Since the government is relying more on the private sector to reduce U.S. dependence on foreign oil, it is important to know how effective the private sector has been in reducing fuel use. It will also be helpful to know what government programs have accomplished. The U.S. Department of Energy (DOE) is currently undertaking such an assessment of how much energy has been conserved by different parts of the private sector. As part of that analysis, this paper examines the record of the U.S. commercial airline industry in improving fuel efficiency from 1973 to 1980. The analysis should be of interest, certainly for what it reveals about the airline industry and how it responds to rising fuel prices but also because the time frame of the study includes both a period of government economic regulation (before October 24, 1978) and a period of deregulation (after October 24, 1978).

The basic record of the commercial airline industry since the 1973 Arab oil embargo is one of providing much more service than in the past with very little increase in fuel use. In 1973, the industry delivered 162 billion passenger miles; by 1980, that figure had increased 57 percent, to 254 billion passenger miles. Yet fuel use by the industry in 1979 was only 315 million gal, or 3 percent greater than its 1973 level of 9.565 billion gal.

Several questions are raised. The first is, How was the industry able to provide so much more service with virtually no increase in fuel consumption? Clearly, the industry has used fuel more efficiently in delivering service. More specifically, what were the components of the improved efficiency and how much fuel did they save? Second, was the increase in fuel efficiency spurred by rising oil prices or by a continuation of past trends? Finally, what can realistically be done in the future to even further improve the efficiency of delivering service?

This analysis will largely be devoted to answering the first question by identifying the components of the efficiency changes and how much fuel they saved. A base case for fuel use, assuming actual demand from 1973 to 1980 and no changes in the efficiency of service delivery since 1973, will be derived and compared with actual fuel use. The difference between the two cases is then divided into the efficiency components. The questions concerning trends and prospects for the future are also briefly discussed.

The analysis focuses only on the transportation of passengers and excludes helicopter service and flights devoted solely to transporting cargo. The analysis is of the industry as a whole, including domestic, international, local, Alaskan, and Hawaiian carriers. Commuter service is not included. The contributions to efficiency changes made by individual airline companies and manufacturers are not singled out.

BACKGROUND

The real cost of fuel used by the airlines has increased by nearly 400 percent since 1973. While fuel cost 12.8¢/gal in 1973, it cost, in 1973 dollars, 48.2¢/gal in 1980, or 89.4¢ in nominal dollars. Real fuel costs are shown in Figure 1 [data on fuel costs and ticket prices are taken from the Air Transport Association and the Council of Economic Advisors, and data on revenue passenger miles are taken from the Civil Aeronautics Board (CAB)]. With the price of fuel rising, more of the industry's resources were directed toward fuel payments. Based on data from the Air Transport Association, the airlines spent a much higher percentage of their resources on fuel in the latter part of the 1970s than in the mid-1970s, as indicated below:

Year	Portion Spent on Fuel (%)	Year	Portion Spent on Fuel (%)
1973	12.2	1977	20.6
1974	17.4	1978	20.1
1975	19.1	1979	24.8
1976	19.5	1980	30.7

The percentage of total operating costs devoted to fuel rose by 250 percent from 1973 to 1980--from 12.2 to 30.7 percent.

With the cost of a factor of production rising as quickly as the costs of jet fuel, it would follow that the total cost of production would rise. An indicator of the relative change in the total costs of production is the relative change in the price of travel. The price of travel is also of interest because that is what the consumer sees. Unlike the automobile sector, in which consumers are presented with the price of gasoline every time they fill their tank, in the airline sector the price of fuel is subsumed in the ticket price. The ticket price is composed of many factors, such as labor, capital, overhead, and, of course, fuel. Figure 1 is also a graph of the real price of air travel per mile flown from 1968 to 1980. The real price of air travel, which was falling prior to the oil embargo, rose in 1974 and then resumed its decline until 1980. In real terms, the average price of traveling 1 mile was 16 percent less in 1979 than it was in 1973. Only the sharp increases in oil prices in 1974 and 1980 caused real ticket prices to rise. In fact, the price of travel fell even in 1979, when the real cost of fuel rose by almost 9¢/gal.

Figure 1. Trends in economic operating factors.

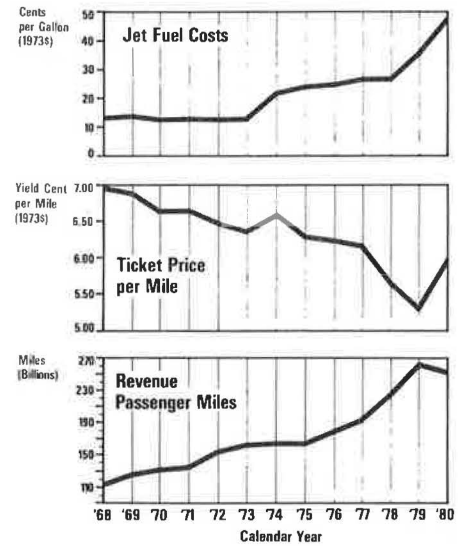


Table 1. Air carrier passenger traffic.

