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Addresses of Authors

Baxter, John R., Federal Highway Administration, U.S. Department of Transportation, 400 Seventh Street, S.W., Washington, D.C. 20590; formerly with Department of Civil Engineering, Clemson University
Berg, Mark R., Institute for Social Research, University of Michigan, Ann Arbor, Mich. 48106
Bevilacqua, Oreste, Bevilacqua Knight, Inc., Suite 205, 492 Ninth Street, Oakland, Calif. 94607-4048
Bloch, Arnold J., New York City Department of City Planning, 2 Lafayette Street, New York, N.Y. 10007
Brunso, Joanna M., Planning Division, New York State Department of Transportation, Albany, N.Y. 12232
Greene, David L., Oak Ridge National Laboratory, 4500 N, P.O. Box X, Oak Ridge, Tenn. 37830
Hartgen, David T., Planning Division, New York State Department of Transportation, Albany, N.Y. 12232
Hennigan, Martha E., Planning Division, New York State Department of Transportation, Albany, N.Y. 12232
Hu, Patricia S., Oak Ridge National Laboratory, 4500 N, P.O. Box X, Oak Ridge, Tenn. 37830
Johnson, Larry R., Center for Transportation Research, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Ill. 60439
Kim, Kwang-Sik, Department of Public Administration, Sung Kyun Kwan University, Seoul 110, Korea
Mader, Gerald, Electric Vehicle Development Corporation, 20823 Stevens Creek Boulevard, Cupertino, Calif. 95014
Millar, Marianne, Center for Transportation Research, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Ill. 60439
Neveu, Alfred J., Planning Division, New York State Department of Transportation, Albany, N.Y. 12232
Pignataro, Louis J., Polytechnic Institute of New York, 333 Jay Street, Brooklyn, N.Y. 11201
Santini, Danilo J., Center for Transportation Research, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Ill. 60439
Saricks, Christopher, Center for Transportation Research, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Ill. 60439
Schneider, J. B., University of Washington, Seattle, Wash. 98195
Singh, Margaret K., Center for Transportation Research, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Ill. 60439
Stafford, Donald B., Department of Civil Engineering, Clemson University, 110 Lowry Hall, Clemson, S. C. 29631
Teotia, Arvind P. S., Center for Transportation Research, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Ill. 60439
Till, Lynn, Computer Sciences Department, University of Tennessee, Knoxville, Tenn. 37916
Vyas, Anant, Center for Transportation Research, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Ill. 60439

Consumer Trade-Offs Between Mobility Maintenance and Gasoline Savings

JOANNA M. BRUNSO and DAVID T. HARTGEN

ABSTRACT

Gasoline use in New York State has steadily declined since 1978. However, travel has steadily increased since 1968, set back only twice by the oil crises of 1973 and 1978. Two analyses were performed to examine this phenomenon: First, aggregate trends in travel, fuel use, price, and efficiency were used to determine the general nature of consumer trade-offs between fuel use and travel. Second, three statewide surveys of consumer response (performed in 1979, 1980, and 1982) were examined for their impact on travel. The trade-offs were clarified by relating conservation impacts to changes in energy use and method of travel. The study found that shifts to fuel-efficient automobiles have helped consumers save significant amounts of money formerly spent on gasoline. However, it was found that consumers were reinvesting some of these savings in additional travel. Consumers claimed to take actions to limit nonwork travel, but when actual trip rates, trip distances, and incidence factors were applied to the survey responses, it became apparent that the major conservation strategies were work and car related. The authors inferred from the data that after an initial reduction in travel in response to gasoline shortages in 1979, consumers appeared to have invested some of the savings made possible by more fuel-efficient automobiles in additional nonwork travel in order to regain the household travel patterns that were most satisfying to them.

Gasoline is a key fuel in transportation energy use and is particularly crucial because it is essential to general public mobility. Since the oil shortages of 1973-1974 and 1979, significant efforts have been made in transportation planning to conserve energy.

To a large extent, plans and programs have focused on work travel as the primary target of consumer response to shortages. But work travel represents only 32 to 40 percent of all travel (1-3), leaving most travel unaffected by conservation plans. The purpose of this study is to examine the ways consumers have responded to energy restrictions and price increases, and the changes in consumer focus that have occurred in the wake of the 1979 energy crisis. This assessment is made through two analyses. First, state-level trends in travel, fuel use, price, and car efficiency are used to determine consumer trade-offs. Second, three statewide surveys of consumer responses (performed in 1979, 1980, and 1982) are examined for their impact on work, nonwork, and other actions. The conservation impacts are then related to changes in gasoline use (energy conserved) and changes in vehicle miles of travel (VMT). By examining the trends of all these factors since 1978, the year of highest gasoline consumption, it should be possible to understand the trade-offs consumers are making to cope with changes in energy price and supply.

BACKGROUND

A number of studies exist on consumer response to the 1973 to 1974 and 1979 energy crises (4-19). Most studies focused on consumer response to price rises and shortages. These studies determined that it was a shortage of fuel rather than an increase in price that initially compelled consumers to conserve. In both cases, consumers emphasized small nonwork actions in terms of frequency of response, but less frequent major actions accounted for most of the energy saved. The introduction of more fuel-efficient automobiles in the late 1970s stimulated car purchasing behavior during the 1979 crisis. One study found that vehicle fleet turnover was the largest single energy-saving action. This in turn allowed household travel to return to precrisis patterns. Subsequent studies also showed that consumers eventually returned to "normal" travel patterns.

RECENT TRENDS IN TRAVEL AND ENERGY USE

Figures 1a through 1d show the recent New York State (NYS) trends in annual vehicle miles of travel, gasoline use, gasoline pump price, and on-the-road average automobile efficiency. National data are similar (20-21). NYS travel has increased steadily since 1968, set back only twice by the oil crises of 1973 and 1979. Gasoline use has declined steadily since 1978. At the time of the shortages, gasoline prices climbed rapidly. By 1978 domestic automobile manufacturers began to make fuel-efficient automobiles increasingly more available. As more of these automobiles entered the used automobile market and the "gas guzzlers" of the past were retired, on-the-road automobile efficiency increased steadily.

The thesis of this paper is that a complex interaction among travel, gasoline usage, gasoline price, and car efficiency is responsible for these trends. As the fuel efficiency of the average automobile rises, less gasoline is needed to travel a given distance. If the rise in efficiency outpaces the rise in gasoline demand, pressure on demand will drop, and gasoline prices will go down. Because fewer dollars are being spent on gasoline for current travel patterns, household funds can now be reinvested in

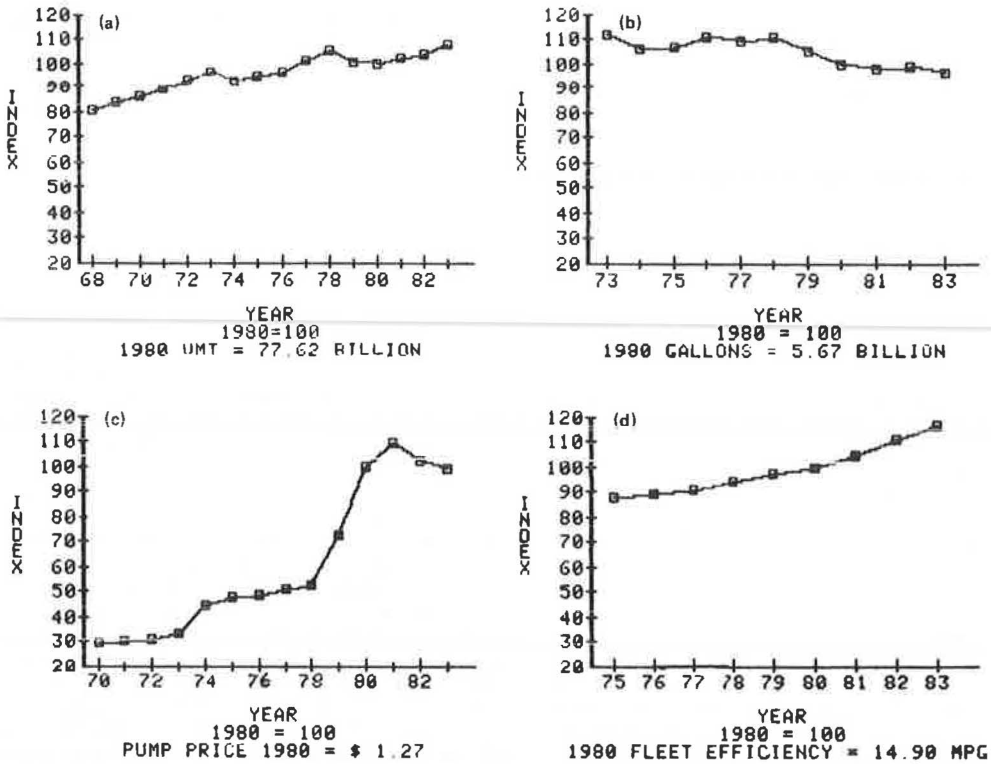

FIGURE 1 Recent trends in travel and energy use: (a) vehicle miles of travel, (b) annual highway gasoline usage, (c) nominal pump price, and (d) on-road automobile fuel efficiency.

other goods and services (including new automobiles) or be used to travel still more miles. In essence, households can reinvest gasoline savings in travel that might have been foregone under tighter financial circumstances.

Table 1 and Figure 2 show recent trends in NYS gasoline use and VMT. In the 1979 energy crisis, gasoline consumption dropped about 340 million gal from 1978, while travel dropped 3.68 billion VMT from 1978. Statistics for 1980 showed continued drops. But since 1980, travel has slowly increased from its low point of 77.62 billion VMT, and 1983 numbers show that travel totaled 83.78 billion VMT, or 6.16 billion VMT above the 1980 low. However, gasoline consumption has continued to fall. (Gasoline in NYS is used about 98 percent of the time for private or personal travel.) Although the VMT changes might partly be due to background population growth or demographic shifts, the VMT changes between 1980 and 1983 (+7.9 percent) are more than 10 times as fast as population changes in the same time period.

Additional travel above the 1980 low point may be thought of as additional mobility needs expressed through actions. The gasoline necessary for additional travel may be thought of as gasoline that could have been saved, had travel remained at 1980 levels. However, consumers appear to have chosen to purchase more gasoline, in exchange for increased mobility, rather than to save gasoline.

Figure 2 shows how much gasoline would be needed to power the increased mobility. For instance, in 1983 about 350 million gal of gasoline would have been required to power the additional 6.16 billion VMT. The 350 million gal of reinvested gasoline came partly from increases in fuel efficiencies (.20 = 6.16/17.38 - 6.16/16.45) and partly from gasoline that was "not saved" (.35 - .20). The authors interpret the 350 million gal as conservable gasoline that was spent to allow growth in mobility. Compared with the savings already achieved between 1978 and 1983 (820 million gal) the amount of reinvested gasoline is considerable and is growing as a percentage of savable gasoline.

In the authors' view, consumers are using improvements in vehicle efficiency, combined with selected additional gasoline use, to travel more. A

TABLE 1 Gasoline Reinvested in Travel, New York, 1978 to 1983

Basic Data				Change from 1978		Rebound After 1979		Source of Reinvested Gasoline		
Year	Gasoline (gal millions)	Travel (VMT billions)	Mpg[a]	Gasoline (gal millions)	Travel (VMT billions)	Travel Change from 1980	Reinvested Gasoline to Support ΔT[b]	Fuel Efficiency	Gasoline Not Sold	Percent Reinvested as Percent of Total Savable
1978	6.29	81.50	14.00							
1979	5.95	77.82	14.50	-.34	-3.68					
1980	5.67	77.62	14.90	-.62	-3.88					
1981	5.57	79.13	15.60	-.72	-2.37	+1.51	-.10	-.10	.00	12
1982	5.62	80.48	16.45	-.67	-1.02	+2.86	-.17	-.05	-.12	20
1983	5.47	83.78	17.38	-.82	+2.28	+6.16	-.35	-.20	-.15	30

[a]Avg automobile efficiency.
[b]Column 8 = Column 7/Column 4.

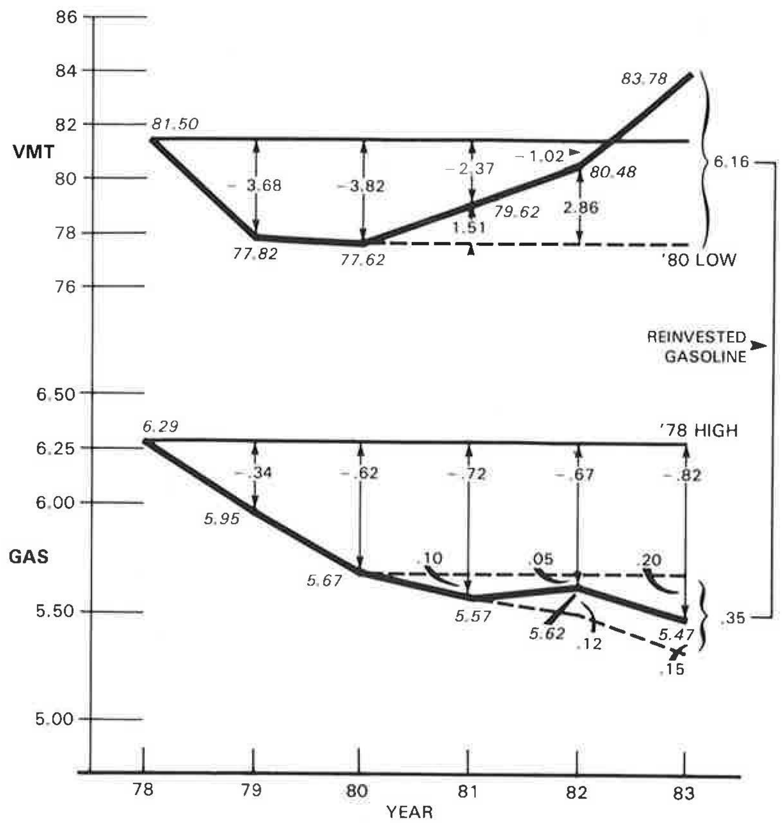

FIGURE 2 Trends in travel and gasoline use in New York State.

considerable and growing portion of the gasoline potentially savable (30 percent in 1983) is being reinvested in more travel by way of greater fuel efficiency and other factors.

CONSERVATION TRADE-OFFS

To better understand conservation trade-offs, the New York State Department of Transportation (NYSDOT) conducted a series of telephone surveys that investigated many actions consumers took to conserve gasoline. The first of these surveys was taken in October of 1979, shortly after the 1979 oil crisis. This was followed in October of 1980, and again in January of 1983 (1982 data). The surveys were of the simple-random-sample type and were representative of the number and gender of the population within the various counties of the state. Details of these studies are available in other documents (14,22-25).

Initial and Subsequent Responses to the 1979 Crisis

Results of the percent responses to these surveys are summarized in Table 2. The 1979 data indicate that "small-frequent" options, such as trip chaining, driving slower, and increased maintenance, were most frequently mentioned by consumers. Reducing vacation travel was also an important response, given the timing of the shortage (summer 1979). Mode switching behavior was not frequently mentioned. During the 1979 crisis, a surprisingly large percentage of consumers also mentioned "buy fuel-efficient cars" as an action to conserve fuel. Although the authors recognize that the lack of a clear baseline (i.e., 1978 behavior) clouds these data, they nevertheless believe that the data show the overall pattern of 1979 responses.

The responses to the 1980 survey generally paralleled the previous survey. The percentage of affirmative responses was highest in the nonwork actions category, and was greater in 1980 than in 1979. But mode shifting (transit to work and carpool to work) declined slightly in frequency. Upstate New York residents placed more emphasis on shopping actions; persons aged 65, households without automobiles, and low-income households adopted fewer actions than others.

NYSDOT repeated the survey in early 1983. Data were collected in the same fashion as in earlier surveys. The 1983 survey shows that conservation behavior was far more prevalent in 1983 than in 1980 or 1979, only 2 years earlier. Of 17 items compared in Table 2, all but 1 ("drive slower") were up in frequency of response, and the increase was substantial.

It appears that by 1983 a conservation attitude had permeated a much broader spectrum of society. The items most frequently mentioned and increasing most rapidly were "combining shopping and other trips," "shopping closer to home," and "shopping on the way home from work." Included among the top-ranked actions were three actions that were not included in the previous surveys: "sharing rides to nonwork activities," "choosing social and recreational trips closer to home," and "walking and bicycling to nonwork activities."

Energy Savings from Conservation Actions

An estimate of the gallons of gasoline saved by each household can be calculated from these data by applying trip rates developed either from these or

TABLE 2 Actions to Conserve Gasoline Taken in 1982

					Area				Household Income ($000s)		
Rank Order	1979 (N=1,520)	1980 (N=1,560)	1982 (N=1,503)	Δ1982-1980	NYC (N=585)	LI (N=95)	West/Rock (N=223)	Upstate (N=600)	<10 (N=309)	10-25 (N=565)	>25 (N=496)
1. Combine shopping and other trips	47	54	76	+22	71	76	76	80	66	82	78
2. Shop closer to home	41	47	65	+18	68	66	57	64	71	70	58
3. Share rides to nonwork activities	–	–	59	–	53	60	67	63	51	63	60
4. Make fewer shopping trips	35	53	54	+1	48	53	46	61	59	58	47
5. Choose social and recreational activities closer to home	–	–	52	–	52	54	44	51	54	58	46
6. Walk or bicycle to nonwork activities	–	–	51	–	58	49	45	45	45	53	52
7. Shop on way home from work	24	30	50	+20	52	43	48	51	27	58	58
8. Use a train, bus, or airplane for vacation	16	21	45	+24	56	42	52	33	37	43	52
9. Driver slower	42	43	35	-10	28	36	29	41	26	38	38
10. Have car tuned more often	37	26	29	+3	29	11	26	34	17	34	33
11. Take bus or subway to work	15	14	28	+14	50	9	20	10	22	30	29
12. Take bus or subway more often for nonwork activities	15	15	25	+10	43	16	20	11	29	29	19
13. Buy fuel-efficient car	15	17	25	+8	19	31	25	30	14	26	33
14. Vacation closer to home	17	19	22	+3	21	21	15	26	16	28	21
15. Cancel a vacation trip	16	12	18	+6	18	18	12	18	20	19	15
16. Walk or bicycle to work	8	11	16	+5	18	7	17	16	10	20	17
17. Carpool to work	14	13	14	+1	10	7	16	18	8	16	16
18. Job closer to home	5	4	11	+7	10	15	15	11	6	16	11
19. Sell car (do not replace)	8	5	7	+2	7	7	4	6	5	7	2
20. Move closer to work	2	3	7	+4	8	6	5	7	6	9	7

Note: Values given in table are percentage of respondents mentioning these actions. Dashes indicate data not available.

other surveys, along with assumptions concerning the opportunity to curtail energy use.

There are two methods of undertaking this computation: the simplified method used by Neveu et al. (4) and a more detailed method used for the 1983 data only (25). Both methods yield similar results.

For both methods, the savings in fuel is calculated as follows:

$$S_{ij} = (Z)(L_aR_a - L_bR_b)(1/mpg)(I) \quad (1)$$

where

- S_{ij} = weekly savings for action j for household i,
- L = trip length before (b) and after (a) the change in behavior,
- R = trip rate (per week) before and after change in behavior,
- mpg = miles per gallon of average automobile,
- Z = 1 if action taken, 0 if action not taken, and
- I = incidence factor (the percentage of conservation opportunities that are actually taken advantage of).

Weekly savings for each household can then be determined by summing the 18 actions proposed or each action can be analyzed separately or in relation to the other actions:

$$S_i = \sum_{j=1}^{18} S_{ij} \quad (2)$$

The total weekly savings for NYS can be computed by expanding the survey by the number of households in the state. Thus,

$$\text{NYS weekly savings} = \sum_{i=1}^{N} (S_{ij})(6.4 \text{ million households}/N) \quad (3)$$

where N is the number of respondents in each survey.

The simplified method uses a single estimate of trip length and rates for each action j and one overall incidence factor for all actions. The incidence factor is determined by comparing the estimated total savings from Equation 3 with the actual savings shown in Table 3. The computation in Equation 3 yields a total savings of 2,141 million gal for 1982 compared to 1978. However, Table 3 shows that the actual 1982 savings in gasoline is only 665.8 million gal, or about 31 percent of the total possible. The reason for this difference is that not every opportunity for savings actually results in conserved gasoline. In other words, the incidence factor is about 0.31. Similar factors for 1979 and 1980 are 26 percent and 46 percent, respectively.

Table 4 shows the NYS energy savings from each action for each year. If these savings are summed over all of the actions, the total number of gallons saved in the average week of the year indicated is computed for NYS. This number can then be divided by the number of households to arrive at the average savings per household per week. The data in Table 4 show that since 1979 the greatest fuel savings has been achieved through automobile-related actions, but that this proportion is declining. The major proportion of these savings has been attributed to the purchase of more fuel-efficient automobiles. During 1979, 44 percent of all savings were due to automobile-related actions; by 1982 this proportion had declined to 34 percent. As the automobile fleet ages, the gas guzzlers of the past are being phased out; by 1980 (and even more so in 1982) consumers also sought more fuel-efficient used automobiles.

Nonwork savings are attributable to shopping-related and vacation actions. Together, these have varied little as a proportion of savings, rising from 30 percent in 1979 to 34 percent in 1980 and 1982.

Each of the shopping actions saves a small amount of fuel. From a gallon-saved point of view, shopping on the way home from work and shopping closer to home appear to be most effective. However, the data in Table 4 show that shopping actions, although mentioned by an increasing percentage of the respondents as the years progress, accounted for a decreasing amount of energy saved in terms of absolute gallons and percentage of total fuel sold.

TABLE 3 New York State Gasoline Savings Since 1978

Year	No. of Households in NYS (x 10^6)	Fuel Sold per Year (gal x 10^3)	Gallons per Household per Week	Δ Gallons from Previous Year	Δ Gallons Change per Household per Week	Δ Gallons from 1978	Δ Gallons per Household per Week from 1978
1978	–	6,286,240	19.05	–	–	–	–
1979	6.345	5,949,975	18.03	-336,265	-1.02	-336,265	-1.02
1980	6.449	5,668,563	16.90	-281,412	- .84	-617,677	-1.84
1981	6.449	5,569,749	16.61	- 98,814	- .29	-716,591	-2.14
1982	6.523	5,620,407	16.42	+ 50,658	+ .15	-665,833	-1.96
1983	6.563	5,467,682	16.02	-152,725	- .45	-818,558	-2.40

TABLE 4 New York State Weekly Savings per Week

	Energy Savings by Actions Already Taken					
	1979		1980		1982	
Action	Gal (x10^6)	Percent	Gal (x10^6)	Percent	Gal (x10^6)	Percent
Work-related						
Bus/subway	0.84	13	1.30	11	2.3	18
Carpool	0.52	8	1.07	9	1.1	8
Walk/bike	0.13	2	0.24	2	0.2	2
Subtotal	1.49	23	2.61	22	3.6	28
Shopping-related						
Shop closer to home	0.32	5	0.48	4	0.6	5
Combine shop/other	0.13	2	0.35	3	0.3	2
Shop less often	0.19	3	0.48	4	0.3	2
Bus/subway to nonwork	0.19	3	0.24	2	0.2	2
Shop on way home from work	0.26	4	0.47	4	0.6	5
Subtotal	1.09	17	2.02	17	2.0	16
Car-related						
Tune-up	0.38	6	0.47	4	0.4	3
Drive slower	0.13	2	0.24	2	0.1	1
Buy a more fuel-efficient car	1.29	20	2.85	24	2.8	22
Sell a car (do not replace)	1.03	16	1.19	10	1.1	8
Subtotal	2.83	44	4.75	40	4.4	34
Vacation						
Cancel a vacation trip	0.26	4	0.35	3	0.3	3
Change mode for vacation	0.52	8	1.30	11	1.8	14
Vacation closer to home	0.06	1	0.24	2	0.2	1
Eliminate RV or boat	—	—	0.12	1	—	—
Subtotal	0.84	13	2.01	17	2.3	18
Moves						
Move closer to work	0.06	1	0.24	2	0.2	2
Job closer to home	0.19	3	0.24	2	0.3	3
Subtotal	0.25	4	0.48	4	0.6	5
Total weekly savings	7.2	100[a]	11.88	100	12.8	100
Total annual savings			617.7		665.8	
Weekly savings per household	1.02		1.84		1.96	

[a]Columns may not add to zero due to rounding errors.

Figure 3 is essentially a blow-up of the lower portion of Figure 2, with more detail on the nature of these savings. The drop in gasoline sales since 1978 is apportioned to the various categories of actions, so that the area between the gasoline use curve and the x-axis is divided into the indicated conservation actions. Points A, B, and C represent the trend using the simplified method. Points D, E, F, and G represent the trends using the more detailed method.

As can be observed, over the years the proportion of conserved gasoline attributed to work has increased, while automobile, vacation, and nonwork conservation has decreased. By inference, automobile-related savings appear to have peaked in 1981. Because the three additional conservation actions (sharing rides for nonwork travel, walking or bicycling to nonwork activities, and choosing social and recreational activities closer to home, all under point G in Figure 3) were not surveyed in all three years, it is reasonable to assume that a significant amount of the nonwork-related gasoline conserved would have been attributed to these actions in previous surveys. It is also clear that had these actions not been included in the 1982 survey, conservation of gasoline attributed to nonwork other than vacation would have shown a more significant decrease.

POLICY IMPLICATIONS AND CONCLUSIONS

The responses in each of the three surveys have shown that NYS consumers are saving considerable amounts of gasoline compared with 1978. A significant number of respondents mentioned trip planning, nonwork activities occurring closer to home, and other nonwork actions as gasoline savers, but when gallons conserved were estimated, more gallons were conserved through automobile and work actions than any other

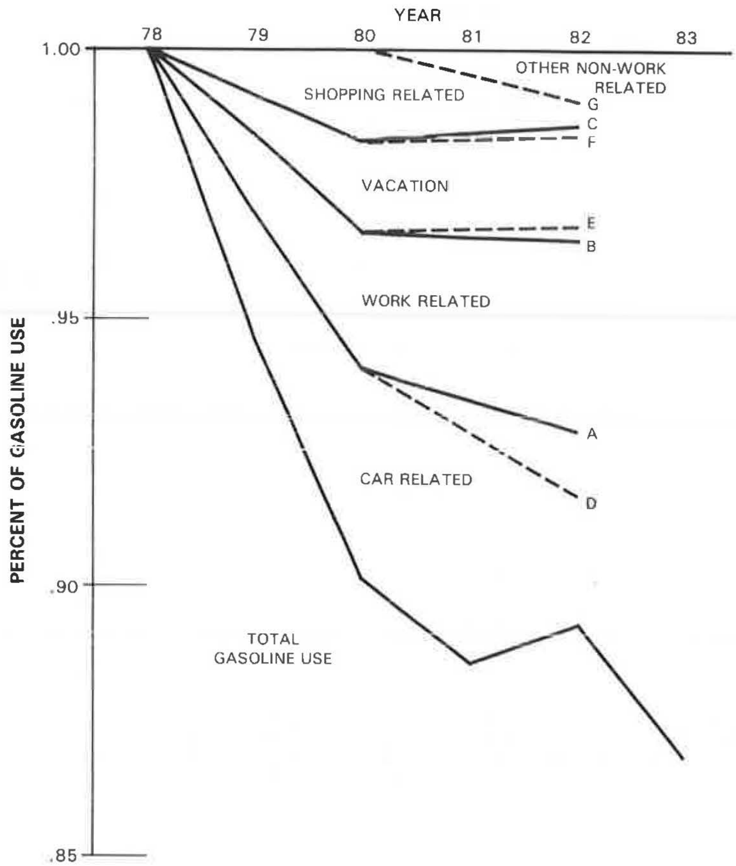

FIGURE 3 Allocation of gasoline conserved by types of conservation actions.

group. Furthermore, when incidence and trip rates determined by the survey were applied in the computations, savings through automobile actions were a bit smaller and gallons saved commuting to work were a bit larger.

The following conclusions may be drawn:

• Shifts to more fuel-efficient automobiles have helped consumers save significant amounts of gasoline. However, as the fleet ages and older automobiles are retired from service, the benefits of fuel-efficient automobile purchases may decrease. With annual VMT rising, cars will have to become even more efficient or other strategies will have to be found to maintain conservation levels.

• Consumers are abandoning a "drive slower" attitude. They appear to believe that driving slower is not worth the effort or loss of time involved.

• Consumers have chosen automobile- and work-related actions as strategies to reduce gasoline cost and consumption.

• Consumers have made less of an effort to conserve gasoline in nonwork travel. There may be many reasons for this, including habit, consumer wants, and a feeling that it is just not worth the effort. However, the large percentage of respondents who replied affirmatively to actions involving shopping, sharing rides to nonwork activities, and walking and bicycling suggests that consumers do think about not using gasoline, whether for energy conservation or cost containment. Although it is not entirely clear why these strategies are not used (as shown in the trip tables), it may be that undertaking one or two of these actions a month may satisfy the respondent's perception of conservation although actually contributing little to total conservation.

• Consumers appear to be reinvesting some of the potential savings in increased travel. In 1983, 30 percent of the savable energy was reinvested.

Within little more than a decade, consumers have experienced two oil supply shortages and a subsequent sharp increase in prices. Trade-offs have gradually been made in travel behavior to return to precrisis patterns. As long as more fuel-efficient automobiles are purchased, less fuel-efficient automobiles are retired from service, and some work-related conservation actions are practiced, NYS consumers will likely continue to make trade-offs. Some gasoline prices will rise rapidly (given the free market approach and absence of controls advocated by the current federal administration) and continue to rise until demand is curtailed. Consumers who have recently purchased more fuel-efficient cars will not immediately purchase newer automobiles. The demand for newer automobiles may well come from lower-income groups who have not yet purchased newer vehicles.

The study suggests that consumers know how to conserve gasoline very well. When asked whether they had taken any of the conservation actions, consumers replied that they had conserved by trip combining, shopping closer and more efficiently, sharing rides with neighbors and friends, and bicycling or walking to social and recreational sites. Furthermore, the percentage responding yes to these actions increased each year. However, when actual trip rates, incidence rates, and trip distances were applied to these responses, it became apparent that the major conservation strategies were work and car related. Shopping actions contributed little to conservation. Most nonwork conservation was contributed by vacation-related actions, particularly in 1982, but it is not clear whether this was caused by the recession rather than conservation.

The study also related trade-offs in gasoline use and the expansion in travel to the pattern of conservation activities. The expansion of the economy was accompanied by an expansion of automobile sales, both new and used. Because many of the pre-1978 gas guzzlers have not yet been retired from service, and because even more recent trades may involve improvements in fuel efficiency, the overall fleet efficiency will probably continue to increase. This will continue to allow consumers the option of conserving gasoline or driving more.

The findings suggest that a complex goal-oriented household decision structure is guiding family travel behavior. The patterns of the behavior (initial "shock" savings and subsequent new car purchasing, followed by a rebound of selected travel patterns) are clear; the causes can only be speculated on. A constant real or relative travel budget may be guiding the process, but current data cannot answer this. What is clear is that households are flexible and resourceful in saving gasoline in a crisis, and are equally adept at regaining mobility in the wake of a crisis.

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Environmental Concerns of Natural Gas Vehicles: Do We Know Enough?

MARGARET K. SINGH

ABSTRACT

Vehicles powered by natural gas are currently used in the United States and other parts of the world. Although the number of such vehicles in the United States is small, there is a potential for substantial growth. An overview of natural gas vehicle technology, markets, and environmental concerns is provided. The environmental concerns discussed are natural gas supply, emissions, and safety. It is concluded that more research is required in the areas of exhaust emissions and safety; no comprehensive data base exists in either area. The availability of natural gas does not presently appear to be a crucial issue.

Vehicles powered by compressed or liquefied natural gas (NG) are currently in use in the United States and other parts of the world. The number of vehicles in the United States is small; estimates range from 20,000 to 30,000, all in fleets (1,2). However, the Gas Research Institute (GRI) has projected that by the year 2000 from 1 to 4 million natural gas fleet vehicles might be operating in the United States (3). The personal-use market is expected to develop after major fleet use begins (1,2,4). Because of the potential for such growth and because natural gas-fueled vehicles have different performance-, emissions-, and safety-related characteristics than those of gasoline- or diesel-fueled vehicles, the U.S. Department of Energy (DOE) sponsored a study to document what is known about environmental concerns related to natural gas vehicles (5). This paper draws from the results of that study to provide an overview of natural gas vehicle technology, markets, and, in particular, environmental concerns.

VEHICLE TECHNOLOGY, FUELING, AND OPERATION

Natural Gas Vehicle Technology

Most current natural gas vehicles are powered by spark-ignition (SI) engines and have been converted to operate on both gasoline and natural gas. The natural gas is stored on board in compressed form at high pressure (approximately 2,400 psig) in steel cylinders; these vehicles are therefore called compressed natural gas (CNG) vehicles. The pressure is reduced to near atmospheric as the natural gas flows through pressure regulators and is delivered to a gas-air mixer that meters the natural gas into the engine. Figure 1 illustrates a typical system. No changes are required in the SI engine, except perhaps for the alteration of spark timing to improve engine power in natural gas operation. A gasoline shutoff valve is activated when the vehicle is operating on CNG; a similar valve shuts off the CNG when the vehicle is operating on gasoline. Some CNG vehicles have been designed to operate exclusively on natural gas; engine parameters (e.g., compression ratio) can then be optimized for natural gas. Ford Motor Company, in particular, has built several such "dedicated" CNG demonstration vehicles and is currently providing 27 of them to gas utilities for a 2-year test program (7).

The CNG cylinders are the dominant items in the natural gas vehicle system, accounting for much of the added weight, volume, cost, and operational constraints (1). Current CNG cylinders typically weigh 100 lb or more and have a capacity of 325 standard ft^3 (scf), or the equivalent of approximately 2.6 gal of gasoline. A two-cylinder system, which adds approximately 250 to 300 lb to a converted dual-fuel vehicle (and occupies a significant portion of the car's trunk volume), can thus provide a driving range of only 60 to 120 mi.

Design of lightweight cylinders for automobiles is under way and might include high-strength steel, aluminum alloy, or composite structures. For example, according to G. Peitsch, Ford Motor Company, Ford's dedicated CNG vehicles use aluminum composite cylinders. An alternative gas storage concept being explored involves adsorption of methane on molecular sieves or activated carbon particles at pressures of 350 to 400 psig (8). Roughly twice the gas could be stored in this manner as in the high-pressure tanks currently in use.

Vehicles with SI engines have also been converted to run on liquefied NG (LNG). Figure 2 is a schematic of an LNG system that has been used for a number of years in dual-fuel automobiles and trucks. It features a low-pressure (5 to 60 psig), cryogenic (<-259°F) tank mounted in the trunk. A combination pressure regulator/heat exchanger reduces pressure and vaporizes the LNG, if necessary, before delivery to the gas-air mixer. As in CNG systems, no changes are required to SI engines. Single-fuel LNG vehicle conversions have been displayed, but vehicle kits for such conversions are not commercially available.

The LNG tank permits a much greater travel range (200 to 400 mi) than CNG cylinders. An 18-gal tank that typically weighs 75 to 100 lb contains roughly the equivalent of 12 gal of gasoline. Like the CNG cylinder, it occupies more space than a gasoline tank. The LNG tank is made of steel and features double-wall construction, with the inner shell thermally isolated from the outer shell as much as possible. In the future, LNG tanks may be made lighter and more compact through the use of more efficient tank shapes, better material combinations (e.g., use of aluminum alloys), and more effective insulation.

Conversion kits designed to allow vehicles powered by compression-ignition (CI) engines (i.e., diesel) to operate on natural gas have only recently become

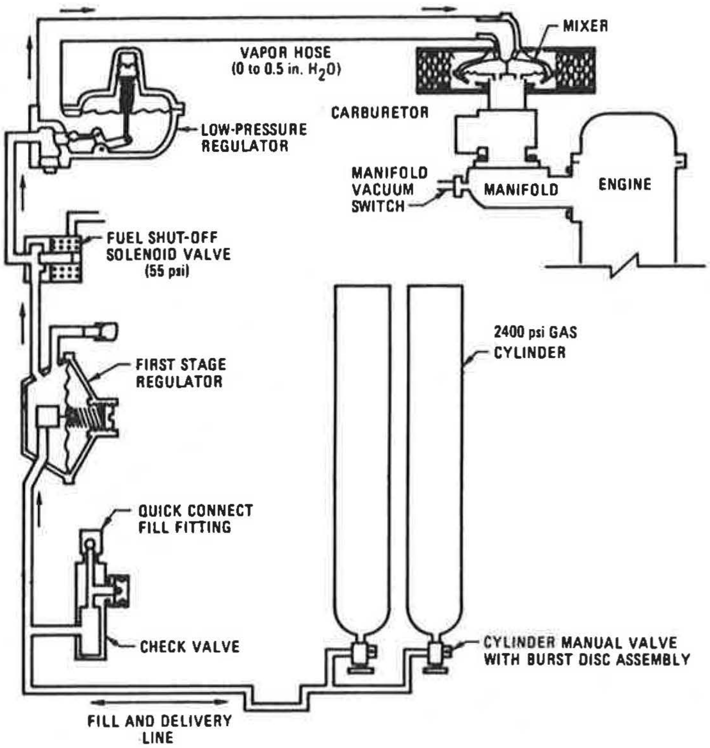

FIGURE 1 Vehicular CNG system for spark-ignition engines *(1,6)*.

commercially available (according to L.C. Elder of Columbia Gas System and R.R. Tison of E.F. Technology, Inc.). For such vehicles to operate on natural gas, ignition aids are required; natural gas is a high-octane fuel that will not autoignite under pressure as diesel fuel will. Such ignition aids include chemical fuel additives, spark plugs, glow plugs or other heated surfaces, and pilot injection of diesel fuel (i.e., a small amount of diesel fuel is injected into the combustion chamber). In this last case, two fuel systems are required and operation on natural gas alone is not possible.

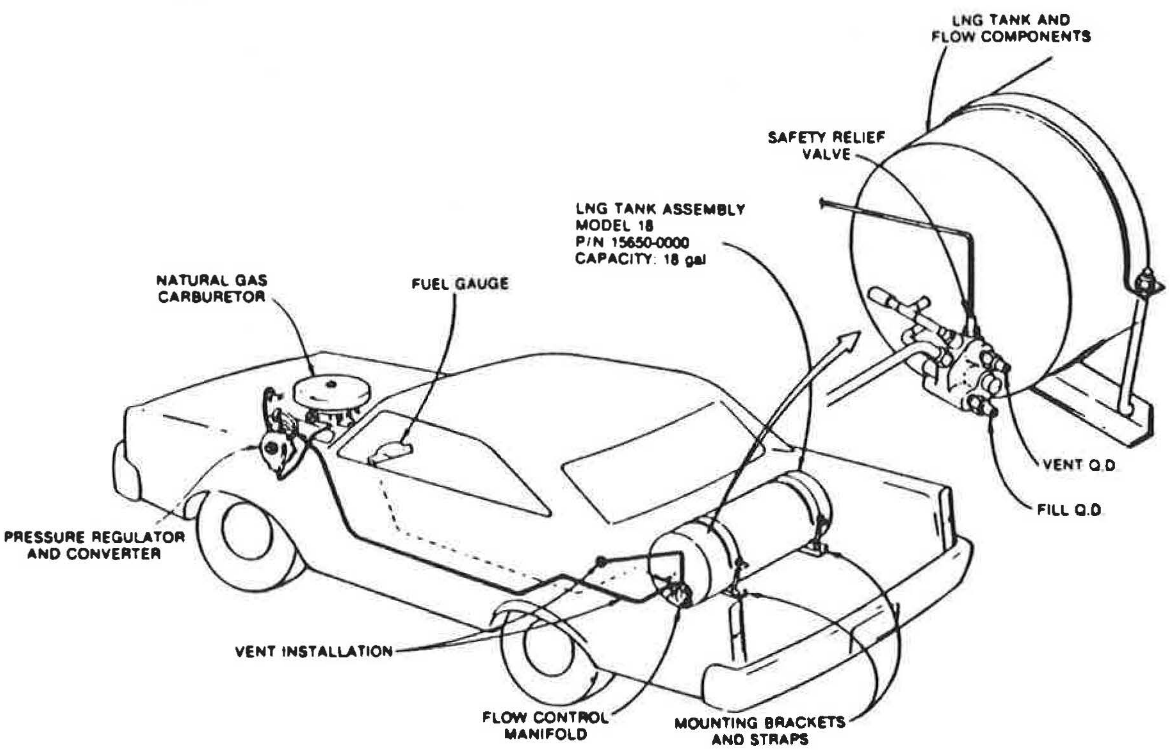

FIGURE 2 Typical LNG conversion kit installation in a passenger car *(1,9)*.

Fueling Methods

Two general approaches to the fueling of CNG vehicles are in current use. In slow filling, up to 80 vehicles can be simultaneously fueled with CNG delivered from a station compressor at approximately final-fill pressure. The time required for slow filling is a function of the number of compressors available, the size of piping and storage, and the number of vehicles being filled; up to 14 hr may be required. In fast filling, one or two vehicles at a time can be rapidly fueled from a cascade of high-pressure (3,600 psig) cylinders previously filled by a compressor, and fill time is only 2 to 5 min. A third approach, now under development, is the slow filling of vehicles from small compressors that may be located at private residences. In LNG vehicle fueling, the liquid fuel is fed from the station storage tank to a dispenser under low pressure. Several vehicles can be filled simultaneously, and fill time is approximately 10 min.

Vehicle Operation

In principle, natural gas (both CNG an LNG) lends itself well to use in SI engines (1). The primary advantage of natural gas as an SI engine fuel is its high research-octane number (estimated to be as high as 130) compared with that of current gasoline (91 to 95). This permits the use of engines with high compression ratios in vehicles designed specifically for natural gas, with accompanying fuel efficiency and performance benefits. In addition, broad flammability limits for natural gas allow engine operation at leaner air/fuel mixtures than with gasoline, which further improves thermal efficiency. Moreover, the gaseous nature of the fuel improves cylinder-to-cylinder fuel distribution and reduces engine pumping losses by replacing air.

On the other hand, natural gas has several disadvantages as an automotive fuel. Its gaseous state tends to result in reduced wide-open-throttle engine power at all vehicle speeds. The natural gas displaces intake air that would otherwise be inducted with partially liquid fuel and that would result in higher power output per piston stroke. Lean operation aggravates the power loss by limiting fuel input. The low flame speed of natural gas increases burning duration and thus decreases engine thermal efficiency. Some of these losses can be recovered through mixture enrichment at full load and advancement of spark timing. In a vehicle designed to use only natural gas, the power loss may also be eliminated by increasing the engine compression ratio and incorporating a turbocharger.

Conclusive data are not yet available on the potential fuel economy and performance of natural gas vehicles, particularly those that are optimized single-fuel vehicles. In one study, data on fuel economy and performance were collected from 13 CNG and LNG fleets and seven tests of experimental vehicles (1). Most of the data were based on dual-fuel vehicles that were not fully optimized for natural gas operation. In all instances in which data were reported, power decreased with natural gas operation, whereas acceleration time increased (from 20 to 55 percent where quantified). Many fleet operators reported substantial increases in fuel economy (up to 30 percent), whereas some indicated substantial decreases (again 30 percent). The more controlled tests of experimental vehicles showed approximately equal energy-equivalent fuel economy for natural gas and gasoline vehicles. Variance in the fleet operator data is attributed to a number of factors, including questionable energy-equivalency factors, differences in driving cycles, and variations in degree of engine optimization. The fuel economy and performance results of the experimental vehicles are shown in Table 1.

In lieu of data on optimized natural gas vehicles, the Aerospace Corporation conducted a simulation of optimized natural gas vehicles and determined that energy efficiency gains of more than 20 percent could be achieved by light-duty, single-fuel LNG vehicles compared with gasoline vehicles with similar power (1). Optimized light-duty, single-fuel CNG vehicles, however, achieved at most a 3 percent fuel economy gain, but acceleration was slower. When acceleration (and range) was comparable with that of a gasoline vehicle, CNG vehicle fuel economy declined 10 percent.

Applicable compression-ignition (CI) vehicle data are minimal, and there are no data on fleet use. However, several sources indicate that the power and thermal efficiency of the natural gas-fueled CI engine are lower than those for normal diesel fuel operation at roughly half load, depending on system design parameters and engine speed, whereas power and efficiency are often increased at high load (10). Thus, the operating cycle of a diesel CI vehicle fueled by natural gas would greatly affect its efficiency and power.

MARKETS

Current Worldwide Use

Compressed natural gas has been used as a fuel for SI engine vehicles in Italy since the late 1930s;

TABLE 1 Fuel Economy and Performance Data for Experimental Natural Gas Vehicles *(1)*

	Vehicle		Percentage Change, NG Versus Gasoline		
Fleet Operator	Model Year	Use	Power	Acceleration Time	Fuel Economy
CNG					
DOE/BETC[a]	1978	Light duty	–[b]	–	1
DOE/Bureau of Mines	1968-1970	Light duty	Decrease[c]	Increase[c]	Decrease[c]
DOE/EPA	1969-1980	Light duty	-27	55	1
Dual Fuel Systems, Inc.	1977-1981	Light duty/ medium duty	–	–	-1
General Motors Corporation	1967	Light duty	-15	–	–
LNG					
Beech Aircraft Corporation	1980	Light duty	–	–	–
Shell Research, Ltd.	1970	Light duty	-24	–	13

[a]BETC = Bartlesville Energy Technology Center.
[b]Dash = no data reported.
[c]No specific value reported.

approximately 275,000 private and fleet vehicles there currently use it. This is by far the largest number in any country (1). New Zealand now has 65,000 fleet and private vehicles operating on natural gas (11). The Canadian government provides incentives to encourage the use of vehicles fueled by natural gas and other alternative fuels. In the United States, CNG is only used in fleet vehicles, of which there are currently 20,000 to 30,000 (1,2). Very few LNG vehicles are in operation here, primarily due to the limited availability of this fuel. Several thousand CNG vehicles are estimated to be in use in other countries.

Potential U.S. Markets

The driving force behind the current and potential use of natural gas as a transportation fuel in the United States is fuel cost savings. Gaseous fuels for vehicles currently cost less, on an energy basis, than do liquid fuels. In 1982, the American Gas Association (AGA) estimated the delivered price of CNG to be 45 cents less per gallon equivalent than the cost of gasoline (2). Some of these savings, however, may be eroded in the future because the price of natural gas is projected to rise more rapidly than the cost of gasoline (10,12).

Whether it will be economical for specific fleets (and eventually personal vehicles) to convert to natural gas will depend primarily on whether the fuel savings can offset the capital costs associated with conversion to natural gas. The current cost of converting fleets to CNG is estimated at $2,300 to $3,600 per vehicle (13,14). This includes the cost of the conversion itself ($1,100 to $1,500) and the construction of the refueling station (13,15). The cost of an LNG conversion (vehicle only) is approximately $2,200, whereas the station costs per vehicle should be lower than those for CNG (16,17). The cost premium of a high-production volume, dedicated natural gas vehicle has been estimated to be one-third to one-half the cost of an after-market conversion (15).

The fleet market is the focus of most discussions of potential markets for natural gas vehicles (1-4, 10,17). Fleet vehicles are particularly appropriate for fueling with natural gas because (a) many fleet vehicles are fueled at a common point, which justifies the costs of a compressor and station, and (b) fleet vehicles are more readily accessible for maintenance by specially trained mechanics (18). Many types of fleets may use CNG. In a recent study conducted for New York State, the fleet types identified as being particularly appropriate for CNG conversion in that state included school buses and newspaper, postal, and parcel delivery fleets (17). The GRI has estimated in its baseline projection of U.S. energy demand that by the year 2000, 1 to 4 million automobiles and trucks in fleets will be converted to natural gas (3).

Penetration in the personal-use automobile and truck market is expected to develop only after major fleet use begins (1,2,4). Public fueling stations will be expensive, and market prospects for personal-use CNG vehicles will have to be more certain before such stations are developed. Drawbacks (such as high costs) associated with home compressors appear to make their use in the near term even more uncertain. Projections of the potential for personal use of these vehicles are sparse. One report indicated that in 1995 approximately 12 percent of urban passenger vehicle miles of travel (VMT) could be in natural gas-fueled vehicles (19). However, the authors of this report caution that these figures actually indicate that there is a substantial market for any alternative-fueled vehicle with performance similar to that of gasoline-powered vehicles and with lower operating costs.

ENVIRONMENTAL CONCERNS RELATED TO NATURAL GAS VEHICLES

The Argonne National Laboratory (ANL) state-of-knowledge report comprehensively documents the environmental issues associated with natural gas vehicles and the regulations affecting them (5). In the following sections major areas of concern are discussed: natural gas supply, exhaust emissions, and safety.

Natural Gas Supply

A key concern about the use of natural gas as an automotive fuel has been whether adequate supplies of natural gas will be available during the next 20 years. The United States has the world's third-largest proven reserves of conventional natural gas (198×10^{12} scf in January 1981) (20). However, at a domestic consumption rate of about 18×10^{12} scf per year, this supply will not last long. In addition to these reserves, however, there may be a much larger, although uncertain, quantity of potential natural gas from conventional and unconventional sources. Gas industry projections of supply indicate that the development of nonconventional sources of gas and Alaskan gas, as well as the increase of imported gas, can meet the nation's needs well into the 21st century (10).

Although natural gas availability does not appear to be a constraint on the use of natural gas as a vehicle fuel, if a large number of vehicles were converted to natural gas, the impact on the domestic natural gas consumption rate could be significant. However, the level of demand projected by GRI in its baseline estimates (0.3 quad by the year 2000) is clearly insignificant (3). Only if a great number of fleets were converted and the personal-use market opened up would there be a significant incremental demand for natural gas.

Exhaust Emissions

Emissions of natural gas-fueled vehicles with SI engines will depend on the degree to which engine calibration and hardware configuration are optimized to take advantage of this fuel (1). For example, engine operation at the lean air/fuel ratios allowed by natural gas reduces carbon monoxide (CO) and nitrogen oxide (NO_x) emissions. Furthermore, because gaseous fuels do not require fuel enrichment for satisfactory vehicle operation during cold-start operation (as do gasoline vehicles), vehicle operation on natural gas results in lower emissions of CO and hydrocarbons (HC) during cold starts. Because natural gas reduces engine power at all speeds, an additional spark advance is often used to recover some of this loss. This, however, causes HC and NO_x emissions to increase. Alternatively, if the engine is designed for natural gas only, the compression ratio can be increased to improve fuel efficiency. This, however, causes increased HC emissions. Experimental data are reviewed in the following paragraphs to illustrate more precisely the emissions impacts from the use of natural gas in vehicles. Available fleet data are limited and based on older model vehicles (1960s and mid-1970s) that used relatively rich air/fuel ratios in the gasoline model and therefore had high levels of emissions; these data are therefore not reviewed here [see Aerospace

TABLE 2 Summary of Emissions Data for Experimental Natural Gas Vehicles (1)

Fleet Operator	Vehicle Model Year	Vehicle Use	Optimization Parameter	Percentage Change, NG Versus Gasoline HC	CO	NO_x
CNG						
DOE/BETC[a]	1978	Light duty	Performance	150	-12	26
DOE/Bureau of Mines	1968-1970	Light duty	Emissions	-47	-87	-22
DOE/EPA	1979-1980	Light duty	Emissions	150	-99	-20
Dual Fuel Systems, Inc.	1977-1981	Light duty/ medium duty	Emissions	340	-96	-46
General Motors Corporation	1967	Light duty	Emissions	0	-81	-50
LNG						
Beech Aircraft Corporation	1980	Light duty	Economy	Similar to gasoline		
Shell Research, Ltd.	1970	Light duty	Economy	-65	-80	47

[a]BETC = Bartlesville Engergy Technology Center.