Year	Revenue Passenger Miles	Seat Miles	Load Factor
1967	98 746 641	174 818 524	56.5
1968	113 958 321	216 445 750	52.6
1969	125 414 212	250 845 906	50.0
1970	131 710 018	265 119 871	49.7
1971	135 651 780	279 869 172	48.5
1972	152 406 276	287 411 214	53.0
1973	161 957 307	310 597 107	52.1
1974	162 918 594	297 006 062	54.9
1975	162 810 057	303 006 043	53.7
1976	178 988 026	322 821 640	55.4
1977	193 218 837	345 566 005	55.9
1978	266 781 182	368 750 719	61.5
1979	261 979 214	416 144 986	63.0
1980	254 000 000	432 000 000	58.7

The drop in the real price of airline travel led to an increase in demand. Figure 1 and Table 1 present data on actual revenue passenger miles (RPMs) from 1968 to 1980 (one paying passenger traveling 1 mile constitutes 1 revenue passenger mile). With the exception of a leveling off in 1974-1975, the upward trend of the 1968-1972 period continued until 1979. Several factors led to the leveling off in demand in 1974 and 1975. The economy is always an important factor in determining airline travel demand. In those years, the United States underwent a deep recession. The price of travel rose in real terms in 1974, but dropped in 1975. The fuel allocation plan, discussed below, also served as a restraint on demand. With the economy improving and real ticket prices falling in 1976 and 1977, demand rose at an average annual rate of 6 percent. In 1978, the airline industry underwent a fundamental change: It was deregulated. The airlines were freed to drop inefficient routes, add

more lucrative ones, and offer more competitive prices. The real price of travel fell at a more rapid rate than it had in the past. With the economy continuing to do well, demand rose at an even faster rate. From 1977 to 1979, revenue passenger miles rose at an annual rate of 10.7 percent. In 1980, however, the price of travel could no longer mask the increased price of fuel. The real cost of travel jumped while the economy cooled off. The result of these factors was that, for the first time in years, there was a significant decline in revenue passenger miles, with demand falling by 3.0 percent.

FUEL USE

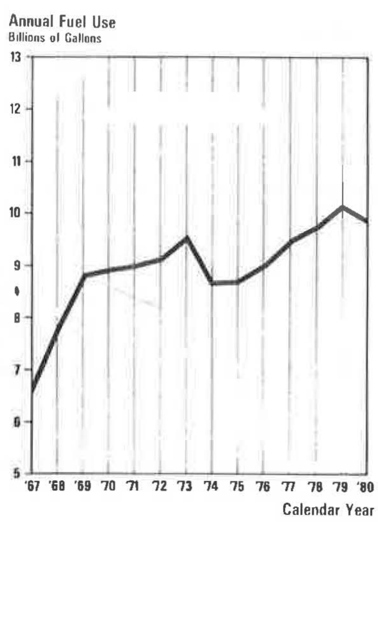
The year-to-year trend in fuel use does not parallel the trend in revenue passenger miles. Figure 2 shows fuel used by the airlines in delivering passenger service from 1967 to 1980. There was a monotonic rise in fuel use before the oil embargo. Following the embargo, the airlines were placed under a fuel allocation plan for 1974 and 1975. Basically, each airline was allocated 90 percent of the fuel it used in 1972. As shown in Figure 2, there was about a 10 percent drop in fuel use from 1973 to 1974. The 1975 level of fuel use was about the same as in 1974. With the restrictions lifted and the economy improving, fuel use by the industry began to grow in 1976. It continued to grow through 1979, surpassing the 1973 level of use in 1978. In 1980, fuel use declined, in part because of a curtailment in demand for passenger miles.

FUEL SAVINGS

The variable that best expresses the overall improvement in fuel efficiency by the airlines is the change in revenue passenger miles per gallon. By stating how many passenger miles were delivered for each gallon of fuel used, this variable measures how fuel efficient the airlines were in actually moving people. The following table gives revenue passenger miles and seat miles per gallon from 1967 to 1980:

Year	Revenue Passenger Miles per Gallon	Seat Miles per Gallon
1967	15.10	26.73
1968	14.62	27.78
1969	14.31	28.63
1970	14.80	29.79
1971	15.10	31.15
1972	16.69	31.48
1973	16.93	32.47
1974	18.82	34.32
1975	18.79	34.98
1976	19.78	35.67
1977	20.33	36.36
1978	23.36	37.83
1979	25.40	40.34
1980	25.73	43.68.

Figure 2. Actual fuel use for revenue passenger service only.



From 1973 to 1980, there was a 52 percent increase in the number of passenger miles delivered by each gallon of jet fuel. This variable is affected by the efficiency of service offered and by demand. If demand for air travel declines, the percentage of seats filled will probably drop, at least in the short run, and revenue passenger miles per gallon will decrease. If one did not want to consider the effects of demand changes, one could examine the efficiency of service offered.

Service offered is seat miles offered, and the fuel efficiency of service offered can be measured in seat miles per gallon, given in the table above. There is a steady rise in the efficiency of service offered from 1973 to 1978 and a large increase in efficiency in 1979 and 1980. The change in seat miles, however, is not quite as dramatic as the change in revenue passenger miles. In 1980, each gallon of jet fuel transported 35 percent more seat miles than did each gallon in 1973.

METHODOLOGY

A brief description of the methodology used in the analysis is given here. The following variables are used:

$\text{Aircraft miles}_i = (\text{airborne hours}_i)(\text{airborne mph}_i)$

$\text{Seat miles}_i = (\text{airborne hours}_i)(\text{seats}_i)(\text{airborne mph}_i)$

$\text{Gallons/aircraft mile}_i = (\text{gallons/block hour})_i/\text{average block-to-block speed}_i$

$\text{Gallons/seat mile}_i = (\text{gallons/block hour})_i/[(\text{seats}_i)(\text{average block-to-block mph}_i)]$

$$\text{Total gallons used} = \sum_{i=1}^{N} [(\text{gallons/block hour hour})_i/\text{average block-to-block mph}_i](\text{airborne hours}_i)(\text{airborne mph}_i)$$

where i is model type.

Fuel-use equations used in the analysis are given below. For load factor,

$$\text{Fuel use} = (\text{fuel use}_b)(\text{load factor}_b/\text{load factor}_a) \quad (1)$$

where a = base year and b = year under analysis; for model mix,

$$\text{Fuel use} = \sum_{i=1}^{N} F_i \times TSM_b \times (\text{gallons/seat mile})_i \quad (2)$$

where i = model type, $F_i = SM_{ia}/TSM_a$, and TSM = total seat miles; for technical and operating efficiency,

$$\text{Fuel use} = \sum_{i=1}^{N} (\text{gallons/aircraft mile})_{ia} \times (\text{aircraft miles})_{ib} \quad (3)$$

and for seating capacity,

$$\text{Fuel use} = \sum_{i=1}^{N} (\text{gallons/seat mile})_{ia} \times (\text{seat miles})_{ib} - \sum_{i=1}^{N} (\text{gallons/aircraft mile})_{ia}(\text{seat miles})_{ib} \quad (4)$$

All of the data used in the analysis are from the CAB. Some of the figures cited (such as Figure 2 on

actual fuel use) were also derived from CAB data.

Base Case

Basically, this analysis accounts for the changes in the fuel efficiency of delivered service that have happened since 1973. To measure the total change in the fuel efficiency of airline passenger service, a base case was constructed that assumed that actual demand was delivered with 1973 fuel efficiency. The difference between the base-case figures for fuel use and actual figures for fuel use is how much fuel was saved by improving the efficiency of delivery of service. The specific measure of efficiency of delivery of service is revenue passenger miles per gallon. That variable is held constant in the base case. For any percentage increase in actual revenue passenger miles traveled from one year to another, there is an equal percentage increase in the base case. Thus, the slope of the base case is the same as the slope of the revenue-passenger-miles line from 1973 to 1980.

Components of Efficiency Changes

The basic components of the improved efficiency of delivery of service are load factor, seating capacity, mix of aircraft, and technical and operating efficiency. Load factor is the percentage of available seats filled (not the number of passengers per aircraft). Seating capacity is the average seats per aircraft for each model type. Mix is the deployment of models to deliver service. Introducing new models, dropping old ones from use, and using existing models in greater or lesser proportion to others are examples of mix change. For the purpose of this analysis, mix is defined as the percentage of total seat miles flown by each aircraft model. Technical and operating efficiency is a measure of fuel use by the aircraft on an aircraft-mile basis. It includes such factors as the weight of the plane, the efficiency of the engines, cruise speed, angles of descent and ascent, altitudes, time spent circling, number of engines used while taxiing, congestion, maintenance, training, and many others.