Corporation report (1) and ANL report (5) for further discussion of the fleet data].

Table 2 presents available data on experimental natural gas-fueled vehicles. The tested vehicles were dual-fuel vehicles and were not fully optimized for natural gas. Some of these vehicles were also older models. However, in general (and particularly when results of the more recent model years are examined), the table shows lower CO and NO_x emissions but higher HC emissions with natural gas.

Of particular interest in Table 2 are the results of DOE's vehicle test program conducted at the Environmental Protection Agency (EPA) Ann Arbor Motor Vehicle Emissions Laboratory (shown as "DOE/EPA" in Table 2). Two dual-fuel vehicles (a 1979 Impala and a 1980 Diplomat) were tested with both gasoline and CNG. Spark timing was not changed and the air/fuel ratio was adjusted for minimum emissions at idle and light load. Emissions were measured over the EPA city and highway driving cycles in accordance with federal test procedures. As Table 2 shows, CO and NO_x were lower with CNG than with gasoline, and HC was higher.

The increase of HC was significant, and the 1980 Diplomat exceeded the applicable federal HC standard of 0.41 g/mi; this increase was due to higher methane emissions. Levels of reactive nonmethane hydrocarbons (NMHC) were lower by 35 to 55 percent per mile. The NMHC fraction was reported to be 12 to 18 percent for CNG compared with 56 to 87 percent for gasoline. Current automotive exhaust catalysts are relatively ineffective in eliminating methane, which is the most stable of exhaust HC and is thus difficult to oxidize in these catalysts. Although methane HC emissions increase with natural gas operation, they are considered environmentally benign (1). Because methane HC emissions are nonreactive, they do not actively participate in processes that form photochemical oxidants or adversely affect the atmosphere's ozone layer (18). In California (the only state known to have an emissions approval program for conversions to natural gas), approval is granted on the basis of NMHC emissions rather than total HC emissions.

The DOE/EPA test program also found that when these dual-fuel vehicles were operated on gasoline, emissions of HC, CO, and NO_x were 5 to 30 percent higher than those from the baseline gasoline vehicle. In some instances the applicable emission standard was exceeded. For example, although the baseline 1979 Impala met the NO_x standard, the converted vehicle operating on gasoline did not, although operation with CNG was in compliance. Other studies have reported similar increases (21).

Also of interest in Table 2 is that NO_x emissions were occasionally reported to be higher with natural gas operation. In particular, for two vehicles in which optimization was for performance or fuel economy rather than for emissions, NO_x emissions were higher with CNG than with gasoline. Use of increased spark advance, plus the particular air/fuel ratio chosen, led to the NO_x increase in the LNG vehicle. It is unclear what adjustments were made that contributed to the increased NO_x in the DOE/BETC vehicle.

Although exhaust emissions data for natural gas SI vehicles are limited and exhaust emissions will vary depending on the degree of optimization for natural gas, some general conclusions can be drawn. In general, relative to gasoline-fueled vehicles, CO emissions from natural gas-fueled vehicles are significantly reduced, total HC emissions are higher, nonmethane (reactive) HC emissions are lower, NO_x emissions can be higher or lower, and dual-fuel vehicles operating on gasoline may produce higher emissions. In contrast, available data are inconclusive with respect to emissions impacts of natural gas-fueled CI vehicles. Few emissions data are available to analyze because, to date, the use of natural gas in CI engines has essentially been restricted to stationary and marine engines. However, the results of two studies indicate the potential for increased CO and NO_x emissions (at least at full load) as well as HC (22,23).

Safety

Safety concerns related to natural gas vehicles focus on fuel-system hazards in normal operation and in accidents. These hazards are based in part on the properties of natural gas. The hazards include fuel leakage in normal operation due to malfunctioning of the fuel system, necessary venting of LNG vapor to relieve pressure buildups, corrosive failure of CNG cylinders, fuel release in an accident because of tank puncture or crushing or from damage to other parts of the fuel system, intrusion of fuel system components into the passenger compartment, and fuel release during vehicle refueling. It is impossible to review each potential hazard in this paper. Such a review can be found in reports by the Aerospace Corporation and Argonne National Laboratory (1,5). Instead, (a) the safety-related properties of natural gas, (b) the safety history of these vehicles, (c) vehicle tests, (d) accident scenario analyses, and (e) applicable safety regulations and standards are briefly summarized in the following paragraphs to provide a perspective on the safety concerns associated with these vehicles.

TABLE 3 Selected Properties of Vehicle Fuels

Property	Natural Gas[a] CNG	Natural Gas[a] LNG	LPG[b]	Gasoline	Diesel Fuel 2
Flammability limits (vol. % in air)	5.3-15.0	–	2.1-9.5	1.0-7.6	0.5-4.1
Detonability limits (vol. % in air)	6.3-13.5	–	3.1-7.0	1.1-3.3	–
Minimum ignition energy in air (mJ)	0.29	–	0.27	0.24	0.3 (est.)
Autoignition temperature (°F)	1,004	–	855	442-880	500
Flash point (°F)	Gas	Gas[c]	Gas[c]	–45	Minimum 125
Energy content (lower heating value)					
Btu per gallon	19,760 at 2,400 psi and 70°F	76,300 at NBP[d] and 1 atm	82,450	116,400[e]	129,400[e]
Btu per pound	21,300	21,300	19,770	18,900[e]	18,310[e]
Diffusion coefficient in air[e] (cm/sec)	0.16	–	0.10	0.05	–
Buoyant velocity in air[f] (m/sec)	0.8-6	–	Nonbuoyant	Nonbuoyant	Nonbuoyant
Density of liquid (g/cm^3)	–	0.4226 at NBP	0.585 at NBP	0.70-0.78	0.82-0.86
Density of gas relative to air (air = 1.00)	0.555	–	1.56	3.4	>4.0 (est.)
Vapor pressure or equivalent (atm)[g]	1	1	1	0.60-0.8 at 311 (100)	0.0005 at 311 (100) (calculated)
Normal boiling point (°F)	–	–259	–44	100-400	405-620
Storage conditions	Compressed gas at 2,400-3,000 psig	Liquid at 25-60 psig	Liquid at 105-140 psig	Liquid at ambient temperature and pressure	Liquid at ambient temperature and pressure

[a]Properties are primarily those of methane. Because natural gas sources vary in composition, values will deviate to a small extent from those of pure methane.
[b]Properties are primarily those of propane. For vehicle applications, only the special grade HD-5 is suitable.
[c]LNG and LPG will flash at all temperatures above their normal boiling points.
[d]NBP = normal boiling point.
[e]Average value.
[f]At normal temperature and pressure.
[g]For gaseous fuels, refers to "equivalent vapor pressure" when released from high-pressure storage container or maximum possible in ambient environment. For liquid fuels, taken as the value of the vapor pressure at maximum ambient temperature.

Safety-Related Fuel Properties

The physicochemical properties of natural gas relative to those of gasoline, diesel fuel, or both result in different safety hazard levels. For example, density affects safety; natural gas released at an ambient temperature from CNG tanks is considerably less dense than air and will rise, diffuse, and disperse in unconfined spaces (1,24). Thus in comparison with gasoline vapor, which is heavier than air, methane vapor at ambient conditions tends to be safer in unconfined areas (1,24). In confined areas, however, the more rapid dissipation of natural gas is a disadvantage because flammable air/fuel mixtures could accumulate more rapidly (1). However, because the flammability limit of natural gas is 5 percent, considerably more fuel must mix with the air to render the mixture combustible than is the case with gasoline and its 1 percent limit (25). Furthermore, the fire hazard would persist longer with gasoline (26).

Selected physicochemical properties of natural gas, gasoline, diesel fuel, and liquefied petroleum gas (LPG) are listed in Table 3. In a study conducted for DOE, Los Alamos National Laboratory developed preliminary relative safety rankings based on specific physicochemical properties in isolation and in combination (24). These rankings are presented in Tables 4 and 5. On the basis of these rankings alone,

TABLE 4 Preliminary Relative Safety Rankings of Fuels Based on Selected Properties *(24)*

Property	Ranking Order of Hazard[a]
Lower flammability limit	D > G > LPG > NG
Diffusion coefficient	NG > G[b] or G > NG[c]
Autoignition temperature	G and D > LPG > NG
Energy content by volume	D > G > LNG > LPG > CNG
Energy content by mass	Approximately equivalent
Ignition energy	Approximately equivalent
Heat release rate	D > G > LPG > NG

[a]NG = natural gas (methane); LNG = liquefied natural gas; LPG = liquefied petroleum gas (propane); G = gasoline; D = diesel fuel.
[b]Confined.
[c]Unconfined.

TABLE 5 Preliminary Relative Safety Rankings of Fuels Based on Selected Secondary Hazards *(24)*

Fuel	Leakage Flow	Thermal Radiation	Dispersion Unconfined	Flammability
CNG	D	A	A	C
LNG	D	A	A-B	C
LPG	C	B	B-C	C
Gasoline	B	C	C	B-C
Diesel fuel	A	D	D	A

Note: The assignment of letters to rank fuels is done qualitatively, with the progression from A through D suggesting greater hazard levels. No mathematical relationship between the letters exists.

Los Alamos concluded that it is difficult to designate any one fuel as significantly safer than another.

In addition, health risks from each fuel can be evaluated on the basis of the toxicity of the fuel when inhaled, ingested, or in contact with the skin. Methane in sufficient quantities acts as a simple asphyxiant by displacing air, but is otherwise nontoxic. A potential LNG health hazard is skin tissue damage from contact with the cryogenic fluid or with cold fueling equipment.

Safety History of Natural Gas Vehicles

The safety history of natural gas vehicles to date has been reported to be good and even excellent (1, 24,27). However, the data to support this statement are acknowledged to be quite limited (1,24,27). Accident data from Italy, for example, are generally not available (24). Reports indicate that explosions associated with accidents have not occurred in Italy in 30 years of operation, although there have been several fires (24). Cylinder failures occurred during the early years of operation, but with better control over gas quality, these have decreased significantly. Even if data from Italy were available, however, they would not be directly applicable to the use of natural gas vehicles in the United States because of the significantly different cylinder design and safety devices employed in the two countries.

In the United States only one study of natural gas vehicle fleet data is known. The AGA prepared a preliminary safety analysis of natural gas vehicles in 1979 with fleet data collected from 1970 to 1979 by three gas utilities and one taxicab company (28). The 2,700 vehicles included approximately 500 sedans, 2,000 light-duty trucks, and 200 medium- and heavy-duty trucks. The total mileage of the vehicles was about 175 million mi; that of the dual-fuel vehicles in the fleets was estimated to be 133 million mi. Of the estimated 1,360 collisions in which CNG vehicles were involved, there were no reported collision-related failures or fires involving the natural gas systems. Several other incidents, however, were reported in which the natural gas system was identified as the fire source. These fires were attributed to faulty installation of the gasoline bypass pipeline and to deficiencies in venting systems (28). No deaths, and only one injury, occurred in accidents where natural gas was a contributing factor.

Vehicle Tests

Tests of natural gas vehicles and their fuel system components appear to be quite limited and in some cases outdated. For example, the only test of the likelihood and severity of fires due to vehicular natural gas leaks reported in the literature was conducted in 1970 by the California Highway Department (29). This test indicated the need for improved venting of the trunk, isolation or venting of the passenger compartment, or both.

Vehicle impact testing was conducted by the U.S. Department of Transportation (DOT) in 1971; no further U.S. government testing has been conducted since then (24,30). Furthermore, the vehicles, fuel systems, and test conditions in these tests were not representative of current lightweight designs. A more recent vehicle impact testing program using 1981 vehicles was conducted in Canada (31). These tests included 50-mph rear-end collisions. No fuel release, fire, or explosion occurred with the CNG vehicles, nor was there any passenger compartment intrusion, although the tanks and supply lines were slightly dislocated. Neither program tested complete LNG vehicles.

Fire tests of CNG vehicles were also conducted in the Canadian test program. Although no explosions occurred, pretest tank pressure was 1,100 psig, far lower than normal.

Current CNG cylinders are quite rugged. However, lightweight tanks now being developed have not been thoroughly tested for their integrity in accidents. Rear-impact tests using these lightweight tanks have been conducted by a cylinder manufacturer and they have been found quite promising to date.

Finally, tank corrosion is a safety concern in CNG vehicles. In the past, corrosive natural gas constituents such as hydrogen sulfide (H_2S) have caused catastrophic failure of a number of steel cylinders used to transport and store natural gas. To date, the maximum allowable safe concentrations of H_2S and other contaminants in natural gas have not been determined, and the long-term effects of H_2S exposure on CNG steel cylinders are unclear. A major research program was recently recommended to examine the effects of differing gas qualities on CNG storage cylinders under stress conditions (32). Testing is also required to determine the corrosive effects of natural gas on aluminum because aluminum cylinders or composite cylinders with aluminum inner shells may replace steel cylinders in CNG vehicles. Few applicable data exist (10).

Accident Scenario Analyses

In the Los Alamos study, several accident scenarios were evaluated in order to rank gaseous and liquid fuels (CNG, LNG, gasoline, and diesel fuel) according to relative safety. (LPG was also evaluated, but the results are not reported here.) The analyses indicated that diesel fuel is relatively and significantly safer than the other fuels and that in some cases CNG and LNG had increased risks relative to gasoline whereas in other cases they were as safe as, if not safer than, gasoline (24). In other words, the relative safety rankings of CNG, LNG, and gasoline depended on the specific scenario being evaluated.

For example, if a fuel leak was assumed in the presence of an ignition source, CNG and LNG were found to have a significant explosion hazard relative to gasoline in a residential enclosed garage. Fundamentally, a confined system exists in a residential garage despite some minimal degree of ventilation. In an underground public garage, where air change is more frequent, no difference was found among CNG, LNG, and gasoline.

In all three collision scenarios (urban, rural, and tunnel) examined, the rapidly dispersing natural gas was found to be relatively safer than gasoline. The likelihood for fire alone was found to be the same as gasoline or slightly higher for CNG and LNG. The likelihood for fire plus personal injury (i.e., burns), however, was greater with gasoline in all three cases. Furthermore, the likelihood of an explosion, although small for all fuels, was determined to be significantly greater for gasoline than for CNG and LNG.

In the fueling line rupture scenarios (rupture during fuel transfer to a personal-use vehicle, and rupture during refill of the station's storage tank), natural gas exhibited a higher relative level of fire hazard. Personal injury was also more likely with CNG and LNG because of injuries from flailing hoses and cryogenic burns, particularly in the station storage tank refueling scenario. However, the explosion hazard with CNG or LNG was lower because of their relatively rapid dispersion.

In another study, conducted by A.D. Little in 1972, what might be termed "worst-case" scenarios were also addressed (33). The operation of vehicles powered by gaseous fuels in Boston harbor tunnels and on connecting toll roads was the setting for the study. One of the scenarios analyzed the consequences of a CNG cylinder failure resulting in a fire in one of the tunnels, assuming that the tunnel was without ventilation. The hot combustion products from 300 scf of natural gas were estimated to fill a 60-ft section of the harbor tunnel. The likelihood of serious damage to an oncoming vehicle or injury to its occupants was deemed slight on the basis of the short residence time in the combustion zone. Hazards to occupants of the CNG vehicle, however, were not considered. Another scenario examined the distance up to which personal injury could occur and the extent of tunnel damage assuming that a CNG or LNG tank burst because of failure of the pressure relief device. Personal injury occurred at greater distances with CNG than LNG. Additional analyses of such worst-case scenarios appear desirable.

Federal Safety Regulations

With the exception of design and inspection criteria for compressed gas cylinders, there are no federal regulations that specifically address natural gas as a motor vehicle fuel. A review of the Code of Federal Regulations (CFR) was conducted for DOE for potentially applicable federal regulations, including regulations for fueling operations (18). This review revealed considerable uncertainty in regulatory agencies regarding which federal regulations actually apply to motor vehicles fueled by natural gas (18).

The Materials Transportation Bureau (MTB) of DOT, which sets regulations for transport of hazardous materials, has established regulations for the design and testing of compressed gas cylinders (49 CFR, Part 173: DOT-3A[CNG] and DOT-4.L[LNG]). The regulations apply to vehicles that transport bulk industrial gas, including methane, but not natural gas. Exemptions are available for the transport of bulk natural gas, but levels of corrosive materials are restricted (1,32). The allowable levels of H_2S and water are more stringent than those for pipeline-quality gas from gas distribution systems used to fuel natural gas vehicles. However, steel cylinders designed to meet MTB specifications are widely used in natural gas vehicles (1). DOT has also issued specifications for the manufacture of one type of aluminum tank for use in methane service (10). No standard exists for composite cylinders, although a series of exemptions does exist that allows their use in specific applications before publication of a standard (L.C. Elder, Columbia Gas System; 10).

DOT's Bureau of Motor Carrier Safety (BMCS) regulations on the safety of interstate trucking cover fuel system integrity in vehicles operated by regulated private, common, or contract carriers, but these regulations do not mention CNG or LNG vehicles specifically (49 CFR, Part 393) (18). BMCS regulations do exist for LPG systems, but disagreement exists within the BMCS as to whether these LPG requirements apply to vehicles powered by LNG (18).

DOT's National Highway Traffic Safety Administration (NHTSA) has promulgated a series of Federal Motor Vehicle Safety Standards (FMVSS) that set forth design and test criteria for various aspects of vehicle design (49 CFR, Part 571) (18). The FMVSS apply to new motor vehicles and, in some instances, vehicles already delivered to the "ultimate consumer." In practice, the only FMVSS likely to be applicable to converted natural gas vehicles is FMVSS 301-75, a vehicle standard that specifies the amount of liquid fuel permitted to escape from a fuel system after a controlled test impact. The standard, however, applies only to vehicles that use a fuel with a boiling point above 32°F. Thus, it only applies to a vehicle converted from gasoline to a dual-fuel natural gas/gasoline system. It does not apply to vehicles converted to operate on natural gas alone.

The federal Occupational Safety and Health Administration (OSHA) is charged with promulgating and enforcing standards in areas not regulated by another agency. No OSHA standards are directly applicable to natural gas as a motor fuel. However, under 29 CFR, Part 1910.101 ("Compressed Gases"), OSHA required that inspections of compressed gas cylinders be conducted as prescribed by the MTB (18). Finally, no federal specifications exist for natural gas transmitted by pipeline or distributed to consumers.

State and Local Safety Regulations

State and local regulation of natural gas vehicles and equipment was reviewed in a study by Jack Faucett Associates (JFA) (18). California was found to have a comprehensive set of regulations applicable to natural gas vehicles and refueling operations. The California Highway Patrol (CHP) has issued design and installation regulations for CNG and LNG vehicles that require construction and inspection of cylinders in accordance with DOT regulations (18). The CHP code has further requirements with respect to the crashworthiness of LNG-fueled vehicles. Other California regulations address LNG and CNG tanks that may be used for storage and refueling (18). New York State recently promulgated vehicle specifications for converting school and transit buses to CNG.

Alternatively--with few exceptions--other state and local regulations applicable to natural gas used as a vehicle fuel are set forth in fire codes and enforced by local fire prevention officials (18). The JFA study concluded that a series of complex and sometimes inappropriate regulations has been developed by local governments because there has been no guidance from federal standards, the National Fire Protection Association (NFPA), or other national standard-setting bodies (18). These regulations are not comprehensively reviewed here, but include tunnel and bridge restrictions, expressway restrictions, restrictions on use in school buses, zoning regulations on refueling stations, and restrictions on parking in garages. One example of the wide variation in these regulations is that the state of Maryland prohibits the use of natural gas fuel for school buses, whereas some school districts in New York State are in the process of purchasing CNG-fueled school buses (18). Finally, state regulations for pipeline gas are usually restricted to odorant content.

NFPA Standard

Recognizing the lack of a national standard for natural gas vehicles and the proliferation of locally developed and widely differing regulations for natural gas vehicles and refueling stations, the NFPA formed a committee in 1982 to develop and review a standard for CNG vehicles and associated fueling systems. In 1984 that standard was adopted.

The NFPA standard is intended for use by manufacturers of natural gas system components and by installers and operators (18). It relies heavily on established compressed gas technology and standards recommended by the DOT, the Compressed Gas Association (which are incorporated by reference in the MTB standards), and others. The standard applies to the design and installation of CNG engine fuel systems in vehicles of all types and to their associated fueling systems. A gas quality standard is included. The NFPA standard will serve as an interim standard until specifications based on a statistically valid data base can be developed. The NFPA standard generally parallels the California regulations, except that the latter are somewhat more specification oriented than those of the NFPA (18). However, standards for LNG vehicles are not included as they are in the California regulations. Furthermore, although the standards for fueling station dispensing are included, standards for home compressors are not.

Although adoption of the NFPA standard is an important step, the standard itself is not a regulation. It will be reviewed by state and local agencies for inclusion in fire codes and can be adopted as written by government entities or its provisions can be amended as deemed appropriate. The standard is expected to be accepted by local fire marshals (18).

CONCLUSIONS: DO WE KNOW ENOUGH?

Of the three areas of concern discussed earlier, it is clear that further evaluation of the safety of the vehicles and fuel systems and of the exhaust emissions associated with their operation is required. The availability of natural gas does not appear to be an issue, although if a large number of vehicles were converted to natural gas, the impact on the domestic natural gas consumption rate could be significant.

With respect to exhaust emissions, it appears that more study is required in a number of areas. Whether an NMHC standard should be developed and what it would be needs further evaluation. If original-equipment-manufactured natural gas vehicles are to be marketed in significant numbers, emission standards must be developed for them. Furthermore, very few data exist on the use of natural gas in CI engines. Now that conversion kits for automotive vehicles have become commercially available, additional testing of emissions is necessary. Even with converted SI vehicles, the effectiveness of conventional emissions control technologies [spark timing, exhaust gas recirculation (EGR), etc.] must be better quantified. Available data are limited, particularly for late-model-year vehicles with electronic feedback systems.

The safety of CNG and LNG vehicle systems remains an important issue that has not yet been completely resolved. A number of studies have concluded that engineering technology and safety regulations can be used to address the risks that exist and that no data have so far been presented that would disqualify natural gas vehicles from public use (1,24,34). However, a documented, comprehensive data set on which the crashworthiness and system integrity of natural gas can be thoroughly evaluated has not been developed (33). Some of the reported data are old and not comprehensive. Two types of studies are required in particular: (a) crash testing of CNG vehicles using both steel and aluminum composite cylinders and LNG vehicles (the last crash tests in the United States were conducted in 1971), and (b) research into the effects of different fuel qualities on steel CNG cylinders and on alternative materials that might be used in the design of lightweight CNG cylinders. In addition, controlled safety-related data collection from test fleets and worst-case accident scenario analyses would be useful.

Finally, some may question the value of conducting extensive safety and emissions tests on vehicles whose total vehicle market share may not be very substantial in the near- and mid-term future. However, 1 to 4 million fleet vehicles by the year 2000 is not an insignificant share of the total fleet market. Furthermore, such testing is essential before the personal-use market can be effectively opened to this alternative fuel.

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Structural Ceramics in Transportation: Fuel Implications and Economic Effects

ARVIND P. S. TEOTIA and LARRY R. JOHNSON

ABSTRACT

A description based on a study at Argonne National Laboratory funded by the U.S. Department of Energy is given of the potential application of structural ceramics in motor vehicle engines. With their high-temperature strength and their resistance to wear and corrosion, these high-technology ceramics are excellent candidates for the harsh environment of the advanced engines being considered for automobiles and trucks. The critical role of ceramics in the adiabatic diesel, gas turbine, and Stirling engines is discussed, along with an indication of the fuel efficiency potential and multifuel capability of each engine. A market penetration analysis of the advanced engines uses two alternative commercialization scenarios for ceramic component engines--one with the United States dominating the market and the other with Japan dominating. Changes in major national economic indicators are noted after simulations of the economy with a macroeconomic model. Effects on the use of strategic materials are also noted.

Research in energy conservation technologies was stimulated by the energy crises of the 1970s. The crisis situation no longer exists, but the interest in improving energy efficiency remains. The transportation sector has historically been vulnerable to energy disruptions and price shocks and remains susceptible to them in the long-term future despite the current petroleum glut. Indeed, as the residential, commercial, and industrial sectors have increased their use of nonpetroleum fuels, the transportation sector has consequently begun to account for a significantly larger share of petroleum use. From the 1950s through the 1970s--even after the first oil crisis--transportation's share of oil use consistently remained between 53 and 55 percent. This share has steadily increased since 1979, and transportation is now responsible for more than 61 percent of the petroleum used in the United States (1).

In the mid-1980s, highway transport continues to dominate transportation energy use, with automobiles and trucks consuming nearly three-fourths of the sector's total energy use (2). As a result, considerable research is being performed on power systems that can potentially provide fuel efficiencies beyond the limits of current gasoline and diesel engines or that can burn nonpetroleum fuels. Much of this research has concentrated on batteries for electric vehicles or on advanced engines such as the gas turbine, Stirling, and adiabatic diesel. The principal limitation of heat-engine technologies has been mechanical strength at high temperatures. If reliable structural ceramics can be produced for vehicle engines, an opportunity will arise for the marketing of new fuel-efficient vehicles that use the advanced engine designs. The potential fuel savings that may result from commercialization of new engine technologies, the associated macroeconomic benefits [e.g., changes in gross national product (GNP), employment, balance-of-trade], and the implications for ceramics in reducing U.S. dependence on strategic materials are described.

FUEL-SAVING POTENTIAL OF CERAMICS IN MOTOR VEHICLE ENGINES

Characteristics of Ceramics

Ceramics are made from common, readily available materials such as carbon, silicon, oxygen, and nitrogen. Consolidation of compounds at high temperatures, sometimes under pressure, is used to form a variety of products from pottery to electronic components. Conventional ceramic products are widely used in many household and industrial applications.

Advanced ceramics, also called engineered ceramics, high-performance ceramics, or--in Japan--fine ceramics (because of the extremely small particle size of the ceramic powders), are relatively new. These materials have been developed for use in electronic components (capacitors, resistors, and semiconductors), cutting tools, bearings, and engine parts. Advanced ceramics differ from conventional ceramics in that the raw materials for the advanced ceramics are based on more sophisticated compounds, such as aluminas, carbides, nitrides, borides, and zirconia, that enhance the desired properties of the ceramics. Engine applications are just beginning to be developed but, of all the possible uses, they have the most potential for growth and ultimate profitability (3).

Structural ceramics (as the term implies, there is a load-bearing requirement for the finished product) have a number of physical and mechanical properties that enhance their use in a variety of industries. Of particular importance in motor vehicle engines is the bonding of ceramics to form a crystalline structure that results in high-temperature mechanical strength plus wear and corrosion resistance. The well-known negative quality of ceramics--extreme brittleness--remains a problem. Substantial research is being directed toward improving ceramic microstructure to overcome its brittleness and toward improving quality control during production.

Ceramics Applications in Vehicle Engines

Government and industry have identified, and conducted research on, a number of alternative heat engines for automobiles and trucks. The most promising are the gas turbine, the adiabatic diesel (both internal combustion engines), and the Stirling (an external combustion engine). The thermal efficiencies of these engines are greatly enhanced by increasing their operating temperatures. To achieve fuel efficiencies that would make these engines competitive with existing gasoline and diesel engines, new materials must be developed to operate at higher temperatures. The most likely candidate materials are superalloys, carbon composites, and structural ceramics. Only ceramics offer the potential low cost to make these engines economically and technically competitive (4). The potential fuel efficiencies and alternative fuel capabilities for each of these engines are described briefly. Select engine components that are candidates for manufacture from ceramic materials are also discussed.

Components for Current Engines

The initial introduction of structural ceramics into heat engines will most likely be in the form of components or parts in existing gasoline or diesel engines. Through the replacement of metal components with ceramics, heat loss can be reduced, wear resistance improved, and weight lowered. The most immediate applications are likely to be in pushrods, tappets, seals, piston heads, cylinder liners, and turbocharger rotors (5). These applications will be more immediate than those in advanced engine designs because the parts are smaller (and are thereby subject to less stress) and consequently easier to produce in terms of controlling critical microstructural flaws. Depending on how extensively ceramics are used in conventional engines, fuel efficiencies should improve by 5 to 15 percent or more.

Of particular interest for the more immediate applications is the use of ceramics for turbocharger rotors instead of the traditional nickel alloys. Rotor weight will be reduced by two-thirds, which will in turn reduce inertia and improve rotor response. Use of a ceramic rotor may also eliminate the need for metal center bearings, the components most likely to fail in current turbocharger designs. The metal bearings can be replaced by ones of ceramic or by a system in which the lightweight ceramic shaft rides on a layer of air. The use of ceramics in turbochargers will eventually allow the entire assembly to be redesigned, eliminating the need for the heavy containment structure that the metal rotor now requires. The total costs of turbochargers should also decline, resulting in wider use (6). As a result, smaller and more fuel-efficient engines can have the performance of larger engines.

The Adiabatic Diesel Engine

An adiabatic process is one with no heat loss. Adiabatic engines accomplish this by eliminating the cooling system and insulating the combustion chamber to minimize the loss of heat. Thermal efficiency is improved by removing the cooling system, which also reduces the size and weight of the engine as well as its cost. Moreover, maintenance costs should be reduced and reliability increased, because 50 percent of heavy-vehicle engine failures are related to cooling systems (7).

A prototype adiabatic diesel engine in a 5-ton military truck has already been highway-tested. In a recent test, round-trip fuel economy between Washington, D.C., and Detroit exceeded 9 mpg, compared with a similar production engine in the same vehicle that averaged 6 mpg. Ceramic coatings were used throughout the combustion zone in the uncooled prototype.

Although adiabatic engine technology will most likely be introduced first in heavier truck applications, the concept applies to automotive vehicles as well. Preliminary assessments of an uncooled light-duty diesel indicate that a 15 percent fuel savings over conventional diesels should be easy to attain (8). Recent modeling efforts indicate that fuel savings could be much higher and that a multifuel capability is possible.

The Gas Turbine Engine

The gas turbine already has a proven record in stationary power generation and in aircraft and marine applications. As an automotive power plant, the gas turbine offers the potential for improved fuel economy, multifuel capability, low maintenance requirements, and high reliability. Its major limitations currently appear to be poor efficiency under part-load conditions and slow acceleration. Higher operating temperatures will be required to improve efficiency, and ceramics are the most likely materials for such advanced designs.

Two separate industrial teams are conducting government-sponsored research on the advanced gas turbine for automotive use. The efficiency goal for a 3,000-lb automobile with a 100-hp gas turbine engine is 42 mpg with diesel fuel (compared with 31 mpg for an equivalent gasoline-powered vehicle or 37 mpg for a conventional diesel) (9).

The multifuel capability of the gas turbine is another major reason for continued interest in this technology. Tests with automotive gas turbines are usually conducted with gasoline, diesel fuel, and kerosene. Further tests are expected to demonstrate that the gas turbine can also use broad-cut petroleum fuels, alcohols, coal-derived fuels, and hydrogen (10).

The Stirling Engine

A third alternative engine for vehicle applications is the Stirling. This external combustion engine uses a working gas, such as hydrogen or helium, that is alternatively heated and cooled to compress and expand it and provide the mechanical force. Although there are no commercial uses for the Stirling as yet, interest in it continues because it has the highest theoretical thermal efficiency of any practical heat engine. In addition, the Stirling offers the advantages of multifuel capability, improved fuel economy, low emissions, and low noise.

An 80-hp reference Stirling engine in a 3,000-lb vehicle is expected to achieve 46 mpg on diesel fuel. This fuel efficiency would require higher engine operating temperatures than are currently achievable. Again, ceramic components are likely to play an important part. From a fuels perspective, the Stirling is attractive because of its adaptability. The P-40 Stirling engine (developed by United Stirling of Sweden and installed in a 1977 Opel) has demonstrated the use of gasoline, kerosene, diesel fuel, and alcohols (10). In addition, shale oil-based diesel fuel and broad-cut aircraft fuel have been tested in the MOD 1 Stirling engine (an improved Stirling developed by Mechanical Technology, Inc., and tested in a 1979 AMC Spirit and a 1980 GM X-body) (9).

MACROECONOMIC EFFECTS OF ADVANCED CERAMICS

International Research Efforts

Major ceramic research programs focused on engine applications are under way in the United States, Japan, and West Germany. Most ceramic researchers in this country consider Japan to be the major U.S. competitor. Mueller, in 1982, noted two areas of concern for the United States (11). First, the United States trails Japan (and West Germany and Australia) in the development of new ceramic materials such as polycrystalline partially stabilized zirconia, a recent advanced ceramic with potential for use in heat engines. Second, a Japanese company has developed and successfully tested the first ceramic diesel engine. Ceramic components in this three-cylinder engine included pistons, wrist pins, cylinder sleeves, tappets, pushrods, and rocker arms.

A more recent survey of ceramic fabricators and engine manufacturers found a variety of opinions about which country was leading in advanced ceramics research, although there was general agreement that the Japanese have the momentum of government and industry cooperation. However, new materials programs in the United States may alter this perspective. Both Japan and the United States have areas of strength. The Japanese probably lead in zirconia-based ceramics and in developing long-range research programs that lead to early commercialization of products. The United States is considered the leader in basic research and has more experience in designing ceramic engine components and evaluating them on test rigs (5).

Methodology for Estimating Economic Effects

A two-step approach was used to measure the economic effects of structural ceramics in a study at Argonne National Laboratory (ANL) funded by the U.S. Department of Energy (DOE). In the first step, a ceramic market penetration model was developed and used to estimate the market penetration of structural ceramic products. In the second step, the Data Resources, Inc., (DRI) annual macromodel of the U.S. economy was used to estimate macroeconomic effects in two alternative ceramic commercialization scenarios (12, 13). Highlights of these models are briefly described in the following paragraphs.

The general market penetration methodology is based on earlier ANL work that estimated the market penetration of new energy-efficient electric motors (14) and new cogeneration energy systems (15). The market penetration analysis was begun by selecting key structural ceramic applications, including bearings and other engine components, turbochargers, and gas turbines. The total market potential was obtained by estimating the 1981 sales of the conventional-material parts that could be replaced by ceramic parts. Most of the shipment value data for the conventional parts were obtained from the 1977 Census of Manufacturers (16). Sales were projected to the year 2005 using the growth rates of the industries from the DRI macroeconomic scenario TRENDLONG2007B (17).

Market penetration of various ceramic components in the year 2000 was subsequently obtained by multiplying the market potential by penetration rates estimated by industry. Several industry sources were asked to provide their expectations of the market potential of various ceramic applications. The results of this approach are expected to lead only to preliminary estimates of market penetration of structural ceramics components. A more thorough approach, such as that used in the previously mentioned ANL work (14,15), would have made use of the relative economics of ceramics and its competing technologies. However, for this analysis, the relative cost data were proprietary and consequently unavailable and cost data could not be developed in the time available.

The other model used in the ANL study was the DRI annual macromodel of the U.S. economy. This simultaneous-equation model contains 266 economic variables and simulates the major economic sectors, including consumption; business fixed investment;

residential fixed investment; trade; federal, state, and local governments; prices and wages; finance; and energy.

In the energy sector--of special interest in this study--this model is particularly strong. For example, total energy demand is estimated for electric utilities and the household, commercial, industrial, and transportation sectors. Energy supply is separated into domestic and imported sources.

Scenarios for Commercialization of Structural Ceramics

Because it is unclear which country will achieve the technical breakthroughs first or how patent rights will be controlled, an accurate forecast cannot be made of the path that commercialization will take. It is clear that significant benefits will accrue to the companies that reach the marketplace first. They will receive direct benefits in terms of profits from the sale of ceramic components or from increased vehicle and engine sales due to the advantages of ceramic parts. However, there are also aggregate economic benefits that apply on a national level. Changes in GNP, employment, energy savings, and balance-of-trade accounts are some of the key quantifiable indicators of the influence of domestic or foreign dominance in a product area such as ceramics.

In this assessment, two separate scenarios were developed to provide a parametric analysis. The scenarios bracket the range of divergent views on commercialization of structural ceramics, focusing on the effects of either U.S. or Japanese dominance in the ceramic market in vehicle heat engines. This methodology is used not because either outcome is considered probable, but because of the magnitude of input variables that could be used to reflect each country's research funding, technical success, market strategy, and eventual market penetration. A base case scenario is provided for comparison; it assumes that there is no concerted government or industry effort to develop and commercialize structural ceramics in vehicle heat engines.

U.S. Dominance

This optimistic scenario assumes considerable government and industry cooperation that effectively results in a national ceramics research and development program. Military applications are excluded from this analysis, but ceramic components (e.g., piston rings) are assumed to enter the market in heavy-truck engines by 1985. Ceramics in advanced engines such as the adiabatic diesel and the gas turbine are assumed to be introduced in the automotive and truck markets in 1990. The assumptions for market penetration are the upper limit of the potential vehicle market as reflected in discussions with industry contacts. For the United States to achieve dominance in structural ceramics one would also have to assume that there would be a reversal, or at least a slowdown, in the current pace of Japanese ceramic research. Such a change is conceivable, based on Japan's recent economic difficulties and budget constraints. The Japanese might view a strong U.S. research program in ceramics as building on the U.S. lead in the 1970s. As a result, the Japanese might decide to focus their research on other areas. In this scenario, U.S. success in the 1990s will cause the Japanese to renew their efforts so that by the end of the decade Japanese automobiles exported to the United States will have comparable technology.

Japanese Dominance

This pessimistic alternative assumes that there will be no major national ceramic research in the United States, while Japan will continue with a substantial government and industry research effort. In this scenario, the U.S. ceramics industry considers the market too risky because of the strong Japanese research effort, although the potential for structural ceramics is recognized. The Japanese have traditionally focused on low-horsepower engines; consequently, they begin to introduce limited ceramic components in automobile engines in 1985. The Japanese share of total U.S. automobile sales naturally increases at the expense of domestic automobile manufacturers. The import market share in this scenario is limited to 30 percent. In view of the current voluntary import restraints, it is anticipated that at a 30 percent import share, trade restrictions, minimum-domestic-content laws, or licensing agreements would be imposed. The Japanese are not expected to enter the U.S. markets for heavy-duty trucks or stationary diesel and gas turbine engines without the alliance of a North American manufacturer.

Comparative Economic Effects in Each Scenario

The largest sales potential and subsequent national economic effects in each of the scenarios can be expected in the automobile market because of its size (compared with that for heavy trucks or stationary engines). Because of the assumptions for market penetration in each scenario (automobile versus truck as the initial market, constrained market share, etc.), the ultimate macroeconomic effects are different from what might be anticipated if there was only an assumption of market penetration but with different countries leading.

Table 1 presents the new automobile sales in each scenario. In the U.S. dominance case, automobiles with ceramic engines gain a market share of 20 percent by the year 2000. This volume of domestic automobile sales would reduce import sales to 15 percent. In the Japanese dominance case, however, limiting foreign ceramic-engine automobile sales to 500,000 annually would keep the import share from exceeding 30 percent.

TABLE 1 United States Automotive Market Penetration by Ceramic-Component Engines for the Alternative Scenarios

	Base Case		U.S. Dominance		Japanese Dominance	
Year	Total (x 10^6)	Import (%)	Ceramic Engine[a] (x 10^3)	Import (%)	Ceramic Engine[a] (x 10^3)	Import (%)
1985	10.9	23.4	0	23.4	10	23.4
1990	11.9	24.5	125	24.4	100	25.2
1995	12.6	24.2	1,270	19.0	500	27.8
2000	12.7	25.2	2,540	15.0	500	29.1
2005	13.0	25.9	3,580	15.0	500	30.0

[a]Automobiles powered by engines using structural ceramics.

For the sake of perspective, Figure 1 illustrates the relationships between the alternative scenarios and the historical share of imported automobiles. The U.S. dominance case would push imports back to their early-1970s (pre-energy crises) levels. The Japanese dominance case would cause imports to rise to a slightly higher level than that of the mid-1980s.

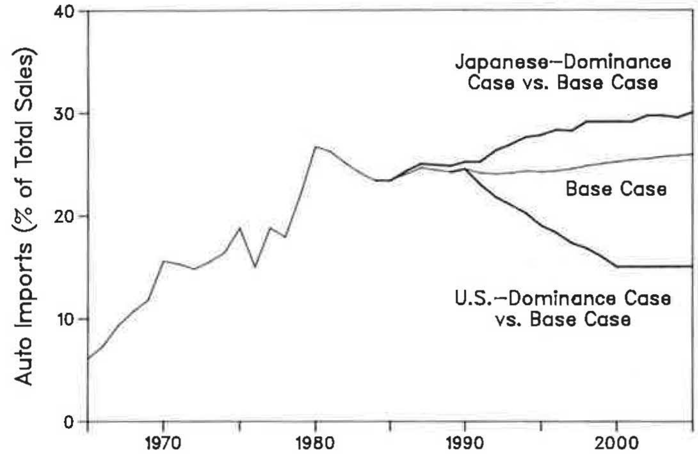

FIGURE 1 U.S. automobile imports: historical and projected.

Petroleum Savings

Because ceramic components will allow even conventional engines (Otto and diesel) to operate at higher-than-normal temperatures and thus greater thermal efficiency, fuel savings will begin with the introduction of the first ceramic-component vehicles. However, energy savings between 1985 and 1990 will be negligible for two reasons. First, the moderate level of sales means that ceramic-engine vehicles will take some time to become a significant portion of the total vehicle stock. Second, because of higher investment in ceramic-related expenditures (e.g., new engine assembly lines), the economy is on a moderately expansionary course concurrent with a slightly greater demand for energy. However, as the stock of vehicles with ceramic-engine components builds up and advanced engines are introduced in 1990, fuel savings will begin to increase at a faster rate. The total petroleum savings will be nearly 0.1 quad by 1995, 0.25 quad by 2000, and 1.1 quads by 2005. One quad (10^{15} Btu) is the equivalent of 8 billion gal of gasoline.

The energy savings in the Japanese dominance case will be minor compared with total petroleum use, principally because of the import restrictions assumed in this case. Direct vehicle energy savings will eventually climb to 0.06 quad by the year 2005. However, the decline in domestic vehicle production will push the economy to lower levels so that total energy demand will decrease. Annual fuel savings will peak in this scenario in 1995 at 0.3 quad. As the GNP gap between this case and the base case narrows, leading to a relatively greater demand for energy, total fuel savings will shrink to 0.2 quad by the year 2000 and 0.1 quad by 2005.

Gross National Product

The economy performs better under the U.S. dominance case than in the base case because this technology alternative is expansionary. Figure 2 illustrates the changes in GNP that could be expected in the scenarios. In the U.S. dominance case, real GNP (in constant 1981 dollars) will peak in the year 2000 at about $28 billion higher than in the base case. The high growth rates in the early stages are inflationary, creating a dampening effect on the economy in the latter periods. These cyclic effects will reduce GNP gains after the year 2000 as the economy tends to return to its original, unperturbed path. Cumulative real GNP gains will approach $280 billion (1981 dollars), which indicates a sizable economic contribution from the ceramic technology.

Real GNP follows a lower trajectory in the Japanese dominance case than in the base case projections. Annual loss in GNP will be greatest in 1995, with a decline of more than $11 billion (1981 dollars). After that, the long-run equilibrium forces

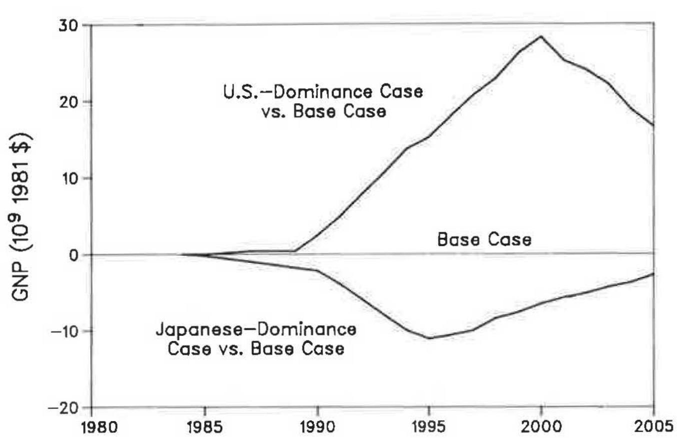

FIGURE 2 Changes in gross national product under the alternative scenarios.

in the economy will narrow the gap to about $3 billion by 2005. Imported automobiles will be sold at the expense of domestic models, shifting production to Japan and thus reducing GNP. The cumulative GNP loss between 1985 and 2005 is $110 billion (1981 dollars) more than in the base case.

Employment

Each of the scenarios can be expected to have significant effects on employment because of the large labor requirements of automobile manufacturers and their suppliers. In the U.S. dominance case, total employment will increase by 25,000 in 1990, nearly 175,000 in 1995, and 250,000 in 2000, relative to the base case. The rate of change in employment would cause the projected national unemployment rate to drop from 6.5 percent in the base case to 6.3 percent in the U.S. dominance case by the year 2000.

The Japanese dominance case, because of its lower level of U.S. economic activity, has lower employment levels. Compared with that in the base case, U.S. employment will decline until the loss of jobs reaches 106,000 by 1995. With trade restrictions stabilizing the level of imports of ceramic engine automobiles at 500,000 annually, the job loss will bottom out in that year.

Balance of Trade

Successful commercialization of structural ceramics in motor vehicles in the U.S. dominance case will improve U.S. balance of trade accounts in two distinct ways. Fewer imported automobiles will be purchased and, as the stock of more fuel-efficient vehicles increases, oil imports will decline. In the Japanese dominance case, the increase in imported automobile sales will offset the reduced imports of fuel. Total import savings in the year 2005 will reach $27.7 billion (1981 dollars) in the U.S. dominance case, but will be a negative $5.5 billion (1981 dollars) in the Japanese dominance case.

As indicated, a substantial portion of the total import savings will come from the projected reduction in petroleum demand that could be achieved with more efficient engines using ceramic components. Almost half of the import savings in the U.S. dominance case will be due to savings in imported petroleum--$10.2 billion (1981 dollars) in the year 2005. Restrictions on imported ceramic-engine automobiles in the Japanese dominance case will limit the fuel component of import savings to $0.6 billion (1981 dollars) for the same year.

STRATEGIC MATERIALS

Some analysts believe that U.S. dependence on foreign strategic mineral resources is far more serious than the reliance on foreign petroleum supplies. Strategic or critical materials are those that (a) the United States must chiefly import (especially if the deposits are in communist countries or in countries whose governments are unstable) and/or (b) are scarce. Structural ceramics are candidates to replace a wide variety of strategic materials, particularly those used as superalloys.

Table 2 (18) lists several strategic materials that are currently used in high-temperature applications and engine systems and that could be replaced by structural ceramics. Demand for many of these materials, despite their high costs, is expected to increase substantially between now and the end of the century. These metals generally have high strength and light weight, and can be used in alloys. However, their desirable properties are overshadowed by economic considerations when the large volumes necessary for use in vehicle engines are contemplated. The fact that so much of this material comes from potentially unstable suppliers (such as South Africa, the USSR, Zimbabwe, and Turkey) simply compounds the difficulties of using these metals in a mass market.

TABLE 2 Characteristics of Selected Strategic Materials *(18)*

Mineral	Range of Imports, 1975-1980 (%)	U.S. Vulnerability to Foreign Disruptions	Major Source
Beryllium	Not available	No	Brazil, South Africa
Cobalt	100	Yes	Zaire, Zambia
Chromium	90-100	Yes	South Africa, USSR, Turkey, Zimbabwe
Manganese	98	Yes	Gabon, Brazil, South Africa
Nickel	70-80	Possibly	Canada, New Caledonia, Dominican Republic, Australia
Columbium	100	Yes	Brazil, Thailand, Canada
Tantalum	98	Yes	Thailand, Canada, Australia, Brazil, Zaire

CONCLUSIONS

Commercialization of structural ceramics in heat engines will have a wide range of benefits for both manufacturers and consumers. Ceramic materials are critical in the development of several advanced engines for motor vehicles, including the adiabatic diesel, the gas turbine, and possibly the Stirling engine. These engines should achieve a 25 to 35 percent improvement in fuel efficiency compared to conventional Otto-cycle or diesel engines. Even in conventional engines, selected ceramic components should reduce heat loss and increase thermal efficiency to improve fuel economy by 5 to 15 percent or perhaps more.

What this improved engine efficiency means in terms of national energy savings depends, of course, on the market success of the vehicles with these engines. As shown by one scenario in this analysis, the annual fuel savings for the nation could be in the billions of gallons of gasoline within a few years of market penetration by these vehicles. More difficult to quantify, yet nonetheless realistic, is the ability of these engines to use alternative fuels. In the event of escalating petroleum prices or shortages of petroleum-derived fuels, the use of alcohol fuels or, in the longer term, synthetic fuels, is feasible with these engines.

Major economic benefits will accrue to the nation that first commercializes structural ceramics, especially if that nation is able to dominate a market as large as that of motor vehicle engines. Gross national product should rise significantly relative to the research and development investment in ceramics, and employment should increase concurrently. Favorable balance-of-trade changes should also be expected as automobile and fuel imports are reduced.

The development of reliable structural ceramics in motor vehicle engines should also reduce the nation's dependence on several strategic materials. Beryllium, cobalt, chromium, manganese, nickel, columbium, and tantalum have uses in heat engines and other high-temperature applications. Because these materials either are sufficiently scarce or come from countries that could be considered unreliable suppliers, the United States stockpiles these metals. Advanced ceramics could replace alloys of these materials in many applications.

Although this analysis was limited to the use of structural ceramics in vehicular engine systems, the research needed to develop such advanced ceramics will also produce ceramics with applications in other product areas. The economic benefits from these other commercial uses may be quite substantial, and additional energy savings may also result from some of these uses.

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Commercialization of Major Efficiency-Enhancing Vehicular Engine Innovations: Past, Present, and Future Micro- and Macroeonomic Considerations

DANILO J. SANTINI

ABSTRACT

Both a general and a particular view of the process and macroeconomic side effects of engine innovation are given. The history of engine innovation in automobiles, railroads, and ships is reviewed and related to the potential path automotive engine innovation may take toward the turn of the century. It is shown that automotive engine innovation in the past has been costly, especially to lower-income consumers, and that potential future adoption of Stirling and Brayton (gas turbine) engines is unlikely to be any different. The danger of negative economic side effects during the innovation process for the automobile industry and nation are noted. Careful corporate and national preparation for automotive innovation is suggested. To that end, advanced (year 2000) engine and vehicle characteristics are used to estimate that the Stirling and Brayton engines are each likely to have specific, different markets. Driving-cycle behavior of the engines in urban and suburban settings is examined to show that the Stirling's most likely market will be as a specialized urban vehicle, whereas the Brayton's best market will be as a specialized suburban and intercity vehicle. It is argued that neither engine has the properties necessary to become a universal replacement for all-purpose vehicles using advanced Otto-cycle and diesel engines, but that proper use of these vehicles could ultimately help to efficiently mitigate national problems of urban air pollution (the Stirling in particular) or excessive fuel consumption or both. Finally, the observation is made that recent methods of the Environmental Protection Agency for evaluating vehicle fuel efficiency could incorrectly lead to a negative economic evaluation of advanced Stirling and Brayton engines, tending to unjustifiably retard their introduction to the market.

Advanced automotive engines were characterized as part of the Argonne National Laboratory's study Technology Assessment of Productive Conservation in Urban Transportation (TAPCUT) (1). In this study, which examined transportation energy use and associated impacts, passenger automobiles powered by Stirling, Brayton, advanced diesel, and improved Otto-cycle engines were characterized in detail for the year 2000. Several of the vehicles characterized in this large study are here examined in further detail to provide an understanding of which elements of each engine would make it the best choice in various vehicle markets in the future.