Fuel-Use Analysis

The amount of fuel saved by improvements in each component in each year under study is estimated by calculating how much fuel would have been needed to deliver actual service in a particular year had the component under study remained at its 1973 level while all other components had their actual values. The difference between the derived figure and actual fuel use is the amount of fuel savings attributable to the change in the particular component. For example, the analysis of savings due to changes in the mix of aircraft involves holding the mix constant at its 1973 level while allowing the other components to vary as they actually did. The difference between fuel use with no mix change and actual fuel use is the savings due to mix change alone.

BASE CASE AND ACTUAL CASE

Figure 3 shows the base case along with actual fuel use for transporting revenue passengers. Most of the improvements in total efficiency are cumulative. An efficiency improvement made this year will save fuel next year. Total efficiency improvements increased roughly at a steady rate until 1977. In 1978 and 1979, there was a substantial increase in efficiency improvements. If 1973 efficiencies were delivered in 1975, an additional 952 million gal of fuel would have been needed. To have delivered the same amount of service in 1980 with 1973 revenue passenger miles per gallon would have required an additional 5.14 billion gal of fuel or another 335 000 bbl of fuel per day. From 1973 to 1980, improvements in the efficiency of delivery of service saved a cumulative total of 19.289 billion gal.

Figure 3. Actual and base-case fuel use.

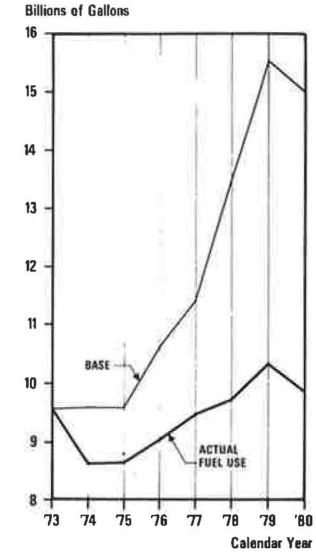
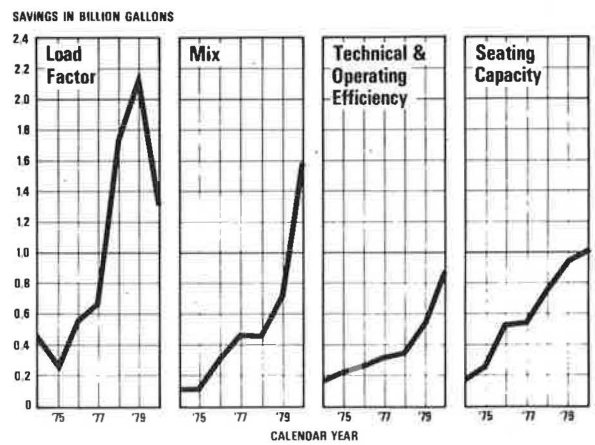


Figure 4. Fuel savings.



ANALYSIS AND RESULTS

Figure 4 shows the year-to-year fuel savings attributable to changes in each component. The numerical savings are presented in Table 2. This analysis is not intended to determine exactly the absolute amounts of fuel saved by each factor, since some of these factors are not completely independent of each other. Rather, the methodology provides a consistent basis on which to compare the relative amounts of fuel saved by each component. The absolute numbers should not be taken literally but can be used to compare efficiency components.

Load Factor

Total cumulative savings due to load-factor changes are estimated to be 7.2 billion gal. Of all of the estimates of savings, load factor may be the most

Table 2. Fuel savings.

	Fuel Use (billion gal)		Fuel Savings (billion gal)			
Year	Actual	Base Case	Load Factor	Mix	Technical and Operating Efficiency	Seating Capacity
1973	9.565	9.565	-	-	-	-
1974	8.655	9.622	0.465	0.107	0.174	0.187
1975	8.663	9.615	0.266	0.107	0.222	0.258
1976	9.051	10.571	0.573	0.316	0.270	0.522
1977	9.505	11.411	0.693	0.472	0.333	0.543
1978	9.748	13.393	1.759	0.463	0.341	0.765
1979	10.313	15.472	2.158	0.723	0.553	0.933
1980	9.871	15.011	1.330	1.417	0.876	1.193

misleading. Load factor is a function of seating capacity and number of passengers, not only number of passengers per aircraft. The savings stated in this analysis are based on the assumption that after 1973 the airlines would not have made better use of available seats. In other words, the percentage of seats filled would have remained constant. With increased seating capacity per aircraft, the number of passengers per aircraft would have risen with a constant load factor.

Although the change in load factor from 1973 to 1977 is only from 52.1 to 55.9 percent, the effect of the change on fuel efficiency is substantial. After 1977, savings due to load-factor changes grew at a much quicker rate. If load factor had been at its 1973 level in 1979, an additional 2 billion gal of fuel would have been needed to deliver the actual passenger miles.