The engines and vehicles defined for the TAPCUT study were assessed for urban passenger use but were not evaluated for rural and intercity applications. Several different levels of success in technology development were assessed, each achieving different fuel efficiency and performance levels by the year 2000. The purpose of the original TAPCUT study was to define relevant energy conservation strategies in urban transportation, test them, and determine their environmental impacts. The present study focuses not only on urban environmental and energy conservation issues, but also on rural and urban markets for the new technologies. The study concentrates mostly on the costs and benefits of achieving fuel efficiency. Attributes of the engines and vehicles, as well as the fuel consumption estimating techniques, were taken from the TAPCUT reports. To expand that information, further detail was developed on fuel efficiency variation between driving cycles experienced by vehicles using the new engines. With these data, the vehicles were compared in different driving cycles to reveal their strong points in terms of fuel economy realized in specific applications. Applications compared were in-city driving versus suburban driving.

BACKGROUND ON THE ECONOMICS OF ENGINE INNOVATION

History of Automotive Engine Innovation

Recent and ongoing research at Argonne National Laboratory's Center for Transportation Research reveals that the process of introducing new, more efficient automotive engines into the marketplace involves a period of very costly adjustment for consumers, motor vehicle manufacturers, and the national economy (2-5). This research reveals that the inflation-adjusted (real) costs of motor vehicles increase sharply during a period of engine innovation, especially for low-income consumers. As a consequence, motor vehicle sales decline, the income-generating side effects of automobile production decrease, consumers have less money to spend, and real national wealth per capita diminishes or stagnates (see Table 1) (2). Prior research revealed that three distinct periods of automotive engine innovation occurred since World War I (WWI). Within each of these periods (1926-1935; 1952-1959; 1979-1984), there were subperiods of very low automotive sales and weak national economic activity. Automobile sales

TABLE 1 Rates of Change in Real Vehicle Price and Horsepower and Other Economic Indicators, 1921-1983 *(2)*

Measure	Annual Change (%)[a] 1921-1926	Innovation Period I, 1926-1934: 1926-1932	Innovation Period I, 1926-1934: 1932-1934	1934-1952	Innovation Period II, 1952-1960: 1952-1958	Innovation Period II, 1952-1960: 1958-1960	1960-1977	Innovation Period III, 1977-1983[b]
Vehicle price[c] and engine power								
Ford								
Cost (1921 $)	-7.25	17.8	-3.7	1.3	3.8	-13.3	-1.7	4.1
Horsepower	0	16.5	17.7	0.7	5.3	-37.9	-0.1[d]	-8.4[e]
Chevrolet								
Cost (1921 $)	-9.5	10.2	-12.5	2.8	3.9	-3.5	-1.8	2.0
Horsepower	0	15.0	7.2	1.4	7.9	-25.7	-1.3[d]	-3.5[e]
Dodge								
Cost (1921 $)	-9.6	6.7	-7.9	0.9	3.0	-11.3	-0.6	0.8
Horsepower	0	9.4	20.4	0.9	4.6	-13.5	-0.1[d]	-7.2
Buick								
Cost (1921 $)	-9.0	4.9	-9.9	0.9	3.6	-3.8	-1.0	2.7
Horsepower	5.4	3.1	6.0	1.8	18.9	-11.3	-2.3[d]	-3.3
Cadillac								
Cost (1921 $)	-5.8	6.8	-11.1	-3.9	5.0	-1.5	0	-3.7
Horsepower	1.6	5.1	6.3	1.3	9.3	0	-3.7[d]	-10.4
Lincoln								
Cost (1921 $)	-0.5	1.1	3.1	-5.1	5.9	-6.4	-1.3	3.0
Horsepower	-1.1	5.6	9.5	0.4	18.6	-7.2	-4.7[d]	0.9
Other economic indicators								
Index of relative motor vehicle prices[f]	NA	5.0	-6.4	-0.02	1.5	0.2	-1.2	0.1
Passenger car sales per capita	18.4	-19.0	39.1	2.7	-2.0	22.8	0.7	-6.1
Real GNP per capita (1958 $)	6.6	-5.5	2.8	4.1	0.3	2.5	2.8	0.9

[a]See Table 1.1 *(2)*, footnotes a-d; these footnotes identify slight variations in years of data.
[b]The method used tends to understate cost increases here because new, smaller, lower-cost models were added by many makes. When interior volume is held constant, costs go up much faster than shown here. The author's favorite examples are the two American automobiles he bought in 1978 and 1980. From 1980 to 1984, the minimum cost of an equivalent volume (same body style) vehicle of the same make went up in real terms by 11.0 percent per year for the cheaper four-cylinder model, and 5.2 percent per year for the more expensive model in which a V-6 replaced the V-8.
[c]After World War II, model-year introduction prices are used for costs in the calendar year "before" the model year.
[d]Use with caution; the method of computing horsepower changed in the middle of the time interval.
[e]Diesels are used in 1983, although they are not the lowest-cost models.
[f]NA = not available. Relative prices computed from wholesale price indices.

were lower at the beginning than at the end of each of the subperiods 1929 to 1932, 1955 to 1958, and 1979 to 1982, and real gross national product (GNP) per capita had declined (these subperiods are not illustrated in Table 1). Intervening periods, however, were characterized by relatively consistent peacetime economic growth fostered by a general increase in affordability and sales of automobiles. Table 1 illustrates these facts by presenting statistics on real costs (based on deflation with the wholesale price index) for the lowest-cost car available from a range of economy to luxury makes. Rates of change of costs are averaged over critical intervals from 1921 to 1983, enabling comparison between innovative and noninnovative engine development periods.

The annual rate of real cost increases of six representative makes of car is shown for selected time intervals from 1921 to 1983 in Table 1. These makes were selected because they represent the full price range of vehicles available from U.S. producers. They are roughly ranked according to their position in the lowest to highest price range and highest to lowest sales range.

Three graphs (Figures 1 to 3) based on information from Table 1 help to illustrate some key features related to the automobile engine innovation process. First, Table 1 uses horsepower change as an indicator of the rate of introduction of new engines. A high rate of change in horsepower (positive or negative) is used to define an innovative period. The term innovation is used to mean "the introduction of something new" (as defined in Webster's New Collegiate Dictionary), referring to the widespread introduction of new engines by all automobile manufacturers. Table 1 and Figure 1 show that three periods of relatively stable engine horsepower (1921-1926, 1934-1952, and 1960-1977) have been followed in each case by an unusually rapid change of horsepower in nearly all makes. Table 1 shows that during periods of stable engine horsepower, relative motor vehicle prices for all makes mostly tended to decline, while any increases were moderate. In contrast, the initial years of engine innovation (1926-1932, 1952-1958, and 1977-1983) were characterized by real price increases in lower-priced makes that were more rapid than the average for all motor vehicles (see Figure 2) and that also represented a significant increase from the preceding price trend for the make. Figure 1 graphically shows the latter pattern for the two lowest-priced makes, Chevrolet and Ford.

After each of the cost-increasing periods of engine innovation was well under way, sales of automobiles dropped to a depressed level at the same time that economic activity (as measured by real GNP) dropped into what has subsequently been recognized as one of the worst slowdowns of that historical period. The end of the first innovative period, 1932, is now recognized as the lowest point of the Great Depression. The end of the second innovative period (1958) is within a period now labeled the "Eisenhower Stagnation" in economics texts, and the most recent of the three innovative periods has also been described as a time of economic stagnation.

The typical economic interpretation of the link between national economic activity and automobile sales views national economic aggregates (interest rates, national output, and unemployment) as pushing the motor vehicle industry down. Few economists have emphasized the possibility of a systematic reversal of causality in which internally created cost increases pull automobile sales down, with the automobile sector in turn pulling the rest of the economy down. Nevertheless, the evidence presented here is consistent with the latter interpretation. Admittedly, this evidence only addresses three of the worst business downturns since WWI. It does not show a causal link to each U.S. recession. It does show,

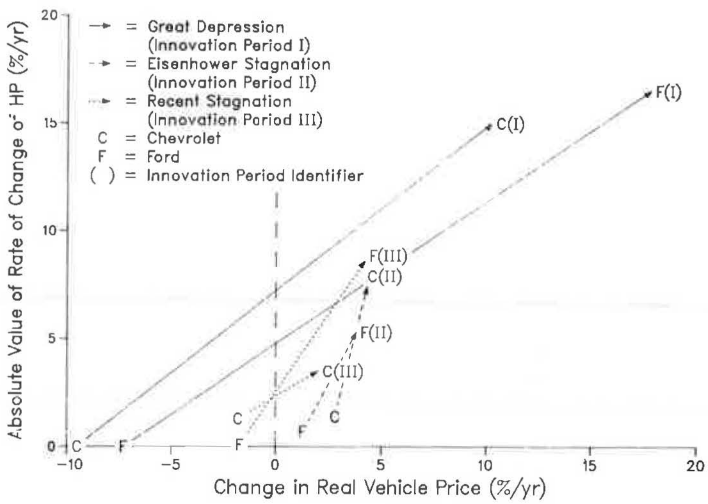

FIGURE 1 Historical relationship between automobile price and engine innovation: Ford and Chevrolet base models, 1921 to 1983 (from Table 1).

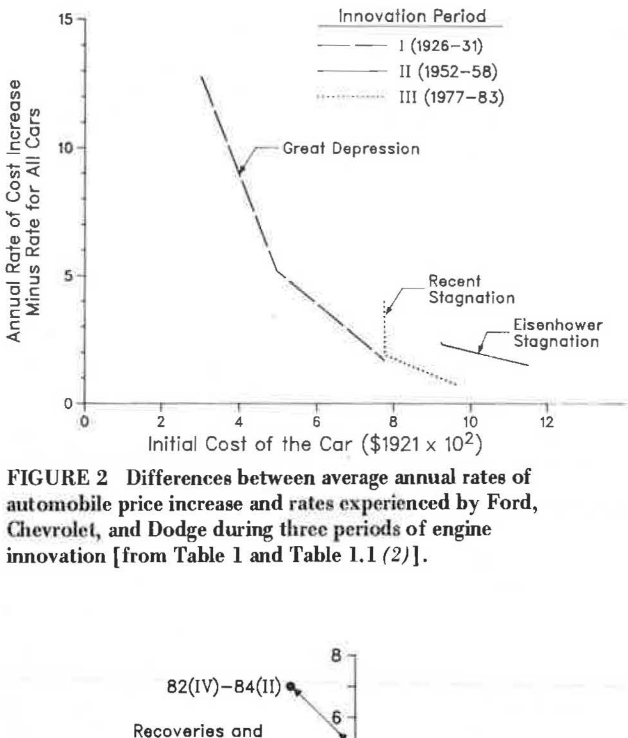

FIGURE 2 Differences between average annual rates of automobile price increase and rates experienced by Ford, Chevrolet, and Dodge during three periods of engine innovation [from Table 1 and Table 1.1 *(2)*].

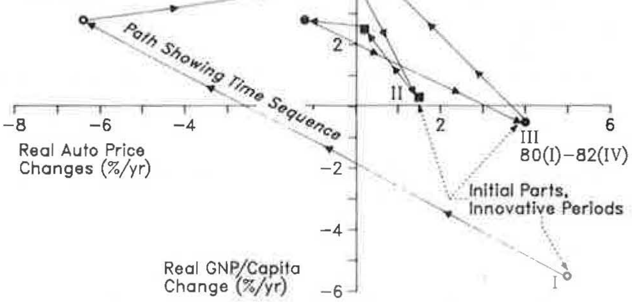

FIGURE 3 Relationship between annual rates of change of aggregate real motor vehicle price and real GNP: selected sequential time intervals, 1926 to 1984 (from Table 1 and text).

however, that costly automotive innovation can logically be argued to be causally linked to many of the periods of low macroeconomic growth occurring since the automobile became the transport vehicle with the largest value of output in the nation.

Figure 3 traces the history of aggregate real automobile price increases and real GNP increases over substantially the same time intervals shown in Table 1. The only change is a shift to carefully selected quarterly data for the 1980 to 1984 time period (2,6). This selection is made desirable by the automobile industry's recently adopted strategy of introducing new makes in the spring, with regular but unscheduled price adjustments. Use of quarterly data also illustrates the fact that the current economic recovery can be argued to have been promoted by real motor vehicle price reductions. Using Figure 3 for the third innovation period and Table 1 for the first two, one can see that each rapid price increase at the start of a period of engine innovation was followed by a period of relatively rapid reduction of prices for many, if not all, makes. This reduction in price occurred in conjunction with a nominal "recovery" that left the economy at a higher but still unsatisfactory (from a political point of view) level of activity in these cases.

The evidence presented here is intended to set the background on the importance of proper preparation to allow engine innovation to take place with minimal cost. A comparison of the three innovative periods discussed most recently implies that the greater the positive shift in trend of cost of low-cost vehicles (and the greater the positive shift in trend of aggregate vehicle costs), the worse the effect on GNP per capita. One interpretation of this pattern is that moderate rates of introductions of innovative engines, accompanied by moderate increases in aggregate vehicle costs, might allow a more successful transition (in the sense of less negative macroeconomic side effects) than would an attempt at an abrupt, industry-wide transition from one set of engine technologies to another.

Arguments Concerning Causes of Engine Innovation and Its Side Effects

Before moving from the discussion of the automobile's past to the automobile's future, one should consider the history of vehicular engine innovation processes in order to develop some judgment about the future. First, the evidence suggests that some triggering mechanism caused all automobile manufacturers to simultaneously change their engine characteristics. One possibility would be competitive pressure as described by the economic model of "perfect competition." However, this is a poor explanation, because competitive pressures are supposed to push price down and sales up. The sensible explanation is that a transition in fuel characteristics (price or quality or both) precedes and triggers an engine innovation period. Another frequently observed factor is the effect of environmental regulation (2-5).

When one introduces fuel price and quality as causal factors in creating incentives for consumers to change and delay engine--and perhaps vehicle--choices, then a theoretical explanation is provided for recently published statistical evidence that crude oil price shocks have been causally linked to nearly every U.S. recession since WWII (7,8). Hamilton's statistical study (7) begins to fill in the gaps in Table 1 with evidence consistent with the hypothesis that changing consumer preferences for automotive engines may be a consistent cause of recessions.

The view that changing consumer purchasing habits are the causes of recessions and depressions is not a new one. Keynes was the most notable proponent of the view that changes in the "propensity to consume" caused business downturns (9). However, although Keynes suggested several reasons for such changes, he performed no empirical evaluation of those reasons. None of Keynes' suggested reasons had anything to do with energy. In the arguments presented here, economic actors rationally change their propensity to buy certain engines based on fuel price and quality shifts. Vehicle and engine manufacturers attempt to meet changed purchaser preferences by investing in the production of new or innovative engines. The limited evidence presented here suggests that this process drives up engine and vehicle costs, thereby depressing vehicle demand. It has been argued elsewhere (3,5) that if this process becomes prolonged because of continuing synergistic interactions between fuel and engine attributes, a depression could result. The more rapidly the process comes to a halt, or the less costly the innovations undertaken, the less severe the business downturn should be.

The downturns examined in Table 1 and Figures 1 to 3 have each been fairly long, and the engine innovations have been costly to the vehicle purchaser. The behavior of the economy during these periods is consistent with the earlier interpretation of events, given that economists have used the words "depression" and "stagnation" to distinguish these periods from other periods of rather steady growth interrupted by occasional recessions. In more lengthy investigations it has been found that the engine innovations attempted during recessions are either immediate and clear successes or immediate and clear failures. Furthermore, they have generally been treated by engineering historians as refinements rather than significant technological innovations (4). The clear absence of significant engine innovations in the noninnovative periods in Table 1 implies that any changes adopted during intervening recessions were relatively minor. However, the author's investigations indicate that minor engine innovations were often characteristic of recessions (4), whereas Hamilton's work suggests that, during the post-WWII period, such changes were induced by positive shifts in crude oil price (7,8).

Since the mention of Keynes' theories concerning the importance of shifts in the propensity to consume, the terminology has been changed from "consumer" to "purchaser" or "economic actor" when changes in the propensity to consume engine and vehicle combinations are discussed. This has been done because, if fuel price and quality shifts occur, there is no reason to believe that only final consumers will readjust their purchase plans. Businesses that use engines should also be expected to alter their choice of engine. In fact, it can be argued that businesses are even more likely than consumers to make economic calculations that might lead them to choose a new engine. Thus, although Keynes emphasizes the importance of the final consumer, this model of engine purchaser behavior recognizes that both purchasers of final goods (consumers) and intermediate goods (businesses) will simultaneously reevaluate their choice of engine after a shift in fuel price and quality.

Pre-1900 Historical Evidence Supporting the Causal Arguments

Research for this paper on the subject of the link between engine innovation and the business cycle has gone as far back as the late 1700s. Although the negative side effects arising from altered engine purchasing patterns can be explained in terms of a consumer response since WWI, one must recognize the similar nature of transport-sector business responses to see that it is essentially the same phenomenon that was consistently repeated in the 1800s and early 1900s. A brief discussion of the 19th-century engine innovation process can help put possible future innovations in perspective.

The steam engine was introduced as a stationary engine in the late 1700s. It was later applied to marine use, railroad use, and finally, by the 1890s, to automotive use. Its introduction to railroads in the United States created competitive pressures on canal builders. In 1836, a form of locomotive was invented that became the mainstay of the U.S. rail transportation system until the 1890s. This was the 4-4-0, or "American" locomotive, a single locomotive type deemed worthy of its own book (10). This locomotive type led to the use of far more expensive locomotives than had been used in the 1830s. Nevertheless, from 1839 to 1842 it almost completely supplanted the outmoded 4-2-0 in production, while the late-1830s boom in canal construction was completely choked off (see Figure 4). Canal spending never revived. The years of 1839 to 1842 were described by

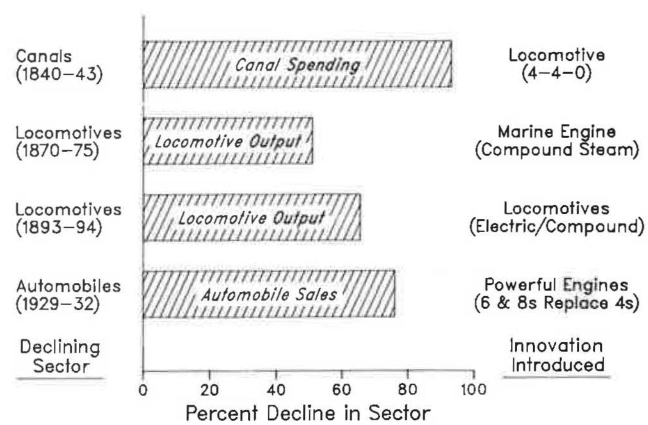

FIGURE 4 Depression-inducing peak-to-trough decline of output of old transport technologies made obsolete by innovative competing technologies [cases given occur at outset of four worst U.S. depressions *(4)*].

Milton Friedman and Anna Schwartz as the "second worst monetary collapse in history" (11). (The period of the worst monetary collapse occurred during the most rapid automotive horsepower change in history, labeled "Innovation Period I" in Table 1).

In the early 1870s, the costly but efficient compound marine steam engine was introduced on the Great Lakes and along the eastern seaboard by integrated transportation companies that owned both railroads and shipping lines. Construction of ships expanded rapidly at the same time that railroad locomotive (see Figure 4), freight car, and track mileage construction dropped sharply. At the time, most railroad mileage was in the Northeast and Midwest regions where competition from Great Lakes to Erie Canal to Long Island Sound shipping routes was prevalent. The drop in rail activity coincided with a decline in business output that followed the Panic of 1873. The low level of business activity lasted for 5 years, a period described by historians as a depression.

Compounding in a reciprocating steam engine adds complexity and increases first cost in order to improve efficiency. Compounding involves stepwise expansion of steam in separate, increasingly large cylinders. As more compounding steps were added, the pressure of the steam in the first cylinder was increased. Similar procedures are now used in electric generating steam turbines (steam is expanded in small, high-pressure turbines first, then in larger low-pressure turbines). In marine reciprocating steam engines, the stages of expansion were increased sequentially over a period of time from two to five. Triple expansion, first widely adopted in the mid-1880s (during a recession) proved to be the most economically successful. Quadruple- and quintuple-expansion ships were few in number, given their lack of economic success. The reciprocating, external combustion marine steam engine was eventually replaced by the external combustion steam turbine and the internal combustion diesel.

The reciprocating internal combustion engine is currently going through a similar sequence. More and more devices are being appended to the engine (turbochargers and intercoolers, for example) in the search for more efficiency (12). In the case of the reciprocating marine steam engine, the process ended when this engine was supplanted by the steam turbine. Today, both the high-pressure steam turbine and the diesel are used in marine applications, with the diesel used in low-speed applications and the turbine in high-speed applications. Later in this paper, the systematic evaluation of the diesel and the internal combustion turbine for automotive applications leads to the conclusion that the greatest advantage of the diesel is in low-speed stop-and-go applications, whereas the turbine is comparatively better when used at higher, steadier speeds. It is also seen that the internal combustion turbine is the next logical step up from the internal combustion reciprocating engine, just as history shows that the same sequence was followed for external combustion (i.e., steam) engines.

Only three stages of steam expansion were tried in locomotives. Severe space and weight limitations prevented further evolution. Two-stage compounding was introduced in U.S. locomotives in 1889, and was widely adopted during the depression of the 1890s, which began in 1892 (see Figure 4). Electric locomotives, which cost two-and-a-half times as much as steam locomotives per unit power, were also adopted for specialized uses where high power, reliable service, dependable cold-weather operation, smokeless operation, or all four were required. A boom in street railway construction occurred during this depression, as urban rail systems almost completely replaced the horse with the electric railcar. Steam locomotive sales dropped precipitously (see Figure 4) and several different models were introduced. The next stage of compounding in locomotives was not tried until the next depression. The only triple-expansion locomotive ever built for a U.S. railroad was the "L.F. Loree," the only locomotive delivered in the Great Depression year of 1933 (13).

The period between the depression of the 1890s and the Great Depression is an informative one because it reminds us that several forms of motive power occasionally coexist in various transportation modes. The gasoline-powered automobile was introduced during the 1890s depression. During the interdepression period, both electric and steam locomotives had significant shares of the market. Early in the period, both electric and gasoline automobiles had significant shares of the market. Electrics were preferred for urban driving by women, because of their quiet, clean operation and the elimination of the manual starting problem of the early gasoline models. The automatic starter was a major cause of the demise of the electric car. Steam-engine cars, which never used the principle of compounding, were successfully introduced before gasoline cars and remained in production until the increase in horsepower of gasoline-powered vehicles during the 1926 to 1932 time period.

The diesel-electric locomotive was introduced in 1924 for railroad yard switching. It also found applications in urban areas where legislation required smokeless running. This was stop-and-go service, for which the diesel is well suited. Although diesel-electrics cost five times as much as steam engines per unit of power (13), they cost only twice as much as electrics, the principal competition in smoke-restricted areas. They carried their own power plant and therefore did not require the costs of rail electrification. Smoke laws and pollution control (the latter related to horses) had played a role in the introduction of the first electric locomotives. Smoke laws also played a role in the introduction of diesel locomotives. Environmental legislation thus forced the initial use of these two innovative locomotive engines (5,13).

Conclusions and Summary of Historical Discussion

Four key points can be derived from this discussion:

1. It is apparent that historically significant engine innovations have consistently begun just before U.S. depressions and have continued during the depressions. However, when one looks at history from the long-term point of view it is doubtful that one would want to prevent engine innovation in order to avoid its negative side effects. The alternative, then, is to recognize that these events must take place but to plan ahead of time so that they cause less damage to the economy.

2. The possibility that the almost universally used internal combustion reciprocating automotive engine may be partially replaced by other engine types is not without historical precedent, given the prior simultaneous existence of steam and electric locomotives and steam, gasoline, and electric automobiles.

3. The eventual economic failure of the reciprocating steam engine was presaged by the increasing complexity of the engine as more and more stages of compounding were attempted. The fact that the internal combustion reciprocating engine is becoming more complex in the quest for efficiency (turbocharging, turbocharging plus intercooling, increasing

the number of valves per cylinder, and possibly turbocompounding) (12) may also presage its slow demise.

4. The role of environmental regulation in forcing the adoption of the first electric locomotive (5) and the first diesel locomotive (13) suggests that the possibility of such effects should not be ruled out when considering costly new engines. It is also true that the regulations that forced the introduction of new locomotive engines also caused the introduction of far more efficient engines that later found use in applications where their environmental virtues were not the critical determinants of their success. This might also happen with the automotive Stirling engine.

In the latter half of the paper the potential introduction of the Brayton internal combustion turbine or the Stirling, an external combustion reciprocating engine that uses a low-molecular-weight gas as a working fluid, is examined. Some of the reasons that diligent advance work should be done on these engines are that such work can allow the engines to be introduced without uncertainty, at a lower initial cost, and perhaps at an earlier time but at a more gradual rate. All of these attributes of engine introduction should reduce the apparent consumer shock effects that caused the kinds of vehicle output declines shown in Figure 4.

There is certainly a possibility that the 1890 to 1930 pattern of multiple-engine locomotive and automobile history might repeat itself in the automotive sector. Ironically, the diesel, previously encouraged by environmental laws and currently one of the engines that enhances fuel efficiency, might in the future be restricted in some urban areas for environmental reasons. The Stirling engine, although costly and economically unproven in any major market, offers the potential for very low emissions, thus making it of interest for potential use in urban applications. The Brayton, already successful in stationary, marine, and aircraft applications, may be able to use cheap (low-octane) fuel efficiently while cruising. However, it might be ruled out for everyday urban use in large metropolitan areas because of smog-promoting nitrogen oxide emissions and poor idle performance. Other attributes of these engines, which are described in this paper, make them potential candidates for specialized future automotive uses, much like the specialized uses of the electric, steam, and gasoline cars in the 1890 to 1926 period.

Future Versus Past Automotive Engine Innovation Costs

Table 1 and Figure 3 show that the real costs of lower-priced makes increase at the greatest rate during a period of engine innovation. This is not a coincidence. In fact, the same behavior observed in the past has now been unintentionally "predicted" by two recent economic studies of future engine innovation. The first, a Los Alamos study (14) estimated such a pattern of 1980 to 1990 cost increases as discussed in the earlier version of this paper (15). The second study, TAPCUT (1), provides the information necessary to calculate the percentage increases in real vehicle cost by vehicle price that would arise if U.S. automobile manufacturers were to shift from Otto-cycle internal combustion engines in 1990 to either diesel, Brayton (gas-turbine), or Stirling engines by the year 2000 (see Table 2) (1). Regardless of the engine type selected, real costs are projected to increase at a higher rate for lower-income buyers. However, as one might expect, a conversion to Brayton or Stirling engines is projected to be far more costly than a conversion to advanced diesel engines.

The TAPCUT-based estimates of the total real-vehicle-cost percentage increases for the introduction of Stirling and Brayton engines (Table 2) are somewhat lower than those of the 1926 to 1932 period that initiated the Great Depression (Table 1) but are greater than the engine and vehicle innovations of the mid-1950s and early 1980s (Table 1). Consequently, given the typical consumer reaction, one might expect a period of general economic difficulty surpassing that of the mid-1950s and early 1980s if future events were to cause a similarly rapid and universal conversion from reciprocating internal combustion automotive engines (diesels and Otto-cycle engines) to Stirling and Brayton automotive engines. However, as this study illustrates, a partial conversion is far more likely and desirable.

Study Purpose

The introductory discussion of the economic impacts of engine innovation suggests that the solution of the technical problems in engine design is only the first step in successful introduction of the engine

TABLE 2 Projected Real Costs of Adopting Innovative Engines in Place of the Otto-Cycle Engine to Improve On-Road Urban Fuel Efficiency, 1990 to 2000 *(1)*

		Advanced Diesel			Stirling			Brayton		
Vehicle Type	1990	2000	Percent Change	Percent per Year	2000	Percent Change	Percent per Year	2000	Percent Change	Percent per Year
Automobile										
Mini										
Cost	5,460	6,550	20.0	1.8	8,160	49.5	4.1	8,460	54.9	4.5
Mpg	36	57	58.3	4.7	57	58.3	4.7	55	52.8	4.3
Small										
Cost	6,144	7,180	16.9	1.6	8,790	43.1	3.6	9,060	47.5	4.0
Mpg	33	51	54.5	4.4	51	54.5	4.4	50	51.5	4.2
Medium-sized										
Cost	7,908	9,010	13.9	1.3	10,600	34.0	3.0	10,790	36.4	3.2
Mpg	23	33	43.5	3.7	36	56.5	4.6	35	52.2	4.3
Large										
Cost	10,200	10,910	7.0	0.7	13,600	33.3	2.9	13,140	28.8	2.6
Mpg	19	29	52.6	4.3	29	52.6	4.3	29	52.6	4.3
Van										
Cost	7,555	8,670	14.8	1.4	10,130	34.1	3.0	10,340	36.9	3.2
Mpg	27	42	55.6	4.5	42	55.6	4.5	41	51.9	4.3

Note: cost is expressed in 1980 dollars.
Fuel economy based on prior TAPCUT work. Methods in this study are related derivatives. Fuel economy estimates are "as driven" estimates and tend to be less than pre-1985 EPA estimates when used for 1980 automobiles.

into the marketplace. The rather negative side effects of the three prior periods of new automotive engine introduction suggest that a careful plan for slow introduction of new engines into the marketplace (with acceptance of slower recovery of engine R&D costs) might help to reduce the negative short-term side effects while allowing the long-term benefits of improved engine designs to be realized.

The purpose of this paper is to take previously developed engineering-based cost and performance information on the expected "post-breakthrough" behavior of Brayton and Stirling engines and systematically evaluate the best potential markets for those engines. It is assumed that if technical breakthroughs occur, they should inevitably lead to the introduction of new engines. However, it is also assumed that early, targeted introduction of new engines, accompanied by a slow expansion of market share, could prevent the problems that previously accompanied the widespread, rapid introduction of new engines. An accurate depiction of the most advantageous uses of new engines will help consumers and producers make better decisions concerning their use, as well as prevent early abandonment of otherwise successful engine technologies. For example, in view of current engine characteristics, it is questionable whether the almost complete abandonment of four-cylinder engines in the early 1930s was economically or technically desirable.

VEHICLE CHARACTERISTICS

The vehicle characteristics used in this study were based on slight modifications of the projected vehicle designs developed for the TAPCUT study (15, 16). Vehicle design variables that were altered over the 1980 to 2000 time interval included (a) materials composition, (b) weight, (c) engine-to-road system or "cruise" efficiency, (d) idle fuel-flow rate, (e) engine location (front-wheel drive), and (f) drag coefficients. Costs of realizing the design characteristics were also estimated. General driving-cycle equations were developed to simulate urban, highway, and combined driving. Characteristics of large and small vehicles that this study projects for the year 2000 are given in Table 3.

In an earlier draft of this paper, further details on materials use, aerodynamics, and the fuel consumption model were given in a discussion that focused more on the Stirling and Brayton evaluation methodology and far less on the historical aspects.

FUEL CONSUMPTION TRADE-OFFS

The properties shown in Table 3, along with engine costs, make the comparison of the Stirling and Brayton to the diesel and Otto-cycle engines a more complex task than the comparison of the diesel to the Otto. The diesel is superior to the Otto both in terms of idle fuel-flow rate and system efficiency. The Stirling is similarly superior to the Otto in both of these categories. However, the Stirling is projected to be superior to the diesel in system efficiency, but inferior in terms of idle fuel-flow rate. Consequently, in terms of vehicle fuel efficiency, the Stirling can do worse or better than the diesel, depending on the percentage of trip time spent in braking and at idle. In contrast, the diesel can never do worse than the Otto, so the recent use of simple point estimates of fuel efficiency was generally acceptable for consumer comparisons of diesel and Otto engines. In the case of the Stirling, however, knowledge of its behavior as a function of its driving cycle would be much more valuable to the consumer.

If this case can be made for the Stirling engine, it can be made with even more vigor for the Brayton. The Brayton has the best cruise and acceleration system efficiency of all of the combustion engines characterized in the TAPCUT study, while also having the worst braking and idle fuel-flow rates. The system efficiencies of both the Brayton and Stirling engines come dear in terms of estimated initial vehicle cost, as Table 2 illustrates. The diesel's 16 percent system efficiency gains with respect to the 1990 Otto engines come at a real cost of about 7 to 20 percent, with the lowest percentage of cost increases occurring in larger six-passenger vehicles. Another 33 percent gain in system efficiency can be obtained in the year 2000 for 20 to 30 percent additional real cost if one purchases a Brayton. The Brayton and Stirling vehicles consistently cost more than the diesel, but shift positions relative to one another as vehicle size increases. In a large vehicle, the Brayton costs less than the Stirling. In all other vehicles, the Stirling costs less. Although these results might appear to be speculative, it should be remembered that extremely small versions of the Stirling engine have been successfully operated, and the Brayton has increased its aviation market by a gradual reduction from larger sizes. The Brayton can thus be expected to enter the automotive engine market from the top end of the horsepower range in larger vehicles. It might have to be successful in heavy-duty vehicles before being introduced into large automobiles.

DRIVING CYCLES

For the purposes of this paper, urban, suburban, and "combined" driving cycles were disaggregated from the TAPCUT SAE J1082 driving cycle, which included urban and suburban segments. For purposes of rough

TABLE 3 TAPCUT Small and Large Vehicle Characteristics for Year 2000

Vehicle and Engine	Laden Weight (lb)	Horse-power	Idle Fuel Flow Rate (gal/min)	System Efficiency (%)	Vehicle Cost (1975 $)	Cost Increment ($) Versus Otto	Cost Increment ($) Versus Diesel
Small							
Otto	1,990	103	0.0094	18	4,005	–	-664
Diesel	1,950	101	0.0027	21	4,669	+664	–
Stirling	2,071	107	0.0059	25	5,720	+1,715	+1,051
Brayton	1,845	97	0.0100	28	5,894	+1,889	+1,225
Large							
Otto	2,940	156	0.0141	18	6,850	–	-593
Diesel	2,887	153	0.0039	21	7,443	+593	–
Stirling	3,015	159	0.0087	25	8,847	+1,997	+1,404
Brayton	2,726	146	0.0142	28	8,553	+1,703	+1,110

comparison, the urban cycle used in this study averages 15.9 mph, whereas the Environmental Protection Agency (EPA) "city" cycle averages 19.6 mph. This study's suburban cycle averages 40.2 mph, whereas EPA's "highway" cycle averages 48.2 mph. The TAPCUT study focused on urban and suburban driving only, but EPA must account for rural and intercity use in the driving cycles that it uses to evaluate vehicle efficiency. Additional details are available from the author.

Large Automobile/Large Engine Driving Patterns

The Brayton's slight cost advantage over the Stirling in large automobiles, which tend to be powered by large engines (see Table 3), suggests that it might have its best market opportunity in large automobiles. A 1975 GM study (see Table 4) (17) shows that large automobiles are driven more miles per day than are medium-sized and small automobiles. It also shows that those with larger engines are driven more miles per day. Geographically, the study shows that residents of low-density zip code regions drive their automobiles the most. These drivers also achieve mileage closer to the EPA ratings than do drivers in more densely populated regions. Because automobiles with low EPA mileage ratings (presumably large vehicles with large engines) were consistently closer to their EPA ratings than other automobiles, it seems reasonable to assume that these vehicles were driven less in heavy traffic and in stop-and-go driving. The low-residential-density region appears to be a good potential market for the fuel-efficient Brayton engine, because the figures in Table 4 imply that automobiles are driven intensively in that region and they are driven relatively less frequently in a stop-and-go fashion. Consequently, the Brayton's superior cruise efficiency could be used to its advantage, allowing the vehicle to realize better on-road mileage than its competition. Given the intensive use of the vehicle, its lower fuel expenses could more rapidly repay its high initial cost. The national benefits of a more fuel-efficient engine technology for rural and suburban use could be very substantial, given the fact that about two-thirds of the mileage driven is in such regions (see Table 4).

This study and other studies cited in the earlier paper (15) have found that the diesel's relative fuel-efficiency advantage in small automobiles increases when it is driven fewer miles per day (a surrogate for urban driving) and at lower speeds. This behavior is due to both the relatively flat torque and power curves of the diesel engine and its low rate of fuel consumption at idle. It is worth noting that General Motors now plans to abandon diesel engines in its large- and medium-sized automobiles, but will retain the diesel option in the small Chevette (15). Good low-speed torque and low idle fuel-flow rates are also characteristics of the Stirling engine, making it a logical urban competitor to the diesel. Furthermore, the front-end aerodynamic penalties arising from the bulk of the Stirling engine are unimportant in urban driving-cycle applications.

In this paper discussion will be limited to automotive applications. A discussion of other possible vehicle applications of Stirling and Brayton engines can be found in the earlier version of this paper (15).

Year-2000 Economic Payoff Estimates Comparing Engines in Selected Markets

Table 3 shows the weight, horsepower, idle fuel-flow rate, system efficiency, and year-2000 vehicle costs for large and small vehicles with Otto-cycle, diesel, Stirling, and Brayton engines. Differential 1975 dollar costs for the Stirling and Brayton engines in comparison to Otto and diesel engines are also presented.

Table 5 shows the incremental benefit-cost ratio obtained by comparing a Stirling or Brayton engine with an Otto or diesel engine. It is assumed that the vehicle is driven in a suburban cycle in a relatively lightly populated area, where average miles per day (AMPD) values are high (17,776 mi/year or

TABLE 4 Dependence of AMPD on Population Density and Other Factors, Model-Year 1975 GM Automobiles *(17)*

Selected Characteristics of Various Size Regions	Population (Owner Zip Code)[a] 25,000	25,000-999,999	≥1 million	U.S. Avg Sample-Weighted	VMT-Weighted
Percentage of cars in sample	48.0	47.6	4.4	NA	NA
Percentage of vehicle miles of travel[b]	66.3	27.3	6.4	NA	NA
AMPD	46.6	39.1	29.6	42.3	43.5
Standard deviation of AMPD	61.3	41.2	18.0	NA	NA
Average slip, road/EPA	0.90	0.86	0.80	0.87	0.88
AMPD versus vehicle weight (lb)					
3,000	40.9	31.3	28.1	35.9	37.5
4,000	44.8	36.6	29.1	40.2	41.6
5,000	48.7	41.9	30.0	44.5	45.6
AMPD versus engine displacement (in.^{3})					
150	42.3	34.3	23.1	37.9	38.9
250	44.5	36.8	26.2	40.2	41.2
350	46.8	39.3	29.4	42.4	43.6
Road mpg/EPA mpg					
10 (EPA)	0.92	0.86	0.80	0.89	0.90
15 (EPA)	0.89	0.83	0.78	0.85	0.87
20 (EPA)	0.86	0.81	0.76	0.83	0.84
27.5 (EPA)	0.82	0.77	0.74	0.79	0.80

Note: NA = not applicable; AMPD = average miles per day.
[a]As a rule, zip code regions with fewer residents are actually larger in area than those with many residents. Thus, the assumption that the low population of a zip code region means low population density is justified.
[b]Nationwide Personal Transportation Study, Report 7 *(17)*.

TABLE 5 Incremental Year-2000 Benefit/Cost Ratios for Innovative Engines in Large Automobiles Driven in a Suburban Cycle in Low-Density Areas

		Actual Fuel-Saving Benefit Versus Incremental Engine Cost for Correctly Projected Suburban-Cycle Use					Misestimated Fuel-Saving Benefit Versus Incremental Engine Cost for Incorrectly Assumed Combined-Cycle[a] Use				
			Very High Fuel Cost Versus		High Fuel Cost Versus			Very High Fuel Cost Versus		High Fuel Cost Versus	
Engine	Vehicle Cost (1975 $)	Mpg with Cold Start	Otto	Diesel	Otto	Diesel	Mpg with Cold Start	Otto	Diesel	Otto	Diesel
Otto	6,850	30.1	–	0.21[b]	–	0.59[b]	24.2	–	0.13[b]	–	0.36[b]
Diesel	7,443	42.6	4.72	–	1.69	–	39.6	7.53	–	2.79	–
Stirling	8,847	46.2	1.56	0.22	0.57	0.09	37.5	2.06	No benefits	1.07	No benefits
Brayton	8,553	49.9	2.14	0.73	0.80	0.32	35.5	2.20	No benefits	1.22	No benefits
Brayton (revised)[c]	8,164	49.9	2.78	1.12	1.03	0.49	35.5	2.85	No benefits	1.58	No benefits

Note: It is assumed that vehicle is driven 17,776 mi/yr or 48.7 AMPD (see Table 4).
[a]Combined-cycle mileage developed with a 7.5-mi urban trip, 10.2-mi suburban trip, 55 percent urban driving, and 45 percent suburban driving.
[b]Engine cost reduction benefits versus fuel cost increases.
[c]The Brayton engine is estimated to cost 2.5 times the Otto engine in the same car (15).

48.7 mi/day; see Table 4). Estimates in Tables 5 and 6 are based on the assumption that the vehicle is driven for 7 years and then scrapped (regardless of total mileage) and that future real dollars are discounted at a rate of 5 percent. The unrealistic but usefully illustrative assumption that the vehicle is driven the same number of miles in each year of its life is used. (This was judged to be a useful way to simplify approximation of estimates of present values of fuel savings. In reality, vehicles are driven longer but annual mileage declines.) Cold-start calculations are based on an assumption of four equal-length trips per day for suburban and city driving cycles, while EPA city and highway driving-cycle distances are used for combined-cycle estimates. The estimator of the value of innovative new, rather than advanced existing, engines is based on a ratio of the present value of the expected fuel savings to the additional cost that must be paid for the innovative new engines. The ratio should be greater than 1.00 if consumers are to buy the alternative engine. The high year-2000 fuel costs from the TAPCUT study are used ($2.53/gal for gasoline and $2.42/gal for diesel fuel in 1975 dollars), along with "low"--but still higher than current--gasoline and diesel fuel costs equal to $1.00/gal in 1975 dollars. In this study, these two price levels are referred to as "very high" and "high" fuel costs. Gasoline is used in the Otto cycle engine (at 115,400 Btu/gal), while diesel fuel is used in all other engines (at 127,200 Btu/gal). The frontal area of all large automobiles is 26 ft^2; for small automobiles it is 20 ft^2.

The first set of estimates in Table 5 is based on the assumption that a large vehicle is driven in a suburban cycle and its fuel economy is evaluated on the basis of suburban-cycle performance. Under this assumption, the advanced diesel has the highest benefit/cost ratio compared to the Otto engine; the ratio is greater than 1.0 regardless of whether high or low fuel cost is used. The question then is whether the Stirling or Brayton offers any other advantage over the diesel. The Brayton has the best suburban-cycle mileage of any of the engines, but its high cost reduces its benefit/cost ratio below 1.0 compared to the diesel. However, when fuel costs are very high, the ratio is close to 1.0. If the annual mileage of the large vehicle was 24,200, then the Brayton vehicle would be just as good an investment as the diesel. A market for a dependable, high-mileage Brayton vehicle could therefore develop in suburban and rural areas if fuel prices rise enough.

The TAPCUT engine cost equations may overestimate the cost of a Brayton engine. Volkswagen expected to be able to build a smaller Brayton than that in these large cars for 2.5 times the cost of an Otto-cycle engine (15). The TAPCUT estimates cause the Braytons of Table 5 to cost 3.6 times more than the Otto engine. If this ratio is reduced to 2.5, a Brayton vehicle becomes economically attractive with very high fuel costs if driven in an average low-density suburban pattern (17,776 mi/year).

The latter set of estimates in Table 5 shows how critical the consumer's estimating information can be. Since the Brayton has very poor urban-cycle mileage, a combined-cycle mileage figure lowers its "estimated mpg" by EPA-type methods (55 percent urban, 45 percent highway) so much that the suburban-driven large Brayton would be judged an unqualified loser compared to the advanced diesel. Yet these estimates would unfairly penalize an engine that, when used appropriately, could save fuel for consumers and the nation. Furthermore, such an estimating technique would retard efficiency-enhancing engine innovation when it was most needed (i.e., if fuel

TABLE 6 Incremental Year-2000 Benefit/Cost Ratios for Innovative Engines in Small Automobiles Driven in an Urban Cycle in High-Density Areas

		Actual Fuel-Saving Benefit Versus Incremental Engine Cost for Correctly Projected Urban-Cycle Use					Misestimated Fuel Saving Benefit Versus Incremental Engine Cost for Incorrectly Assumed Combined-Cycle[a] Use		
			Very High Fuel Cost Versus		High Fuel Cost Versus				
Engine	Vehicle Cost (1975 $)	Mpg with Cold Start	Otto	Diesel	Otto	Diesel	Mpg with Cold Start	Very High Fuel Cost Versus Otto	High Fuel Cost Versus Otto
Otto	4,005	31.1	–	0.30[b]	–	0.79[b]	35.4	–	–
Diesel	4,669	55.5	3.36	–	1.26	–	57.4	2.62	0.97
Stirling	5,720	47.8	1.06	No benefits	0.39	No benefits	NE[c]	NE	NE
Brayton	5,894	41.4	0.71	No benefits	0.25	No benefits	NE	NE	NE

Note: It is assumed that vehicle is driven 10,256 mi/yr or 28.1 AMPD (see Table 4).
[a]Combined-cycle mileage developed with a 7.5-mi urban trip, 10.2-mi suburban trip, 55 percent urban driving, and 45 percent suburban driving.
[b]Engine cost reduction benefits versus fuel cost increases.
[c]NE = not estimated.

prices reached very high levels). The suburban-driven large Stirling is economically squeezed between the diesel and the Brayton. If fuel prices are high enough to make a Stirling economically desirable compared to the advanced diesel, the Brayton will be even more attractive.

Table 6 compares year-2000 engines in small automobiles driven and evaluated on urban cycles in high-density regions where the automobile is driven only 28.1 mi/day, or 10,260 mi/year (see Table 4). In this situation, the Stirling and Brayton engines are simply not desirable when compared with the diesel. They cost more and get worse mileage than the diesel, making them unqualified losers by these criteria. With the TAPCUT characteristics, neither of these engines is destined to take over the urban automotive market on the basis of fuel consumption economics alone. The diesel looks good even when fuel costs in the year 2000 are $1.00/gal in 1975 dollars ($1.73 in 1983 dollars). Its benefit/cost ratio exceeds 1.0 in both cases, but it is close to 1.0 in the high-fuel-cost case. Interestingly, the diesel would not be attractive at 1985 fuel prices, which is consistent with the weak 1985 market for diesels. If the diesel is ruled out on environmental grounds, the Stirling would be a better urban alternative than the Brayton, but it would only be a desirable innovation relative to the Otto engine if fuel costs rose to a very high level.

The last two columns of Table 6 illustrate that the averaging problem inherent in the "combined" EPA fuel economy and corporate average fuel economy (CAFE) ratings could retard the urban adoption of diesel engines. If engines are driven in an urban pattern but are evaluated using a combined rating, the incremental benefit/cost ratio of the diesel drops. In the high-fuel-cost case, the ratio drops 23 percent, enough to bring the ratio below 1.0. This would make consumers evaluate the diesel as a loser even though they could save fuel and money by using this engine in an urban setting.

Taken together, the results of the calculations presented in these tables suggest that the efforts by EPA to present separate, realistic estimates of expected city and highway mpg are of great value in helping consumers to make an economically efficient engine choice for their vehicle. However, reliance on the current CAFE estimating method, with its statistical fiction that vehicles are driven 55 percent in city use and 45 percent in highway use regardless of vehicle type or ownership location, might someday lead to disincentives toward engine innovation on the part of producers. If a producer knows that a Brayton-powered vehicle can get high enough mileage in suburban and rural use to make the added engine expenditure worthwhile to those consumers, but at the same time expects to be penalized on his CAFE ratings because EPA assumes that the vehicles will be used differently, what will the producer do? Given the likely long period before fuel prices rise enough to make this question important, there is probably enough time for policymakers to consider it carefully.

CONCLUSION

It has been shown that the Brayton and Stirling engines are likely to have very well defined, limited, but nevertheless significant, markets. It is important to verify this analysis so that it may be used as a framework to define research and policy changes that can lead to successful and timely introduction of the Brayton and/or Stirling engines when and if fuel and environmental market conditions make them desirable.

This research tends to support established directions in Stirling and Brayton engine research. Because these engines are long-term technological options and are suitable for a limited market, they are not likely to get adequate R&D support from the private sector alone. From the national point of view, these are technologies that, it is hoped, will never be needed, but if conditions arise that make them desirable (i.e., a return of high fuel prices or unacceptable urban pollution, or both), it would be good to have them "on the shelf." These are technologies that could offer a high payoff to the nation in very high national risk situations that have a low probability of occurring in any one year in the near- or medium-term future. However, it can be argued that these events have a high probability of occurring in some future year. It is generally recognized that this defines an area in which basic government R&D is appropriate and necessary. If that is not enough, the macroeconomic penalities implied to exist for a nation that fails to plan ahead for its engine technology transitions should encourage advanced government preparation for the inevitable next transition.

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A Quick Assessment of Local Area Impacts Resulting from National Energy Shortages

MARTHA E. HENNIGAN and ALFRED J. NEVEU

ABSTRACT

A method to aid in estimating the local area impacts of national energy shortages is presented. Using data from the 1977 Nationwide Personal Transportation Study and forecasting models developed in NCHRP Report 229, the study examines the potential travel impacts of fuel shortages in six different-sized urban areas under seven different energy future scenarios. These scenarios are defined by fuel supply shortfall, by government actions taken to offset this shortfall, and by whether long-range conservation actions are taken by the public. The study found that the most effective actions for reducing fuel use were long-range conservation actions such as moving closer to work or buying a more fuel-efficient automobile. In the absence of a fuel shortage, the 1990 scenario with long-range actions showed a decline in fuel use from 1980 of 13 to 15 percent, while the 1990 scenario without these actions showed a decline in fuel use of only 2 to 4 percent. The most effective type of transportation system management (TSM) actions for reducing fuel use are those that discourage solo driving. In addition, there is a significant difference in the amount of fuel saved by work versus nonwork TSM actions in future scenarios that do not contain long-range adjustments. However, in future scenarios with long-range adjustments, the amount of fuel saved by work versus nonwork travel becomes more of an even split. Smaller-sized urban areas will be affected the most by future energy shortages because of lack of available transit and fewer opportunities for carpooling. The impact of long-range actions on fuel use is greater in these areas because of a greater proportion of automobile travel. However, this does not fully compensate for the reduced availability of alternatives to automobile use in these areas.

The two energy crises of the 1970s highlighted the need for methods to incorporate energy considerations into travel forecasting procedures. It became evident during these fuel shortages that disruptions in energy supply were an eventuality that transportation planners should consider in their estimates of future travel needs.

At the same time, it also became evident that urban areas were affected differently by supply shortfalls and that consumers chose certain transportation-related actions over others to adapt to crisis conditions (1,2). The different reactions to fuel shortages were due to a variety of factors, for example, region of the nation, population, geographic characteristics, transportation options, and season of the year.

This study had three goals. First, a procedure was developed to aid local planners in predicting the travel impacts of potential energy shortfalls in their areas. Second, the study analyzed the effectiveness of some general actions the government could take to alleviate some of the travel disruptions due to any fuel shortages. Finally, the effectiveness of several long-term actions that could be adopted by the public to reduce fuel demand was examined.

In the following sections the models used in the study are described, the various future energy scenarios are defined, and the data used in the analysis are discussed.

METHODOLOGY

The methodology used in this paper is a version of the model developed by Charles River Associates in NCHRP Report 229 (3). Although the method is identical to the NCHRP procedure for incorporating energy considerations into travel forecasts, this analysis differs from that found in NCHRP Report 229 in two ways. The definitions of the future scenarios are changed, and the analysis is performed on several urban area types using actual instead of hypothetical data. These data were derived from the 1977 Nationwide Personal Transportation Study (NPTS).

Work Trip Model

The work trip model is an incremental logit model that forecasts new mode shares based on modifying the base mode shares by changes in three independent variables: trip cost, in-vehicle travel time, and out-of-vehicle travel time. Trip cost includes gasoline-related costs as well as out-of-pocket costs such as tires and maintenance. In-vehicle travel time includes line-haul time as well as wait time in minutes. Out-of-vehicle travel time is the walk time for each mode in minutes.

In order to reduce the bias that results from aggregation, work trip makers in the data set are divided into the following six traveler classes, based on mode choice set and trip length:

1. Full choice set--long trip,
2. Full choice set--short trip,
3. Drive alone/shared ride--long trip,
4. Drive alone/shared ride--short trip,
5. Shared ride/transit--long trip, and
6. Shared ride/transit--short trip.

A long trip is any work trip that falls above the mean work trip distance for the entire data set and a short trip is any work trip that falls below the mean.

The formula for creating the new mode shares is as follows:

$$MS_{ij}^{N} = MS_{ij}^{B} \exp(\Delta V_{ij}) / \sum_{k} MS_{kj}^{B} \exp(\Delta V_{kj})$$

$$\Delta V_{ij} = a_1(X_{ij1}^{N} - X_{ij1}^{B}) + a_2(X_{ij2}^{N} - X_{ij2}^{B}) + \ldots a_{\ell}(X_{ij\ell}^{N} - X_{ij\ell}^{B}) \quad (1)$$

where

MS_{ij}^{N} = forecast share for the ith mode and the jth class,
MS_{ij}^{B} = base share for the ith mode and the jth class,
$X_{ij\ell}^{N}$ = value of the ℓth independent variable for the ith mode and the jth class for the forecast period,
$X_{ij\ell}^{B}$ = corresponding variable for the base period, and
a_{ℓ} = coefficient of that variable.

The number of automobile vehicle miles of travel (VMT) is calculated by multiplying the new mode share percentage in each class by the number of trips in that class. This number is then multiplied by the trip length. The shared-ride classes are divided by the average occupancy of the vehicle to get VMT. The formula to calculate VMT is as follows:

$$VMT = \sum_{j=1}^{6} [(MS_{Dj}^{N} T_{Dj} TL_{Dj} + MS_{Sj}^{N} T_{Dj} TL_{Sj})/LF_S] \quad (2)$$

where

D = drive alone,
S = shared ride,
T = number of trips,
TL = trip length, and
LF = average vehicle occupancy.

Automobile fuel consumption is calculated by dividing VMT by the average fuel efficiency of the private vehicle fleet.

The formula for bus miles of travel is identical to the automobile VMT formula except that transit mode share is used.

$$BMT = \sum_{j=1}^{6} MS_{Tj}^{N} T_{Tj} TL_{Tj}/LF_T \quad (3)$$

Transit fuel consumption is calculated by dividing bus miles of travel by the average fuel efficiency of the transit vehicle.

The outputs of the model produce automobile and transit VMT and fuel consumption rates. Average daily automobile and transit trips can also be derived from the model.

Nonwork Trip Model

The model used to estimate nonwork trips and fuel use is a simultaneous linear equation model. It is also used in an incremental form. The two equations in the model predict household nonwork VMT for a 4-day period and nonwork transit trips for the same time period. These predictions must be divided by 4 to yield daily estimates and to be compatible with the work model results.

A set of 13 independent variables is used in the

TABLE 1 Nonwork Models

	Coefficient	
Variable	Automobile VMT	Transit Trips
TMMI	-7.838	-0.009959
TDOL	-0.2422	–
GDOL	-51.01	–
PPL	-14.128	0.7877
URBAN	-3.394	–
SMSA	-2.897	–
PLACE	-1.979	–
LICD	15.14	–
PKAV	-20.04	–
TTIME	0.2414	–
TAV	-41.38	1.707
HDOL	0.0007728	-0.00003188
HHSIZE	9.022	-0.3722

two equations. Each model is presented in Table 1. The variable definitions are as follows:

- TMMI: average travel time per mile for an automobile nonwork trip by a household, in minutes per mile.
- TDOL: average travel time per mile for a nonwork automobile trip by a household multiplied by the household wage per minute, in cents per mile. (Household wage per minute is household annual income in dollars divided by 120,000 min and converted to cents.)
- GDOL: average gasoline price per mile of a nonwork automobile trip for a household divided by the household wage per minute, in minutes per mile. (See note in previous entry.)
- PPL: number of household members aged 5 or older.
- URBAN: coded variable indicating population of urban area [(3), Table 7].
- SMSA: coded variable indicating population of a standard metropolitan statistical area (SMSA) [(3), Table 7].
- PLACE: coded variable indicating population of place of household residence.
- LICD: total number of licensed drivers in the household.
- PKAV: fraction of household's nonwork automobile trips for which free parking was available.
- TTIME: average travel time for a nonwork transit trip by a household.
- TAV: fraction of a household's nonwork automobile and transit trips for which transit is available within six blocks.
- HDOL: household income in dollars per year.
- HHSIZE: total number of household members.

To apply the equations, changes in each of the independent variables between the base and future years are multiplied by their respective coefficients and summed to calculate the change in the dependent variable (either 4-day household VMT or transit trips). These changes in the dependent variable are then added to the base year values to produce the future estimates. The general equations are as follows:

$$\Delta\text{VMT} = \Sigma a_i \, \Delta X_i \quad (4)$$

$$\Delta\text{transit trips} = \Sigma b_i \, \Delta Y_i \quad (5)$$

$$\text{Future VMT} = \text{base VMT} + \Delta\text{VMT} \quad (6)$$

$$\text{Future transit trips} = \text{base transit trips} + \Delta\text{transit trips} \quad (7)$$

Automobile fuel consumption is obtained by dividing VMT by average vehicle fuel efficiency. To get transit VMT, transit trips per household are multiplied by the number of households in the SMSA group and divided by 4 to get areawide ridership. Areawide ridership is then multiplied by a transit mile-per-trip factor to get bus miles of travel. Transit fuel consumption is then estimated by dividing bus miles by average transit vehicle fuel economy. A more detailed discussion of the models can be found in either NCHRP Report 229 (3) or the report by Hennigan and Neveu (4).

Definition of Urban Area Sizes

Several different area types defined by population size were investigated. Population is used to represent transit system availability as well. The larger areas will generally have larger transit systems, denser cores, and longer commuting distances. Table 2 shows the SMSA size groupings used in this study.

TABLE 2 Urban Area Sizes

Type	Population Range
Small	Under 100,000
Small to medium	100,000–249,999
Medium	250,000–499,999
Medium to large	500,000–999,999
Large	1,000,000–2,999,999
Very large	3,000,000 and over

Definition of Future Scenarios

The various energy scenarios used in this study are listed in Table 3. The base year for the analysis is 1980, which represents current travel and demographic conditions for the six city sizes.

Several future energy scenarios for 1990 are used, covering a wide range of possible situations. These scenarios are defined in terms of supply shortfall and duration, government actions taken to offset the shortfall, and whether long-range conservation actions are taken. Three shortfall levels are considered: 5, 15, and 20 percent. These shortages are assumed to last from 3 to 6 months, which was the approximate length of the previous two crises. A shortage of longer duration would begin to affect the household's long-term decisions, and an analysis of that type of situation is beyond the scope of this study.

The reduction in energy supply resulting from shortfall conditions is represented in both the work and nonwork models as an increase in gasoline price. This increase translates into increased trip costs. The following formula is used to calculate the new gasoline price resulting from a fuel shortage:

$$P_s = P_n \, [1 - (s/\eta)] \quad (8)$$

where

P_s = shortfall price,
P_n = nonshortfall price,
s = shortfall level (e.g., 5, 15, or 20 percent expressed as a decimal), and
η = price elasticity of gasoline (assumed to be -0.2).

The first of the 1990 future scenarios is termed the "1990 Null" scenario. This scenario represents the future travel and demographic characteristics of the various city types under a condition of no fuel supply shortage. The areas are assumed to grow, following the historic trends for each of the variables

TABLE 3 Scenario Definitions

Type	Supply Shortage (%)	Fuel Price (cents/gal)	Automobile Mpg	Government Action	Long-Range Actions[a]
Base (1980)	–	99.27	15	–	No
1990 Null	–	134.4	17.7	–	No
1990 Price	5, 15, 20	168, 235, 268.8	17.7	Price only	No
1990 TSM1	5, 15, 20	168, 235, 268.8	17.7	Nonrestrictive TSM (transit/carpool incentive)	No
1990 TSM2	5, 15, 20	168, 235, 268.8	17.7	Restrictive TSM (automobile disincentives)	No
1990 Null with LRA	–	134.4	20.2	–	Yes
1990 Price with LRA	5, 15, 20	168, 235, 268.8	20.2	Price only	Yes
1990 TSM1 with LRA	5, 15, 20	168, 235, 268.8	20.2	Nonrestrictive TSM (carpool/transit incentives)	Yes
1990 TSM2 with LRA	5, 15, 20	168, 235, 268.8	20.2	Restrictive TSM (automobile disincentives)	Yes

Note: TSM = transportation systems management, LRA = long range adjustments
[a]Long-range actions are defined as a rise in average fleet efficiency to 20.2 mpg and a shift of 5 percent of long work trips to short work trips.

used in the work and nonwork models. This is used as the baseline against which the other 1990 scenarios are measured. In this fashion, national VMT and fuel use increases can be accounted for, and a better estimate of the effectiveness of the various government and long-term actions can be derived.

Three types of government actions aimed at alleviating the fuel shortage are used. The first of these actions is really no action at all, but simply to let the price of gasoline reach the market clearing level, which is the price that causes demand to decrease by the amount of the shortage. This is called the "1990 Price" scenario and would occur under current decontrolled market conditions.

The second type of government action is a set of nonrestrictive transportation systems management (TSM) actions (1990 TSM1), which is generally a package of incentives to use more efficient means of travel. The nonrestrictive TSM actions used in this analysis are free tolls for carpools, bus priority treatment at intersections, and exclusive bus lanes. The use of these actions is reflected in the model by changes in the input variables. Because no tolls were indicated for automobile trips in the NPTS data, the free tolls for carpool action had no effect on the inputs used in this analysis.

The third type of government action is a restrictive one that comprises TSM disincentives (1990 TSM2). The restrictive TSM actions used in this analysis are a parking surcharge in the central business district (CBD) and reduced on-street parking near employment centers.

It should also be noted that the effects of one future scenario carry over to the next. In other words, the high price of gasoline in the 1990 Price scenario is also found in the nonrestrictive TSM scenario and nonrestrictive actions are found in the scenario with restrictive TSM actions. Government actions thus have a cumulative effect across the future scenarios.

The last set of future energy scenarios is identical to the first set, differing only in that it is assumed that the public has adopted some long-term conservation action to help reduce fuel demand. It is assumed in these scenarios that people react to past energy shortages, or to concern for future ones, by making major adjustments. These conservation adjustments are reflected in shorter work trips resulting from moving closer to work and higher fuel efficiencies resulting from buying a more fuel-efficient automobile.

The 1990 Null, Price, TSM1, and TSM2 future scenarios with long-range adjustments are identical to the future scenarios without long-range adjustments except that 5 percent of long work trips are shifted to short work trips and automobile fuel efficiency is increased to 20.2 mpg. The changes in nonwork travel as a result of making long-range adjustments are reflected in increased automobile fuel efficiency only.

FINDINGS

The results of tests for three different shortfall levels in six different area sizes provide insight into which city types will be most affected by future shortage conditions, what impacts government policies will have on travel under such conditions, and what impacts long-range conservation adjustments will have on travel under such conditions.

A comparison of the two 1990 Null scenarios to the base year (1980) is shown in Table 4 (figures in the table are expressed as percentages). Without long-range adjustments made by the public (buying a more fuel-efficient automobile and moving closer to work), fuel use drops by 2 to 16 percent. This is primarily due to the natural increase in automobile fleet fuel efficiency. With long-range adjustments made by the public, the fuel reduction increases significantly to the 12 to 25 percent range. The major factor behind the increased fuel use reduction is the acceleration of fleet turnover implied by increasing the efficiency of the automobile fleet above the natural increase. Although this is not a government action taken in response to a short-term fuel shortage, any program that would keep the pressure on increasing fuel efficiency could limit the public hardship of a fuel supply reduction.

TABLE 4 Fuel Use Changes from 1980

Scenario	Percent by Urban Area Size: Small	Medium to Small	Medium	Medium to Large	Large	Very Large
1990 Null	-2.0	-2.7	-2.1	-2.6	-3.9	-15.6
1990 Null with long-range adjustments	-13.7	-14.0	-13.6	-14.1	-15.2	-24.8

The base and future total fuel usage in each SMSA group at the 15 percent shortfall level are shown in Figures 1 through 6. The results for the 5 and 20 percent shortfalls are not shown because the pattern is basically the same.

In Figures 1 through 6 the bars represent the amount of fuel used under each future scenario, including both work and nonwork travel. The 1990 Null scenario is shown to facilitate the fuel use comparison. The horizontal line across the bars represents the amount of fuel available given a 15 percent shortfall from the 1990 Null level. If the fuel use bars fall below this line, this indicates that, under these scenarios, the demand for fuel does not exceed the supply. In cases where the bars are higher than the horizontal line, the demand for fuel exceeds the supply.

Figures 1 through 6 indicate some interesting results when various city sizes are compared. In the smaller cities (Figure 1), some sort of government action is required to reduce fuel use below the shortfall supply level when no long-range conservation actions are taken by the public. Market forces

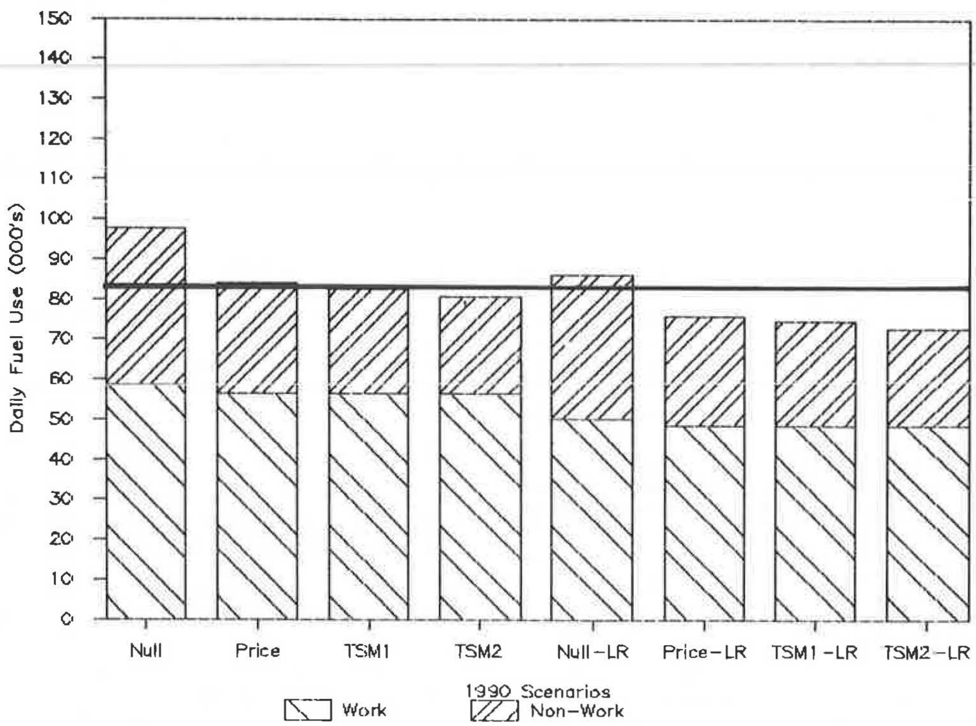

FIGURE 1 Small cities (under 100,000).

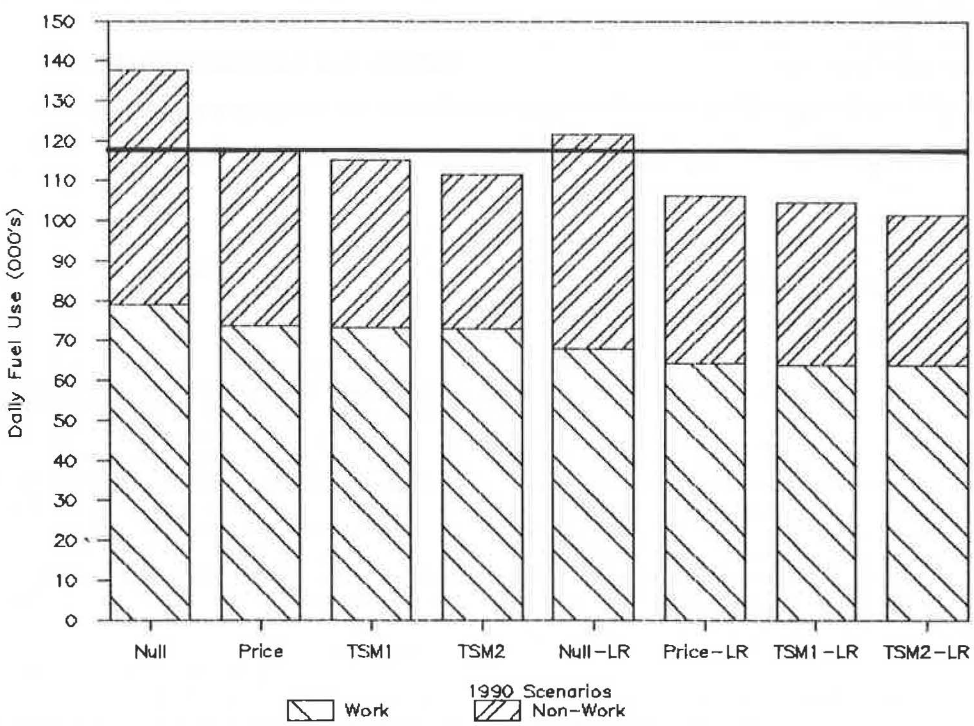

FIGURE 2 Medium to small cities (100,000 to 249,000).

are not quite effective enough. Both TSM strategies reduce fuel use below the shortfall level.

In the larger urban areas, the relative contribution of work and nonwork travel to reductions in fuel use approaches a 50-50 split. Work travel assumes a much larger burden of the fuel savings needed in the larger urban areas.

It is useful to compare the results of this analysis with what happened in the previous two energy crises in terms of shortfall level, fuel consumption, and travel impacts to determine how closely these results compare with how the public actually responded to shortfall situations. However, it should be noted that no widespread, mandatory government actions were taken during the previous two crises that can be associated with the potential shortfall

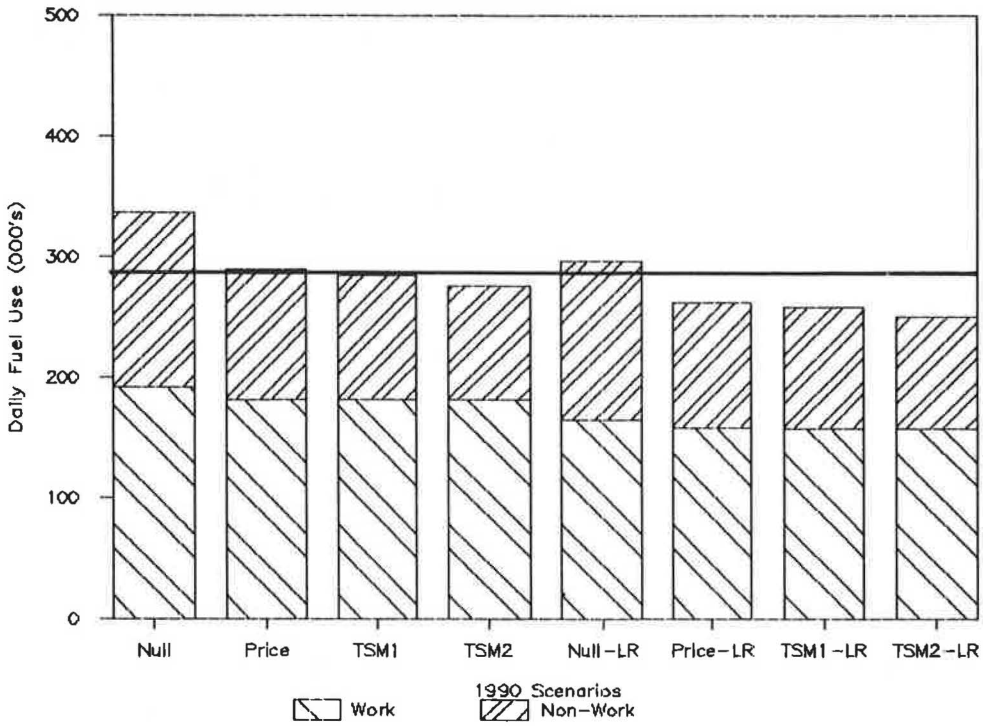

FIGURE 3 Medium cities (250,000 to 499,999).

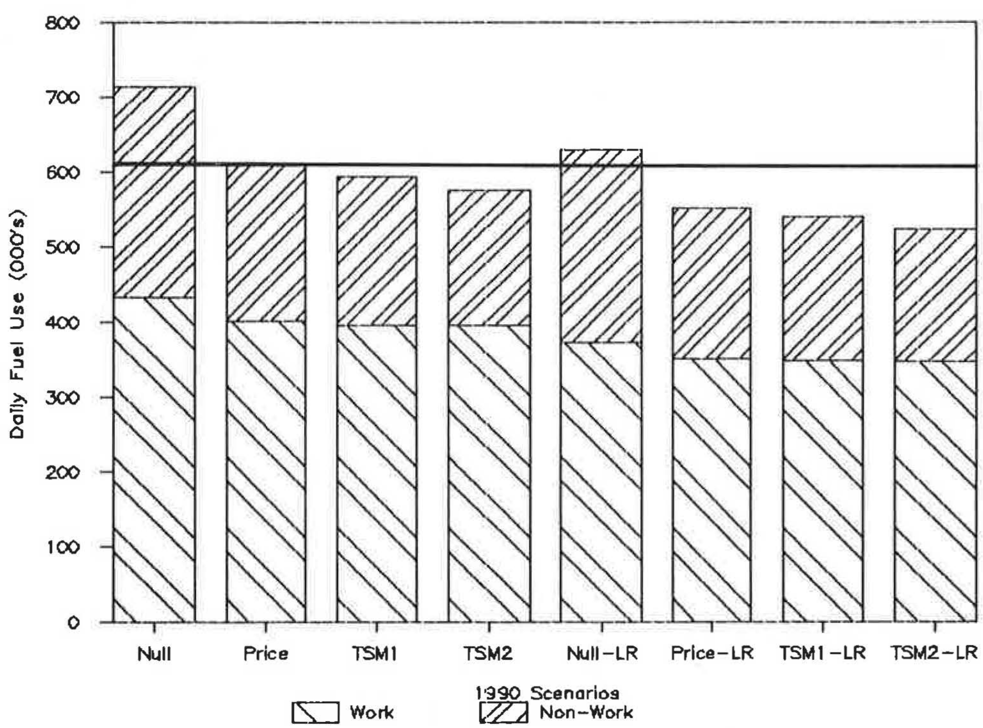

FIGURE 4 Medium to large cities (500,000 to 999,999).

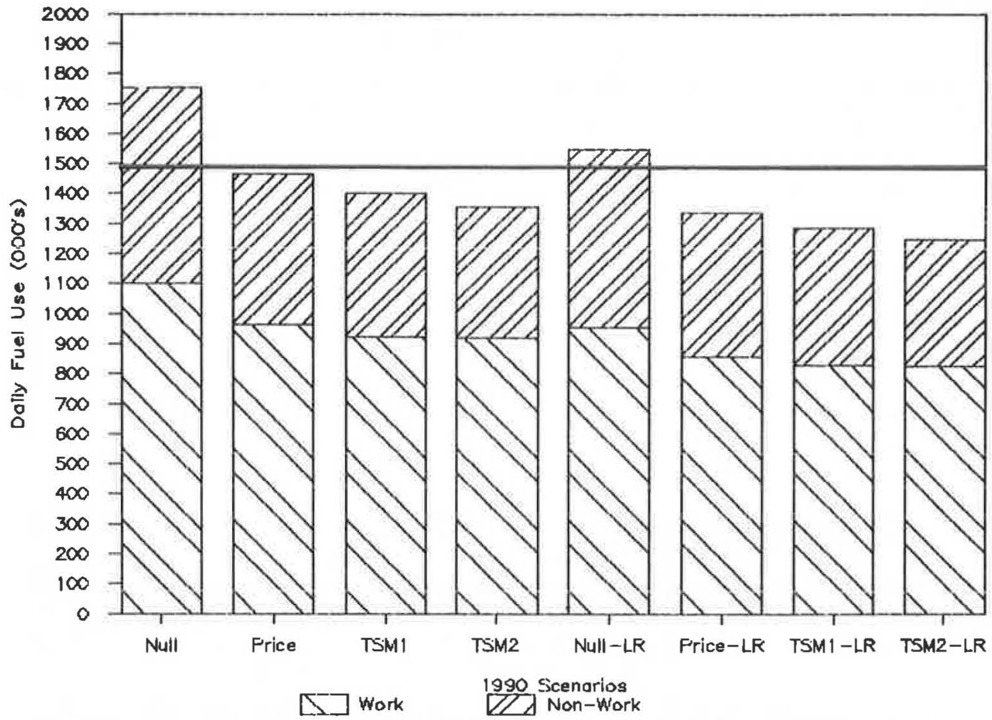

FIGURE 5 Large cities (1,000,000 to 2,999,999).

situations. There were instances of odd-even rationing and dollar limits on the sale of gasoline, but these occurred mainly in the areas with the greatest supply problems.

The effects of the 1973 to 1974 and 1979 crises can be seen in the following table (5, Table MFG-33; 6):

Percent Change	1974	1979
Fuel use	-8.2	-6.0
VMT	-6.0	-4.3
Fuel use	-4.0 (annual)	-3.4 (annual)

The gasoline shortfall and VMT reduction figures represent peak quarterly percentage changes from the year before. The fuel use values represent overall annual percentage changes from the previous year. These figures are compared with the work and nonwork results summed from the potential shortfall scenarios that are summarized as follows:

	Percent Shortage		
	5	15	20
Automobile fuel use	-5 to -15	-15 to -30	-20 to -40

As can be seen, the impacts of the potential shortfalls if long-range actions are not taken are similar to the impacts of the previous two fuel crises at the 5 percent level.

The difference between the results from the previous two crises and the results from the potential shortfalls becomes greater as the shortfall level increases. This is to be expected because the previous two crises did not reach nationwide shortfall levels of 15 and 20 percent. In addition, because the potential shortfalls include widespread institution of government actions to offset the shortages, one can expect a greater impact on VMT, fuel use, and transit ridership.

CONCLUSIONS

In this paper a procedure is presented to be used by local planners to predict the travel impacts of potential energy shortfalls in a given area. The most important conclusions to be drawn from this analysis deal with the following four questions:

1. Areas of what size will be most affected by future shortage conditions?
2. What government policies will be most effective in alleviating crisis conditions?
3. What impacts will long-range conservation actions have on travel under energy shortfalls?
4. What will be the roles of work and nonwork travel under future shortage conditions?

In regard to the first question, it was found that the smaller the size of the area, the greater the impact future crises will have on that area. This is because there are fewer opportunities for transit and carpooling in smaller areas. However, it was also found that because small areas have proportionally more automobile travel, there is more potential for fuel savings to result from long-term conservation actions such as moving closer to work or buying a more fuel-efficient automobile.

Another finding for smaller-sized SMSAs is that when long-range conservation actions are not taken, TSM actions targeted for work travel alone will not be successful in reducing fuel use enough to alleviate crisis conditions. However, nonwork-related TSM actions reduce fuel use enough to compensate for supply shortfalls.

Larger areas with a population of over 1 million will not be as severely affected by future energy crises. In these areas, work-related TSM actions alone are able to cause fuel use reductions that could alleviate crisis conditions. These larger areas tend to have significantly more opportunities for transit and enough commuter congestion to encourage carpooling.

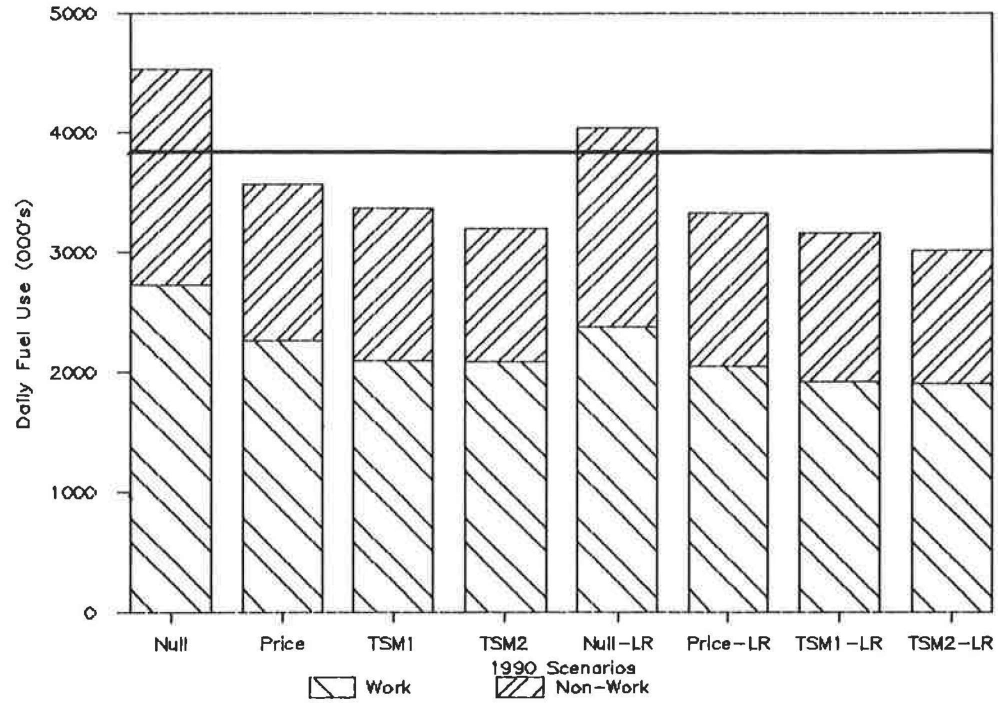

FIGURE 6 Very large cities (over 3,000,000).

In regard to the second question, the government policies that are most effective in alleviating crisis conditions are the nonrestrictive and restrictive TSM policies. Restrictive policies have the most effect on reducing fuel consumption. However, they may overcompensate for the lack of supply and may not be necessary. The nonrestrictive TSM actions are effective in reducing fuel demand and present a less painful way to conserve, thus making them more attractive to consumers.

The third group of conclusions to be drawn from this paper concerns what impacts long-range conservation adjustments will have on travel under shortfall conditions. Long-range conservation adjustments such as buying a more fuel-efficient automobile or moving closer to work reduce fuel use significantly in and of themselves. In addition, once these adjustments are combined with TSM actions in a crisis situation, they provide the greatest fuel-savings capability of all the scenarios examined in this paper. It should also be noted that long-range conservation actions, by virtue of causing a more rapid rate of fleet turnover, may help prevent future crises by reducing the demand for fuel.

The final conclusion to be drawn from this paper concerns the roles of work and nonwork travel under shortfall conditions. The greatest reductions in fuel use under the future scenarios used in this analysis were realized by TSM actions targeted at nonwork travel in future scenarios with and without long-range actions. However, in cities with a population of over 1 million, the fuel savings due to work and nonwork travel actions becomes more evenly distributed.

In addition, there may be more of a shift in the future to work-related conservation actions in smaller areas if the trend of the availability of more fuel-efficient automobiles continues. This is because substantial savings in fuel used in work travel can be realized by using a fuel-efficient automobile, and once such an action has been taken, the TSM actions that have been most effective in reducing nonwork fuel use may become less important.

The model presented here is not without its problems, primarily on the transit side where transit system size should be considered and where a shortfall level variable should be included for nonwork trips. On the other hand, one must consider that transit is not the mode of choice in a crisis situation. Studies have shown that most consumers responded to the previous crises by taking automobile-related actions (2,7).

Therefore, the automobile side of the model is perhaps more important because it provides a reasonable method for calculating VMT and the effect of supply shortages on fuel use. It also produces results that are in the range of those found in previous crises. By far the most important aspect of this analysis is that it presents a procedure for local planners to estimate the effects of a given shortfall level on their particular areas. The fact that the model is data-intensive and that these data may be available only in national averages or default values is a drawback. However, the results of this study provide some insights that should prove useful to local planners facing future energy shortages.

When long-range actions are taken by the public, the situation brightens somewhat. In this case, government actions will not be required to reduce fuel demand below the shortfall level. Price increases due to the supply shortfall provide the impetus to reduce fuel demand below the shortfall level.

Looking at the very large cities (Figure 6), a different pattern of fuel savings emerges. In these cities, market forces are more than sufficient to reduce fuel demand. In fact, significant fuel savings result when fuel prices rise to the shortage-induced level.

Long-range conservation actions can play an important role in the larger cities. The impact of the fuel shortfall is alleviated somewhat if these long-range conservation actions are taken by the driving public. Although these are not government actions, special care should be taken to ensure that other

TABLE 5 Fuel Savings by Work and Nonwork Travel During a 15 Percent Fuel Shortage

	Urban Area Size					
Scenario	Small	Medium to Small	Medium	Medium to Large	Large	Very Large
Work						
Price	16	25	21	31	47	48
Nonrestrictive TSM	14	25	20	31	50	54
Restrictive TSM	12	22	17	27	45	48
Null/long-range	73	68	68	71	72	71
Price/long-range	45	46	45	51	58	56
Nonrestrictive TSM/ long-range	43	45	43	49	58	59
Restrictive TSM/ long-range	40	41	39	45	54	54
Nonwork						
Price	84	75	79	69	53	52
Nonrestrictive TSM	86	75	80	69	50	46
Restrictive TSM	88	78	83	73	55	52
Null/long-range	27	32	32	29	28	29
Price only/long-range	55	54	55	50	42	44
Nonrestrictive TSM/ long-range	57	55	57	51	42	41
Restrictive TSM/ long-range	60	59	61	55	46	46

Note: Values in the table are expressed as percentages.

government policies do not adversely affect these consumer responses.

The relative contribution of work and nonwork travel to overall fuel savings also varies by city size. Table 5 lists the percentage of fuel savings attributable to work and nonwork travel for each city size for all scenarios with a 15 percent fuel shortfall. (Again, the other shortfall levels yield similar results.) In the smaller cities, work travel provides a small portion of total fuel savings. In fact, by examining the earlier figure, it can be seen that work travel actually changes very little under the various energy future scenarios for the small urban areas. Long-range conservation adjustments affect work travel fuel demand significantly, but government actions taken after these long-range strategies are adopted do not affect work travel to a great degree.

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Defining Relationships Between Urban Form and Travel Energy

KWANG-SIK KIM and J. B. SCHNEIDER

ABSTRACT

The objective of this study was to define some of the relationships between urban form and transportation energy consumption. Such knowledge should be useful in generating and evaluating alternative plans for guiding the future development of metropolitan areas. A three-part approach was designed to attain this objective. First, a land use/transportation simulation model and a spatial statistics software package were obtained in order to make quantitative measures of urban form and associated travel requirements. Second, a number of experimental cities were designed with simulated travel requirements. Various urban form measures and associated travel measures (including transportation energy consumption) of these cities were computed by the statistics package and the simulation model. Third, these measures were interpreted and analyzed to test the main hypothesis of this study: the less centralized the urban form, the greater the travel distances between home and various destinations and thus the greater the city's transportation energy consumption.

In this study two computer programs were used to investigate the relationships between urban form and energy consumption in passenger transportation: the MOD3 simulation model and the Urban Form Statistics (UFSTAT) program. The MOD3 model, developed by Peskin and Schofer (1), is a large-scale computer program used to simulate the effects of alternative transportation and land use policies, such as those aimed at reducing transportation energy consumption. By simulating the travel requirements of a particular urban form, the MOD3 model can calculate a variety of transportation performance measures such as total vehicle miles traveled, level of congestion, transit ridership, and average trip length, and determine the total energy requirements resulting from work and nonwork passenger travel.

The conceptual structure of the MOD3 model is shown in Figure 1. It consists of four major submodels: a Lowry-type land use model, a binary logit modal choice model, a capacity-restrained equilibrium assignment model, and a transportation energy consumption model. The Lowry-type model locates residence and service employment given the structure of the transportation network, descriptors of urban travel behavior such as travel time and cost, and the location of basic employment. Using a gravity model concept, the model locates population on the basis of accessibility to basic employment. The gravity concept causes locations close to employment to be more desirable than those more distant, resulting in higher densities near employment locations. Service employment locations are based on accessibility to population, so the model has to be iterated through several cycles before it arrives at a spatial distribution of activities that is in equilibrium. The Lowry-type model predicts work trips by distributing workers to home sites and service employees to work sites using travel impedance factors. The work trip estimate is split between automobile and transit based on free-flow travel times and the dollar costs of travel. Automobile trips are assigned to the highway network using a capacity-restrained equilibrium assignment algorithm

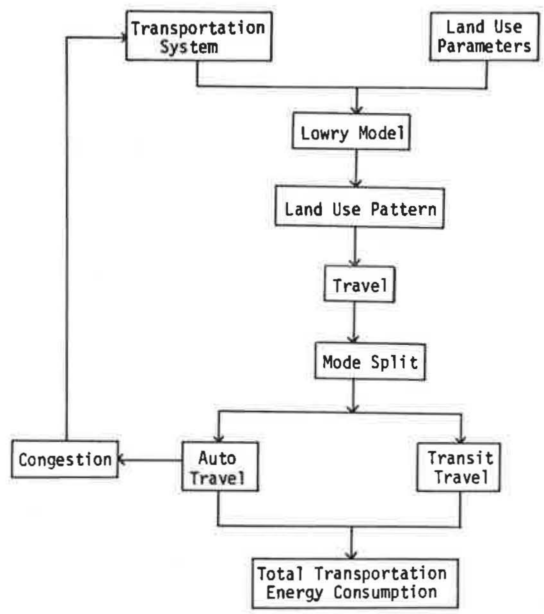

FIGURE 1 Conceptual structure of MOD3 model.

that explicitly considers congestion. The energy consumption of each vehicle on each link of the network is then summed to compute the total energy required for transportation. This process is repeated until an equilibrium between transportation and land use is reached, or, in other words, until differences between iterations become suitably small.

The UFSTAT program, initially developed by Schneider et al. (2), was designed to calculate various urban form measures. UFSTAT computes 57 urban form measures grouped into six categories: the Lorenz curve and derived measures; Bachi measures; centrographic and related measures; and potential, aggregate travel, and density gradient measures.

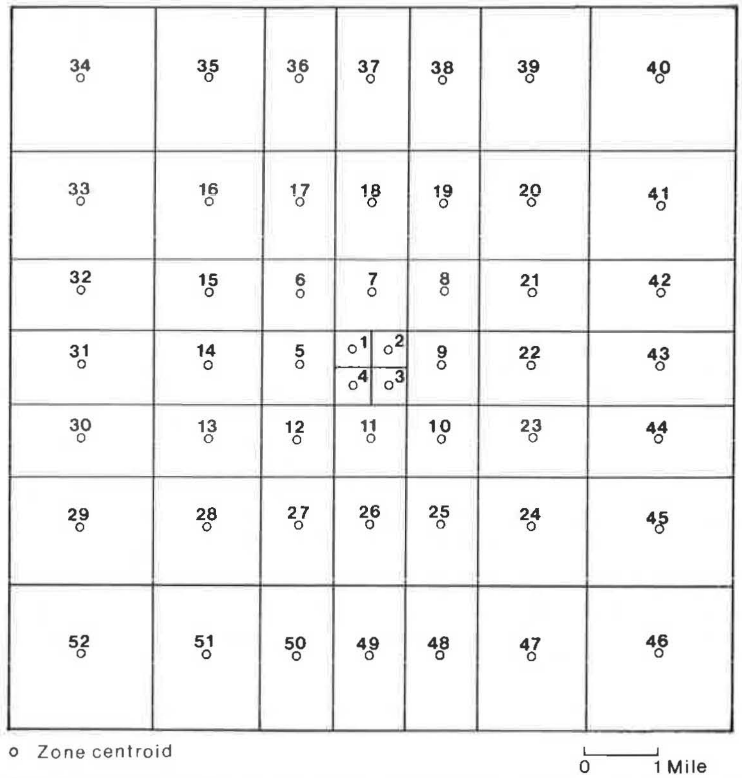

FIGURE 2 Geographic structure of the hypothetical city.

Some of these measures describe the degree of concentration of population, employment, or other attributes in an urban area. Others measure the degree of dispersion, the mean and standard distance from a central point, the directional tendency of the distribution, the shape of the distribution, and the slope of the density gradient. The mathematical definitions of the urban form measures are discussed elsewhere (3).

EXPERIMENTAL DESIGN

A hypothetical test city was used as a base for various experiments. The basic attributes of this test city were constructed from the urban transportation studies and land use plans of several American cities. The selection of a small hypothetical city for the experiments was based on several factors. First, by avoiding the complexities of a large metropolitan area, data requirements and computational difficulties are reduced considerably. Second, a smaller city model allows all the policies to be simulated in a realistic environment and also allows for a thorough analysis of the results. Finally, it is possible to isolate the effects of one or more independent variables on a dependent variable, thus allowing direct inferences to be made about relationships between the two.

The test city is composed of 52 zones arranged in a square 10 mi on each side (see Figure 2). It consists of a central business district (CBD) with an area of 1 mi^2 divided into four zones. Three additional rings of zones surround the CBD, resulting in a grid pattern. Zone sizes increase progressively toward the periphery in a symmetrical manner. The population is 100,000 and includes 15,000 employees in basic industries (out of a total employment of 40,000) for the base run of the MOD3 model. Given

0	0	0	0	0	0	0
0	460	305	305	305	460	0
0	305	1000	1000	1000	305	0
0	305	1000	375 375 375 375	1000	305	0
0	305	1000	1000	1000	305	0
0	460	305	305	305	460	0
0	0	0	0	0	0	0

FIGURE 3 Basic employment distribution pattern for the base case.

the location of basic employment, the model allocates population and service employment among the zones. Figures 3, 4, and 5 show the locations of basic and total employment and population, respectively, for the base case. It should be noted that, by virtue of the city structure and the assumptions in the model, the base-case city is quite centralized; that is, over 50 percent of the population

105	162	231	242	229	166	110
174	751	773	766	760	778	175
260	746	2032	2012	2053	799	247
283	794	2017	1591 1589 / 1589 1590	2024	778	258
281	828	2051	2019	2046	762	241
203	808	775	779	789	777	172
134	196	265	265	242	172	111

FIGURE 4 Total employment distribution pattern for the base case.

281	458	776	784	675	457	357
448	897	1472	1634	1632	1134	517
955	1368	5417	5260	5551	1690	810
957	1864	5245	4281 4283 / 4274 4277	5334	1772	892
994	2010	5320	5256	5465	1623	704
694	1265	1727	1663	1539	1130	535
426	715	891	871	693	520	317

FIGURE 5 Population distribution pattern for the base case.

and total employment are located in the CBD and its fringe. This is because 63 percent of the basic employment is also located in this area.

The street network was initially defined as arterial streets that form a grid network. Local access and collector-distributor streets are not modeled. Highway link intersections meet at zone centroids. With 184 one-way interzonal links, the link-to-node ratio is 3.538 and the total one-way roadway length is approximately 233 mi. Free-flow capacities, free-flow speed, and the overall highway link structure are depicted in Figure 6. The transit network is a set of radial bus routes focused on the CBD. As shown in Figure 7, all zones, including the

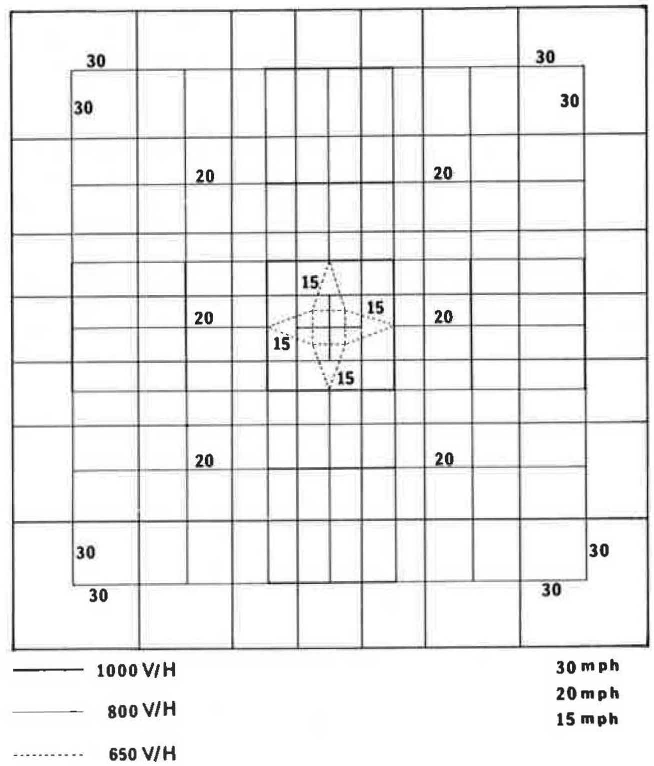

FIGURE 6 Link capacity and speed.

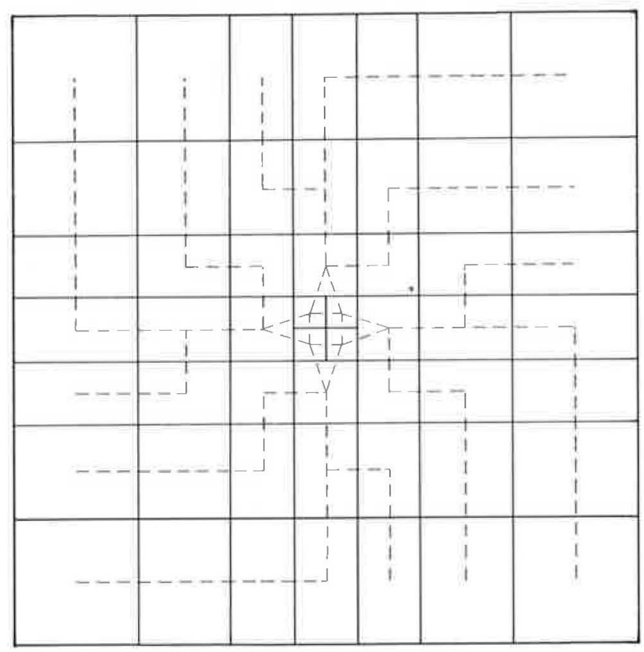

FIGURE 7 Transit network.

CBD, are served by at least one of the six bus routes, and each route begins and ends in an outlying residential area of the city. One would expect that the modal share of transit in the downtown area would be much higher than that of the outlying areas because the CBD has better service in terms of walking time to, and wait time at, a transit stop.

In order to simulate the experimental cities and obtain useful results with limited resources, three design principles were established in this study: (a) all urban forms were to have a 20 percent increment of basic employment growth, (b) three types of urban growth patterns (concentration, dispersion, and polynucleation) were to be examined, and (c) no other changes in input variables other than the location of basic employment were to be made. With these design principles, 18 experiments were formulated and simulated to obtain the data needed to examine the relationships between the urban form and transportation requirement measures. These experiments were classified according to three urban form groups, each containing six different forms. All 18 experiments were compared with the spatial attributes of the base case to derive measures of spatial change in the population distributions.

The first set of experiments was in the concentrated urban form category. As shown in Figure 8, it included six urban forms, numbered 201 to 206. In general, all additional basic employment, a total of 3,000 new jobs, was assigned to the CBD and CBD-fringe zones to create a strongly centralized city. The primary difference between the experiments in this group was the quantity of new jobs assigned to each "growth" zone. The second set of experiments, numbered 301 to 306, was designed to define several dispersed urban forms. The distinguishing characteristic of these experiments was that the additional basic jobs were allocated to zones beyond the CBD and the first ring of zones. Figure 9 shows the location and number of new jobs assigned to each zone. The last set of experiments was conducted to

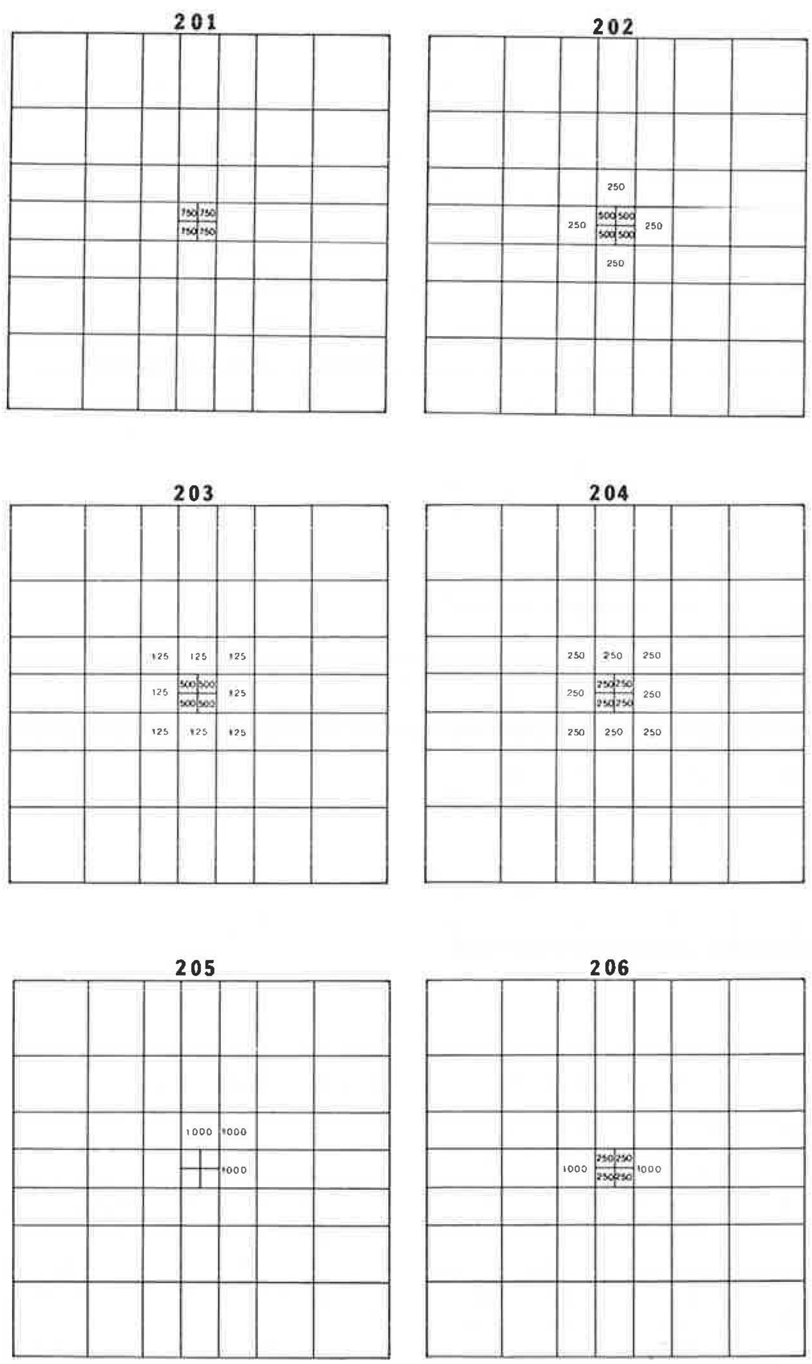

FIGURE 8 Location of additional basic employment in six concentrated cities.