Two factors had a major influence on the change in load factor from 1973 to 1980. The first is economic deregulation. With deregulation, the airlines were able to drop from service many of the inefficient routes that had low load factors. There is a marked change in load-factor levels following deregulation. The other factor that influences load factor is the economy. As the economy improved following the 1974-1975 recession, demand for service rose and the airlines were able to put more passengers in available seats. The 1980 recession and the increase in the real price of travel combined to lower demand and the load factor.

Seating Capacity

From 1973 to 1980, increased seating capacity saved a cumulative total of 4.2 billion gal of fuel. Perhaps the easiest way, in terms of cost, for the airlines to counter the effects of rising fuel and operating costs is to put more seats on individual aircraft. This can be accomplished by ordering more seats on new planes from the manufacturer or by replacing seats in older planes with a greater number of new seats (reseating). In 1973, the average Boeing 747 used in domestic flights had 328 seats. By 1980, the average 747 contained an additional 50 seats. From 1973 to 1980, the Boeing 727-200 logged more vehicle miles than any other model. The average 727-200 used by trunk lines for domestic purposes had 125 seats in 1973 and 133 seats in 1980. Local carriers using the same model jet had 147 seats in 1980. Of course, when seating capacity is increased, there is a cost to the passenger in terms of reduced average floor space per person. Adding more seats can add more weight to an aircraft, thereby increasing gallons per vehicle mile. Since additional seats allow more passengers to be placed on planes, the net effect of increased seating capacity on revenue passenger miles per gallon is positive.

Mix

After increased seating capacity, the next most important component of improved efficiency of delivery of service is mix. Mix is not just the number of different models in service but also the frequency of use. Mix changes saved an estimated cumulative total of 3.9 billion gal of fuel from 1973 to 1980.

In the 1970s, some very noticeable changes were made in the mix of aircraft models. Perhaps the most noticeable was the introduction of wide-body aircraft. The Boeing 747, the McDonnell Douglas DC-10 series, and the Lockheed L-1011 were first introduced in the early part of the decade. Within a couple of years, the wide bodies were transporting most of the passengers on long-distance trips. The DC-10, which logged 99 million aircraft miles in 1973 to provide passenger service, flew 167 million miles in 1980. The 1980 figure is an increase of 18 million miles over the previous year. Although wide bodies actually consume more gallons per vehicle mile, they are more fuel efficient because they transport more passenger miles per gallon. In 1980, the typical turbofan three-engine wide-body jet (DC-10 or L-1011) produced 51.2 seat miles/gal, whereas the typical turbofan three-engine regular-body jet (B-727) yielded 36.5 seat miles/gal.

With the wide bodies came new, more fuel-efficient jet engines such as the Pratt and Whitney JT9D, the General Electric CF6, and the Rolls Royce RB211, which superseded the much less fuel efficient JT3D, the standard engine on the B-707.

Another aspect of the mix change is the change in deployment of similar-sized aircraft with different efficiencies. The mix among 727-100s and 727-200s illustrates the point. The only major difference between the two models is that the 727-200 is a stretch version of the 727-100. Both are classified by CAB as three-engine, regular-body, turbofan aircraft. In 1973, the typical 727-100 had 96 seats available and delivered 27.4 seat miles/gal. Meanwhile, the 727-200 had 125 seats and got 31.9 seat miles/gal. In that year, the 727-100 flew 309 million aircraft miles and the 727-200 logged 306 million aircraft miles. Seven years later, the 727-100 had declined in its total use, flying 287 million aircraft miles, but the aircraft miles flown by the 727-200 jumped to 804 million miles. This mix change was a relative change, since the use of the less fuel-efficient aircraft was held constant while the use of the more fuel-efficient aircraft more than doubled.

The mix shift in 1980 had a larger impact on fuel efficiency than changes in any of the other components that year. The most significant change in mix from 1979 to 1980 was a major reduction in the use of inefficient four-engine, regular-body jets. Boeing 707s yielded 37.5 seat miles/gal in 1979 and flew 149 million miles. In 1980, their use was cut by 30 percent to 104 million miles. DC-8s, which delivered 96 million aircraft miles in 1979, were flown only 57 million miles in the following year, a 41 percent reduction. The DC-8-50, which flew 36 million miles in 1979 and only got 32.6 seat miles/gal, was dropped from use in 1980.

Technical and Operating Efficiency

The final component of improved efficiency in delivery of service is technical and operating efficiency. Although this aspect of fuel economy has probably received more attention in the media than the other components, its contribution to the change in efficiency of delivery of service has been relatively small. Improvements in the technical and operating efficiency of aircraft saved a cumulative total of 2.8 billion gal of fuel from 1973 to 1980.