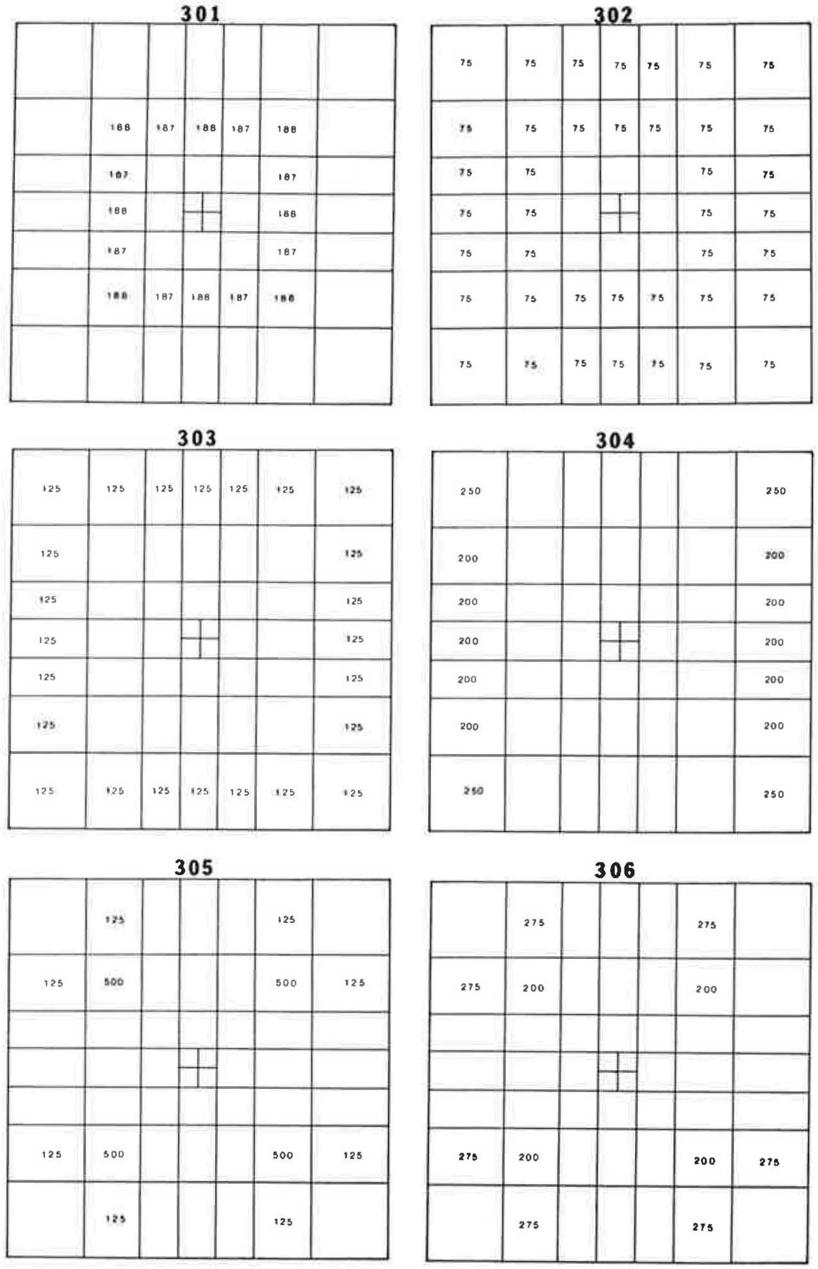

FIGURE 9 Location of additional basic employment in six dispersed cities.

define several polynucleated urban forms, each of which had several relatively high-density clusters of activity. As can be seen in Figure 10, four growth centers were selected for experiments 401, 402, 405, and 406; two centers for experiment 403; and eight centers for experiment 404. These growth centers included a high concentration of retail and service activities located within a relatively compact land area, blended with high-density residential development and certain kinds of basic industries.

ANALYSIS OF THE RELATIONSHIPS BETWEEN URBAN FORM AND TRANSPORTATION ENERGY CONSUMPTION

This section describes some functional relationships between urban form and transportation energy consumption that are based on the measures derived from the experimental cities. Hypothetically, the more compact an urban form is in terms of population distribution, the less travel energy requirements it will have. This hypothesis is based on the assumption that as the degree of urban spatial concentration increases, various urban activities locate closer together, resulting in a decrease of automobile vehicle miles of travel and average trip length. This in turn results in a decrease of transportation energy consumption.

A simple linear regression model was used to test this hypothesis. Total energy consumption is the dependent variable and each urban form measure is an independent variable. The urban form measures used in the regression analysis are the Gini coefficient, standard distance, potential measure, aggregate travel measure, and population density in CBD.

There are two reasons why simple regression rather than multiple regression was used in this analysis. First, the small sample size would have resulted in a marked decrease in statistical power

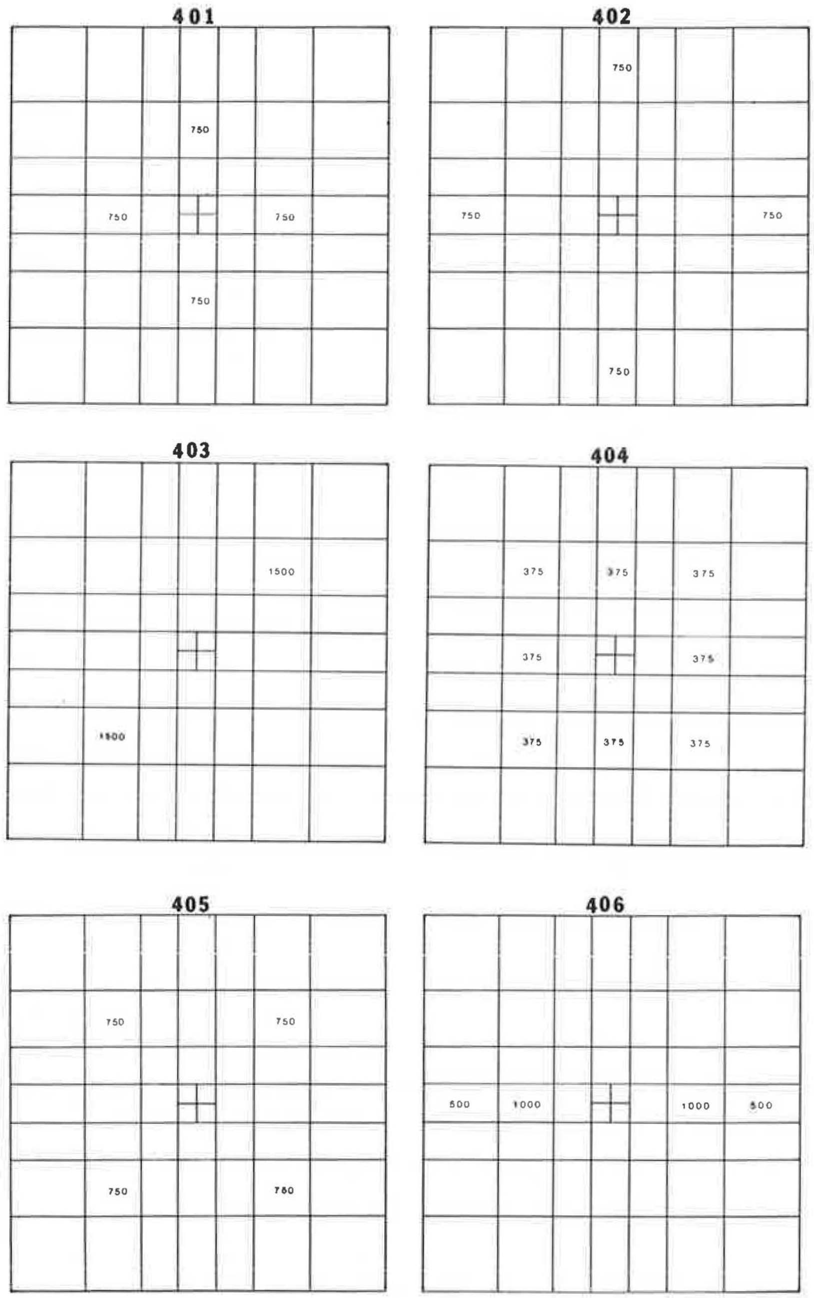

FIGURE 10 Location of additional basic employment in six polynucleated cities.

if several independent variables had been used. In this research, only 18 cases were designed to simulate different types of urban form. Second, the high level of intercorrelation among the urban form measures would prevent multiple linear regression from discovering the relative importance of each measure. It was important to avoid this multicollinearity problem.

The results of the regression analyses relating total energy consumption to each of the five urban form measures are shown in Table 1. Looking at the correlation coefficients (r), it can be seen that total energy consumption is highly and inversely related to the measures of spatial concentration such as the Gini coefficient, potential measure, and population density in CBD. Energy consumption is also highly and positively related to spatial dis-

TABLE 1 Regression Results of Transportation Energy Consumption Versus Urban Form Measures

Regression Equation	r	r^2
ENERGY = 21,602 - 15,158 GINI	-0.87	0.76
ENERGY = 19,695 - 158 RELOC	-0.85	0.73
ENERGY = 2,896 + 2,798 MEANDIST	0.88	0.78
ENERGY = 6,482 + 357 DISTVAR	0.89	0.79
ENERGY = 1,349 + 2,711 STANDIST	0.89	0.79
ENERGY = 19,392 - 0.108 POTENT	-0.85	0.73
ENERGY = 2,868 + 0.23 AGGREG	0.89	0.79
ENERGY = 16,180 - 0.693 DENSITY	-0.86	0.75
ENERGY = 19,641 + 14,230 GRADIENT	0.88	0.78

Note: Variables are defined as follows: ENERGY = total energy consumption by automobile for all trip purposes in 10^6 Btu, GINI = Gini coefficient, RELOC = reallocation index, MEANDIST = mean distance, DISTVAR = distance variance, STANDIST = standard distance, POTENT = potential measure, AGGREG = aggregate travel measure, DENSITY = population density in CBD, and GRADIENT = density gradient.

persion measures such as the standard distance and aggregate travel measure. The coefficients of determination (r^2) range from 0.73 to 0.79, indicating that 73 to 79 percent of the variance in total energy consumption among the 18 cases can be explained by any one of the urban form measures.

Figure 11 is a scatterplot of the total transportation energy required in each experimental city in relation to the Gini coefficient. As would be expected, there is a wide variation in transportation energy consumption for different urban forms. The 300-level cities, which are characterized by decentralized urban spatial patterns, have energy consumption levels much larger than the compact 200-level cities, with the polynucleated urban patterns of the 400-level cities falling in between. For example, experiments 201 through 204, which have higher Gini coefficients, occupy the more energy-efficient locations in the trade-off space. By contrast, experiments 302 through 306, which have lower coefficients, occupy the upper left-hand portion of the space, representing high energy consumption.

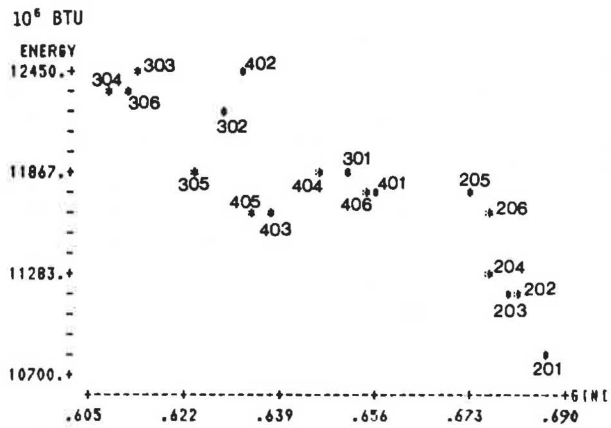

FIGURE 11 Transportation energy consumption versus Gini coefficient.

It is interesting to observe that, with the exception of the 402 city, the polynucleated cities do not vary much in terms of energy consumption, although their spatial concentration measures show a wide range of variation. Another interesting observation is that experiments 403 and 405, which are not very concentrated, are more energy-efficient than experiments 205 and 206, which are highly concentrated. This suggests that polynucleated urban patterns are comparable with some concentrated urban forms in terms of energy consumption. This result was expected because higher concentrations of activity in the city center create traffic congestion, which increases the gasoline consumed per mile.

Figure 12 is a plot of total energy consumption as a function of the standard distance. The plot clearly shows that there is a positive relationship between energy consumption and this spatial dispersion measure. A longer standard distance produces a greater level of transportation energy consumption. Although the dispersion measure does not take urban travel behavior into account, it suggests that a spatial dispersion measure can be used as a macroscale indicator of the level of transportation energy consumption in an urban area. The rationale for this argument is that if the population distribution pattern is dispersed around the CBD, longer trips are made and more transportation energy is consumed.

Figure 13 is a plot of energy consumption and the

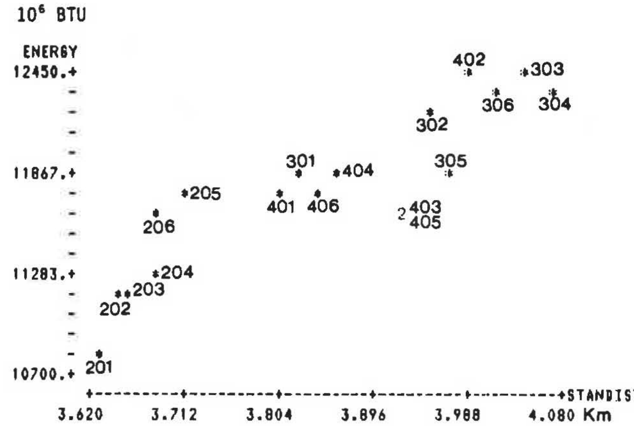

FIGURE 12 Transportation energy consumption versus standard distance.

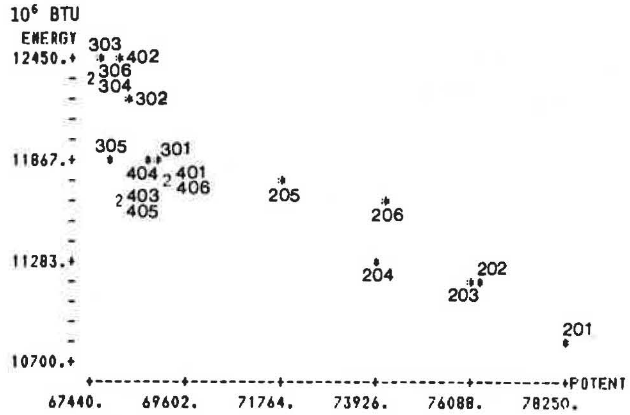

FIGURE 13 Transportation energy consumption versus potential.

potential measure of the CBD, a measure of aggregate accessibility. The general trend shows the two variables to be inversely correlated, indicating that higher accessibility levels in the inner city reduce energy requirements. As expected, the dispersed 300-level cities require more energy, whereas the concentrated 200-level cities are more energy-efficient. The polycentric (400-level) cities fall in between. An exception is the 402 case, which is probably due to an edge effect caused by the boundaries of the city.

The relationships between total energy consumption and the aggregate travel measure are plotted in Figure 14. The positive relationship is quite similar to that of the standard distance. It is evident that increases in passenger travel from each zone to the CBD increase the transportation energy requirements. The clustering pattern of each city group is similar to those shown in the previous plots.

Figure 15 shows total energy consumption plotted in relation to the population density in the CBD. This plot clearly shows that urban forms with higher population densities in the city core require lower levels of transportation energy. This observation agrees with the results of some previous research that examined the impact of urban spatial structure on transportation energy consumption, using population density as an urban form measure (4,5).

In summary, the regression results indicate that the concentrated urban form is the most energy-efficient and the dispersed urban form is the least energy-efficient, with the polynucleated form fall-

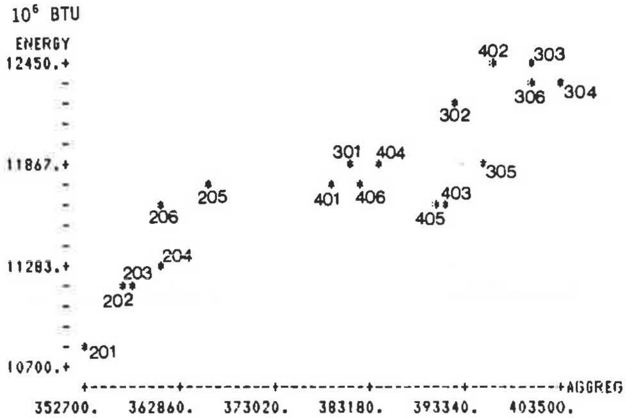

FIGURE 14 Transportation energy consumption versus aggregate travel.

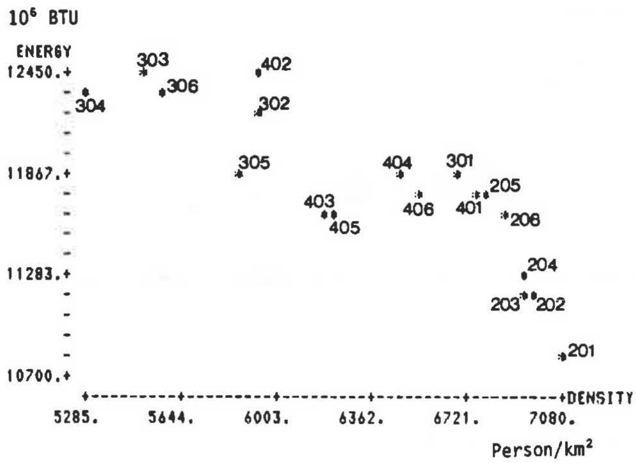

FIGURE 15 Transportation energy consumption versus population density.

ing in between. However, some polynucleated urban forms show lower transportation energy consumption measures than some concentrated urban forms, although the former is more spatially dispersed and less well served by transit in its outlying growth centers. A close examination reveals that the concentrated urban forms contain highly congested highway links in and around the CBD, resulting in high energy consumption.

CONCLUSIONS

The first conclusion is that the urban form measures used in this study are useful techniques for defining the major characteristics of an urban spatial structure. These measures clearly described the degree of concentration or dispersion and the shape of the urban form for all the experimental cities. None of these results was counterintuitive. This implies that planners and decision makers can use these measures as macroanalytical tools to obtain an overall sense of the spatial characteristics of various urban form concepts.

The second major conclusion of the study is that most of the urban form measures are highly correlated with transportation energy consumption. Overall, the regression results indicate that higher concentrations of population in the center of the city, better access to the center, and higher population densities can reduce transportation energy consumption. This suggests that marked reductions in transportation energy requirements can be made by altering urban spatial structure. However, congestion will increase substantially, necessitating large investments in expanded facilities and services.

The third conclusion of the study concerns the comparison of concentrated urban and polynucleated urban forms in terms of their transportation energy consumption requirements. The urban form measures indicated that the polynucleated urban form was more dispersed, less accessible, and less dense in the CBD than the concentrated urban form. Nevertheless, it was evident that transportation in some polynucleated cities was more energy efficient than in some concentrated cities due to the high congestion level of downtown access streets. The implication of this observation is that there is a great potential to reduce energy consumption by encouraging present polycentric urban form trends and policies. It is clear that the horizontal spread of cities must be controlled if energy consumption is to remain constant or be reduced. Compact urban forms consisting of major suburban employment centers with a relatively dense residential area surrounding them appear to be both feasible and desirable urban configurations for an energy-short future.

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An Analysis of Trends in Automotive Fuel Economy from 1978 to 1984

DAVID L. GREENE, PATRICIA S. HU, and LYNN TILL

ABSTRACT

Between 1978 and 1984, the fuel economy of new automobiles increased by an estimated 6.7 miles per gallon. Previous analyses have shown that fuel economy improvements have been primarily achieved by lowering the average weight of the automobile and reducing the size of the engine. Detailed sales data were used to analyze the contributions of consumer sales shifts and engineering and design improvements to the 1978 to 1984 gain in fuel economy. Most of the gain (70 percent) was found to have resulted from changes in vehicle offerings by manufacturers, whereas only 30 percent of the gain was attributed to sales shifts. The lack of improvement in fuel economy of new automobiles since 1982 is attributed to both consumer selections and manufacturer decisions.

Between 1978, when new automobile fuel economy standards became effective, and 1982, the fuel economy of new automobiles increased by one-third, from 19.7 to 26.4 miles per gallon (mpg) (1). The 1982 fuel economy increased nearly 90 percent from the 1974 estimate of 14.2 mpg. However, the fuel economy of new automobiles has not increased since 1982. The estimated fuel economy of new automobiles for the first 6 months of model year 1984 stands at 26.3 mpg, just slightly below the 1982 value (2). If this estimate holds true for the remainder of 1984, it would be the first year the efficiency of all new automobiles fell below the standard mandated for individual manufacturers (27 mpg in 1984). The recent change in fuel economy trends creates doubt about whether the 27.5 mpg standard for 1985 and beyond can be achieved.

Substantial information is available to explain how fuel economy improvements since 1978 have been achieved (3,4,5). Studies of vehicle engineering and design changes indicate that automobile weight reduction and associated reductions in engine size have been primarily responsible for improved mpg. The actions of consumers responding to new vehicle offerings and fuel prices, and producers changing vehicle designs and offerings, are examined to determine new automobile fuel efficiencies. Detailed vehicle sales and fuel economy data from 1978 to 1984 are also analyzed. By means of a decomposition technique, each year's change in fuel economy is broken into eight components that quantify the effects of sales shifts and changing manufacturer offerings. The results indicate that although sales shifts were only a secondary contributor to improved automobile efficiency through 1982, they are a primary contributor to the lack of fuel economy improvements over the past 2 years.

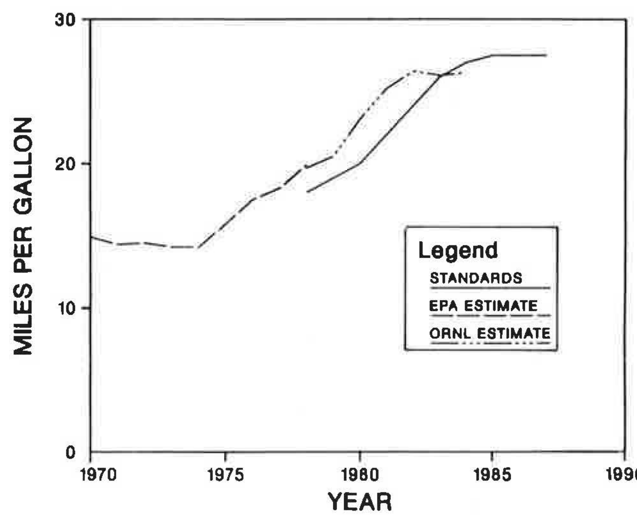

FIGURE 1 Estimated new automobile fuel economy and federal fuel economy standards.

HOW FUEL ECONOMY GAINS WERE ACHIEVED

In 1974 the fuel efficiency of new automobiles was at its lowest point (14.2 mpg) after years of gradual decline (see Figure 1). In the same year, gasoline prices jumped from 39 to 53 cents per gallon (current dollars) as a result of the worldwide increase in petroleum prices. The realization that cheap petroleum fuels in a stable market were a thing of the past stimulated Congress to pass the Energy Policy and Conservation Act of 1975 (P.L. 94-163), which established corporate average fuel economy (CAFE) standards. Consumers began to demand more efficient vehicles, and manufacturers responded with significant engineering improvements and design changes that combined to nearly double the fuel efficiency of new automobiles. Some of the improvement in the average fuel economy of new automobiles is the result of consumers' decisions to buy smaller automobiles and trucks or more efficient models and configurations. Some of the improvement can also be attributed to the fact that manufacturers made vehicle design and engineering changes to meet the demands of both consumers and CAFE standards. In the following section the changes that have been made, the types of technology used to improve fuel economy, and their relative contributions are examined.

ENGINEERING AND DESIGN CHANGES THAT IMPROVED FUEL ECONOMY

In 1973, 46 percent of all vehicles sold were large automobiles, according to the U.S. Environmental Protection Agency's (EPA's) vehicle classification system. Today, large automobiles compose only 13 percent of total sales. Difiglio and McNutt (6) calculated that the market shift to smaller cars improved new car fuel economy by 1.2 mpg from 1973 to 1975. From 1975 to 1979, although fuel prices were stable or slightly declining, there was essentially no increase in new automobile fuel economy (in fact, there was a decrease) from a shift in sales among size classes. In the 1980 model year, following the 25 percent real gasoline price increases in the summer of 1979 and during an equal increase in 1980, there was another gain of about 1.3 mpg because consumers chose to buy smaller automobiles. Overall, from 1973 to 1981 Difiglio and McNutt calculated a 1.6 mpg improvement because of size class sales shifts out of an overall 10.9 mpg improvement above the average in new automobile fleets.

Manufacturers have mostly improved automobile efficiency by decreasing the exterior vehicle dimensions of all size classes and using lighter materials to reduce vehicle weight. A statistical analysis of new automobile fuel economy from 1976 to 1981 (7) found that changes in vehicle curb weight explained almost all of the change in fuel economy. Statistically significant effects of changes in performance (measured by the horsepower-to-weight ratio) and transmission types were not found. It was also found that, as a control for these variables, imported automobiles were not significantly more efficient than those of domestic manufacture.

As part of its monitoring and analysis of automobile fuel economy pursuant to the Department of Energy Act of 1978 (P.L. 95-238), the U.S. Department of Transportation (DOT) conducted a detailed analysis of improvements to fuel economy of new automobiles from model year 1978 to 1981 (8). The greatest improvements in fuel economy over that time period were found to have resulted from a reduction in vehicle weight. The average inertial weight (equal to the curb weight plus 200 lb) for new passenger automobiles was reduced from 3,627 lb in model year 1978 to 3,155 lb in 1981, which is a loss of 472 lb, or 13 percent. Decreased vehicle weight within size classes, as opposed to sales shifts from large to small automobiles, accounted for almost 75 percent of the total weight loss.

Many other changes resulted in smaller improvements to fuel economy. DOT's analysis of the effects of these changes is summarized in Table 1 (8). Of the total improvement that could be attributed, 54 percent was due to weight reduction. Reduced vehicle performance, measured by the horsepower-to-weight ratio, was the next largest single factor. A 9 percent reduction in average horsepower per pound accounted for 18 percent of the attributable gain in fuel economy. All types of transmission modifications, including an increased market share for manual transmissions (16 to 30 percent), greater use of lock-up torque converters in automatic transmissions, (7.7 to 34.5 percent), and an increased number of gears in both manual and automatic transmissions constituted 13 percent of the attributable improvement. Improved aerodynamics followed at 9 percent and increased use of diesel engines contributed only 6 percent of the estimated 4.35-mpg gain. One mpg of improvement could not be attributed because of the inherent limitations of the analysis. Some of this improvement is surely due to sales mix shift effects unrelated to weight reduction. The rest of the improvement was due to factors not explicitly accounted for (e.g., radial tires and improved lubricants).

The same DOT report contains a similar but less detailed analysis of the gains in fuel efficiency of domestic light trucks from 1978 to 1981. The DOT analysis calculated the weight loss of average domestic light trucks from 1978 to 1981 at 440 lb, or about 10 percent (4,600 to 4,160 lb). At the same time engine sizes were also reduced from an average of 340 to 290 in^3. Installation of automatic transmissions declined slightly from 76 to 64 percent, but, more important, use of lock-up torque converters grew from nil to about half of all automatic transmission installations. Use of four-speed manual overdrive transmissions increased from negligible to 10 percent.

It is evident from the various analyses of the factors responsible for the improved fuel efficiency of automobiles and light trucks that very little of the improvement was actually due to technological advances. Downsizing, improved aerodynamics, an increase in the number of gears and the use of manual transmissions, and reductions in vehicle performance are primarily vehicle design changes. To the extent that these are more expensive than historical designs, or are perceived by consumers as less desirable, the improvements made thus far could be reversible. The extent to which a period of declining fuel prices could lead consumers to once again demand larger, heavier, more powerful, and less fuel-efficient vehicles is an interesting subject for research.

TABLE 1 Summary of Engineering and Design Contributions to New Automobile Fuel Economy Improvement *(8)*

	1978	1981	Mpg Change
Average new automobile fuel economy (mpg)	19.9	25.2	+5.3
Inertial weight (lb)	3,627	3,155	+2.35
Diesel engine (%)	1.1	5.9	+0.25
Vehicle performance (horsepower to inertial weight)	0.339	0.310	+0.80
Aerodynamic drag (dynamometer power absorption, hp)	10.4	9.4	+0.37
Total transmission changes	–	–	+0.58
Increased manual (%)	16.0	29.6	+0.14
Lock-up torque converter (%)	7.7	34.5	+0.27
Four-speed automatic (%)	0.4	8.7	+0.08
Five-speed manual (%)	5.1	14.4	+0.09
Total change attributable (mpg)			4.35

METHOD FOR DECOMPOSING FUEL ECONOMY TRENDS

New automobile fuel economy has improved little since 1981. Average vehicle weight, engine size, and combined EPA mpg are about the same in 1984 as they were in 1981 (see Table 2) (2).

TABLE 2 Light Vehicle Weight, Engine Size, and Fuel Economy *(2)*

	Automobiles				
Year	Weight (lb)	Interior Volume (ft^3)	Engine Size ($in.^3$)	Fuel Economy (mpg)	Light-Truck Fuel Economy (mpg)
1979	3,003	107	232	20.5	17.2
1980	2,799	105	198	23.1	17.9
1981	2,742	106	182	25.2	19.8
1982	2,727	106	176	26.4	20.4
1983	2,787	107	182	26.1	20.6
1984[a]	2,791	108	182	26.3	19.3

[a]Based on sales for the first 6 months of the model year (October to March).

The factors accounting for this recent trend can be determined by analyzing detailed data on vehicle sales and fuel efficiencies. A data system for tracking new automobile and light truck sales and fuel economy trends has been developed at Oak Ridge National Laboratory [refer to the "Decomposition Formulas" section of this paper; the report by Hu et al. (2); and the report by Patterson et al. (4)]. The system uses nameplate (e.g., Ford Tempo) sales data published by Wards' Automotive Reports (9) together with EPA fuel economy estimates, which are grouped by engine and transmission combination. The unadjusted, combined city-highway estimate is used. The nameplate sales data are distributed among engine-transmission categories using the percentage distribution of vehicle production by engine type and transmission type. The details of data manipulation are described by Hu and Roberts (1). This data system has been maintained on a monthly basis, with data going back to model year 1978. For the sake of consistency, model years are defined as the 12 calendar months from October to September. This detailed data system provides a rich resource for analyzing how manufacturer and consumer actions have contributed to fuel economy changes over a period of time.

The total change in fuel economy from one model year to the next can be thought of as comprising (a) shifts in sales from one type of vehicle to another, (b) introductions or discontinuations of vehicle types, and (c) improvements in the fuel economy of continued vehicle types. For example, an increase in sales of larger, less efficient automobiles, or of configurations with less efficient, larger engines and automatic transmissions, will tend to depress new automobile fuel economy. At the same time, however, manufacturers may introduce new, more efficient models and discontinue older, less efficient ones or they may employ engineering and design changes, such as lock-up automatic transmissions or the use of lighter materials, which all tend to improve fuel economy. With appropriate data on vehicle sales and fuel economies, each component can be identified and measured.

The first step is to define vehicle types. Three hierarchical levels of vehicle types, in descending order, will be used:

1. Size class, as defined by EPA interior volume;
2. Nameplate (e.g., Chevette, Escort, and Reliant); and
3. Configuration, which is the engine-transmission combination of a nameplate.

The smallest unit in the analysis is therefore a configuration of a nameplate, for instance, a four-cylinder diesel Rabbit with a four-speed manual transmission. Because this approximates the level at which the EPA certifies vehicle fuel economies, it is a logical choice for the basic unit.

Sales shifts effects are always computed by holding fuel efficiency constant at last year's level (for each configuration) and contrasting that year's sales distribution with that of the year before. All changes in efficiency within a continued configuration are thus attributed to an improvement in efficiency. The decomposition of efficiency changes is summarized in Figure 2. The mathematical formulas that correspond to the elements in Figure 2 are provided in the following section.

DECOMPOSITION FORMULAS

The formulas used to calculate each of the eight fuel economy change components (see Figure 2) are presented in the following paragraphs. A complete derivation can be found elsewhere (2).

The analysis of fuel economy changes is carried out in terms of gallons per mile rather than miles per gallon to simplify the arithmetic. The mean of different gallons per mile is the arithmetic mean, whereas the mean of miles per gallon is the harmonic mean.

Because neither all nameplates nor all configurations will be the same from one year to the next, the following three sets of vehicles are defined for the analysis.

V: the set of all (nameplate) configurations existing in either year t or t-1 (this is the universe of configurations);

C: the subset of V containing all configurations of nameplates that continue from year t-1 to year t;

C': the subset of C containing all configurations that continue from one year to the next.

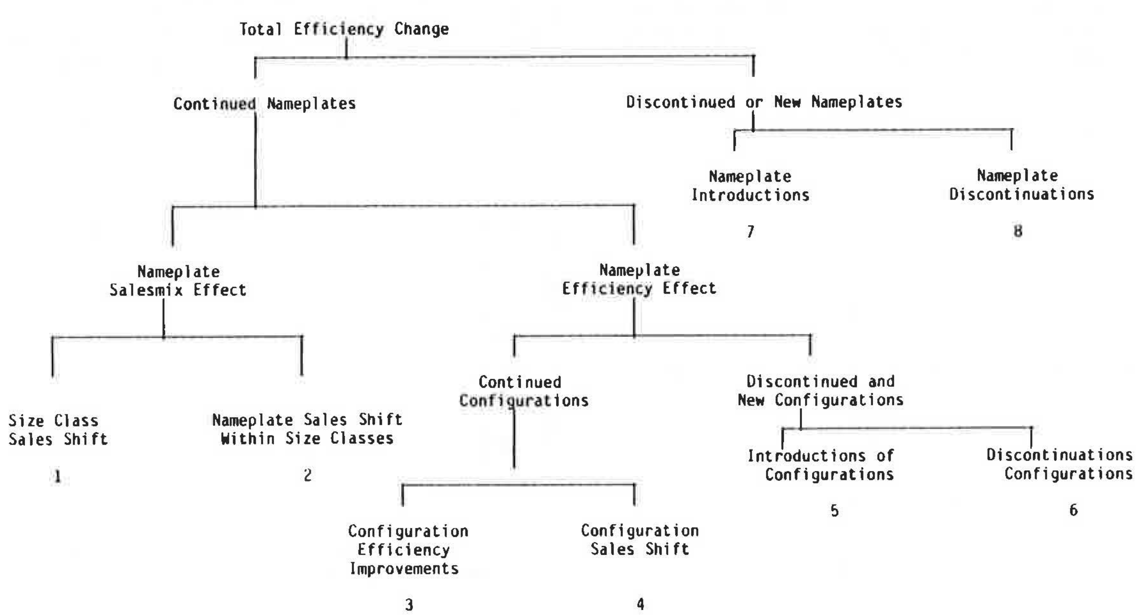

FIGURE 2 Decomposition of efficiency changes.

Total fuel economy change must be calculated on the set V, including all vehicle configurations. It makes sense to compute nameplate and configuration sales shifts only over the sets C (continued nameplates) and C' (continued configurations), respectively. Size class sales shifts could be computed over V or C. It was decided to compute the effect of size class shifts over C only. As a result, size class shifts associated with the introduction or discontinuation of nameplates will be attributed to nameplate changes in order to make a clearer distinction between the effects of consumer choice and those caused by changes in the range of options offered to consumers.

The following definitions are required:

- E = vehicle efficiency (gal per mile),
- ΔE = change in efficiency from year t-1 to t,
- S_{Kt} = nameplate K's share of total sales in year t,
- f_{iKt} = configuration i's share of nameplate K's sales in year t,
- i = configuration,
- K = nameplate (note that $\sum_i f_{iKt} = 1$ and $\sum_K S_{Kt} = 1$),
- ℓ = size class, and
- t = year.

Also,

$$S_{\ell t} = \sum_{K \in \ell} S_{Kt}$$

$$\bar{E}_{\ell t-1} = \sum_{K \in \ell} \left(S_{Kt-1} / \sum_{K \in \ell} S_{Kt-1} \right) \bar{E}_{Kt-1}$$

and

$$\underset{\text{in C}}{\bar{E}_{t-1}} = \sum_{\substack{K \\ \text{in C}}} \left(S_{Kt-1} / \sum_{\substack{K \\ \text{in C}}} S_{Kt-1} \right) \bar{E}_{Kt-1}$$

$S_{\ell t}$ is the sales share of size class ℓ in year t (for continued nameplates only if summed over the set C). $\bar{E}_{\ell t}$ is the average efficiency of size class ℓ (in gallons per mile) and $\underset{\text{in C}}{\bar{E}_{t-1}}$ is the average efficiency in year t-1 of all continued nameplates.

The eight components of efficiency change are summarized as follows (also see Figure 2). Summing all components will return the total change in efficiency, ΔE.

1. Size class sales shift:

$$\Delta EB_C = \left[\sum_{\substack{\ell \\ \text{in C}}} S_{\ell t} \bar{E}_{\ell t-1} + \left(\sum_{\substack{K \\ \text{not C}}} S_{Kt} \right) \underset{\text{in C}}{\bar{E}_{t-1}} \right] - \left[\sum_{\substack{\ell \\ \text{in C}}} S_{\ell t-1} \bar{E}_{\ell t-1} + \left(\sum_{\substack{K \\ \text{not C}}} S_{Kt-1} \right) \underset{\text{in C}}{\bar{E}_{t-1}} \right]$$

2. Nameplate sales shift within size classes:

$$\Delta EW_C = \sum_{\ell} \left(\sum_{K \in \ell} S_{Kt} \right) \sum_{K \in \ell} \left(S_{Kt} / \sum_{K \in \ell} S_{Kt} \right) \bar{E}_{Kt-1} - \sum_{\ell} \left(\sum_{K \in \ell} S_{Kt} \right) \sum_{K \in \ell} \left(S_{Kt-1} / \sum_{K \in \ell} S_{Kt-1} \right) \bar{E}_{Kt-1}$$

3. Configuration efficiency improvements:

$$\Delta EE_{C'} = \sum_{i}\sum_{K} S_{Kt} f_{iKt} E_{iKt} - \sum_{i}\sum_{K} S_{Kt} f_{iKt} E_{iKt-1}$$

4. Configuration sales shift:

$$\Delta ES_{C'} = \left(\sum_{i}\sum_{K} S_{Kt} f_{iKt} E_{iKt-1} + \sum_{\substack{i\,K \\ \text{C not C'}}}\sum S_{Kt} f_{iKt} \bar{E}_{Kt-1} \right) - \left(\sum_{\substack{i\,K \\ \text{C not C'}}}\sum S_{Kt} f_{iKt-1} \bar{E}_{Kt-1} + \sum_{i}\sum_{K} S_{Kt} f_{iKt-1} E_{iKt-1} \right)$$

5. Introductions of configurations:

$$\underset{\text{C not C'}}{\Delta ECI} = \sum_{\substack{i\,K \\ \text{C not C'}}}\sum S_{Kt} f_{iKt} E_{iKt} - \sum_{\substack{i\,K \\ \text{C not C'}}}\sum S_{Kt} f_{iKt} \bar{E}_{Kt-1}$$

6. Discontinuations of configurations:

$$\underset{\text{C not C'}}{\Delta ECD} = \sum_{\substack{i\,K \\ \text{C not C'}}}\sum S_{Kt} f_{iKt-1} \bar{E}_{Kt-1} - \sum_{\substack{i\,K \\ \text{C not C'}}}\sum S_{Kt} f_{iKt-1} E_{iKt-1}$$

7. Nameplate introductions:

$$\underset{\text{not C}}{\Delta ENI} = \sum_{\substack{K \\ \text{not C}}} S_{Kt} \bar{E}_{Kt} - \left(\sum_{\substack{K \\ \text{not C}}} S_{Kt} \right) \underset{\text{in C}}{\bar{E}_{t-1}}$$

8. Nameplate discontinuations:

$$\underset{\text{not C}}{\Delta END} = \left(\sum_{\substack{K \\ \text{not C}}} S_{Kt-1} \right) \underset{\text{in C}}{\bar{E}_{t-1}} - \sum_{\text{not C}} S_{Kt-1} \bar{E}_{Kt-1}$$

These components are expressed in units of gallons per mile. They can be converted back to units of mpg by multiplying each by the term $-(MPG_t MPG_{t-1})$.

COMPONENTS OF THE NEW AUTOMOBILE FUEL ECONOMY CHANGE FROM 1978 TO 1984

Improvements in automobile fuel efficiency since 1978 have been achieved by a combination of consumer sales shifts in response to higher fuel prices and changes in the products offered by manufacturers. Between 1978 and 1984, new automobile efficiency increased from 19.7 to 26.4 mpg in 1982 and remained nearly constant through 1984. During the same time period, the price of unleaded gasoline rose from \$1.02 to \$1.51 per gallon (1983 dollars) but has since declined to \$1.21 per gallon (see Figure 3). By means of a simple model, a crude estimate of the relative impacts of fuel price (in the short run) and other factors can be calculated from these data.

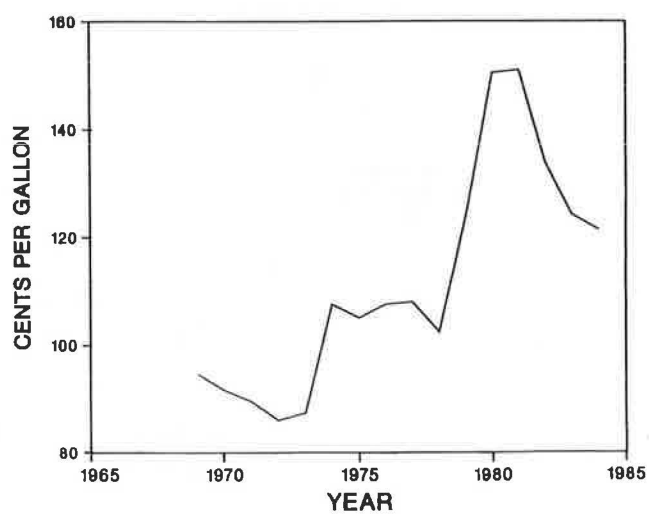

FIGURE 3 Gasoline prices, 1969-1984, in constant 1983 dollars.

TABLE 3 Fuel Economy and Gasoline Price Changes, 1978 to 1984

Year	Fuel Economy		Gasoline Price[b] (1983 cents)	Δ Price[c]
	Mpg[a]	Δ Mpg		
1978	19.7		102.3	
1979	20.5	0.8	123.9	21.6
1980	23.2	2.7	150.5	26.6
1981	25.3	2.1	151.0	0.5
1982	26.4	1.1	133.8	-17.2
1983	26.1	-0.2	124.1	-9.7
1984	26.3	0.2	121.3	-2.8

[a]Report by Hu et al *(2)*.
[b]U.S. Department of Energy *(11)*.
[c]U.S. Department of Commerce *(12, 13)*.

Let mpg in year t be expressed by a linear function of gasoline price and a linear time trend:

$$(\text{MPG})_t = a + b(\text{PRICE})_t + c(\text{TREND})_t \qquad (1)$$

The time trend is intended to capture efficiency improvements caused by factors other than immediate consumer response to gasoline price changes. This would include engineering and design improvements by manufacturers as a long-term response to current or anticipated higher fuel prices as well as technical advances. The differences of Equation 1 create a simple formula that can be computed on a programmable hand calculator using the data in Table 3.

$$\Delta(\text{MPG})_t = b\,\Delta(\text{PRICE})_t + c$$

The results of this formulation by using a programmable hand calculator are

$$\Delta(\text{MPG})_t = 0.0340\,\Delta(\text{PRICE})_{t-1} + 1.009 \qquad n = 6, \quad r^2 = 0.28 \qquad (2)$$

The low r^2 is not surprising for a differenced equation.

This result implies that between 1978 and 1984, a 6.0-mpg improvement could have been expected without any short-term consumer response to price increases. This is about 90 percent of the actual 6.6-mpg improvement. A short-term (mid-point) price elasticity [e(p)] can be computed from Equation 2:

$$e(p) = 0.0340\,(126.65/23.05) = 0.19$$

This result suggests that consumers would respond to a 10-percent price increase by shifting their purchases to more efficient cars in the following year, resulting in about a 2-percent improvement in efficiency. These rather crude calculations indicate that most of the improvement in fuel economy from 1978 to 1984 was due to long-term decisions by manufacturers, motivated by fuel economy standards or expectations of higher fuel prices, to offer more efficient vehicles to the public.

The manner in which changes in fuel economy have actually been made can be better understood by using the decomposition method to analyze annual sales and fuel economy data. For each year from 1979 to 1984, the change in mpg was broken down by using the data and method described earlier. The calculations that resulted are presented in Table 4. These calculations indicate that the single largest contributor to fuel efficiency over the 1979 to 1984 time period was an improvement in the efficiency of continued configurations. This component alone accounted for almost one-third of the total gain in fuel economy. New introductions of configurations and nameplates together accounted for another 29 percent of the total gain in fuel efficiency. Discontinuations of less efficient models were responsible for about 12 percent of the total gain.

Sales shifts of all types improved fuel efficiency a total of 1.8 mpg, or 27 percent. This is broadly consistent with the 10-percent improvement predicted by the simple model presented earlier. Sales shifts among nameplates within a size class composed the single largest component, accounting for half of the sales shifts improvements. The method of calculation, however, may overstate the importance of this factor. Because the model year was arbitrarily defined as being from October to September, new nameplates introduced in August or September, for example, would be counted as having been introduced in the previous model year and continued in the current year. Most of the contribution to fuel efficiency would, therefore, be attributed to nameplate sales shifts from the previous to the current model year. The importance of this effect has yet to be quantified.

Size class shifts have proven to be a relatively minor factor. Consumers' primary strategy for buying a more efficient automobile is not to buy a smaller one, at least not in terms of interior space, but to shop around for a more efficient nameplate or configuration. The combined contributions of nameplate and configuration sales shifts within size classes are nearly 2.5 times the size of sales shifts among size classes. This fact has some interesting implications. First, it underscores the importance of providing accurate fuel economy information to new automobile buyers to enable them to distinguish more efficient from less efficient models in the same size class. Second, it aids in understanding why consumers did not strongly resist downsizing, as had been predicted before the fuel economy standard had fully gone into effect (10). Consumers appear to be reluctant to accept downsizing in terms of interior volume, but are willing to accept downsizing in terms

TABLE 4 Components of New Automobile Fuel Economy Change, 1978 to 1984

	Fuel Economy		Size Class Sales Shift		Configurations				Nameplate	
	Mpg	Mpg Change	Between (17.7%)	Within (14.0%)	Improvement (33.3%)	Sales Shift (6.0%)	Introduction (10.7%)	Discontinuation (3.6%)	Introduction (18.1%)	Discontinuation (6.3%)
1978	19.72									
1979	20.52	0.80	0.29	0.17	-0.13	0.14	-0.03	-0.01	0.30	0.07
1980	23.24	2.72	0.43	0.59	0.89	0.25	0.30	0.03	0.12	0.11
1981	25.30	2.06	-0.18	0.37	1.05	0.04	0.08	0.01	0.61	0.08
1982	26.36	1.06	0.15	-0.20	0.62	-0.04	0.38	0.02	0.07	0.06
1983	26.12	-0.24	-0.06	-0.12	-0.08	-0.12	0.00	0.08	0.12	-0.05
1984[a]	26.34	0.23	-0.12	0.12	-0.14	0.13	-0.02	0.11	-0.02	0.15
1978-1984		6.63	0.51	0.93	2.21	0.40	0.71	0.24	1.20	0.42

Note: Total sales shifts = 1.84 mpg; total manufacturer changes = 4.78 mpg.
[a]Based on a comparison between the first 6 months of model year 1984 and the first 6 months of model year 1983.

TABLE 5 Sales Shift and Manufacturer Improvement Components of New Automobile Fuel Economy Changes, 1978 to 1984

	Sales Shifts (Δ mpg)	Manufacturer Improvements (Δ mpg)	Gasoline Price Change (1983 cents/gal)
1978-1979	0.60	0.20	21.6
1979-1980	1.27	1.45	26.6
1980-1981	0.23	1.83	0.5
1981-1982	-0.09	1.15	-17.2
1982-1983	-0.30	0.06	-9.7
1983-1984[a]	0.13	0.10	-2.8

[a]Based on first 6 months of each year.

of vehicle weight or exterior dimensions. This explains why consumers have been able to make the transition from the large American cars of the early 1970s to the more European-sized fleet of today.

A more precise calculation of the sensitivity of fuel efficiencyto fuel prices in the short term can be made by using the results of the decomposition of fuel economy changes. Table 5 summarizes the year-to-year changes in fuel economy from 1978 to 1984 in terms of sales shifts versus manufacturer improvements. The same simple model estimated earlier by using total changes can be used to estimate the effect of price changes through sales shifts only. The results of estimation on a programmable hand calculator are

$$\Delta MPG_t(\text{sales shift}) = 0.212 + 0.030\,\Delta PRICE_t \qquad n = 6, \quad r^2 = 0.85$$

The mid-point elasticity implied by these results is small:

$$\epsilon_p = (126.65/23.05)\,0.030 = 0.16$$

This elasticity estimate indicates that a 10-percent price increase would cause a 1.6 percent improvement in fuel efficiency through consumer sales shifts in the same year. It is interesting that the trend of a 0.21-mpg per year improvement is still not accounted for by price changes; this could be evidence of a long-term sales shift price response.

The summarized results shown in Table 5 suggest that manufacturers have also responded to short-term price changes, but with a time lag. Since 1982, it appears that manufacturers have also relaxed their efforts to improve fuel economy by introducing new, more efficient models and retiring older, less efficient models. Over the past 2 years, the contribution to fuel economy from these actions has been virtually nonexistent. This undoubtedly reflects a response to a change in consumer demand for fuel economy. Yet it is clear that over the last 3 years manufacturers did not initiate improvements in fuel economy but simply followed market trends.

SUMMARY

New automobile fuel economy has improved from 19.7 mpg in 1978 to 26.3 mpg for the first 6 months of model year 1984. Detailed sales data have been used to break annual changes down into eight separate components associated with sales shifts or manufacturer decisions to improve or discontinue models, or introduce new, more efficient models. Overall, manufacturer engineering changes have dominated sales shifts, accounting for 70 percent of the total improvement in fuel efficiency. Sales shift improvements in fuel economy have been shown to be insensitive to gasoline price changes in the short term although the presence of a long-term effect is indicated.

New automobile fuel economy has not improved since 1982. Sales shifts have tended to decrease mpg slightly, whereas manufacturers' design changes have only improved enough to offset the small effects of sales shifts. In the absence of fuel price increases, the full burden of meeting the 1985 standard of 27.5 mpg will fall on the manufacturers.

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Long-Term Outlook for Transportation Energy Demand

MARIANNE MILLAR, ANANT VYAS, and CHRISTOPHER SARICKS

ABSTRACT

A forecast of U.S. transportation energy demand by mode and fuel type is presented, and the forecast methodology, principal assumptions, and key findings are discussed. Results show steady growth in 1980 to 2010 travel demand (ranging from 28 percent for domestic waterborne commerce to 61 percent for personal vehicles, 74 percent for commercial trucks, and 157 percent for rail freight). As a result of relatively modest technological improvements and modal shifts, total transportation energy demand declines through 1990 and then rises at an increasing rate. Automobiles per household, vehicle miles of travel per household, and energy consumption per capita decline through the year 2000. Transportation energy per dollar of gross national product, freight energy per ton-mile, and passenger energy per capita continue to fall (but at a declining rate) through 2010. The forecast is compared with other long-range transportation energy forecasts that recently appeared in the literature, and certain underlying factors that influenced the forecast results are discussed. The paper concludes with several observations on the appropriate role of and focus for forecasts in general and transportation energy forecasts in particular.