Since, in this analysis, technical and operating efficiency is defined as fuel consumed from gate to gate, changes in anything from engines to cruise speeds to taxiing procedures affect the component. There have been a host of technical and operating improvements in recent years, especially in 1979 and 1980. Fuel is saved by using a steeper angle of descent in landing. Recently, the airlines have made an effort to reduce the weight of their planes. Lighter seats have been installed on many aircraft. Eastern Airlines scraped the paint off many of its jets (paint on a jet can weigh as much as 400 lb) and removed the 410-lb mechanical airstairs from the front of its 727s (1). Many jets now taxi with one or more engines shut down in order to save fuel. Maintenance procedures have been improved to make jets run more efficiently.

Summary of Components

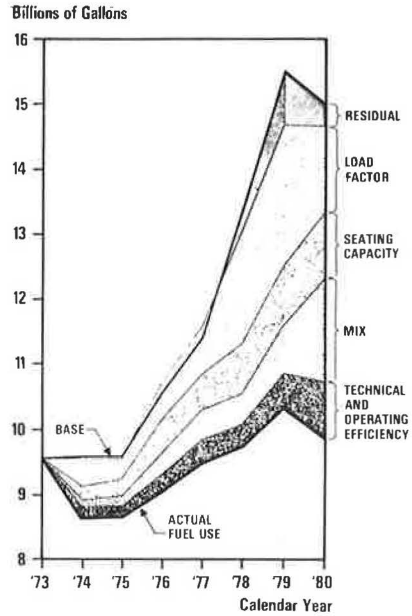
In Figure 5, the difference between the actual case and the base case is divided among the four components of improved efficiency. Of all the components, load factor appears to have had the largest effect on improved efficiency of service delivery. Load-factor improvements account for 42 percent of the improvement in efficiency in delivery of service from 1973 to 1979. Small changes in load factor make a relatively large difference in efficiency. Load factor rose from 52.1 percent in 1973 to 55.9 percent in 1977. Yet, in those years, the savings attributable to load factor are slightly larger than savings caused by changes in the other components.

Changes in seating capacity have the second-largest effect on efficiency in delivery of service. Increased seating capacity accounts for 22 percent of the total efficiency improvement from 1973 to 1980, mix changes contribute 20 percent, and changes in technical and operating efficiency account for 15 percent of efficiency improvements.

Residual Savings

As can be seen in Figure 5, in all of the years under study there is a residual of unexplained or overexplained efficiency savings. For most years, the residual is less than 10 percent of the difference between the base case and the actual case. There are at least two reasons for the existence of the residual. First, this "bottom-up" analysis should not explain the entire difference between the base case and the actual case. Second, the base case and the actual case are not from the same population. The actual case includes fuel used in charter service, whereas the base case only measures the percentage change in scheduled traffic. This would not pose too much of a problem if the ratio of scheduled to charter service remained constant over the period under study. In the late 1970s, the level of charter service delivered fell off dramatically. If the analysis were based solely on scheduled service, the base case would have the same shape it has now. However, the location of both lines and the shape of the actual case would be different. The slope of the actual case from 1976 to 1979 would be steeper. Such an adjustment would narrow the size of the residuals in 1978, 1979, and 1980.

Figure 5. Components of fuel efficiency improvements in U.S. commercial airline industry.



IMPACT OF OIL PRICE CHANGES ON FUEL EFFICIENCY

A substantial change took place in the fuel efficiency of service in the airline industry from 1973 to 1980. Yet the airline industry was not unique, since almost all industries will improve the efficiency of production over time. As can be seen in the earlier text table that gives 1967-1980 revenue passenger miles and seat miles per gallon, the efficiency of delivery of service in the airline industry was improving even before the oil embargo. The question here is whether the rise in the price of jet fuel caused the industry to improve efficiency at an even more rapid rate than it had in the past. To answer this question, a historic trend line of year-to-year changes in fleet seat miles per gallon in the pre-embargo period was derived and compared with actual seat miles per gallon for the post-embargo period. Seat miles per gallon was chosen as the unit of measurement because it includes all other components of efficiency change except load factor. Load factor is excluded, since it is directly affected by exogenous changes in demand for air travel--i.e., short-run economic cycles. The components that determine seat miles per gallon are mix, technical and operating efficiency, and seating capacity. Although mix, operating efficiency, and seating capacity can be changed relatively quickly, changes in those components have, in the past, not been a direct result of short-run economic cycles. Economic cycles in the pre-embargo period will have little effect on the trend line of seat miles per gallon developed for that period. Therefore, these are reasonable variables to include in the trend analysis.

The historical trend is derived from 1967-1972 seat miles per gallon. The results, for 1974-1980, are given below:

	Seat Miles per Gallon	
Year	Projection	Actual
1974	33.76	34.32
1975	34.76	34.98

	Seat Miles per Gallon	
Year	Projection	Actual
1976	35.76	35.67
1977	36.76	36.63
1978	37.76	37.83
1979	38.77	40.34
1980	39.77	43.68

From 1974 to 1978, the trend line almost exactly predicts actual seat miles per gallon. In 1979, actual seat miles per gallon exceed the historic trend by 4 percent. In 1980, the improvement over the historic trend is 10 percent. This would suggest that the airline industry made no improvement in efficiency over its historic trend until 1979.

This interpretation is supported by Figure 4, which shows the components of efficiency improvement. With the exception of load factor, there is a relatively steady increase in the amount of fuel "saved" by improvements in each component. These improvements do not appear to be sensitive to variations in oil prices until 1979. There are no sudden jumps in total efficiency in response to the fuel price rise in 1974, nor is there any leveling off of the rate of change in total efficiency as fuel prices leveled off in the mid-1970s (the jumps in technical and operating efficiency correspond with the oil price shocks of 1974, 1979, and 1980). In 1979, the savings from each component were significantly increased, and the combined effect (savings) was almost twice as much as the previous year-to-year changes.

Several factors explain this trend. One is that oil prices did not seriously affect the airline industry until 1979. The effect of oil price changes on total cost must be considered. Whereas the percentage of total operating expenses represented by fuel increased substantially from 1973 to 1974 (from 12.2 to 17.4 percent), as indicated in the first text table in this paper, there was a gradual change in the percentage from 1974 to 1979. This was reflected in the real price of travel, which increased slightly in 1974 but then fell for the next five years. Since the real price of travel is a rough measure of total costs, it can be concluded that, until 1979, increases in the price of fuel were made up for by economies in other factors of production.

By 1979, fuel prices again started to rise rapidly. This created two effects. First, fuel cost increased to 25 percent of total operating costs. This may have exceeded a "threshold" beyond which airline industry management had to deal with the problem quickly and effectively. Second, the cost of fuel rose too quickly to be offset by increased operating economies. This is reflected in the low airline profits in 1979 ($215 million compared with $1.36 billion in 1978 despite rising load factors and revenue passenger miles) and a rise in the real price of travel in 1980. In the face of these problems, the airlines may have made a more conscious effort to improve fuel efficiency.

Another factor that explains the relatively consistent trend is that the airlines were increasing the number of seat miles offered in both the pre-embargo and post-embargo periods and a side effect of this was to increase seat miles per gallon at a fairly constant rate. Before the oil embargo, the airlines introduced the wide-body jets in order, among other reasons, to offer more seats on longer routes. The B-747, DC-10, and L-1011 were introduced in 1970 and 1971 and by 1973 were playing a major role in providing air transportation. Since these planes deliver service more efficiently, the effect of this mix shift was to increase seat miles per gallon.

In the post-embargo period, there was a much smaller mix shift. From 1967 to 1971, 1288 jets were purchased by commercial airlines (including foreign flag carriers) from Boeing, the major manufacturer of commercial jets in the United States, but only 590 jets were purchased from 1973 to 1977. Following the 1974-1975 recession, the demand for air transportation began to rise. To service the rising demand, the airlines needed to expand their capacity. This could not be accomplished by bringing on new, larger models because no new models were available. Furthermore, the wide bodies had practically reached their saturation point in the market. To expand their capacity, the airlines increased the seating capacity on existing airplanes. This also increased seat miles per gallon and thus helped to keep the year-to-year change in the measure of fuel efficiency on its historic trend line.

In 1980, a substantial mix shift occurred. The major aspect of this shift was reducing the use of inefficient planes, such as the DC-8 and the B-707. A lower level of demand in 1980 than in the previous year made this possible. Had demand been rising, the airlines would have needed these inefficient planes more. If these aircraft had been used more extensively, the fleet fuel-efficiency improvement from 1979 to 1980 would not have been so dramatic. Thus, the flexibility of the airlines in making mix shifts is constrained by changes in the demand for air travel.

The long lag time between changes in economic conditions and the introduction of new-model aircraft in response to those changes may also help explain why efficiency did not improve at a rate above this historic trend. It takes a long time to design a new model and introduce it into the commercial airline fleet. Five years may elapse between the initial design of a new aircraft model and the beginning of production. It may take another three years of deliveries to accumulate enough planes to make a noticeable impact on fuel use. It could take eight years or more to bring on a new model to counter changing economic conditions.