The transportation sector now accounts for about 60 percent of U.S. petroleum consumption (1). This share has grown over the past decade as other sectors have shifted from petroleum to coal, electricity, or natural gas, and it is expected to continue to grow as industries and electric utilities opt for fuel flexibility in their new equipment. Transportation is the most petroleum-dependent sector; therefore, at least for the foreseeable future, analyses of petroleum demand and dependence on declining and at times unreliable fossil fuel sources must focus on the future activity and energy efficiency of transportation.

This paper presents the results of ongoing work by staff of the Center for Transportation Research at Argonne National Laboratory (ANL) in forecasting transportation energy demand by mode and fuel type to the year 2000 and beyond. Sponsored by the U.S. Department of Energy (DOE), Office of Transportation Systems (OTS), this effort is designed to provide the planning details required to guide long-range research and development program review and development. Two prior ANL forecasts, also sponsored by OTS, were published in 1979 and 1982 (2,3).

The remainder of this paper is organized into three sections: (a) an overview of the latest ANL forecast, including a brief description of methodology and key assumptions; (b) a comparison of selected features of the ANL-83N forecast and other recently published efforts; and (c) a series of observations and conclusions on both forecasting in general and the behavioral assumptions embedded in the forecasts.

THE ANL-83N FORECAST

Methodology and Key Assumptions

The ANL forecast, known as ANL-83N, was based on the latest (1983) National Energy Policy Plan (NEPP) (4). The purpose of this forecast was to provide a finer level of detail on future activity levels and energy consumption within the transportation sector consistent with the overall economics, demographics, and price assumptions of NEPP. Table 1 presents the economic and demographic assumptions and fuel prices used in the ANL-83N forecast. The spring 1983 run (TRENDLONG2008A) of the Data Resources, Inc. (DRI), long-range macromodel was used to supplement those inputs not specifically addressed in the 1983 NEPP forecast (according to J. Stanley-Miller of the Office of Policy, Planning and Analysis, DOE) (5).

The ANL-83N forecast relies on a series of models collectively known as the Transportation Energy and Emissions Modeling System (TEEMS) (3,9). Various components of the TEEMS package have been used for forecasting personal vehicle fleet mix and purchase patterns (8), projecting freight volumes and mode splits during a petroleum shortfall (9), estimating urban demographic shifts by household type and composition (10), and investigating the relationship between commercial air carrier financial yield and air passenger miles of travel (11).

Model Structure

On the passenger side, the TEEMS package starts with a base-year distribution of households according to a five-variable identifier and a base file of household vehicle and travel characteristics for each of the associated descriptor cells, as revealed in the 1977 Nationwide Personal Transportation Study (12).

A demographic forecast is generated for each of the five variables and is deployed in an iterative proportional fitting technique to generate future household counts by cell. These in turn are input to a vehicle choice model (with personal vehicles as characterized for the given forecast year) to first generate the future household vehicle holdings by type and then, through a travel-elasticity function, total personal VMT and energy consumption by type of vehicle and length of trip. For intercity travel, a 1977 base-year file of passenger miles of travel from standard metropolitan statistical area (SMSA) to SMSA was developed from the National Travel Survey and is maintained together with Bureau of Economic Analysis (BEA) population and employment data and base and forecast travel time and cost factors by mode (13). These files are input to an intercity

TABLE 1 Key Economic and Demographic Assumptions and Fuel Prices Used in the ANL-83N Forecast

Parameter	1980	1982	1990	2000	2010	Avg Annual Change, 1980-2010 (%)
Economic and demographic assumptions						
GNP ($1982, billion)	3,053	3,056	3,978	5,065	6,275	2.43
Personal income ($1982, billion)	2,511	2,579	3,353	4,534	6,242	3.08
Industrial production index (1982=100)	106	100	141	191	257	3.00
Median household income ($1982)	20,750	20,170	21,850	24,240	29,115	1.14
Total population ($\times10^6$)	225.5	234	250	268	283	0.76
Total household ($\times10^6$)	80.4	83.5	101	116	125	1.54
Avg household size[a]	2.75	2.72	2.41	2.25	2.21	-0.73
Fuel prices ($1982)						
Crude oil ($/bbl)[b]	39.40	33.59	31.90	57.40	83.60	2.55
Gasoline ($/gal)[c]	1.41	1.28	1.39	2.00	2.62	2.90
Diesel ($/gal)[c]	1.16	1.14	1.29	2.03	2.79	2.97
Jet fuel ($/gal)	1.04	1.15	0.97	1.72	2.48	2.94
Electricity (¢/kW·hr)	6.24	6.90	7.20	8.20	8.40	1.00

Note: Sources are as follows: GNP, personal income, industrial production index, Data Resources *(5)*; population, DOE and Census Bureau *(4)*; households, DOE *(4)*; median household income, Census Bureau *(7)* for 1980 and 1982, ANL estimates for forecast years based on trends by Data Resources *(5)*; fuel prices, DOE and Saricks et al. *(4,8)*.

[a]Population (excluding persons in group quarters)/household.
[b]World oil price.
[c]Includes taxes. Assumes a constant state tax rate of $0.09/gal in 1982 dollars, and a federal tax rate of $0.04/gal for 1980 and 1982 and a constant $0.09/gal (all in 1982 dollars) for 1983 and beyond.

travel demand and mode split model in which origin-destination flows for business and nonbusiness trips are based on projected travel time and cost by mode, population, employment, and hotel sector receipts.

On the freight side, base-year data from the 1977 Commodity Transportation Survey and other mode-specific sources on ton-miles of travel (TMT) by commodity sector and mode are coupled with Truck Inventory and Use Survey (TIUS) data on base-year trucks, vehicle miles, and fuel efficiency, and the output of an economic driver model. This is used to generate forecasts of commodity TMT, with intermodal shifts governed by fuel price changes and/or specific service constraints (according to L. Fowler of the Association of Oil Pipelines) (14-17). Truck TMT are converted to VMT based on historical and forecast estimates of average loads by commodity sector, and fuel consumption is computed as a function of truck VMT and forecast fuel efficiency by truck size. Rail, water, pipeline, and air freight energy consumption are computed as a function of forecast TMT and energy intensity (Btu/ton-mile) by commodity sector and mode.

Results

Tables 2 and 3 present the ANL-83N forecast of passenger and freight activity and energy consumption

TABLE 2 Projections of Transportation Activity by Mode and Submode, ANL-83N Forecast

Transportation Mode and Submode	Activity ($\times10^9$)[a] 1980	1990	2000	2010	Change, 1980-2010 (%) Total	Annual
Automobile (VMT[b])	1,111.9	1,457.0	1,622.4	1,787.3	60.7	1.6
Small	306.9	491.3	612.1	684.3	123.0	2.7
Medium	421.0	607.4	654.6	742.3	76.3	1.9
Large	384.0	358.3	355.7	360.7	-6.1	-0.2
Personal light truck (VMT)[c]	194.6	277.3	306.4	315.5	62.1	1.6
Bus (VMT)	5.8	6.9	7.8	-[d]	-	-
Commercial truck (TMT[e])	637.5	818.5	1,046.7	1,251.2	96.3	2.3
Commercial truck (VMT)[f]	205.7	249.7	306.4	357.8	73.9	1.9
Light (VMT)	104.5	129.2	159.8	187.7	79.6	2.0
Heavy (VMT)	91.9	110.1	135.4	158.1	72.0	1.8
Rail						
Freight (TMT)[g]	934.2	1,305.7	1,830.4	2,401.1	157.0	3.2
Passenger (PMT)[d,h]	4.5	4.5	4.1	-[d]	-	-
Marine (TMT)[i]	927.1	995.1	1,076.1	1,186.4	28.0	0.8
Aviation						
Domestic passenger (PMT)	204.4	213.3	273.8	-[d]	-	-
International passenger (PMT)	63.4	84.5	113.2	-[d]	-	-
Freight (TMT)	4.3	5.9	8.5	11.2	160.5	3.2
Pipeline (TMT)	858.0	813.6	743.8	670.1	-21.9	-0.8
Natural gas	269.1	268.0	252.0	222.2	-17.4	-0.6
Petroleum	587.6	570.4	531.7	525.2	-10.6	-0.4
Coal slurry[g]	1.3	1.3	1.3	1.3	0	0

[a]Mode value may not equal submode totals due to rounding.
[b]Vehicle miles of travel.
[c]Includes mini-vans.
[d]Not projected beyond 2000.
[e]Ton-miles of travel; trucks include some local travel.
[f]Includes government trucks.
[g]Potential growth in coal slurry (i.e., throughput of slurry projects with permit applications pending) included in rail traffic.
[h]Intercity only.
[i]Domestic waterborne freight only.

TABLE 3 Projections of Transportation Energy Consumption by Mode and Submode, ANL-83N Forecast

Transportation Mode and Submode	Quads (10^{15} Btu)[a] 1980	1990	2000	2010	Change, 1980-2010 (%) Total	Annual
Automobile	9.18	8.01	7.31	7.66	-16.6	-0.6
Small	2.05	2.23	2.32	2.40	17.1	0.6
Medium	3.47	3.63	3.34	3.61	4.0	0.1
Large	3.67	2.38	1.96	1.89	-48.5	-2.2
Personal light truck[b]	1.88	1.78	1.67	1.62	-13.8	-0.5
Bus	0.14	0.17	0.27	-[c]	-	-
School[d]	0.05	0.05	0.05	0.07	40.0	1.0
Transit[d]	0.06	0.09	0.10	0.11	83.3	1.9
Intercity	0.03	0.03	0.05	-[c]	-	-
Commercial truck	3.40	3.38	3.76	4.22	24.1	0.7
Light	1.01	1.02	1.08	1.19	17.8	0.5
Heavy	2.39	2.36	2.68	3.03	26.8	0.8
Rail	0.61	0.81	1.11	-[c]	-	-
Freight	0.55	0.75	1.04	1.36	147.3	3.1
Passenger	0.07	0.06	0.07	-[c]	-	-
Transit/commuter[d]	0.04	0.05	0.05	0.06	50.0	1.2
Intercity	0.02	0.01	0.01	-[c]	-	-
Marine	1.78	2.23	2.78	3.42	92.1	2.2
Domestic freight	0.39	0.42	0.46	0.50	28.2	0.9
International freight[e]	1.22	1.56	2.03	2.56	109.8	2.5
Recreational[d]	0.18	0.23	0.29	0.35	94.4	2.3
Aviation	1.58	1.61	1.73	-[c]	-	-
General aviation	0.18	0.24	0.30	-[c]	-	-
Domestic passenger	1.22	1.14	1.15	-[c]	-	-
International passenger[f]	0.14	0.17	0.19	-[c]	-	-
Domestic freight	0.04	0.06	0.08	0.11	175.0	3.3
Pipeline	0.84	0.83	0.78	0.71	-15.5	-0.6
Natural gas	0.68	0.68	0.64	0.56	-17.6	-0.6
Crude oil	0.09	0.09	0.08	0.08	-11.1	-0.4
Petroleum products	0.07	0.07	0.06	0.06	-14.3	-0.3
Coal slurry[g]	0.00	0.00	0.00	0.00	0	0
Miscellaneous vehicles[h]	0.20	0.19	0.21	0.25	25.0	0.7
Total[i]	19.61	18.99	19.55	21.49[j]	9.6	0.3[j]

[a] Mode values may not equal submode totals due to rounding.
[b] Includes mini-vans.
[c] Not projected beyond 2000.
[d] Projections from ANL *(3)*, extrapolated to 2010.
[e] U.S. sales of bunker fuels; includes foreign-flag and some military consumption.
[f] Fuel purchases in United States by domestic carriers; assumes 50 percent of their fuel is purchased overseas.
[g] Assumes no new construction of coal slurry pipelines.
[h] Includes motorcycles, snowmobiles, and off-highway trucks (excludes farm tractors).
[i] Excludes military consumption and all lubricants.
[j] Rough estimate derived by extrapolating 1980-2000 growth of modes, for which 2010 forecast is not shown.

by 10-year intervals from 1980 to 2010. For highway modes, significant improvements in fuel efficiency result in declining consumption for light-duty vehicles and only modestly rising consumption for heavy-duty vehicles despite substantial increases in VMT. This is shown most clearly in Table 4, which provides average fuel economy (in miles per gallon) and percentage of fuel economy improvement by vehicle size and fuel type for each of the forecast years. The fuel economy improvement of light-duty vehicles is more than twice that of heavy-duty vehicles, largely because of already achieved progress in response to mandated fuel economy standards, some size shifts (primarily toward the compact light truck for personal use and the small automobile), and increased diesel penetration. Between 1980 and 2010, the share of diesels in the automotive and personal light truck fleets rises from less than 1 percent to nearly 10 percent. The percentage of diesels in the commercial truck fleet increases as follows:

Truck Type	1980	2010
Light (Classes 1 and 2)	1	28
Medium (Classes 3 to 5)	2	54
Light-heavy (Class 6)	10	88
Heavy-heavy (Classes 7 and 8)	83	100

The increased penetration of diesel automobiles and personal light trucks is attributable to the characteristics of the diesels represented in the vehicle choice model that are equal in performance (i.e., horsepower per pound), have only moderately higher maintenance and capital costs, and achieve significantly better fuel economy than their gasoline counterparts. All future diesel automobiles are assumed to be turbocharged. For commercial trucks, increases in diesel use are an input to the forecasting process and are based on historical trends in stocks and sales, fuel price assumptions, and technology forecasts from the literature (17-20).

The following are highlights of the ANL-83N forecast:

- The automotive fleet is projected to stabilize at about 40 percent small (including two-seat minicompacts), 40 percent medium, and 20 percent large (including sports and specialty models).
- By 2010, "equal performance" turbodiesels are projected to represent nearly 10 percent of automotive and personal light truck stocks, assuming a diesel fuel wholesale price somewhat higher than that of gasoline and comparable tax rates.
- With nearly flat post-1985 improvements in the efficiency of new automobiles, fuel economy is projected to rise to a fleet average of 27.7 mpg in the year 2000 and 29.1 mpg in 2010.
- Because of slower economic growth, rising fuel prices, and an aging population, post-2000 travel by private vehicles (passenger car and light trucks) is projected to grow at only 0.9 percent per year, compared with 2 percent per year from 1980 to 2000. Nonetheless, automotive energy use falls

TABLE 4 Fleet Average Fuel Economy by Vehicle Size Class and Fuel Type, ANL-83N Forecast

Size Class and Fuel Type	On-Road Fuel Economy (mpg)				Improvement, 1980-2010 (%)
	1980[a]	1990	2000	2010	
Automobile	15.2	22.7	27.7	29.1	91.4
Small	18.7	27.6	33.2	34.7	85.6
Medium	15.2	22.4	27.2	28.4	86.8
Large	13.1	18.8	22.8	24.0	83.2
Gasoline	15.1	22.6	27.4	28.7	90.1
Diesel	21.5	31.2	36.1	38.5	79.1
Truck	9.8	13.3	14.9	15.3	56.1
Personal light[b]	13.0	19.6	23.2	24.6	89.2
Gasoline	12.9	19.3	22.7	23.8	84.5
Diesel	17.0	23.7	27.6	30.1	77.1
Commercial light (Classes 1 and 2)	14.0	17.2	20.4	21.7	55.0
Gasoline	14.0	17.0	19.3	19.9	42.1
Diesel	17.0	20.9	24.2	26.0	52.9
Medium (Classes 3 to 5)	7.0	8.3	8.9	9.3	32.9
Gasoline	7.0	8.2	8.5	8.7	24.3
Diesel	7.3	8.8	9.5	9.8	34.2
Light-heavy (Class 6)	5.8	6.8	7.6	8.0	37.9
Gasoline	5.8	6.4	6.7	6.9	19.0
Diesel	6.0	7.2	7.8	8.1	35.0
Heavy-heavy (Classes 7 and 8)	4.9	6.1	6.6	6.8	38.8
Gasoline	4.4	4.9	5.2	5.2	18.2
Diesel	4.9	6.1	6.6	6.8	38.8

[a]The low variation in historical gasoline versus diesel truck fuel economy within size classes is attributed to relatively more demanding mission requirements for diesel vehicles. With increased diesel use by vehicles with less demanding missions, average diesel fuel economy should increase and the gasoline versus diesel variation should widen.
[b]Includes mini-vans.

through 2000 as fuel economy improvements outstrip growth in travel demand.

• Assuming 1983 NEPP trends in general economic conditions and the rate of household formation, and also assuming an aging population, the forecast indicates that the number of automobiles in use should grow from 104.6 million in 1980 to 150 million by 2000 and 167.3 million by 2010. Light trucks (including mini-vans) should grow from 30.1 million in 1980 to 45.8 million by 2000 and 49.6 million by 2010. Again, changes in household demographic characteristics produce faster growth during the years 1980 to 2000 than post-2000 (1.8 and 1.2 percent annual growth for 1980 to 2000 versus 1.1 and 0.8 percent for 2000 to 2010 in numbers of automobiles and personal light trucks).

• Truck use is projected to become increasingly associated with the service sector and pickup-and-delivery portions of intermodal movements.

• Improvements in the energy efficiency of trucks--as a result of both shifts from gasoline to diesel engines and technical improvements in engines, drivetrains, aerodynamics, and rolling resistance--are projected to restrain the growth in truck energy consumption in the near-term future. In the longer term, growth will resume in the absence of more radical improvements not considered in this forecast.

• Given anticipated increases in coal production and use, continued growth in intermodalism for domestic and international shipments, and cost and service competition in a deregulated environment, rail is projected to capture an increasing share of freight traffic.

• Because of few improvements in energy efficiency, rail and maritime energy consumption are projected to grow at much the same rate as rail and maritime ton-miles.

• Excluding coal and chemicals, the production of bulk commodities (especially ores and petroleum) is projected to grow much more slowly than production of manufactured goods. Thus, rail and truck ton-miles grow faster than domestic maritime ton-miles.

• Assuming no further development of coal slurry pipelines, pipeline energy consumption is projected to decline.

• Air travel (as measured in revenue passenger-miles) is projected to grow at annual rates of 1.5 percent for domestic flights and 2.9 percent for international flights between 1980 and 2000. However, because of significant improvements in aircraft fuel efficiency (due to operational improvements and to introduction of technologies now under development in NASA's Aircraft Energy Efficiency Program), energy consumption declines by 0.3 percent annually for domestic travel and grows by only 1.6 percent annually for international travel.

The more significant macroresults of the forecast concern the growth trajectory of total consumption and the changing mix of fuels consumed by the transport sector. As can be seen in Table 3, although total consumption declines through about 1990, it then begins to rise at an increasing rate (reaching 1 percent annually between 2000 and 2010). This is largely attributable to near-constant fuel efficiency for highway vehicles. Fuel efficiency is not a high priority either among the populace or in public policy. Although energy prices rise substantially, particularly after 1990, the price shocks of the 1970s do not recur and there is no major push for fuel-efficient technology. As a result, efficiency improvements already at or very close to commercialization enter the market, but there is little further development. This relative flattening of post-2000 energy intensities can be seen in Table 4.

Figure 1 shows the changing mix of fuels consumed by the transportation sector. Gasoline (including avgas) declines sharply from nearly 65 percent of sectoral consumption in 1980 to 49 percent in 2000 and 46 percent in 2010. Diesel fuel nearly doubles its share of sectoral consumption (from 13.7 percent in 1980 to 26.9 percent in 2010) and more than doubles in quantity (from 2.8 quads in 1980 to 6.0 quads in 2010). Diesel growth is particularly strong between 1990 and 2000 as technical improvements in trucks become less of a factor, and strong coal growth increases rail diesel consumption. Jet fuel use rises only moderately--because of increased seating densities, high load factors, and new fuel-efficient aircraft--as does its share of sectoral consumption (from 10.7 to 11.8 percent by 2010, ad-

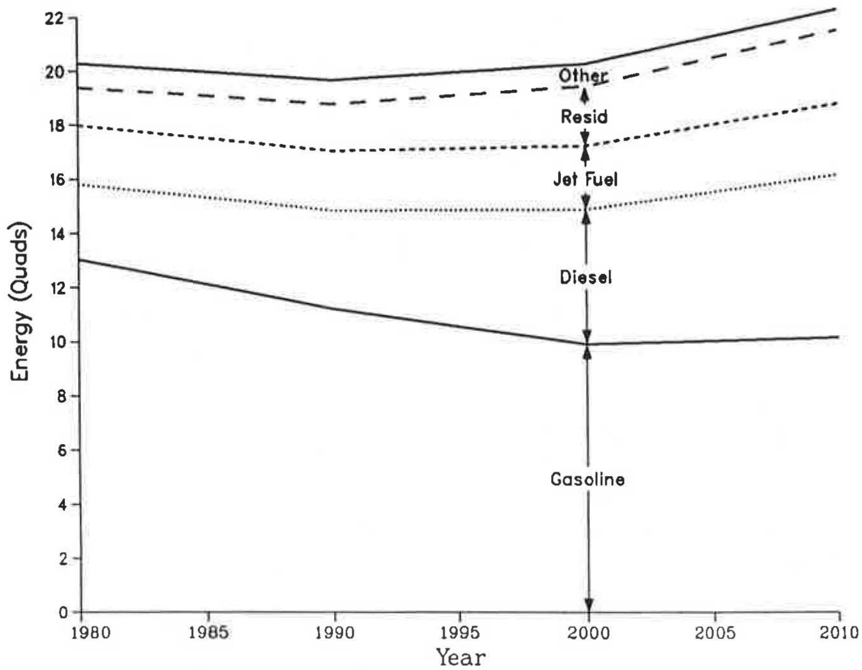

FIGURE 1 Transportation energy use by fuel type: ANL-83N forecast (all U.S. purchases, including military).

justed to include military and foreign-flag purchases in the United States). Use of residual fuel rises steadily because of increased foreign trade and no assumed improvements to maritime fuel efficiency or changes in bunkering practices (see later discussion). "Other" fuel use--primarily natural gas and electricity for pipeline compressors, and small amounts of electricity for rail passenger modes--remains stable through 2000, then declines because of a reduction in shipments of natural gas and petroleum products.

As stated earlier, the TEEMS package is driven by a combination of (a) 1983 NEPP forecasts of fuel price, general economic conditions, household formation, and energy supply, and (b) DRI's spring 1983 forecasts of personal income and economic activity of nonenergy sectors (5). In two key areas, the assumptions in these driver models combine to produce surprising results:

1. The ANL-83N forecast of personal vehicle stocks, VMT, and energy consumption is significantly greater than that of a 1981 ANL forecast that used the same methodology (3) (see Table 5 for the ANL-83N stock forecast). The difference is due to demographics; the year 2000 population is approximately 3 percent greater in the later effort and the number of households (the most significant parameter in our models) differ by nearly 12 percent. Although a higher number of households reduces median household income (estimated from the economic aggregate, personal income), which tends to depress vehicle purchase and use, this downward effect is more than offset by the shear number of households available to own and use vehicles.

2. In the ANL-83N forecast, rail freight activity (TMT) grows by more than 150 percent between 1980 and 2010 (a compound rate of 3.2 percent annually and rail freight energy use grows nearly as fast (3.1 percent annually). Assuming that rail maintains its current share of the freight market, one would expect rail TMT to grow at nearly the same rate as the overall economy, that is, about 110 percent (2.5 percent annually). The "excess growth" is largely attributable to (a) the 1983 NEPP coal forecast (1,286 million tons produced in 1995), which is 15 percent higher than the National Coal Association's medium-growth forecast, (b) the authors' assumption

TABLE 5 Projection of Motor Vehicle Stocks, ANL-83N Forecast

Vehicle Type and Size Class	Vehicles (x10^6)[a] 1980	1990	2000	2010	Avg Annual Change, 1980-2010 (%)
Automobiles	104.56	129.33	149.97	167.26	1.58
Small	28.38 (27)	42.14 (33)	56.03 (37)	63.90 (38)	2.74
Medium	38.81 (37)	52.47 (41)	58.19 (39)	66.78 (40)	1.83
Large	37.37 (36)	34.72 (27)	35.75 (24)	36.58 (22)	−0.07
Trucks[b]	34.17	44.11	50.58	56.44	1.69
Personal light	19.14	25.86	29.29	30.45	1.56
Commercial light	11.00	13.48	16.47	19.19	1.87
Medium	0.85	1.03	1.26	1.47	1.84
Light-heavy	1.68	2.03	2.50	2.93	1.87
Heavy-Heavy	1.50	1.71	2.06	2.40	1.58
Total	138.73	173.44	201.55	223.70	1.61

[a]Numbers in parentheses represent percent share among the three size classes.
[b]Includes mini-vans and government vehicles.

that all coal production above the historical high of some 580 million tons will come from western sources with an average rail length of haul comparable with that of western coal in 1978, and (c) an above-average growth (the average is 2.5 percent annually) for such relatively heavy rail users as chemicals and transportation equipment manufacturers (5,15,21).

FORECAST COMPARISONS

In addition to NEPP and ANL, two other forecasts of transportation energy use have been released in the past year: the Energy Information Administration (EIA) forecast contained in the 1983 Annual Energy Outlook and DRI's latest TREND84 forecast from their spring 1984 Energy Review (22-24). The following comparisons focus on energy consumption by fuel type and by type of highway vehicle (i.e., automobile, light truck, and heavy truck) and on the technical, economic, and other factors responsible for much of the variation among the forecasts.

Consumption by Fuel Type

Table 6 compares the four energy forecasts by fuel type. With the exception of the 1983 NEPP forecast, the most striking feature of this comparison is the consensus regarding total sectoral consumption. As can be seen in Figure 2, gasoline and diesel consumption trends also stand out as areas of strong agreement (because of variations in base-year estimates among the sources, the indices shown are relative to the 1980 values reported by each source). Jet fuel consumption trends are somewhat more dispersed, partly because of differences in passenger travel demand forecasts and partly because of different assumptions regarding the introduction and penetration of new fuel-efficient aircraft. Most dispersed of all are the residual fuel trends (Figure 3), which range from a 1990 low of 56 percent of 1980 consumption in the EIA forecast to a high of 124 percent in the ANL forecast and maintain a similar spread in the year 2000. This divergence is due to differences in modeling scope; in the ANL forecast, demand for residual fuel is solely a function of increased shipping activity, and the share of fuel purchased in the United States is assumed to remain at historical levels. In the EIA, NEPP, and DRI forecasts, shipping competes with other demands for residual fuel (most notably for power generation and refinery feedstock), and overseas purchases satisfy an increasing share of demand. Although price controls undoubtedly distorted the 1980 share of bunker fuel purchases in the United States (producing a significant but unknown amount of "double-bunkering"), the 1981 to 1983 world recession has probably exacerbated the post-1980 decline in U.S. bunker sales. It is hoped that with monthly data for 1984 indicating a firming in U.S. bunker sales, residual fuel forecasts can be revised shortly to reflect current (and presumably stable) fuel purchasing patterns (25).

Consumption by Vehicle Type

In all four forecasts, automobile energy use is projected to decline through about the year 2000, and truck energy is projected to rise continuously during the forecast period. This may be seen in Figure 4 where, again because of considerable variation in base-year estimates, consumption values have been indexed to the source's 1980 estimate. Although automobile and truck energy use show consistent trends across the four forecasts, there are major differences in rates of increase (or decrease), time frames in which rates of change begin to increase or decrease, and absolute growth over the forecast period. These differences can be attributed to variations in the respective stock and activity forecasts, price effects, and technological assumptions.

Stock Forecasts

Three of the four forecasts estimate motor vehicle stocks as an intermediate output. Because NEPP uses a stock model driven by DRI's forecast of new automobile and truck sales, the NEPP and DRI results are

TABLE 6 Recent Forecasts of Transportation Energy Use by Fuel Type, 1980-2000

	1980				1990				2000[a]		
Fuel Type	ANL-83N	NEPP-83	EIA-83[b]	DRI-TREND84	ANL-83N	NEPP-83	EIA-83	DRI-TREND84	ANL-83N	NEPP-83	DRI-TREND84
Gasoline	13.05		12.71	12.46	11.22		12.24	11.89	9.89		10.63
Motor gasoline	12.98	12.5	12.65	12.40	11.15	9.3	12.14	11.83	9.81	8.4	10.57
Aviation gasoline	0.07		0.06	0.06	0.07		0.10	0.06	0.08		0.06
Jet fuel	1.52[c]	2.2[d,e]	2.18[d,e]	2.20[d,e]	1.54[c]	2.3[d,e]	2.61[d,e]	2.62[d,e]	1.66[c]	2.4[d,e]	3.13[d,e]
Diesel	2.77		2.78	2.55	3.61		3.54	3.58	4.96		4.91
Highway	1.98	2.0			2.58	2.9			3.59	4.1	
Rail	0.55				0.76				1.06		
Water	0.21				0.23				0.28		
Off-highway and other	0.03				0.03				0.04		
Residual fuel[d]	1.40	2.3[e,f]	1.40	1.01	1.74[g]	2.2[e,f]	0.78	0.95	2.21[g]	1.9[e,f]	1.10
Natural gas	0.65	0.7	0.63	0.61	0.64	0.7	0.92	0.56	0.61	0.6	0.54
Electricity	0.24[h]	–	0.01	0.01	0.24[h]	–	0.01	0.02	0.24[h]	0.1	0.02
Renewables	–					0.1				0.2	
Liquefied gases			0.01	0.01			0.01	0.01			0.01
Total	19.61 19.82[i]	19.7	19.72	18.86	18.99 19.20[i]	17.5	20.45	19.63	19.55 19.78[i]	17.7	20.32

Note: Forecast energy use is expressed in quads (10^{15} Btu).

[a]The EIA-83 forecast extends only to 1995.
[b]1980 estimates from DOE *(24)*.
[c]Fuel purchases in the United States by domestic carriers only. Excludes military consumption.
[d]Fuel purchases in the United States by domestic or foreign-flag carriers.
[e]Includes military consumption.
[f]Includes nonhighway diesel fuel.
[g]Assumes historic foreign-flag shares of U.S. bunker fuel sales.
[h]Includes consumption of oil pipeline compressors.
[i]Including all military consumption and excluding electricity use by pipeline compressors.

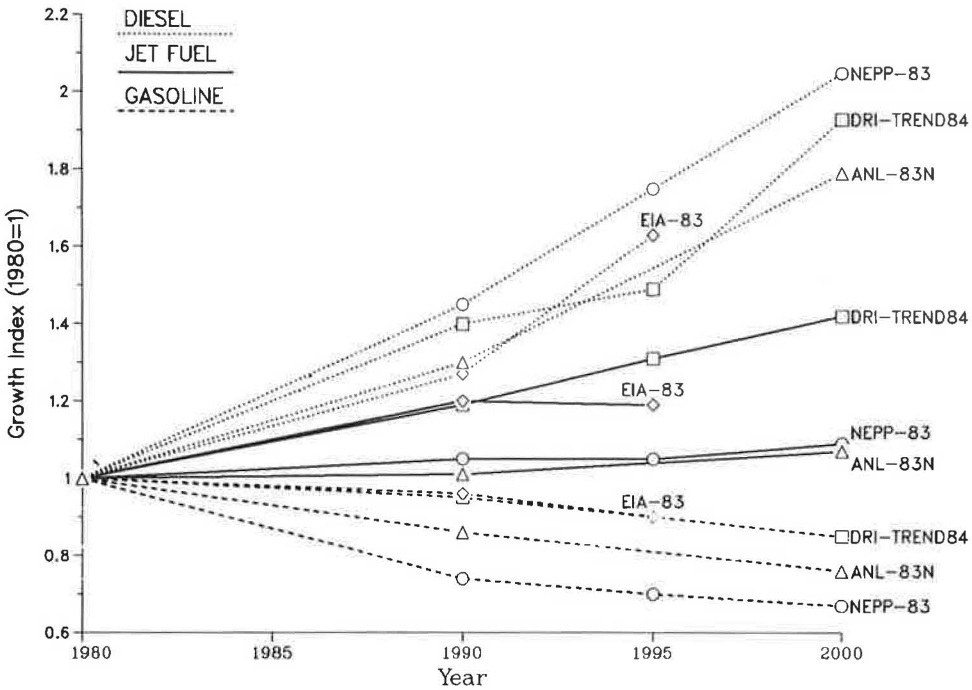

FIGURE 2 Trends in gasoline, diesel, and jet fuel demand in the transportation sector under four forecasts.

nearly identical. Small variations in the early years are due largely to differences in vehicle scrappage assumptions.

ANL's heavy truck stocks grow at much the same rate as DRI's but automobile and light truck stocks differ markedly (see Figure 5). As can be seen in Figure 6, this is largely a difference in market shares; in ANL-83N, automobiles capture a larger share of the light-duty market than in the DRI or NEPP forecasts. The similarity in light-duty stock forecasts can also be attributed to comparable economic trends: 2.54 percent annual GNP growth for 1980 to 1995 in the EIA forecast versus roughly 2.6 percent annually between 1980 and 2000 (2.65 percent for 1980 to 1995) in the other three forecasts.

Activity Forecasts

As shown in Figure 7, ANL's forecast of truck VMT growth is the lowest, and automobile VMT growth the highest, of the four forecast efforts. This is at-

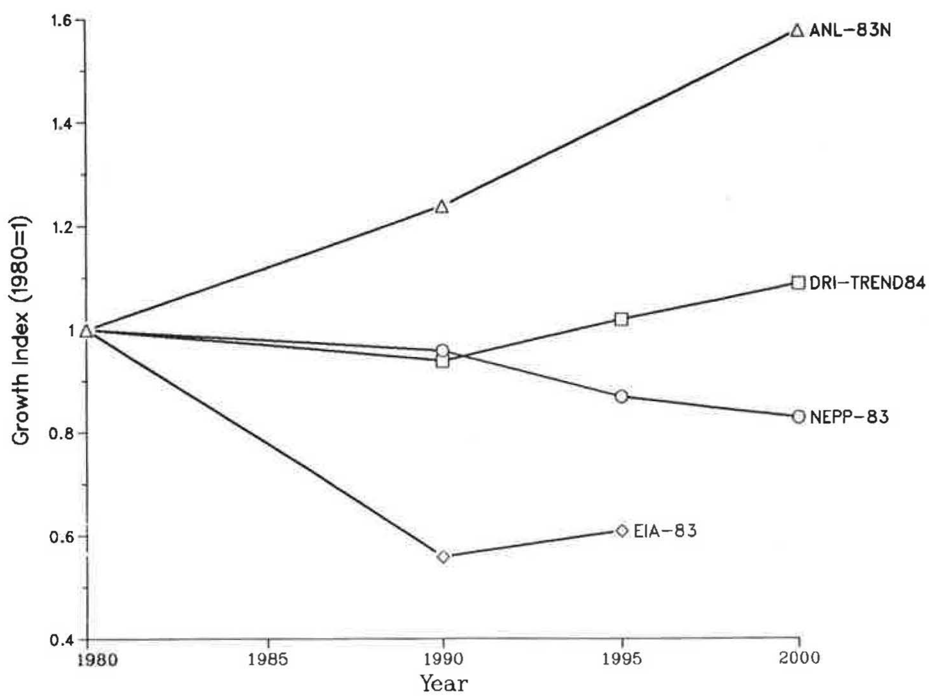

FIGURE 3 Trend in residual fuel demand in the transportation sector under four forecasts.

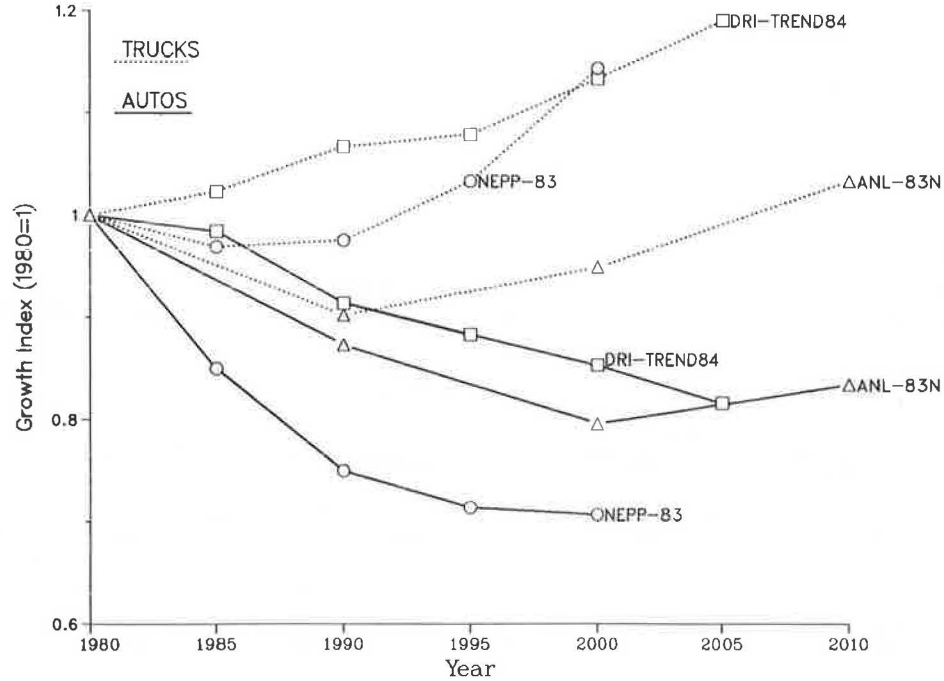

FIGURE 4 Trends in automobile and truck energy use under three forecasts.

tributable to the stock forecasts discussed earlier as well as to fairly high cost-of-travel assumptions that further depress truck VMT (see the following discussion). EIA's VMT forecasts are considerably higher than the others', partially because of technological assumptions that reduce the cost of travel and, perhaps, to relatively high price elasticities.

Technological Assumptions

Fuel economy may improve as a result of (a) shifts in consumer behavior induced by high price or uncertain fuel availability, (b) shifts in production or marketing emphasis induced by corporate or public policy (e.g., from gasoline to heavy diesel trucks), or (c) technological development in general. All these factors appear to have influenced the four forecasts.

As shown in Figure 8, the DRI forecast assumes the lowest gasoline price in the year 2000 (about $1.50/gal versus $2.00/gal in the other efforts) and sustained price moderation thereafter. Given this low market incentive, DRI also assumes the lowest automotive fuel economy: 25.4 mpg in the year 2000

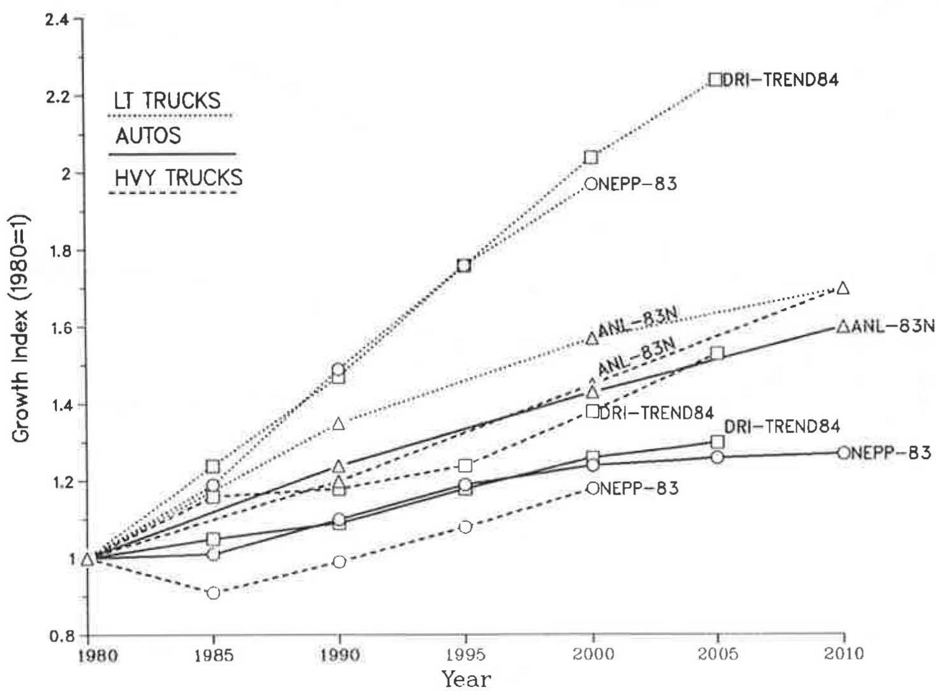

FIGURE 5 Trends in motor vehicle stocks by type under three forecasts.

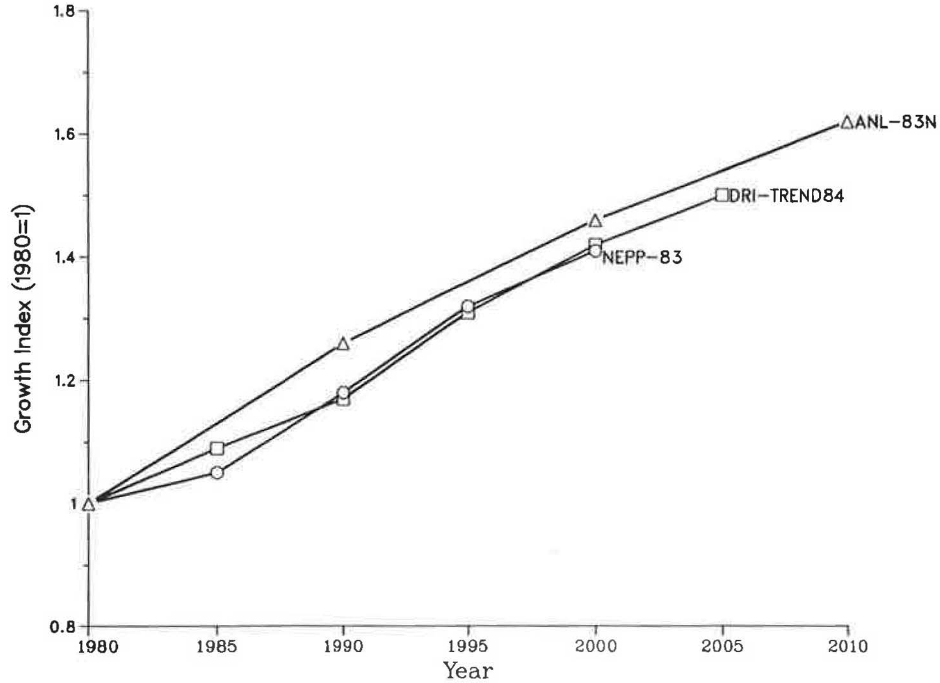

FIGURE 6 Trends in light-duty vehicle stock under three forecasts.

(see Figure 9). The combined effects of much lower-priced fuel and somewhat lower mpg produce substantially lower fuel operating costs (see Figure 10). DRI evidently assumes a fairly low price elasticity (or, conversely, the other forecasts assume a high price elasticity), because automobile and truck VMT are not appreciably higher in the DRI forecast.

At the other extreme, NEPP assumes the highest fuel economy improvement (automotive mpg rises from 15.15 in 1980 to 32.6 in 2000 and 34.3 in 2010, and truck mpg increases from 8.1 in 1980 to 14.4 in 2000), which also moderates the cost impact of rising fuel prices. EIA assumes a fairly high mpg improvement, particularly for trucks (although automobiles rise to 27.9 mpg, trucks rise from 10.2 mpg in 1980 to 17.5 by 1995). Because the EIA forecast appears particularly sensitive to travel cost, the resulting reduction in travel costs (at least through 1990) sharply increases VMT. By contrast, with the lowest truck and nearly the lowest automobile improvement, the ANL forecast has relatively high travel costs and reduced rates of VMT growth.

With comparable fuel prices, the variation in fuel economy among ANL, EIA, and NEPP must arise

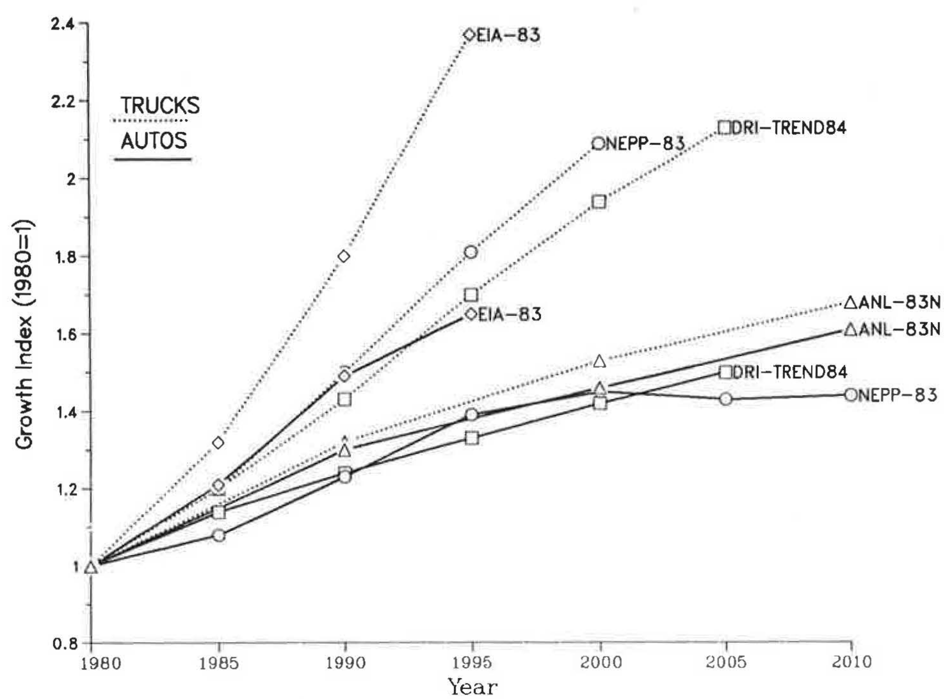

FIGURE 7 Trends in automobile and truck VMT under four forecasts.

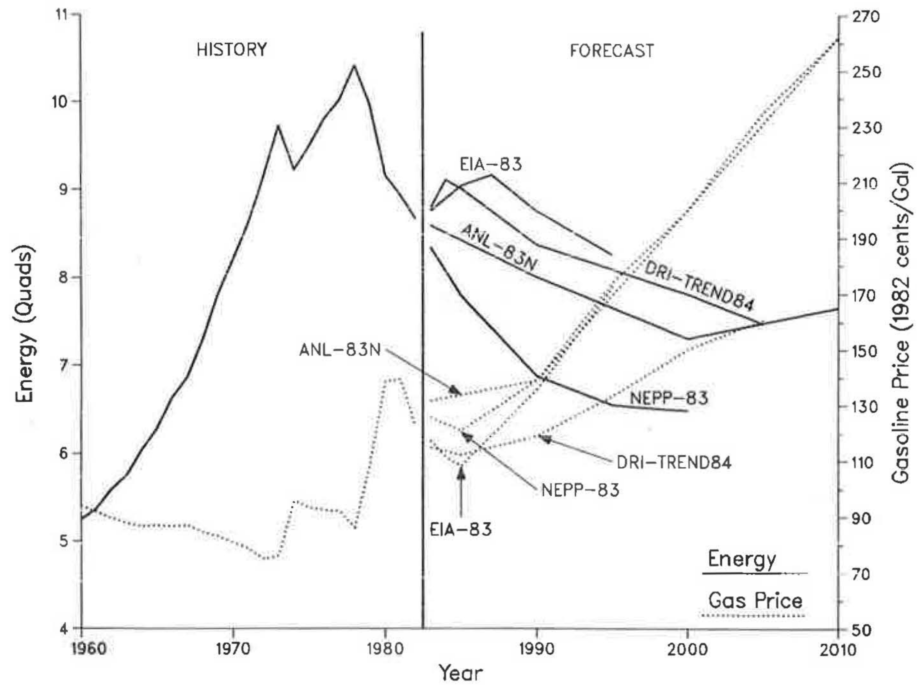

FIGURE 8 Automobile energy use versus gasoline price under four forecasts.

from assumed differences in either production and marketing emphasis or technological development. Although both are difficult to measure, one indicator of production and marketing shifts likely to influence fuel economy is the diesel share of automobile and truck fuel use. As shown in Figure 11 for those sources reporting consumption by fuel type (DRI, NEPP, and ANL), estimated diesel shares for the year 2000 vary no more than those for 1980. Diesel penetration is therefore probably not a factor in explaining mpg differences.

Rather, the rate of technological development appears to be the major influence. Although researchers agree that technological progress does not occur in a vacuum, its relationships with such other factors as fuel price, disposable income, R&D expenditures, and consumer preferences are not well understood. Recent evidence suggests some stability in consumer preferences for such vehicle attributes as interior volume and performance (which strongly influence fuel economy) and a possible trade-off between increased (or decreased) vehicle operating

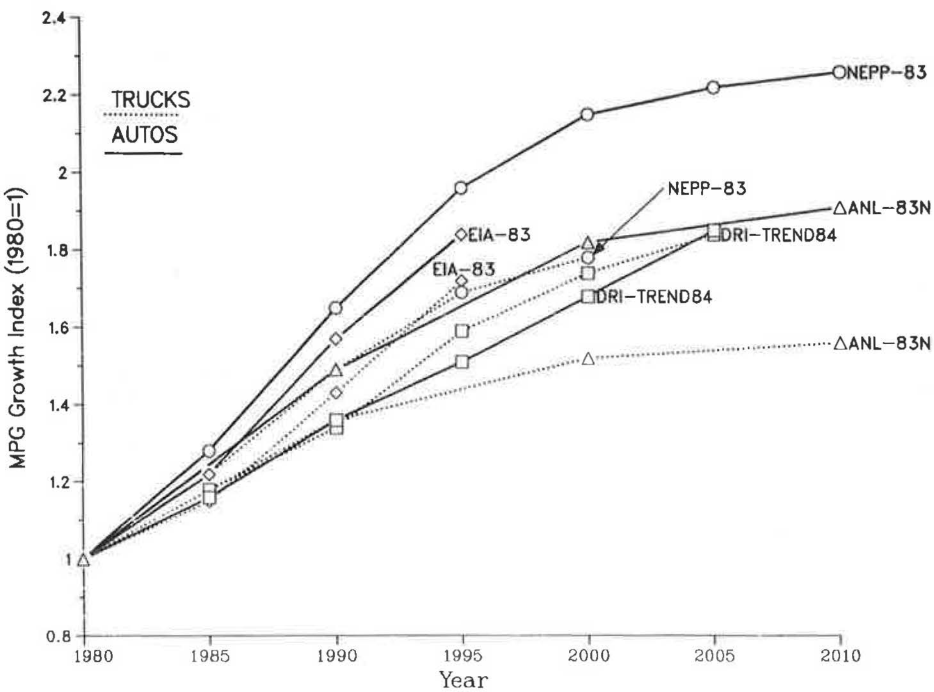

FIGURE 9 Improvements in automobile and truck fuel economy under four forecasts.

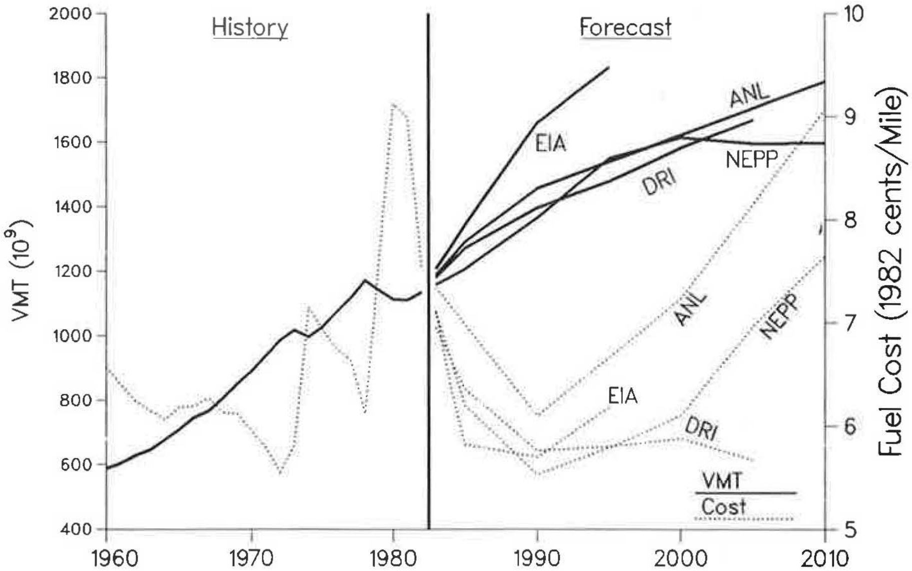

FIGURE 10 Automobile VMT versus fuel cost per mile under four forecasts.

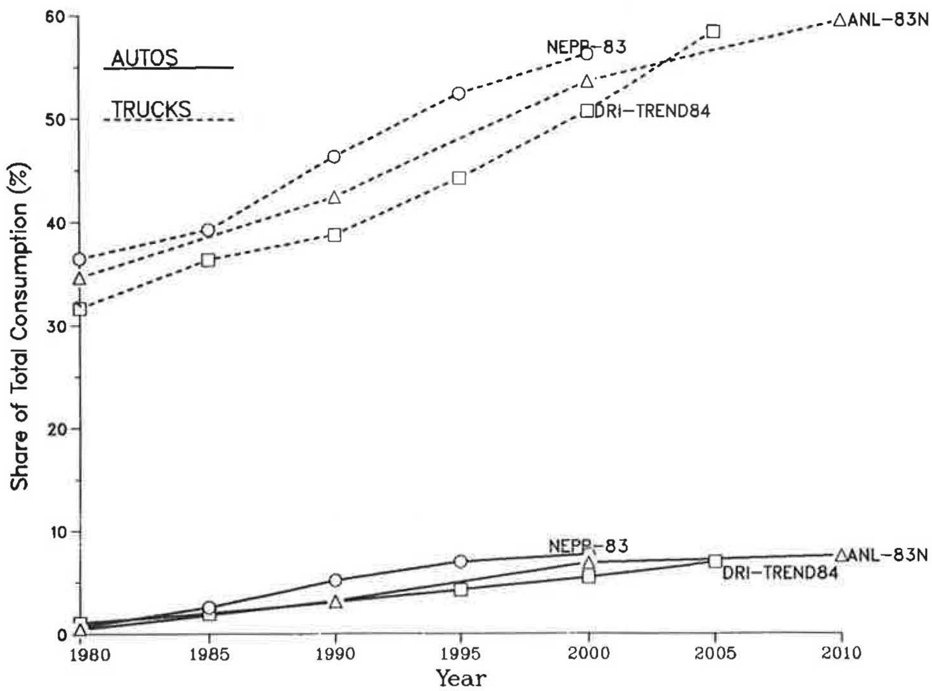

FIGURE 11 Diesel share of automobile and truck fuel use under three forecasts.

costs and purchase prices. However, these findings have not yet been incorporated into an explicit formulation of technological development as a function of fuel price and macroeconomic parameters (26,27). Although each of the efforts discussed here relies on some model of the fuel economy impact of various technological improvements and the diffusion rates of new technology into the vehicle fleet, engineering assumptions--not behavioral modes--dictate the technological "menu" that is presumed to be available in the marketplace at any given time. Thus, observed differences in the rate of technological development among the four forecasts relate solely to engineering perspective (i.e., whether and when a particular improvement is technically possible) and vehicle replacement assumptions (i.e., how quickly the fleet of old-technology vehicles is replaced by new-technology vehicles). Moreover, because fuel economy improvement is primarily responsible for the fuel consumption differences among the forecasts, these two factors--engineering perspective and vehicle replacement assumptions--also explain much of the overall variation among the forecasts.

CONCLUSIONS

The ANL-83N forecast indicates moderate growth in transport activity levels over the long-term future. Energy use declines through 1990 because of the continued effect of fuel economy improvements already achieved in highway vehicles and under development

TABLE 7 Selected Energy-Use Ratios, ANL-83N Forecast

Parameter	1980	1990	2000	2010
Transportation energy				
10^6 Btu/capita	86.96	75.96	72.95	75.94
10^3 Btu/\$GNP (\$1982)	6.43	4.78	3.83	3.34
Passenger transport energy[a]				
10^6 Btu/capita	56.98	46.52	41.00	40.23
10^3 Btu/passenger-mile	5.13	3.57	3.32	NA
Freight transport energy[a]				
10^9 Btu/\$GNP	2.17	1.81	1.64	1.53
10^3 Btu/ton-mile	1.61	1.42	1.35	1.32
Automobiles				
Automobiles/capita	0.46	0.52	0.56	0.59
Automobiles/household	1.31	1.28	1.29	1.34
Automobile VMT				
10^3 VMT/capita	4.93	5.83	6.05	6.32
10^3 VMT/household	14.06	14.43	13.99	14.30
10^3 VMT/automobile	10.63	11.27	10.82	10.69
Light-duty VMT				
10^3 VMT/capita	6.26	7.45	7.79	8.09
10^3 VMT/household	17.84	18.45	18.01	18.32
10^3 VMT/vehicle	10.48	11.05	10.67	10.56

Note: NA = not available.
[a]Domestic only.

for commercial aircraft. Beyond 1990, and particularly beyond the year 2000, growth in travel demand exceeds the rate of efficiency improvement, and consumption begins to rise. As shown in Table 7, transport energy intensity continues to decline on the basis of total Btu per GNP, but by 2010 it regains its 1990 level (87 percent of its 1980 level) on the basis of total Btu per capita. Freight Btu per ton-mile and passenger Btu per capita level off at 82 percent and 71 percent, respectively, of their 1980 levels.

The ratio of automobiles per capita apparently nears saturation--increasing at a decreasing rate--whereas that of automobiles per household fluctuates. Likewise, per-capita and per-household travel rates and vehicle utilization rates also fluctuate, primarily with changing fuel costs per mile.

Compared with other recent forecasts of long-term transportation energy use, the ANL forecast is not appreciably different as far as aggregate consumption is concerned. On a disaggregate level, however, there are differences between the ANL forecast and the NEPP, EIA, and DRI forecasts in fuel type distributions, light-duty market shares (i.e., between automobiles and light trucks), and fuel economy assumptions.

The most significant difference in consumption by fuel type occurs in the residual fuel forecasts. Although the ANL forecast is a function of projected waterborne trade, the other forecasts employ a macro orientation based on supply, demand, and sectoral allocation. Differences in light-duty market shares also arise largely from orientation, demographics produce relatively greater automobile growth (and slower light truck growth) in the ANL forecast compared to the macro relationships that produce greater light truck growth in the other forecasts. Differences in fuel economy assumptions are less readily categorized, but appear to stem from the engineering models used as input to the forecasts.

The forecasting effort itself and the comparison of the four forecasts suggest the following:

• Because a forecast provides a means of making decisions, and is not an end in itself, the level of detail should be in accordance with its intended use (in the ANL case, for assisting in planning and evaluating energy conservation programs). Given its relatively specific purpose, the ANL-83N forecast has considerably more detail on transport (including nonhighway modes not discussed here) than the other forecasts.

• The absolute numbers in a forecast are less important than the trends revealed and the sensitivity of results to key assumptions. Forecasting has risen to prominence as a strategic planning tool for (a) determining that range of conditions under which a particular decision produces desirable results and (b) thereby identifying those relatively low-risk or "robust" alternatives with desirable outcomes across a wide range of assumptions. Depending on the precise task at hand, each of the four forecasts serves this general purpose.

• The basic assumptions and other exogenous inputs in a forecast are nearly as important as the methodology used. While the forecasts discussed earlier employed significantly different methods, their aggregate results are relatively consistent because many of their economic and demographic inputs are similar. Many differences can be attributed to price (and perhaps income), elasticity of travel demand, and fuel economy assumptions.

• Technological forecasting is not well integrated into transportation energy forecasting. While the latter generally incorporates substantial socioeconomic detail, technological forecasts are largely devoid of such input. An explicit linkage between the engineering models used to forecast technological development and the socioeconomic assumptions of the forecast would surely improve the quality and consistency of results.

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The Potential Market for Electric Vehicles: Results from a National Survey of Commercial Fleet Operators

MARK R. BERG

ABSTRACT

Successful commercialization of electric vehicles has been hindered by a lack of data pertaining to both desirable vehicle configurations and potential market size. The objective of the study on which this paper is based was to redress these data inadequacies pertaining to commercial sector fleet vehicles through information obtained from fleet managers about vehicle travel requirements, cost and range trade-offs, and operational practices. The study was commissioned by the Electric Power Research Institute and the Detroit Edison Company as part of their ongoing research agendas that focus on electric over-the-road vehicles (EVs). The study's findings with respect to the size and characteristics of the potential market for electric vehicles in commercial fleets are presented. Information is given on fleet size, range requirements, and vehicle use patterns. In addition to general information about commercial fleets, the data are analyzed in terms of key factors associated with EV performance, such as miles traveled per day, availability for recharging, and the need for high-speed travel. Data for the study were obtained through telephone interviews with fleet managers in commercial establishments throughout the United States. A total of 583 interviews were conducted during 2 months of the fall of 1983. The probability sample of establishments was drawn from a comprehensive list compiled by Dun and Bradstreet. Because scientific sampling procedures were used, it was possible to translate the sample data into estimates for the entire nation with known degrees of precision.

Although electric-powered vehicles date to the earliest part of the automobile age, they have never gained prominence as a means of over-the-road transportation. Although emerging technology has enhanced their potential to do so, successful commercialization has been hindered by a lack of data pertaining to both desirable vehicle configurations and potential market size. The objective of the study on which this paper is based was to redress these data inadequacies pertaining to commercial sector fleet vehicles through information from fleet managers about vehicle travel requirements, cost and range trade-offs, and operational practices. The study was commissioned by the Electric Power Research Institute (EPRI) and the Detroit Edison Company as part of their ongoing research agendas, which focus on electric over-the-road vehicles (EVs).

In this paper the study's findings with respect to the size and characteristics of the potential market for EVs in commercial fleets are presented. Information is presented on fleet size, range requirements, and vehicle use patterns. In addition to general information about commercial fleets, the data are analyzed in terms of key factors associated with EV performance, such as miles traveled per day, availability for recharging, and the need for high-speed travel.

STUDY DESIGN

A probability sample of establishments was drawn from a comprehensive list compiled by Dun and Bradstreet. Fleet managers in establishments throughout the United States were contacted by telephone and 583 interviews were conducted during 2 months of the fall of 1983. The overall response rate for these interviews was 92 percent. Because scientific sampling procedures were used, it was possible to translate the sample data into estimates for the entire nation with known degrees of precision. To the extent that there is systematic bias in the data (because of undercoverage in the list used for sampling), estimates of market potential reported here can be considered conservative. A complete discussion of the survey, sample, and procedures can be found in the final project report (1).

MARKET POTENTIAL VERSUS MARKET PENETRATION

In a discussion of the market for electric vehicles in commercial fleet operations, two different but related issues should be distinguished: the size of the potential market, and possible EV penetration into it. An extreme upper boundary on the potential market for commercial EVs is the total number of commercial vehicles in use. A more practical definition of market potential, and the one used for this study, recognizes that EVs available in the near-term future cannot substitute for all commercial vehicles because of such performance characteristics as limited range and speed, and recharging requirements.

Market penetration, the degree to which EVs capture the potential market, must take additional market-limiting factors into account. Some of these are specific to EVs and some are more general and affect the adoption of many innovations. As shown in the following list, factors that influence market penetration tend to be more qualitative and uncertain than those that define market potential. Market penetration will be affected by

- The costs of purchasing, operating, and maintaining EVs compared with conventional vehicles;
- The cost of electricity and the cost and availability of petroleum fuels;
- The quality and reliability of services provided by the EV infrastructure (e.g., the availability of repair facilities and parts);
- Attitudes and perceptions about the benefits of EV adoption (e.g., their quiet and clean operation, low maintenance, and protection against oil cut-offs);
- Attitudes and perceptions about the risks of EV adoption (e.g., their inability to meet all performance requirements, their unproven track record, their uncertain battery life, and the existence of a limited and immature infrastructure); and
- Organizational and individual resistance to changes made necessary by the adoption of EVs.

This study concentrated on market potential and touched only indirectly on likely penetration. The primary reason for this was that potential buyers cannot be expected to provide accurate information about whether they would purchase EVs or conventional vehicles under different sets of circumstances because they do not have, and indeed cannot have, any real experience with EVs in commercial fleet operations. It should be recognized, for example, that even commercial EV users in the U.S. Department of Energy (DOE) EV Demonstration Program have not had experience with EVs in a context that simulates mass market EV quality and infrastructure (2).

Furthermore, it is unfortunately true that there is no adequate theory to guide the estimation of the extent to which EVs might actually penetrate their potential market. Readers differ substantially in the assumptions they make regarding technology, price elasticities, individual and institutional resistances to change, future energy prospects, and commercial vehicle requirements. Because these varying assumptions must be thought of as largely educated guesses, the following data are presented in a manner that permits the reader to estimate market potential under alternate assumptions of potential EV range and other attributes.

CHARACTERISTICS OF COMMERCIAL FLEET VEHICLES AND TRIP PATTERNS

Total Number of Vehicles

On the basis of data collected in the survey, the total number of light-duty, over-the-road vehicles in commercial fleets is estimated to be 12.7 million. Somewhat less than half of these (5.6 million) are cars and station wagons, and the remainder (7.0 million) are light-duty trucks and vans. These estimates are lower than many other previously published estimates of commercial vehicle fleet size (2-6). Although the nature of the sampling frame may have produced some mild undercounting, the sampling procedures used in the study are considered far more reliable than those employed by other data sources. Comparison across the different data sources is hindered by the problem of noncomparable definitions. As used in this study, the terms vehicles, cars, trucks, and vans refer to light-duty over-the-road vehicles of these types weighing less than 5,000 lb. Hereafter, the term "cars" should be understood to include station wagons.

Typical Mileage Patterns

The distribution of fleet vehicles by miles typically traveled in a day is shown in Figure 1. As is evident, approximately one-fifth (19.8 percent) of all light-duty over-the-road vehicles are typically driven less than 30 miles per day (mpd), and almost half (46.1 percent) are typically driven less than 60 mpd. Only about one-third (35.4 percent) are typically driven over 90 mpd, a range that makes them unlikely to be replaced by EVs in the near future, given existing trip patterns and the lack of infrastructural facilities that make opportunity recharging feasible.

As can also be seen in Figure 1, light-duty trucks and vans compose more than half of the vehicles in

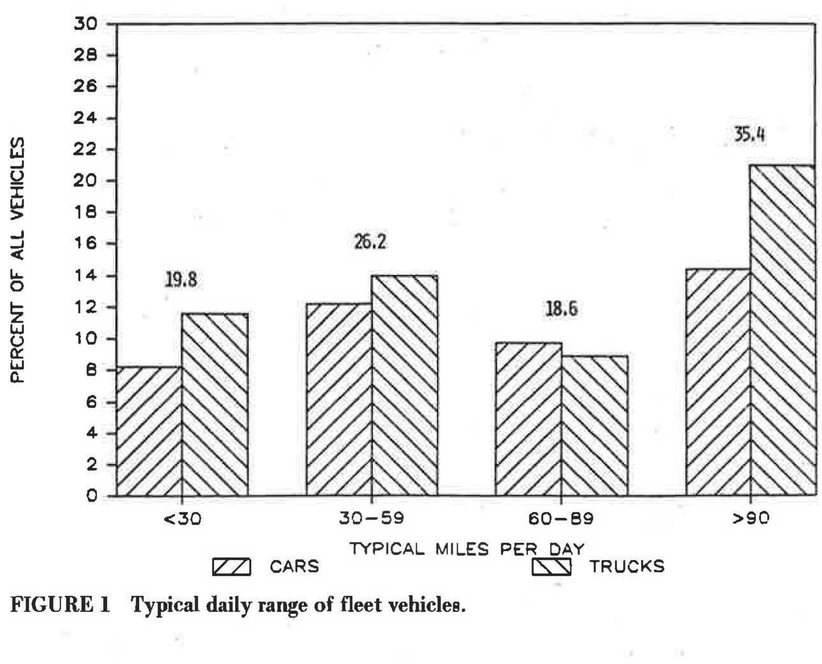

FIGURE 1 Typical daily range of fleet vehicles.

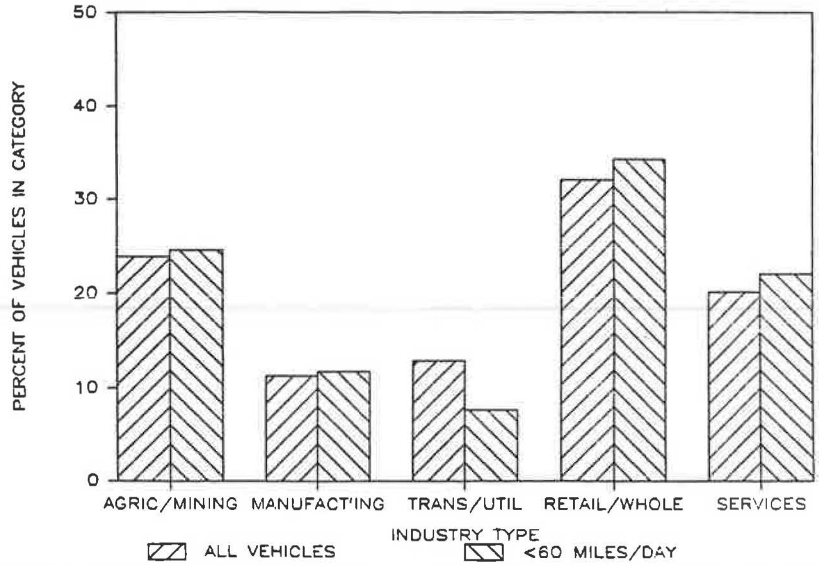

FIGURE 2 Distribution of vehicles by industry.

the two lower-mileage classes (they compose 59 percent of vehicles typically driven less than 30 mpd and 53 percent of those typically driven 30 to 59 mpd). Thus, in terms of vehicles typically traveling less than 90 mpd, the potential market for electric cars, trucks, and vans appears to be substantial (65 percent of all commercial vehicles). Based solely on this mileage criterion, market potential is somewhat greater for trucks and vans than for cars.

Industry Type

If those vehicles typically driven less than 60 mpd are defined as having potential for near-term EV substitution, the next issue from a market perspective is the industries in which they are concentrated. Figure 2 shows the industrial distributions of all light-duty over-the-road vehicles and those typically driven fewer than 60 mpd. As is evident, these two distributions are quite similar. This suggests that EV marketing should be directed toward the same industries as those toward which internal combustion engine (ICE) vehicle marketing is currently directed.

Currently, the primary users of ICE vehicles and potential users of EVs are retailers and wholesalers (32.1 percent of low-mileage vehicles) followed by construction, agricultural, and mining establishments (23.9 percent of all vehicles and 24.6 percent of low-mileage vehicles). In terms of numbers of vehicles, the least promising industries for EV adoption are those in the transportation, communications, and utility sectors. Of interest, however, is a related finding that the relatively limited number of vehicles in these sectors may be offset by a higher-than-average willingness to consider using EVs on the part of their fleet managers.

Fleet Size

Figure 3 partitions the data by fleet size and shows that about half (50.5 percent) of all light-duty

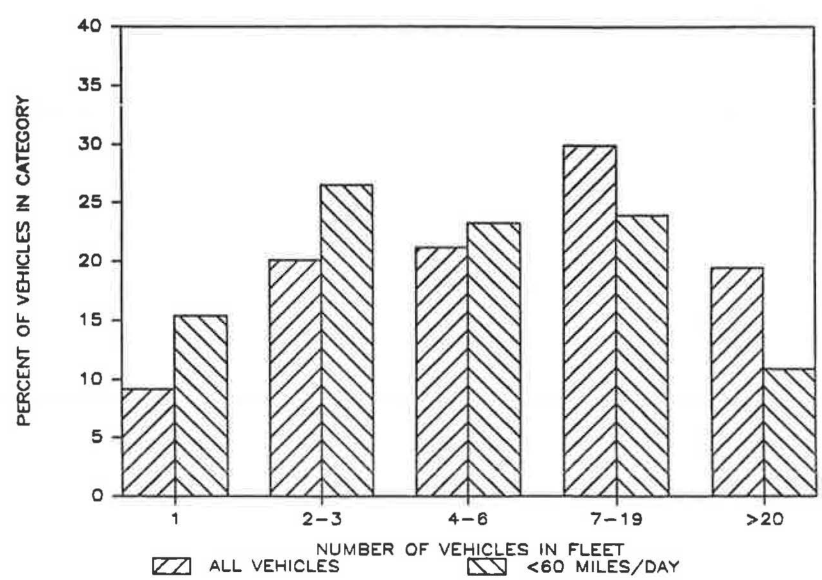

FIGURE 3 Distribution of vehicles by fleet size.

over-the-road vehicles are in fleets with six or fewer vehicles. These smaller fleets, however, account for approximately two-thirds (65.2 percent) of all low-mileage vehicles. In other words, low-mileage vehicles tend to be concentrated in relatively small fleets. Although large fleets (those with more than 20 vehicles) account for about one-fifth of all commercial vehicles (19.5 percent), only about half of these have trip patterns commensurate with the expected mileage limitations of EVs.

Ability to Modify Trip Patterns

The discussion has thus far centered on proportions of vehicles typically driven less than 30, 60, or 90 mpd. But typical low-mileage usage is not a sufficient mileage criterion for EV substitutability; occasional, but nonetheless necessary, high-mileage trips would render such EV substitution unfeasible. Thus, two further mileage attributes must be considered: whether typical low-mileage vehicles are occasionally driven more than the likely EV maximum range, and if they are, whether different vehicles could be used to make the occasional higher-mileage trips.

The data given in Table 1 indicate that although 20 percent of all vehicles in commercial fleets are typically driven less than 30 mpd, over half of these (56 percent) must occasionally be driven beyond the 30-mi range. Looking next at the 26 percent of all vehicles typically driven between 30 and 60 mpd, over half (59 percent) are occasionally driven over 60 mpd and over two-fifths (41 percent) are occasionally driven over 90 mpd.

TABLE 1 Mileage Attributes of Light-Duty Commercial Cars and Trucks Typically Driven Less Than 90 mpd

Attribute	Typical Daily Mileage (mpd) <30	30-59	60-89
Estimated no. of vehicles (millions)	2.5	3.3	2.3
Percent of all vehicles in commercial fleets	20 (±4)[a]	26 (±4)	18 (±3)
Average mpd traveled	17	44	72
Occasional higher-mileage trips (%)			
>30 mpd	56	na[b]	na
>60 mpd	38	59	na
>90 mpd	na	41	60

[a]All ± values given in this report represent 95th percentile confidence ranges.
[b]na = not ascertained.

A comparison of mileage patterns for cars and trucks shows them to be relatively similar; however, cars are more likely to take occasional longer trips than trucks.

Although the occasional need for longer trips could substantially reduce EV substitution potential, a closer review of the data provides a somewhat different perspective. Overall, 46 percent of the fleets had vehicles that averaged less than 60 mpd, but that occasionally traveled more than this range. About 25 percent of all vehicles fell into this category. However, 21 (±6) percent of these establishments indicated that it would be quite easy to assign the longer trips to other vehicles, and another 16 percent said that it would not be difficult to do so. In terms of vehicles (rather than establishments), approximately 21 percent of the vehicles surveyed never had to travel over 60 mpd, and the trip patterns of an additional 9 percent (25 x 37 percent) could be somewhat easily modified to remain within a 60-mi range. Overall, then, the trip patterns of 30 percent of the commercial fleet could be structured, with little or no change, to never exceed a range of 60 mpd. Although the 30 percent figure represents a reduction of one-third from the 46 percent of all vehicles that typically do not exceed 60 mpd, it still represents over 3.5 million vehicles.

Fixed Routes

Another dimension of range variance that could affect EV substitution potential is the extent to which low-mileage vehicles are assigned to fixed routes. For example, in the case of EVs with a 60-mpd range, fixed routes of just under 60 mpd would be excellent candidates for EV substitution because the probability that vehicles would have to exceed the maximum mileage limits would be greatly reduced. In this regard, however, the number of vehicles with fixed route assignments does not provide cause for great optimism, especially with respect to cars. Only 4 percent of cars and 20 percent of trucks typically driven 30 to 60 mpd (see Table 2) are currently assigned to fixed routes. Although not a large percentage even for trucks, this suggests that as many as half a million light-duty trucks operate on fixed routes of less than 60 mpd.

Mileage, of course, is not the only criterion affecting EV substitutability. Fleet managers were therefore asked a number of questions about other use patterns of relatively low-mileage vehicles that would affect substitutability. The responses to these questions, presented in Table 2, allow market potential to be estimated under more refined assumptions of substitutability.

Frequent Stops and Starts

One advantage of EVs relative to ICE vehicles is their efficiency in situations requiring frequent

TABLE 2 Selected Use Attributes of Commercial Vehicles

Attribute	Typical Daily Mileage (mpd) Cars and Wagons <30	30-59	60-89	Trucks and Vans <30	30-59	60-89
Stopped more than 100 times/day with engines running (%)	2	12	29	9	9	36
Engines stopped and restarted more than 20 times/day (%)	1	8	37	11	27	51
Compact or smaller (%)	22	15	19	11	8	15
Assigned to fixed routes (%)	na	4	5	na	20	5
Left on company premises overnight (%)	na	21	25	na	66	68
Parked 2 or more hours at a time during day	na	82	78	na	90	69
Average miles driven at >40 mph	na	5.8	8.0	na	3.4	11.2

stops during which engines are left running, or where engines are frequently stopped and restarted. With regard to these two stop/start patterns, current low-mileage car usage is not overly favorable. Only 2 percent of cars typically driven less than 30 mpd and 12 percent of cars typically driven between 30 and 60 mpd are stopped with their engines left running more than 100 times a day. The numbers for trucks--9 percent for each mileage category--are somewhat more favorable in terms of EV market potential.

With regard to engine stopping and restarting, the outlook for electric trucks is considerably better than for electric cars. Eleven percent of trucks typically driven less than 30 mpd, and 27 percent typically driven between 30 and 60 mpd, stop and restart their engines more than 20 times a day. This represents over 500,000 light-duty trucks and vans. The comparable percentages for cars are only 1 and 8 percent, respectively, or fewer than 150,000 vehicles.

Vehicle Size

Most EV designs to date have been built around relatively small and light (exclusive of batteries) body shells. To the extent that ICE vehicles with relatively low mileage requirements are also small, the potential for EV substitution is enhanced. As can be seen in Table 2, the percentage of low-mileage cars that are compact or smaller models is relatively low (22 percent of cars typically driven less than 30 mpd and 15 percent of cars typically driven between 30 and 60 mpd) as is the percentage of trucks (11 and 8 percent, respectively). Although this does not bode well for EV substitutability, it should be noted that the larger car and truck models currently in use might not be necessary from a functional standpoint. It is possible that compact or smaller models might be used equally well but, for some reason, they currently are not. This conjecture would certainly be suggested by the fact that only about 30 percent of all commercial trucks and vans typically carry payloads greater than 500 lb. Furthermore, only 38 percent of all truck and van payloads are considered especially large for their weight (i.e., have relatively large volume).

Availability for Recharge

Because EVs require "overnight" (6- to 10-hr) recharging, market penetration is more likely if recharging is a straightforward and easily initiated task. Although EVs could be recharged wherever there is access to electricity, it would clearly be more convenient (from the perspective of metering and facilities) to have them charged on company premises. In this regard, electric trucks appear to be far more promising than electric cars because approximately two-thirds (66 percent) of light-duty trucks and vans driven between 30 and 60 mpd are parked on company premises overnight, whereas only one-fifth (21 percent) of comparable cars remain on the premises overnight.

Vehicles typically traveling as many as 90 mpd could be replaced by EVs if parked long enough to permit opportunity recharging. Such recharging, of course, depends on the availability of recharging facilities, but the infrastructure is unlikely to be in place if the need is not demonstrated. In this regard, data are extremely encouraging. Over four-fifths (82 percent) of cars typically driven 30 to 60 mpd and three-fourths (78 percent) of those typically driven 60 to 90 mpd are parked for 2 or more hours at a time during the day. The numbers are equally optimistic for trucks and vans (see Table 2). Opportunity recharging would not make near-term EVs a viable alternative for vehicles traveling more than 90 mpd or less than 30 mpd. Therefore, in the interest of brevity, information about overnight and daytime parking was not obtained for these groups.

High-Speed Driving Requirements

Finally, EV range performance is typically better in situations that do not require extensive travel at speeds exceeding 40 mph. In this regard, data are quite encouraging for EV adoption. Cars typically driven 30 to 59 mpd average only 5.8 mpd at speeds exceeding 40 mph; comparable trucks average 3.4 mpd. Not surprisingly, higher-mileage vehicles (60 to 89 mpd) tend to be driven longer at these speeds (8.0 mi for cars and 11.2 mi for trucks).

The general picture that emerges from these statistics is that the potential market for EVs tends to be substantial, even under the assumption of some fairly stringent technological constraints. Of the two classes of vehicles studied, trucks appear to be more likely candidates for EV substitution than cars although neither type should be ruled out in terms of market potential.

Types of Vehicles Applications

Of concern from an EV design standpoint is what EVs are likely to be used for. To address this question, fleet managers were asked to what uses their low-mileage vehicles were applied. The type of applications vary quite widely with vehicle type, but only slightly with range. This is, cars and trucks are used for considerably different purposes, whereas the use patterns are relatively similar for vehicles in the less-than-30-mpd group and the 30- to 60-mpd group. Figure 4 shows the data for vehicles typically traveling less than 30 mpd. For cars typically traveling less than 30 mpd and for those typically traveling between 30 and 60 mpd, the most frequently mentioned use was for business appointments followed by commuting and use as executive vehicles. Also frequently mentioned was use for making pickups and running errands. The most common use for low- and relatively low-mileage light-duty trucks and vans was hauling and dumping (including snow removal), followed by commuting to and from jobs and making deliveries.

VEHICLE SUBSTITUTION CRITERIA

As indicated earlier, the maximum potential for substitution by EVs is in large part determined by the match between EV performance and the actual requirements of fleet vehicles. As the range, speed, and acceleration performance of EVs increase, so does the number of conventional commercial vehicles that might be replaced by EVs. In the previous section the use patterns of vehicles that fell within two alternative range specifications for future EVs (i.e., less than 30 mpd and less than 60 mpd) were examined. Each of these range specifications can be thought of as the first criterion for judging whether an EV might be substituted for a particular commercial vehicle.

In this section the 30- and 60-mpd criteria plus two additional substitution criteria are considered. The first is a more broadly defined criterion referred to as 60 mpd+, within which are all vehicles traveling less than 60 mpd plus those traveling

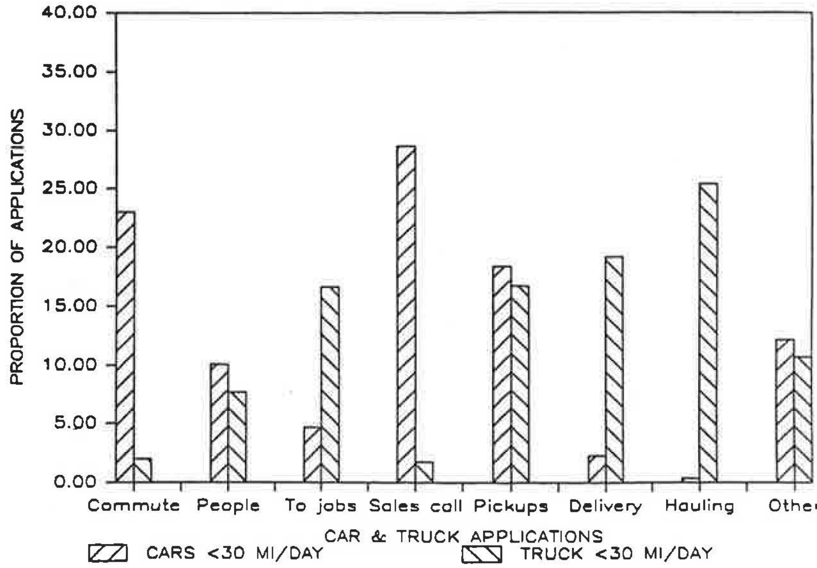

FIGURE 4 Applications for cars and trucks.

between 60 and 90 mpd that are parked for 2 or more hours during the day, and that also travel less than 8 mi at speeds greater than 40 mph. Falling within the second new criterion are those vehicles traveling less than 30 mpd plus those traveling between 30 and 60 mpd that are parked for 2 or more hours during the day, and that also travel less than 8 mi at speeds greater than 40 mph. This criterion is referred to as 30 mpd+. Electric vehicles parked for 2 or more hours could potentially extend their daily range capability through opportunity recharging (7). Similarly, EVs subject to only limited high-speed travel would have a greater overall range capacity.

The following analysis identifies the extent to which the trip patterns of existing vehicles can be met by EVs that have performance levels corresponding to the four criteria of 60 mpd+, less than 60 mpd, 30 mpd+, and less than 30 mpd. The analysis focuses on the total number of vehicles falling within each criterion.

Market Potential as Measured by EV Substitution Criteria

It will be recalled from the earlier discussion that the total number of light-duty, over-the-road commercial fleet vehicles was estimated to be roughly 13 million. As can be seen in Figure 5, over 7 million vehicles fall within the broadest substitution criterion (60 mpd+), and over 2.5 million fall within the narrowest criterion (less than 30 mpd). If only compact and subcompact vehicles are considered, as is done in the right-hand portion of Figure 5, the corresponding numbers are roughly 1.5 million and 0.4 million.

Although even the most conservative 0.4 million figure would represent quantity production from a manufacturing standpoint, the range of 0.4 million to 7 million is very large from a business planning standpoint. This uncertainty in the size of the potential EV market is a reflection of the vehicle

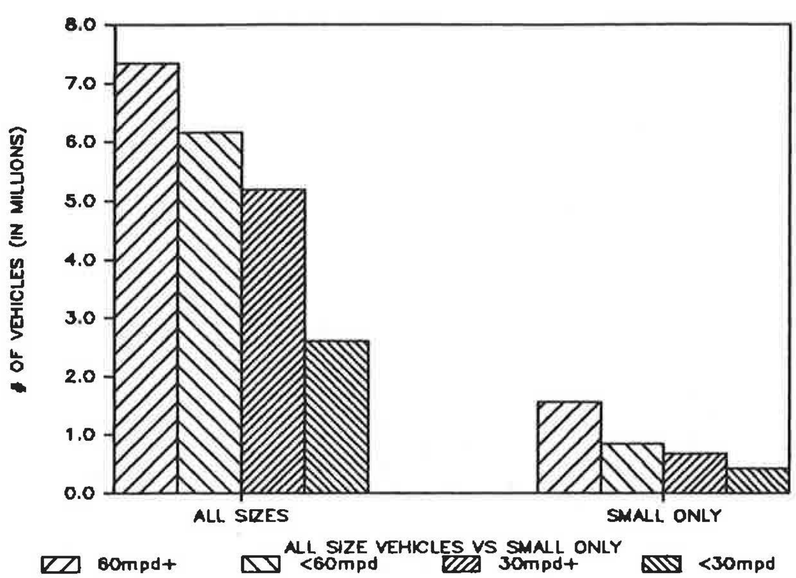

FIGURE 5 Maximum EV substitution potential under alternative substitution criteria: all size vehicles versus small only.

range assumptions built into the four substitution criteria. It is important to recognize then that future choices with respect to EV performance specifications are not just technical decisions. They are also choices about the size of the potential EV market.

Characteristics of the potential EV market are examined in the following section along other dimensions relevant to the marketing and vehicle specification choices that would need to be made for successful commercialization to occur. The findings are broken down in terms of fleet size, vehicle type and size, percentage of trucks in fleet, truck payload, regional differences, and industry groupings.

FLEET CHARACTERISTICS AFFECTING MARKET POTENTIAL

Fleet Size

As shown in Figure 6, the largest overall market for EVs is composed of moderate-sized fleets comprising 2 to 19 vehicles. This group represents about 75 percent of all vehicles falling within the EV substitution criteria. Of interest is that the large fleets (20 or more vehicles) represent only 5 to 10 percent of the commercial sector market for EVs.

High EV Substitution Potential of Trucks and Vans

The data suggest that light-duty trucks and vans represent the most promising initial market for EVs. The number of vehicles falling within each of the substitution criteria increases substantially with the percentage of trucks and vans in the fleet. Among fleets with no trucks or vans, for example, just under 1 million vehicles fall within the broadly defined 60 mpd+ criterion. By contrast, fleets composed of 75 to 100 percent trucks and vans contain over 2.5 million vehicles that meet the criterion. A similar pattern holds for each of the four criteria. Overall, less than 15 percent of all vehicles with

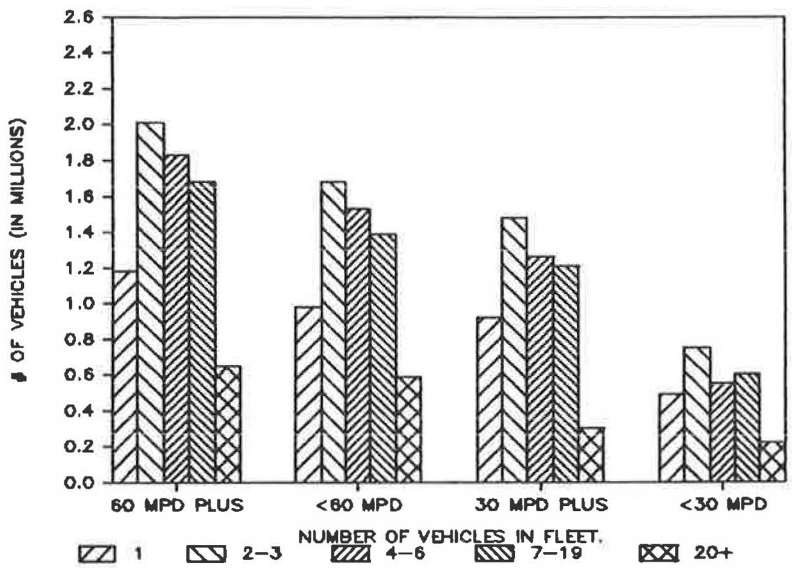

FIGURE 6 Maximum EV substitution potential under alternative substitution criteria: number of vehicles in fleet.

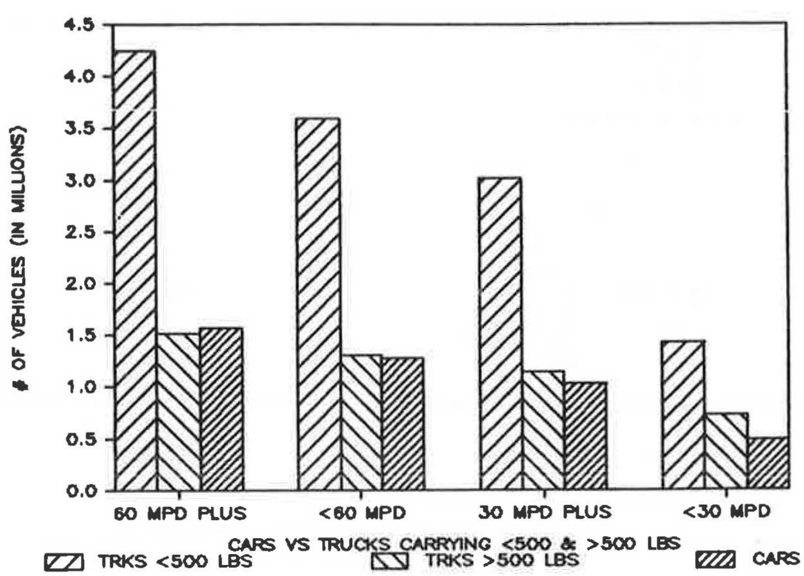

FIGURE 7 Maximum EV substitution potential under alternative substitution criteria: cars versus trucks carrying <500 lb and >500 lb.

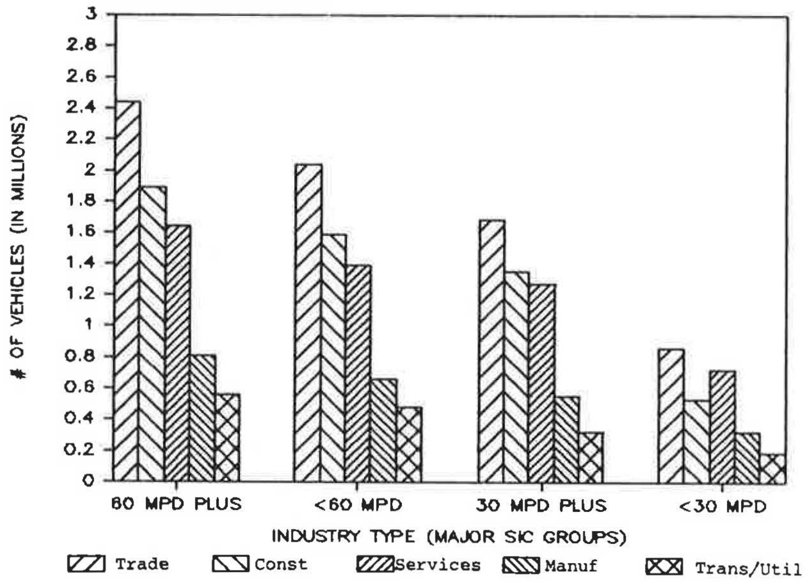

FIGURE 8 Maximum EV substitution potential under alternative substitution criteria: industry types.

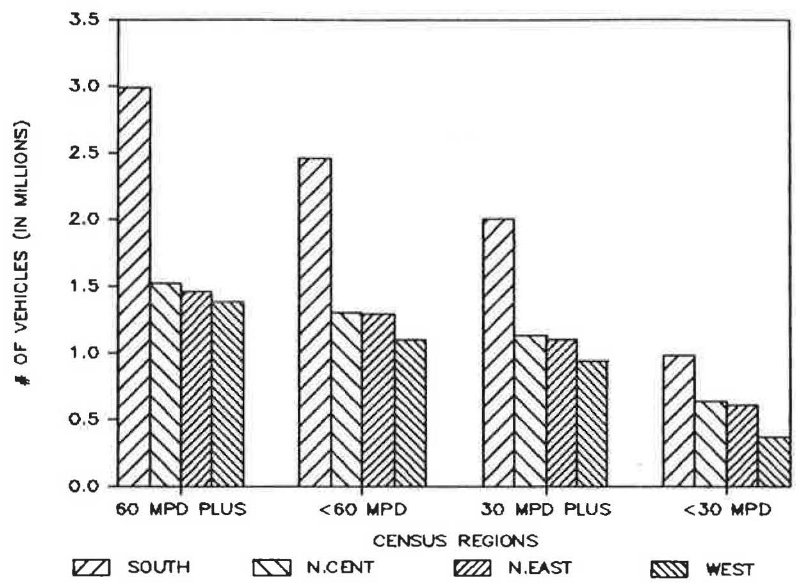

FIGURE 9 Maximum EV substitution potential under alternative substitution criteria: census regions.

high substitution potential reside in fleets having no trucks or vans.

Related evidence for the important role of trucks and vans is found in Figure 7, which divides all of the light-duty vehicles into three groups: trucks and vans carrying less than 500 lb of payload, trucks and vans carrying more than 500 lb of payload, and cars. Trucks and vans that typically carry payloads of less than 500 lb account for over 50 percent of all vehicles that fall within the high substitution potential criteria. In terms of number of vehicles, this group represents over 4 million vehicles within the 60 mpd+ criterion, and almost 1.5 million vehicles within the narrowly defined less than 30 mpd criterion. Overall, trucks and vans represent approximately 80 percent of all vehicles with high substitution potential as defined by the four criteria.

EV Substitution Potential by Industry Type

Figure 8 organizes the data in terms of the number of vehicles with high substitution potential in each of five major industry groupings: wholesale and retail trade; construction, mining, and agriculture; services; manufacturing; and transportation, communication, and utilities. The relative number of vehicles in each of the five groups shows a generally stable pattern across the four criteria. This suggests that design choices about range will not significantly change the types of industries in which EVs have their greatest, or least, appeal. Overall, the trade, construction, and services sectors show the most promise for EV substitution.

EV Substitution Potential by Region

Figure 9 examines the distribution of vehicles with high substitution potential within four major census regions of the United States. Notice that the four range criteria show noticeable differences in the regional relationships. In the case of the 60-mpd+ criterion, for example, the South, with nearly 3 million vehicles, shows twice as many high-potential vehicles as does any other region. Furthermore, with about 1.5 million vehicles each, the north central, the northeast, and the western regions all show about equal potential. These patterns change significantly, however, if the vehicle range is limited to less than 30 mpd. In this case, the northern industrial states composing the northeast and north central census regions show a combined potential considerably higher than the South. In addition, the West shows considerably lower potential than any of the other regions. The significant change in pattern as range drops below the 30-mpd level appears to reflect the higher density that characterizes the northern industrial region in contrast to the West and South.

SUMMARY

The results reported in this paper suggest that a quite sizable potential market for electric vehicles does exist in the commercial sector based on currently existing patterns of vehicle usage. Depending on the eventual performance capabilities of production EVs, the potential market could be expected to be between 2.5 million and 7 million vehicles. Although many factors are likely to reduce actual market penetration to a level significantly below this market potential range, the data tend to support the view that, based on functional criteria, quantity production of a reliable and economical electric vehicle is a realistic objective.

ACKNOWLEDGMENT

The author wishes to thank his colleagues Muriel Converse and Daniel Hill of the Institute for Social Research, who were coauthors of the project report from which much of this paper is drawn. Their considerable skills and efforts were important and integral elements in the successful completion of the study.

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Alternative Fuels for Buses: Current Assessment and Future Perspectives

ARNOLD J. BLOCH and LOUIS J. PIGNATARO

ABSTRACT

The issue of alternative fuels for transit buses is examined from the perspective of the 1980s and beyond. At a time when federal involvement in alternative fuel development is of lesser significance and marketplace actions appear to be of greater value than government intervention or investment, it is relevant to examine the objectives of developing diesel fuel alternatives for public transportation vehicle use. Four fuel groups are evaluated: alcohols, vegetable oils, methane (or natural gas), and hydrogen. An assessment is made of current development status and conclusions are presented regarding future research efforts.

The issue of alternatives to petroleum-based fuels has been around as long as the internal-combustion engine. However, in the 1970s a renewed and intensive effort was made to explore, develop, and test alternative fuels. The reason for this sudden surge of interest in nonpetroleum-based fuels is obvious: the tremendous uncertainty over oil price and supply due to the emergence of the Organization of Petroleum Exporting Countries (OPEC) as a powerful force. Before the 1970s, the only oil supply problems ever faced by the United States were related to military allocation of fuel during World Wars I and II. During the 1970s, the United States faced two supply disruptions, predicated by OPEC as a means of limiting worldwide oil production and thereby obtaining higher prices (as well as prolonging their own supply). Prices rose, not only because of these two disruptions but also because of a decade-long effort to maintain OPEC production quotas. U.S. oil prices had risen by only 7 percent for the entire 80-year period from 1890 to 1970 (in 1972 dollars). From 1970 to 1980, domestically produced crude oil, which was still subject to government price controls, rose by 250 percent (in constant 1972 dollars). The issue had clearly become one of U.S. vulnerability to a price and supply mechanism that it could no longer adequately control.

ALTERNATIVE FUELS IN THE 1980s AND BEYOND

Large segments of the alternative fuel research and development movement lost considerable financial and political support in the 1980s as a result of an altered oil supply and demand picture. Spurred by the major increases in worldwide oil prices in 1979 to 1980 and the deregulation of U.S. oil prices in 1981, worldwide production soared while consumption dropped. The result was an oil glut, beginning in the spring of 1981 and extending to this day, accompanied by lower oil prices and the diminished pricing and production influence of OPEC. U.S. oil production in 1982 was at its highest level in years. Suddenly, the urgency of alternative fuel development appeared to diminish and the boundary of economic competition appeared further away. Interest in synthetic fuels on the part of the federal government in particular decreased.

After 1985 the world is expected to increase oil consumption, and OPEC is simultaneously expected to regain significance as a determinator of oil prices and supply. This would once again create a situation ripe for oil price increases and supply disruptions. However, the United States and other nations appear better, although differently, prepared to handle future disruptions by using major petroleum storage reserves, international fuel sharing, and, at least in the United States, marketplace mechanisms. All these actions are intended to reduce the magnitude and duration of future disruptions, and to return to normal modes of international fuel trading as quickly as possible. Energy independence is therefore a lesser national and international goal of the 1980s and beyond, although reduced vulnerability and uncertainty remain important objectives.

Where does this leave alternative fuel development, particularly for transit buses? Basically, it can be assumed that federal involvement in alternative fuel research and development beyond 1985 will not reach the levels once expected. Furthermore, if the United States and developed countries are successful in reducing the disruptive influence of OPEC, then there clearly will be little need for any such involvement. On the other hand, the objectives of bus fuel research are still relevant because

- Contingencies may still occur and although the market mechanism may work well for private or individual oil consumers, government-sponsored transit services will face the double-bind of (a) being expected to continue to provide basic public services while (b) not having the financial means to do so;
- Environmental concerns persist and extend beyond the concerns of energy use;
- Transit systems face a further federal financial constriction, that of diminished operating subsidies, so there is greater pressure to improve productivity both from the services standpoint (e.g., articulated buses) and the maintenance standpoint--the coordination of improved productivity with more economical fuel is a natural link; and
- Finally, although the short-term payoffs may not be apparent, in an era of diminishing energy resources there are long-term benefits to serving public transportation needs with an appropriate and adequate level of energy.

POSSIBLE ALTERNATIVE FUELS FOR BUSES

Those fuels most often suggested as alternatives to bus fuels can generally be classified as liquid and gaseous. Liquid fuels include alcohols (namely methanol and ethanol) and vegetable oils. Gaseous fuels include methane, hydrogen, and other miscellaneous gases (e.g., ammonia and producer gas). Liquid fuels can be viewed as either diesel fuel extenders or diesel fuel substitutes. Gas fuels can be viewed only as diesel fuel substitutes. Some fuels require minor adjustments to current diesel-fuel bus engines, whereas others require major modifications or complete engine redesign.

LIQUID FUELS

Alcohols

Effectiveness

There is probably more published research on alcohol fuels than any other alternative fuel type. The most notable and accessible examples include general discussions of alcohols as transportation fuels (1-3); specific evaluations of alcohols as diesel fuel substitutes (4-7); and the economic and policy issues related to alcohol fuel development (7,8). Alcohols comprise carbon, hydrogen, and oxygen, whereas gasoline and diesel fuel are simply hydrocarbon fuels. Alcohols can be operated in diesel as well as spark-ignition engines, but the following serious problems must be considered:

- Energy content of alcohols versus diesel fuel;
- Cetane quality of alcohols versus diesel fuel;
- Compatibility of alcohols with diesel engine materials; and
- Alcohol fuel emissions.

Energy Content

The net heating values (by volume) reveal that the Btu contents of ethanol and methanol are 60 and 45 percent of that of diesel fuel, respectively. Therefore, the typical 100-gal fuel tank in buses would either have to be expanded or supplemented with an additional tank, or fueling procedures would have to be changed (i.e., multiple fuel fill-ups during the day).