New, more fuel-efficient planes will soon be introduced into the market. Within the next two years, Boeing will begin production of its 757s and 767s. These are highly fuel-efficient, two-engine, wide-body jets designed primarily for use on short- and medium-distance routes. Since the 747, DC-10, and L-1011 came out in the early 1970s, it may have been inevitable that new aircraft models would not be introduced until the early 1980s. Thus, even if it wanted to, the airline industry could not have introduced new, more fuel-efficient jets in the 1970s in response to rising fuel prices.

Taken together, these factors suggest a situation in which the airline industry (a) continued its historic increase in fuel efficiency until 1979, unaffected by fuel prices; (b) absorbed a significant portion of the rise in fuel prices until 1979, without having to raise the price of travel; and (c) was constrained by long-run forces in responding in the short run to quickly rising energy prices.

THE FUTURE

Tremendous potential for even further improving the efficiency of delivery of service still remains. Perhaps the most visible change to expect in the near future is the introduction of two-engine, wide-body jets for short- and medium-range service. Boeing estimates that its 757, which will seat between 178 and 223 passengers, will burn 35 percent less fuel per seat mile than current 727s, and its 767, which will seat between 211 and 289 passengers, will use 41 percent less fuel per seat mile than the 727. The 767 would deliver about 70 seat miles/

gal. The financial health of the airline industry and the level of interest rates will have a strong influence in determining when these new models will begin to be used by the airlines. There are many proposals for improvements in design. Among them are the use of new wings and winglets to reduce drag as aircraft move through the atmosphere. Retrofit improvements, which began in earnest within the past year, will probably become much more ambitious. Perhaps the most far reaching of the proposed changes is to replace the three JT8D engines on B-727s with two PW-2037 (formerly called JT10D) engines. This could reduce fuel use on 727s by about 30 percent. Many changes in operating procedures are being considered. One proposal is for jets that are held at the gate for more than 5 min beyond scheduled departure time to turn off their engines. There will most likely be greater use of simulators for training purposes.

There is no consensus on what will happen to load factor in the future. Many experts believe that load factor has peaked in the low to mid-60 percent range. They feel that further increasing load factors would result in scheduling problems and turning away many ticket buyers because of overbooked flights. Others believe that improvements in the economy will raise load factors into the mid-60 percent range. They maintain that the dropping of marginally profitable routes due to rising costs and the use of more efficient scheduling could raise load factors to more than 70 percent. The weight of opinion supports the former scenario. There is still great potential for increasing seating capacities. Of course, there are technical limits on seating capacity and psychological limits on how much crowding passengers will tolerate.

It is not clear what the relative weight of the components would be if the same analysis were done for 1980-1990. If load factor does exceed 70 percent, it will once again be the component that makes the largest contribution to efficiency improvements. If, as many experts predict, load factor does not rise, it will contribute very little to efficiency improvements. In 1980 alone, mix contributed more than the other individual factors to fuel-efficiency improvements. With the introduction of the 757 and 767, mix shifts could play an even larger role in improving fuel efficiency. As mentioned, there is also tremendous potential for improving seating capacity and technical and operating efficiency. It remains to be seen what the relative weight of the components will be.

CONCLUSIONS

Based on the analysis described in this paper, the following conclusions can be drawn:

1. In 1980, the U.S. commercial airline industry provided 57 percent more service than it did in 1973, using only 8 percent more fuel.
2. Load factor accounted for 37 percent of the efficiency improvement. That variable was followed in order of relative contribution by seating capacity (22 percent), mix (20 percent), and technical and operating efficiency (15 percent).
3. Most of the improvements in the fuel efficiency of delivery of service have come about through better use of existing aircraft. Adding more seats and using available seats more productively through higher load factors have been the most effective ways for the airline industry to meet rising demand with very little increase in fuel consumption.
4. Load-factor changes have been the most effective. Even small changes in load factor had a significant effect on the fuel efficiency of delivery of service. The major government policy decision affecting fuel use by commercial airlines was the deregulation of the industry. The jump in load factor and subsequent effects on fuel savings indicate that this decision had a positive impact on the efficiency of delivery of service.
5. The airline industry did not respond specifically to fuel price increases until the price shock of 1979. This is probably due to three factors: (a) fuel costs did not become a large burden for the industry until 1979, (b) the industry was apparently able to absorb fuel price increases until 1979 through economies in other factors of production, and (c) the short-term response of the industry to rising fuel prices was constrained by long-term forces.
6. In the next several years, there may be a change in the relative order of savings caused by changes in each component of efficiency. Load factor, the component that made the greatest contribution to efficiency improvement in the 1970s, may have reached its peak in 1979. Load factor may not rise in the 1980s and therefore will contribute little to efficiency improvements. Since new jets are soon to be introduced, mix may have a much larger role to play in improving the fuel efficiency of delivery of service in the 1980s.

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