Cetane Quality

Cetane quality is a key concern and requires one of many possible engine modifications. For diesel engines, where the fuel must ignite on compression, the ignition quality of a particular fuel is measured by the cetane number of the fuel. Simply put, the cetane number is a measure of ignition delay, or the time between fuel injection into the combustion chamber and fuel ignition. Current diesel fuels range from 40 to 60. A cetane rating of 15 is generally classified as a minimum baseline number, signifying poor ignition quality. Alcohols, in particular ethanol and methanol, have cetane numbers ranging from 0 to 8.

There are many possible solutions to the issue of poor cetane quality. Some involve fuel additives such as castor oil and nitrated compounds. Others recommend that alcohols only be blended with diesel fuel, although anything greater than a 10 percent blend of alcohol is likely to reduce the cetane level below manufacturers' specifications (1). Finally, others recommend engine modifications. In a recent report, the following five options to adapt U.S. diesel bus engines for methanol operation were analyzed (4):

1. Convert to Otto cycle engine,
2. Convert to Otto cycle engine and vaporized methanol,
3. Add spark ignition,
4. Add surface ignition, and
5. Add indirect, prechamber ignition.

The most promising option was surface ignition, which would involve the use of glow plugs in the combustion chamber to provide a hot surface to vaporize and ignite methanol shortly after injection. The use of these glow plugs may be conserved for cold starts and during the warm-up period.

Compatibility with Diesel Engine and Vehicle Materials

Diesel engines and diesel fuels are naturally compatible. Alcohols, on the other hand, could cause accelerated wear of diesel fuel systems and engine components (9). This is especially true if fuel additives are used. All nitrate compounds are particularly corrosive and prolonged use of castor oil can clog fuel injector tips (1,4). In European experiences, methanol rapidly diluted crankcase oil, requiring more frequent oil changes. Furthermore, methanol corrodes some materials contained in onboard fuel tanks, damaging the tanks and causing downstream deposits (ethanol will do the same for any diesel fuel-related deposits in fuel tanks). Both methanol and ethanol adversely affect most elastomeric (rubber) parts such as fuel-pump diaphragms and fuel hoses.

Alcohol Fuel Emissions

When a Volvo diesel engine operated under transit bus test conditions (although in a laboratory setting) was used, hydrocarbon and carbon monoxide emission levels were higher, and nitrous oxide and particulates were lower for both ethanol and methanol (10). However, a more recent report indicates that, for methanol at least, hydrocarbon emissions are less volatile than diesel-fuel emissions and less likely to cause smog, whereas carbon monoxide emissions vary considerably from test to test because of the relative leanness or richness of the fuel-air mixture (4).

Besides these emissions, which are regulated by the federal government, other relevant emissions include smoke (essentially nonexistent for alcohol fuels) and aldehydes. These emissions (particularly formaldehyde from methanol) are considerably higher for alcohols than for diesel fuel (4).

Development Potential

Economics of Fuel Production and Marketing

Diesel fuel prices currently average around $1.00 per gallon (especially for relatively large users such as transit systems). Ethanol prices range from 50 to 70 percent higher than that, whereas methanol is about 30 percent lower than the price of diesel fuel (11). Methanol is clearly the more cost-effective alcohol option, strictly on the basis of the price of fuel. Methanol costs even show signs of declining to a level nearly half that of diesel fuel.

Market Demand

Alcohols, particularly ethanol, have established a minor foothold in the U.S. transportation sector, primarily as a blend with gasoline. Nearly 10 percent of all the gasoline currently in the United States contains either ethanol or methanol (mostly ethanol) (12). Both, however, are used primarily for industrial purposes. Methanol, for example, is produced at a rate of more than 1 billion gal a year. In 1980 (the most recent year for which data are available), 95 percent of methanol was used as a chemical precursor for industry, 3 percent as a gasoline octane booster, and 2 percent as a direct fuel (13).

Other Interest in Development

Alcohol fuel development was pushed in the late 1970s by the federal government and a number of agricultural states, all of which were looking for alternative uses for various products (e.g., corn grain). Although federal involvement declined, state interest remains strong, particularly in agricultural states and some states with significant alternative energy programs and concerns such as California. Petroleum companies have shown growing interest in ethanol as a gasoline octane booster, but nearly all (except ARCO) reject the use of methanol for similar purposes.

Vegetable Oils

Effectiveness

Vegetable oils particularly lend themselves to applications in diesel engines. As early as 1931, researchers noted that the hydrocarbon structure of vegetable oils had a capacity for compression ignition in diesel engines. A wide range of vegetable oils are possible diesel fuel substitutes or blending agents, including corn, cottonseed, peanut, soybean, and sunflower oils. Most experimental research conducted in the last few years to determine the fuel potential of vegetable oil has centered on cottonseed and sunflower oils (in part because of the availability and market development potential of these oils) and has been confined to laboratory settings. Some of the concerns raised about alcohols do not pertain to vegetable oils, whereas others do.

Energy Content

Unlike alcohols, the Btu content of vegetable oils is relatively close to that of diesel fuel; sunflower and cottonseed oils, for instance, have approximately 90 percent of the Btu content of diesel fuel (14,15). As a result, the fuel volume and associated fuel tank requirements are not much greater than those of diesel fuel.

Cetane Quality

Also, unlike alcohols, vegetable oils have cetane levels much closer to those of diesel fuel. Indeed, cottonseed oil produced by the transesterification process (i.e., lowering the viscosity of the oil) exceeds diesel fuel cetane quality.

Cold Weather Performance

The cloud and pour points of vegetable oils are such that they create potential difficulties with cold weather operation (i.e., fuel flow will be irregular and slow). Significant cold-start problems arose in test temperatures of -1°C (30°F) and -7°C (20°F) when only a 50 percent blend of sunflower oil was used with diesel fuel (14).

Engine Compatibility

Engine durability is a key issue in the use of vegetable oil-based fuels in diesel engines. Vegetable oils have a greater propensity to leave behind carbon deposits after only short periods of operation. As considerable and fast-growing as these deposits can be, they do tend to be blown off to some extent during engine operation. Deposits in the piston and the cylinder liner are more stubborn, however, (and much greater than the amount produced by either diesel or alcohol fuels) because of the oiliness of the blend and the large droplet size of vegetable oils. Research reports point out, however, that deposits would vary among diesel engine designs (no transit-type engines have been tested) and that processes that lower oil viscosity can reduce, but not eliminate, the deposit problem.

Emissions

Relatively sparse data on cottonseed oil and diesel fuel blends and 100 percent, low-viscosity cottonseed oil indicate little difference between the carbon monoxide, hydrocarbon, nitrous oxide, and smoke emissions of these fuels and straight diesel fuel (15). The differences that do exist are insignificant.

Development Potential

Economics of Fuel Production and Marketing

Vegetable oils are considerably more expensive than diesel fuel; the price of cottonseed oil, for example, was approximately $2.25 per gallon in early 1984 (16). Other oils are similarly priced, although prices vary considerably depending on the annual availability of feedstock agricultural products. Peanut oil, for example, sold in early 1984 at a price 52 percent higher than cottonseed oil, primarily because of poor peanut crops.

Market Demand

Vegetable oils are not currently used as fuels in the United States. They are used primarily as food preparations, such as baking or frying fats, margarine, and salad or cooking oil. In 1983, nearly 2 billion lb (or approximately 257 million gal) of oil were used for food preparation (17). There are also other industrial uses. Some oils are exported in substantial amounts, including cottonseed and peanut oils.

Other Interest in Development

The U.S. Department of Energy (DOE) stated that the "availability of [vegetable oils] in quantities to satisfy even emergency [vehicle] fleet appetites is questionable" (18). DOE does point out, however, that such oils may be available, but on a highly localized basis. It is clear that for other than food preparation and a few established industrial purposes, there is no significant interest in developing vegetable oils for fuel-related purposes.

GASEOUS FUELS

Methane

Effectiveness

Methane, or CH_4, is the prime ingredient of natural gas. Typically, 95 percent of natural gas is composed of methane; natural gas is therefore interchangeable with methane in any discussion of methane as a transportation fuel. When used as a transportation fuel, methane is neither stored on board the vehicle nor delivered to the engine in its natural gaseous state. Instead, it is used either in a highly compressed form (at 2,500-3,000 psi) or as a cryogenic liquid (cooled to -260°F). The issues related to methane use as a specific diesel engine fuel are energy content, cetane quality, and safety.

Energy Content

In a pound-for-pound comparison, methane has slightly more energy content, measured in Btu's, than diesel fuel. However, when stored on board a vehicle as a cryogenic liquid, the fuel volume and associated fuel tank requirements are greater than those of diesel fuel (6).

Cetane Quality

Methane has an extremely low cetane number, which corresponds to the fact that the octane quality of methane is among the highest of transportation fuels. For this reason, methane is unsuited for direct use in diesel engines. Various alternatives, as with the alcohol fuels, are to (a) use methane with diesel fuel (via fumigation) with the latter serving essentially as a pilot light, (b) use methane with other fuel additives, or (c) adapt the engine via the use of glow plugs, which provide a hot internal cylinder chamber capable of igniting the methane shortly after injection.

Safety

The safety issues related to methane vehicle use are significant and remain unresolved. The major safety concerns are fuel leakage, boil-off of liquid methane, corrosive failure of compressed methane gas cylinders due to excess hydrogen sulfide in natural gas, and the crashworthiness of both liquid and compressed methane gas cylinders. Crashworthiness is accompanied by other related hazards, including fuel release upon impact and tank rupture due to fire. There are currently no industry-wide standards regarding the design, manufacture, installation, and performance of compressed methane gas fuel systems (19).

Also related to safety concerns are environmental hazards. Tested only in spark-ignition engines, significant reductions in carbon monoxide, nitrogen oxides, and most hydrocarbon emissions were recorded (20). The one hydrocarbon that greatly increased in emissions was, naturally enough, methane, which is nonreactive. Methane also significantly reduces diesel fuel-related smoke emissions.

Development Potential

Economics of Fuel Production and Marketing

Methane gas currently sells for between $3.50 (for electric utility purchases) and $6.00 (for residential purchasers) per thousand cubic feet. Its cost is directly related to federal natural gas regulation. By 1985, the price of natural gas will begin to be deregulated, at which point its price will be uncertain. That uncertainty is based on worldwide trends in natural gas demand and supply as well as similar trends in closely aligned fuels (oil and coal).

Other sources besides natural gas can be exploited for methane, including coal and biomass. However, the price impact of these sources is uncertain because alternative methane production techniques and sources have been neither marketed nor tested.

Market Demand

Methane is mainly used for two purposes: (a) as a natural gas component, it is used for its heating value by the residential and industrial electric utility commercial sectors, and (b) as a chemical feedstock, methane is used to produce methanol and ammonia. The demand of these markets is expected to remain strong, although tied to methane price trends.

Other Interest in Development

In 1980, the Methane Transportation Research, Development, and Demonstration Act was signed into law by the President. Congress is interested in methane as a vehicular fuel because of (a) its ability to reduce oil imports, (b) its ability to reduce vehicle emissions, and (c) development of alternative market uses for methane from natural gas and other sources. This act, however, has not been funded by Congress. Nevertheless, DOE has performed a state-of-the-art assessment of methane-fueled vehicles and is likely to conduct further research in the following three areas:

1. Engine testing is needed to clearly define the limits of efficiency, emissions, and performance of natural gas vehicles, and the development of practical conversion systems for diesel-engine vehicles. In addition, fundamental work on high-energy-density gas storage systems should be encouraged.
2. A test program to determine the crashworthiness and fire safety of state-of-the-art natural gas vehicles is needed, and various compressed natural gas tank designs should be evaluated for resistance to internal corrosion potentially caused by impurities.
3. Assessments need to be made of institutional barriers to natural gas use in vehicles and of the means to overcome those barriers (19).

Hydrogen

Effectiveness

Hydrogen has already become the staple fuel of space transportation and has been called the fuel of the future. It is described as such for three main reasons: it provides the highest energy conversion efficiency obtainable; it burns relatively cleanly, with no emissions of carbon monoxide, hydrocarbons, smoke, or odors; and it can be produced from water. Hydrogen has to date been used in a limited manner, both as a transportation fuel and an overall fuel (its primary use is as an industrial feedstock). It has had a few significant applications in transit systems; in particular, the testing of a hydrogen-powered bus in Riverside, California, in 1980. That bus, however, was not a typical transit vehicle; it was a 21-passenger Winnebago Minbus, originally equipped with a heavy-duty truck gasoline engine. (21). (Hydrogen's high octane value makes it a good gasoline substitute.) The gasoline carburetor was removed and replaced with a gaseous fuel carburation device. Although the Riverside test does not directly apply to most current transit operations, the interesting aspects and results of the operation are worth reporting.

First, the hydrogen fuel was stored on board the vehicle as a metal hydride. Although this methodology had its problems (i.e., in order to release the hydrogen, the metal hydride was heated, which required considerable water and fan cooling), it is often considered the most promising means of hydrogen fuel storage. The other alternatives for hydrogen storage include hydrogen stored as a high-pressure gas, chemical fuels synthesized from hydrogen (e.g., ammonia and hydrazine), and hydrogen stored as a cryogenic liquid (22). Metal hydrides are considered the best option because of fewer handling problems and safety concerns (23). However, because of the significant weight of metal hydrides, a vehicle fueled in this manner must either use an extremely heavy fuel tank or limit its mileage range. In the Riverside test, for example, the latter choice was made and most test runs were no longer than 60 mi before refueling was necessary (24). Major advances in metal hydride storage clearly need to be made before widespread vehicular use can be envisioned.

Second, a number of problems were encountered in the Riverside test. In nearly 20 percent of the test runs, vehicle cold-starting was very difficult. Unusually high amounts of dirt and iron were found in the crankcase oil. Finally, carburetor flashback occurred often, damaging the carburetor diaphragm and causing a loud backfire-type sound. Altogether, these problems suggested that further improvements in hydrogen-fueled buses must be made before further tests in transit revenue service are made.

The other significant ongoing research effort in hydrogen-fueled vehicles concerns diesel applications, although primarily in the railroad sector (25). That effort is investigating the use of high-pressure hydrogen gas and cryogenic hydrogen in converted diesel engines. Hydrogen's low cetane value, for example, requires some type of fuel or engine ignition assistance.

There are still many issues that need to be investigated in terms of hydrogen use in vehicles in general and diesel-powered vehicles in particular. Safety is a major concern, as are all aspects of fuel handling and distribution. Because of the current status of hydrogen fuel research, at least two recent studies rank the possible use of hydrogen fuel as a diesel fuel substitute before the 21st century extremely unlikely (6,9).

Development Potential

Economics of Fuel Production and Marketing

The iron titanium used in the Riverside bus test sells for approximately $13 per pound. The less heavy magnesium hydride sells for twice that amount (23). Liquid hydrogen costs considerably less; depending on the source of production, the cost is between $0.65 per pound ($2.88 per cubic foot) for hydrogen made from methane to $1.44 per pound ($6.38 per cubic foot) for hydrogen made from water via electrolysis (9). Hydrogen is currently produced from two main sources: methane (i.e., natural gas) and petroleum (in about a 73/27 percent split) (26). Electrolysis from water produces less than 1 percent of the hydrogen currently needed.

Market Demand

About half the hydrogen produced in the United States is used by the petroleum and chemical industries; a third is used to make ammonia for fertilizer and other uses; and the rest is used to make methanol and for other miscellaneous purposes, including liquid hydrogen for the National Aeronautics and Space Administration (26). Metal hydrides are primarily used by the petroleum industry in the refinery process (27).

Other Interest in Development

In 1980, Congress identified the following potential uses for hydrogen:

- Mixing hydrogen with natural gas to expand natural gas resources;
- Transportation, including rail and air transportation and such special uses as forklift trucks, mining and agricultural equipment, buses, fleet vehicles, and other multipassenger vehicles designed for short-distance travel;
- Hydrogen fuel cells for electricity generation and other uses; and
- Greater use in ammonia production (28).

NEAR-TERM VERSUS LONG-TERM DEVELOPMENT POTENTIAL OF ALTERNATIVE FUELS

Five fuels were identified as possible alternative fuels for bus transit systems: methanol, ethanol, vegetable oils, methane, and hydrogen. All are currently in production, although it should be noted that only vegetable oils are being produced from renewable resources in any significant quantity in the United States. A small portion of ethanol, that which is used for such automotive fuels as gasohol, is produced from agricultural products. Methanol, ethanol, methane, and hydrogen are principally derived from petroleum or natural gas resources. The technologies for producing these fuels from these resources are well developed, as are the economics. Neither the alternative technologies nor the economics for producing these fuels from alternative resources (e.g., agricultural products, coal, water, and waste products) are fully developed. Thus, only vegetable oils can be considered an immediate alternative fuel for transit systems from the production point of view. In the near-term future, however, ethanol is a likely candidate (the facilities for producing and marketing grain, corn, and sugar alcohol are well established), although not one of major significance. Ethanol production could be expanded to serve the needs of transit systems without any major problems. Long-term candidates from the point of view of fuel production and availability (from nonpetroleum and non-natural-gas resources) include methanol, methane, and hydrogen.

In terms of their use in current bus vehicles, vegetable oils once again are the only fuels with immediate applications. All other fuels would require significant changes to (a) engine design (primarily through the use of glow or spark mechanisms), (b) fuel storage and delivery (both from the vehicle storage tank to the engine and from the facility storage area to the vehicle), and (c) engine parts (particularly elastomers). In addition, further testing is needed to establish appropriate blending percentages with diesel fuel (if that is the procedure chosen), necessary fuel additives, emissions, and so forth, none of which has been well explored in transit-type operations. (Vegetable oils would also have to undergo some of these tests as well.) Among these fuels, both methanol and ethanol are likely near-term candidates for the development of appropriate engine and fuel components, whereas methane is a long-term candidate. Hydrogen's potential goes far beyond the year 2000.

In summary, vegetable oils are the only fuel with immediate development potential. Ethanol has near-term potential; methanol has near-term potential from the end-user point of view (i.e., transit systems) but only long-term potential from the production point of view; methane has long-term potential; and hydrogen has potential as a bus fuel through the 21st century.

EVALUATION OF ALTERNATIVE FUELS

An evaluation was conducted to determine the ability of alternative fuels to

1. Protect the fuel supply during future oil shortages;
2. Reduce the air quality impacts of diesel fuel;
3. Reduce transit system operating costs; and
4. Serve as more energy-efficient fuels.

The results of this evaluation revealed the following:

1. There is no alternative fuel that could serve on any widespread basis as a transit contingency fuel in the event of an imminent oil shortage. However, governments can ensure that transit systems receive an adequate supply of diesel fuel. On a limited basis, vegetable oils could serve as an adequate contingency supplement to diesel fuel during a disruption. Alcohols could serve as adequate supplementary fuels if oil shortages occurred in the near- or long-term future.
2. Alcohols emit far more carbon monoxide and hydrocarbon pollutants than diesel fuel. However, they emit less nitrogen oxides and soot or smoke pollutants; the latter are the major diesel engine pollutants. Other alternative fuels do not have a sufficient test history in transit bus settings for a substantive evaluation of their environmental impacts; however, indications are that vegetable oils, methane, and hydrogen are cleaner-burning fuels. Two problems associated with these latter fuels, methane emissions and nitrogen oxide emissions from hydrogen, are likely to be resolved by engine adjustments.
3. Methanol is clearly the alternative fuel that provides the lowest operating costs for transit systems. However, despite the lower fuel cost of methanol compared with diesel fuel, the overall operating and maintenance costs are higher than those for diesel fuel.
4. Hydrogen is considered the most efficient fuel, but various aspects of its storage properties (either cryogenic or metallic) make it an unsuitable near- or long-term fuel for any extensive use by transit systems. Methane has similar limitations, although those could be solved within a long-term framework. Vegetable oils are excellent fuels from the point of view of Btu's and cetane; however, their cold-start problems and overall availability restrict their immediate applications with transit vehicles except on a limited basis. Alcohols are the most likely near-term candidates for transit use despite necessary engine modifications because of their availability potential, their relative similarity to diesel fuel in storage handling and suitability to withstand urban vehicular accidents, and their ability to reduce nitrogen oxides and soot and smoke emissions. Because of methanol's even greater potential for availability and cost savings, this particular alcohol is considered the likeliest candidate for near-term exploitation in bus transit systems.

FUTURE DEVELOPMENTS

Alternative fuel research and development continue even though the federal government and private industry are less interested than they were in the 1978 to 1981 period. Indeed, expressed federal interest in alcohols, methane, and hydrogen ensure their continued study. However, only alcohols are seriously being considered and tested as transit fuels. In Florida, the Department of Transportation is converting a small number of revenue-making buses for methanol use, utilizing glow plug and other engine modifications. In California, two buses (with modified engines) in the San Francisco region are running on methanol. Elsewhere in the world similar tests are ongoing. No current interest has been generated for vegetable oil research among U.S. transit systems, and methane and hydrogen applications are being studied in nontransit areas.

Should current research and development of alternative fuels for transit buses be expanded? Or is the current level of research adequate? There are factors that support both positions. Three major factors work in favor of maintaining current levels of research:

1. Objectives do not warrant further support,
2. Market demand is too small, and
3. Current economics are unfavorable.

Among the factors that support research expansion are

1. Objectives still hold some significance,
2. There is new competition in the bus manufacturing industry,
3. Future economics are likely to be favorable, and
4. Transit systems could serve as lead developers.

Each factor is discussed in the following paragraphs.

Factors Favoring Maintenance of Research Levels

Objectives

- Governments and transit systems can take other actions besides developing alternative fuels to protect the supply of diesel fuel or fuel budgets or both during oil supply disruptions. These actions include the allocation of necessary supplies to transit systems (via federal or state intervention), the creation of contingency diesel fuel reserves by transit systems, subsidies from the federal government, and so forth. These actions fit within the current fuel procurement and subsidy channels and do not reflect the kind of changes in procurement, fueling, and maintenance that alternative fuel use would require.
- The key urban vehicular pollutants are carbon monoxide, hydrocarbons, and nitrous oxides. Transit buses simply are not major contributors of these pollutants.
- Diesel fuel operating and maintenance costs remain cheaper than all other alternative fuel and engine combinations.
- Years of tandem diesel fuel-diesel engine development have established diesel fuel as the most efficient and best-suited bus transit fuel, considering current bus vehicles.

In summary, when viewed within a larger spectrum, the objectives of transit bus alternative fuel development have not essentially been met.

Market Demand

Transit systems consume only around 3 percent of the on-highway diesel fuel used in this nation and less than 1 percent of all diesel fuel (29). At the same time, there are about 60,000 transit buses in the United States, whereas diesel trucks number at least six times that number (30). There are similar engine manufacturers for both industries. It is difficult to envision an economic environment in which manufacturers will make substantial changes in engine and vehicle design for a relatively small segment of their consumer population. Therefore, unless other alternative fuel development concepts consider the needs of diesel trucks as well as transit systems, they may not receive widespread attention by relevant manufacturers.

Current Economics

An unfavorable economic climate relates to a number of relevant factors: steady diesel fuel prices, high prices of alternative fuels (except for methanol), and fiscally restrained transit systems unwilling to invest heavily in necessary modifications to vehicles and facilities (including those related to methanol).

Factors Favoring Expanded Research

Objectives

Some of the following aspects of development objectives are validated by alternative fuel research.

- Transit systems are operating in a deregulated energy environment along with other oil product consumers. Despite their public standing, it behooves transit systems to act as responsible consumers by mitigating the risks of fuel loss or price changes without relying on government bailout as a first resort. Alternative fuels, particularly methanol in the near term, are a responsible way to guard against possible disruptions. Despite the necessary adjustments in fuel procurement, the move toward alternative fuels is one that recognizes the hazards of letting other governmental bodies solve the problems of transit systems. It is also one that recognizes the need for transit systems to provide important services during fuel disruptions to the best of their ability.
- Although not as crucial as other pollutants, soot and smoke emissions are a visible and uncomfortable intrusion into everyday urban life, one that alternative fuels can help reduce.
- The increase in total operating costs of alternative fuels should be viewed as a possible short-term occurrence; manufacturing and facility processes are likely to be refined and less costly.
- Finally, the current fuel-engine coupling can be uncoupled quickly if other fuels and proper engine modifications occur in a smooth and relatively inexpensive manner.

New Competition

Since 1980 at least four new bus manufacturers have entered the U.S. market for transit buses. Others may also join as a result of prototype tests. Competition will stiffen and manufacturers will search for production and marketing strategies. Although it was stated that there are no major empty product niches (30), manufacturers might view dual-fueled or alternative-fueled buses as a possible product area to exploit. This could be especially true for the large number of foreign entrants into the market [e.g., Volvo, and Maschinenfabrik Augsberg-Nürnberg (MAN)] that have considerably more experience in alternative fuel development and operations than most domestic companies.

Future Economics

Diesel fuel prices will not remain steady; rather, they will most likely rise as oil production demand resumes on a worldwide basis. At that time, the economic potential of alternative fuels will once again become attractive. Furthermore, transit systems, although likely to be in constant need of subsidization, will eventually emerge from the massive rehabilitative phase they are currently in and will have more capital and operating funds available for alternative fuel ventures.

Transit as a Lead Developer

This is turning the market share issue around. Truckers, who use most of the diesel engines and fuel on the highway, are in a constant and fiercely competitive struggle for freight haulage. This competition has only been enhanced by the deregulation of the trucking industry, and it has been characterized largely by significant price competition. This has two implications: (a) trucking firms have less funds available to engage in alternative fuel R&D programs and (b) whatever cost advantages alternative fuels could offer to truckers (during periods of constant fuel shortages) would be of great benefit. Therefore, the transit industry is the proper sector for alternative fuel development. First, such systems are not strictly cost-competitive, although costs must be carefully scrutinized because of the pervasive deficit operations throughout the industry. Second, any cost savings that result are likely to be picked up by the private trucking industry, which in turn will aid transit systems by spurring manufacturer interest.

New Directions in Research and Development

In light of the factors that either support or oppose an expanded alternative fuel R&D effort, what directions should be pursued? This study recommends the following in terms of program initiatives and R&D participants and roles.

Program Initiatives

Current U.S. transit methanol tests and the considerable wealth of foreign expertise suggest that vehicle testing should not be expanded to any large extent. The following actions are recommended instead:

- A joint study between UMTA and the U.S. Departments of Energy and Agriculture would identify the potential role of vegetable oils as contingency fuels. This study would address the key aspects of (a) price and availability issues, (b) identification of regions, markets, and conditions where availability of vegetable oils is ensured, (c) which transit systems (by size, location, etc.) will be the most likely users, and (d) what the benefits and costs are compared with other, nonalternative means of providing assistance to transit systems during fuel disruptions.

• A cooperative effort should be made between one or more bus manufacturers, an alternative fuel producer, and at least one transit system to test the costs and benefits of developing alternative fuels. The costs and responsibilities of this cooperative effort should be divided according to where they properly belong: engine modifications to the manufacturer; fuel quality characteristics and assurance and delivery methods to the fuel supplier; and maintenance and facility redesign and readjustment to the transit system.

Participants and Roles

The relevant participants in future R&D efforts are

• The federal government, including UMTA, U.S. Department of Energy, U.S. Department of Agriculture, and U.S. Department of Transportation, Office of the Secretary;
• Transit systems;
• Fuel suppliers;
• Bus manufacturers; and
• State and local governments.

Their roles should be as follows:

• The federal government should actively pursue the vegetable oil contingency study and relay any positive results to transit systems.
• The federal or state governments should not play an active role in forming the cooperative fuel development program.
• Interested transit systems should contact bus manufacturers and together they should seek out fuel providers to form a cooperative development effort. Any results should be publicized, but the individual profitability of manufacturers and fuel suppliers should not be restricted by federal or state guidelines or mandates.

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User Costs and Fuel Consumption at Drive-Through Facilities

JOHN R. BAXTER and DONALD B. STAFFORD

ABSTRACT

In recent years the drive-through facility has become increasingly popular at fast-food establishments and financial institutions. This study was undertaken to examine the user costs and fuel consumption associated with the use of drive-through facilities and to compare the values obtained with similar data for inside servicing. Three fast-food establishments and three financial institutions in small towns in northwestern South Carolina were used to collect the data. Data on arrival patterns, service times, and waiting times were collected by mechanical counting devices and visual observation. From these data, user cost and fuel consumption associated with both inside service and drive-through service were compared. A linear relationship was found to exist between total transaction times and the customer's position in the drive-through line. It was concluded that there was a break-even point beyond which drive-through facilities became more time-consuming and costly than going inside for service. Drive-through facilities were also found to cause the consumption of an excessive amount of fuel. The average fast-food establishment with 2,000 vehicles per week using the drive-through system would cause an excess of 57 gal of fuel per week or 2,960 gal per year to be consumed. The average financial institution with a two-channel drive-through system handling 2,000 vehicles per week would cause an excess of 62 gal of fuel per week or 3,210 gal per year to be consumed.

Today's drive-through facility is an offspring of the drive-in, which was developed in the early 1930s. Throughout the 1950s and 1960s the drive-through facility for both financial institutions and fast-food chains was refined into the form that is so common today. Only during the past 10 to 20 years, however, has the use of drive-through facilities become widespread. This recent growth may well be one more consequence of the trend toward suburban living patterns. With America's dependence on the automobile, it is safe to assume that the drive-through and other related facilities geared toward the automobile will continue to be dominant factors in the marketing of various products and services in the years ahead.

There are many reasons why the drive-through facility has become so popular in recent years, including (a) convenience to customers, (b) speedier handling of transactions, (c) no stand-in-line waiting, (d) the fact that providing drive-through facilities is more economical for businesses than enlarging lobbies and parking lots, (e) difficulty in finding parking spaces in congested areas, and (f) promotional programs by businesses that encourage the use of drive-through facilities. With advantages such as convenience and waiting in comfort, it is no surprise that the drive-through facility has flourished in our automobile-oriented society.

Six basic drive-through designs have been developed to serve customers: island facilities, annex or peninsula-type facilities, auto-bank facilities, wall-type facilities, drive-through facilities, and garage-bank facilities. The terms used to identify most of the designs are self-explanatory. Modern fast-food chains and financial institutions use the wall-type and drive-through facilities almost exclusively. The wall-type facility is simply a drive-through built onto the side of an existing building; it is particularly popular because it can be retrofitted onto an existing building. The drive-through is a wing adjacent to the main building.

In recent years the fast-food industry has adopted a slight variation of the standard wall-type drive-through facility. Instead of driving directly to the main building and placing an order, customers now place their order at an "order window," or "menu board," and then drive around the building to pay for the food at a pick-up window. This design is a unique solution that is particularly appropriate for fast-food businesses. The effects of this type of design will be discussed in the context of this paper.

PURPOSE AND OBJECTIVES

It is generally assumed that if a person is in a hurry, the drive-through is the quickest and most efficient means of doing business. But is this assumption always correct? Is the drive-through facility always quicker and more economical than doing business inside? One of the primary purposes of this study was to determine at what point, if any, the drive-through became less economical for the customer than doing business inside. From this information, an economic guideline could be established to help customers decide which facility (inside or drive-through) to use.

Until the early 1970s, the United States had what appeared to be an unlimited gasoline supply at its disposal. In 1973, political factors caused the Organization of Petroleum Exporting Countries to limit crude oil supplies, and prices increased rapidly. Long lines developed at service stations and the image of dwindling fuel supplies was particularly disturbing. Again, in 1979, talk of shortages surfaced as gasoline prices rose well over $1 per gallon. If nothing else, this fuel panic made Americans aware of just how much energy they were wasting. Because the drive-through is a convenience that causes automobiles to consume more fuel, one of the objectives of this study was to estimate how much this convenience is costing in terms of excess fuel consumption.

This study involves only drive-through facilities in small towns where adequate parking is not a serious problem. In large metropolitan areas where parking is a problem for the customer, the economics of a drive-through facility may be completely different from that developed in this study.

This study also neglects the economic impact of the drive-through to the owner of the facility. In many cases the drive-through is an efficient means of providing temporary storage of customer vehicles. The drive-through allows the owner to provide fewer parking spaces and as a result requires less land acquisition or allows the use of the available land for other purposes. This economic benefit will become more significant as land costs rise in larger urbanized areas.

PROCEDURES

Drive-through facilities were divided into two general classifications: fast-food establishments and financial institutions. Three financial institutions and three fast-food establishments were selected for the study, each at locations that, it was hoped, would provide high peak-period volumes and long queues (number of automobiles waiting to be served).

Traffic counters were used to establish hourly and daily customer arrival patterns at these facilities. During the same time intervals, a program of observing and recording customer waiting and service times was conducted for actual transactions at the drive-through facilities. From these data, customer waiting times and service times were established based on the customer's position in the queue. Data were also collected for inside service during comparable time periods.

From this information, a comparison was then made of the time required for inside service versus that required for drive-through service, and user costs were estimated for each of these services. Based on computed service times and waiting times, an estimate was also made of how much additional fuel was required to use drive-through facilities.

DESCRIPTION OF THE DRIVE-THROUGH FACILITIES

Fast-Food Establishments

One of the fast-food establishments included in the study was a Wendy's restaurant located at the intersection of Greenville Street and North Fant Street in Anderson, South Carolina. The 1980 population inside the Anderson city limits was 27,313, although the Anderson urban area has a population of approximately 50,000. As is common with fast-food drive-through facilities, this one consisted of a menu board and a pick-up window with sufficient distance between the two locations to accommodate five to six vehicles. The maximum practical queue length at the menu board was approximately 10 to 12 vehicles.

The second fast-food establishment included in the study was a Burger King located at the intersection of North Main Street and West Fredericks Street in Anderson, South Carolina. The drive-through facility consisted of a menu board and a pick-up window with enough space between the two locations to store five or six vehicles. A maximum practical queue length of approximately 15 to 20 vehicles was possible at the menu board.

The third fast-food establishment included in the study was a Hardee's located near the intersection of US-123 and S.C. Highway 93 in Easley, South Carolina. The town of Easley had a 1980 population of 14,264. The short distance between the menu board and the pick-up window at this drive-through facility restricted vehicle storage to only two vehicles. However, the menu board had an almost unlimited queueing potential because a large parking lot was adjacent to the facility.

Financial Institutions

An important criterion in the selection of financial institutions for the study was that there be significantly different levels of capacity as evidenced by a varying number of drive-through channels. With this criterion in mind, the authors chose the American Federal Savings and Loan operation located at the intersection of Pickens Drive and North Main Street in Liberty, South Carolina. The town of Liberty had a 1980 population of 3,167. This financial institution had a single-channel drive-through built on the back of the building. Because of the location and configuration of the access, patrons could cause traffic congestion for vehicles trying to enter the institution's parking lot. The maximum practical queue length at the drive-through window was limited to three or four vehicles.

Another financial institution included in the study was the First Federal Savings and Loan in Easley, South Carolina, at the intersection of US-123 and Pilgrim Drive. The drive-through at this location was a two-channel system with a maximum queue length of seven vehicles for each channel. Because of a significant increase in drive-through customers at this financial institution in recent years, vehicle storage was sometimes inadequate during peak periods.

Another financial institution included in the study was Southern Bank, located at the intersection of North Main Street and Carter Street in downtown Anderson, South Carolina. The drive-through at this location consisted of a three-channel system with adequate space for a long queue length in each channel. The operation of Southern Bank was different from that of the other two financial institutions examined in that the drive-through remained open from 1:00 to 3:00 p.m. when the facilities inside were closed. Thus, the bank patron had no choice but to use the drive-through facility during this period.

ANALYSIS OF THE DATA

Financial Institutions

Traffic Volumes and System Characteristics

Mechanical traffic counters were used to establish hourly and daily traffic patterns at the drive-through facilities of the financial institutions. Roughly 14 percent of the drive-through traffic occurred on Monday, Tuesday, or Wednesday, with Thursday accounting for 22 percent and Friday accounting for almost 36 percent of the weekly volume. Hourly counts revealed peak periods at noon and late in the afternoon. Maximum peak periods occurred during the extended hours of 4:00 to 6:00 p.m. on Friday.

The distribution of service times (defined as the time customers were actually being served) at the drive-through facilities was found to be negative exponential. The mean service time for 676 observations was 1.96 min. Service times were less than 4.0 min in length 88 percent of the time.

The total amount of time the customer spent in the drive-through system was divided into waiting-time and service-time components to better understand the process that a customer experiences while waiting in line to be served. Figure 1 is a plot of waiting times at one-, two-, and three-channel financial institution drive-throughs as a function of queue length. It can be seen that observed waiting times follow a generally linear relationship with queue length. As shown in Figure 2, service times decreased slightly as queue lengths increased. This behavior may be attributed to the addition of extra tellers as lines got longer or to faster work by tellers as queue lengths increased.

By combining waiting and service times, the average total time spent in the system can be plotted against queue length. Figure 3 presents observed data points obtained at one-, two-, and three-channel systems. The data closely approximate a linear relationship with correlation coefficients for each line greater than 0.95 (where 1.0 represents a perfect linear relationship). A theoretical line (broken line) has also been added based on the overall average service time of the three drive-through facilities of 2.0 min. Deviations in the slope in the linear relationships reflect the variation of service times among the three drive-through systems. The single-channel system, with an average service time of 1.45 min, exhibits a flatter slope. The two- and three-channel systems, which have average service times approaching the overall 2.0-min average, have slopes that more closely correspond to the

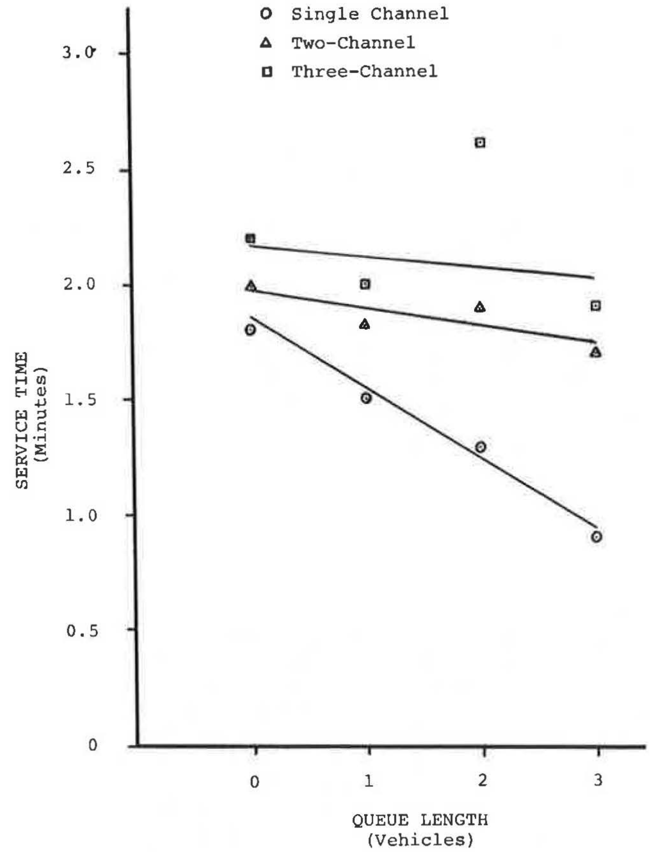

FIGURE 2 Service time versus queue length for financial institutions with one-, two-, and three-channel drive-through systems.

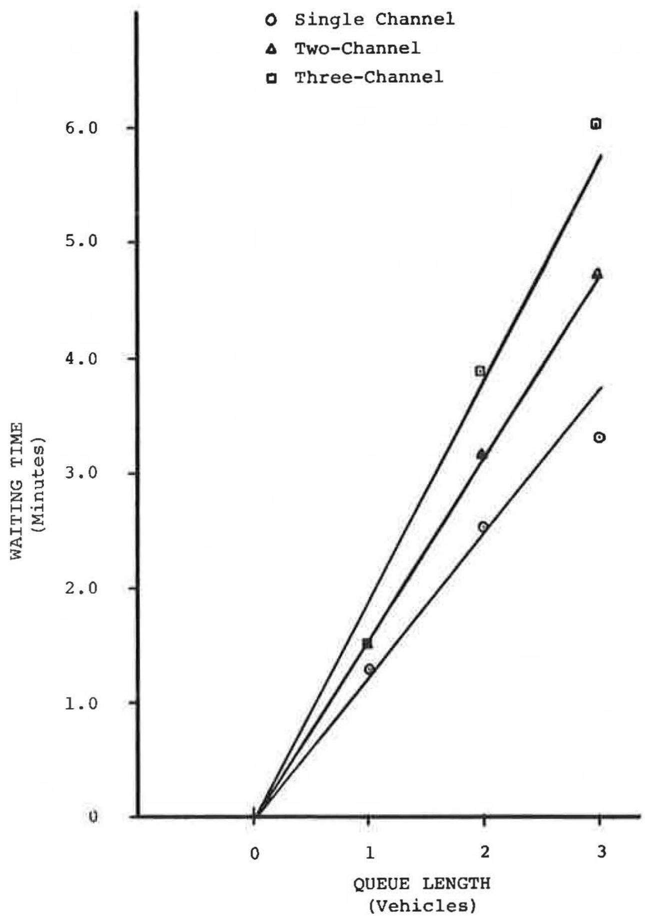

FIGURE 1 Waiting time versus queue length for financial institutions with one-, two-, and three-channel drive-through systems.

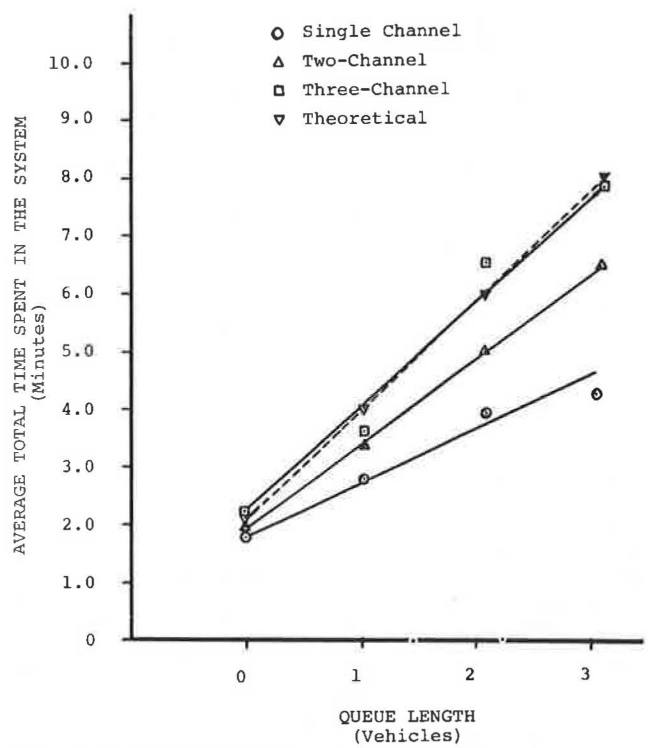

FIGURE 3 Average total time spent in the system versus queue length for financial institutions with one-, two-, and three-channel drive-through systems.

theoretical curve. The following equation describes the linear relationship for the theoretical curve:

$$\text{Total time (minutes)} = 2.00 + 2.00X \quad (1)$$

where X is queue length = 0, 1, 2, 3, ...

This relationship is the basis for the development of user costs at drive-through facilities versus the patron's position in the queue. The total time spent in the system will be used to estimate fuel consumption and to determine the time cost of using a drive-through facility for any queue length.

Average total times (including waiting time and service time) required for operations inside the facility varied between peak and off-peak periods. The average total time was 2.6 min for off-peak periods and 3.4 min for peak periods. The increase in times reflects longer waiting times caused by longer queues during peak periods.

User Costs

Inside Facilities

The cost of inside service at a financial institution is determined by summing the value of personal time and the cost of fuel necessary to start a vehicle engine. The amount of time needed to use an inside facility can be divided into five components: (a) time to park and get out of the vehicle, (b) time to walk into the facility, (c) time to make the transaction (including waiting in line), (d) time to walk back to the vehicle, and (e) time to enter the vehicle and start the engine. A value is obtained by summing the various components of time that will be used to determine user costs associated with inside service. The total amount of time necessary to use the inside service at financial institutions was found to average 3.9 min for off-peak periods and 4.7 min for peak periods. Using a conservative estimate of the value of a person's time as $5.00 per person per hour, the cost of time to the customer becomes $0.325 during off-peak periods and $0.39 during peak periods.

The other component of cost associated with obtaining inside service at financial institutions is the fuel necessary to start a vehicle engine when the customer leaves the facility. Using an engine idling rate of 650 gal per 1,000 hr, a cost of $1.15 per gal of gasoline, and an engine start equivalent to 15 sec of idling time, fuel costs are estimated at $0.03 per engine start.

Combining the costs of time and fuel, the cost of using inside facilities at financial institutions becomes $0.33 (rounded) per customer during off-peak periods and remains at $0.39 during peak periods. It is obvious that time cost is the dominant cost component and fuel cost is almost negligible.

Drive-Through Facilities

The total amount of time a customer spends in a drive-through system is a function of the customer's position in the line or queue. Therefore, it is appropriate to develop a relationship between user costs and queue length. The fuel cost of engine idling and the value of personal time amount to $0.132 per minute and $0.833 per minute, respectively. Thus, the total user cost is $0.965 per minute of time spent in the system. By multiplying this number by the time values obtained from Equation 1 describing the theoretical line in Figure 3, costs can be computed in relation to queue length. Figure 4 shows the costs of using a drive-through facility as a function of the position of the patron in the queue.

Figure 4 indicates that during off-peak periods inside service is more economical for the customer if at least one automobile in the drive-through system is being served. During peak-period operations, inside service is more economical when there are two or more vehicles per channel in the drive-through system.

Using an average weighted value of time spent in the drive-through system of 3.1 min and a range of weekly volume of 500 to 3,000 vehicles, fuel consumption values were computed for various levels of weekly customer volume for drive-through and inside operations. Table 1 shows the results of these computations with column 3 providing fuel consumption data for drive-through operations and column 4 providing fuel consumption data for inside operations. By subtracting the values in column 4 from the values in column 3, the excess fuel consumption associated with the use of the drive-through can be computed. The results in column 5 show that excess fuel consumption varies from 16 to 93 gal per week for the use of drive-through facilities. For a typical two-channel drive-through that handles 2,000 vehicles per week, the excess fuel consumption is 62 gal per week.

Fast-Food Establishments

Traffic Volumes and System Characteristics

On the basis of combined data from the three fast-food establishments, daily counts showed that Friday had the highest volume of drive-through traffic, approximately 18 percent. Sunday had the lowest volume with less than 10 percent of the weekly volume. The peak period of the day was from 12:00 noon to 1:00 p.m., when 13 percent of the total daily traffic occurred.

Based on 834 observations of drive-through operations at fast-food establishments, the average amount of total time spent in the drive-through system was 2.8 min. The observations of drive-through operations comprised 68 percent peak-period data and 32 percent off-peak data. The distribution of the total time was negative exponential. Only 6 percent of the customers spent over 5 min in the drive-through system.

In order to improve efficiency at their drive-through operations, fast-food establishments have adopted what is known as the menu-board concept or the multiple-window system. This system enables customers to place an order and then drive around the building to pay for it. Because of this arrangement, there are no well-defined service-time or waiting-time components for data analysis. As Figure 5 shows, waiting time is defined as the time it takes to reach the menu board to place an order. Service time is defined as the time spent at the pick-up window itself. However, a third component of time involved in this type of configuration is herein defined as the "in-transit" time, which represents a combination of waiting-time and service-time components. In-transit customers are actually being served to a certain degree because their food is already being prepared inside. In order to determine the amount of service being provided, inside preparation techniques would have to be studied.

Figures 6, 7, and 8 graphically show the time components of a vehicle entering a fast-food drive-through facility as a function of queue length. The peak-period waiting time of a vehicle, as shown in Figure 6, increases gradually and then follows a linear pattern as queue length increases. Data were insufficient to develop a waiting-time curve for

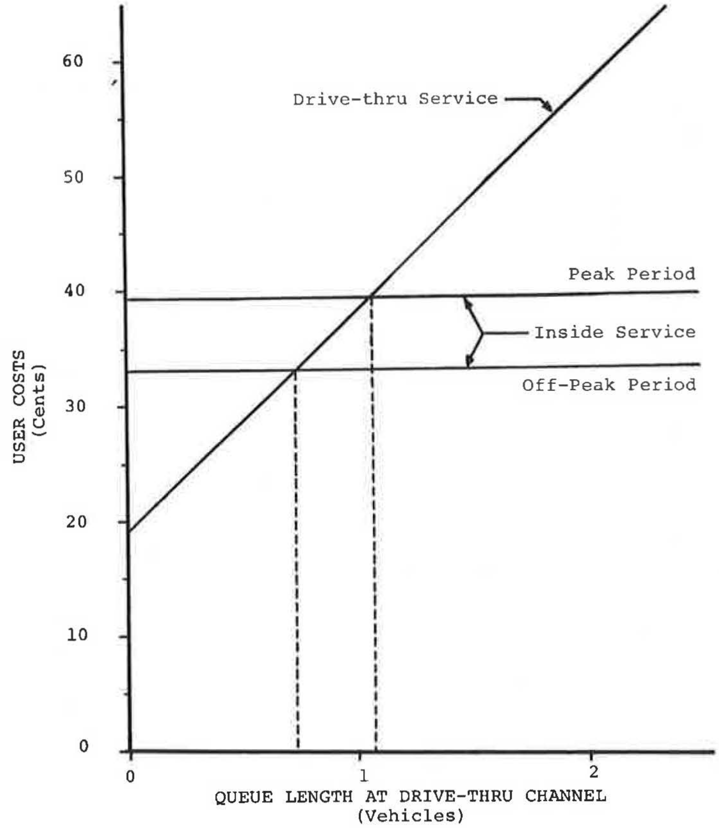

FIGURE 4 User costs for inside service and drive-through service at financial institutions.

TABLE 1 Weekly Fuel Consumption at Financial Institution Drive-Through Facilities for Various Levels of Weekly Customer Volume

Assumed No. of Channels in System	Vehicles per Week	Fuel Consumed in Drive-Through (gal)	Fuel to Start Engine (gal)	Excess Amount of Fuel Consumed (gal)
1	500	17	1	16
1 or 2	1,000	34	3	31
2	1,500	50	4	46
2 or 3	2,000	67	5	62
3	2,500	84	7	77
3 or 4	3,000	101	8	93

off-peak periods. However, a similar linear relationship with a steeper slope would be expected. In-transit times are presented in Figure 7 for peak, off-peak, and overall conditions. The slope of the three curves, as was true for waiting- and service-time curves, depended on the vehicle storage capability of the drive-through facility. The in-transit curves initially increased sharply when queue length increased and then flattened to become approximately constant when the queue was four to five vehicles long. The reason for this was that once a steady queue of five or more vehicles developed, the storage space between the pick-up window and the menu board remained fully occupied. Assuming that there was available storage for five vehicles, patrons entering the queue would first have to wait for the five vehicles ahead of them before they could be served. As seen in Figure 8, service times also became roughly constant as queue length increased beyond four or five vehicles for both peak and off-peak period conditions. Therefore, the constant in-transit times resulted from the product of constant service times and the fixed storage capacity of the drive-through facility. As noted earlier for financial institutions, service times depended on the time of day and the queue position of a vehicle. The leveling of service times at a queue of five to six vehicles, as shown in Figure 8, indicates that maximum system efficiency has been achieved.

The three components of system time are combined in Figure 9. For both peak and off-peak periods, the relationship between queue length and total time spent in the drive-through system is linear. The two equations are as follows:

Off-peak period

$$\text{Total time (minutes)} = 2.20 + 0.89X \quad (2)$$

where X is queue length = 0, 1, 2, 3, ...

Peak period

$$\text{Total time (minutes)} = 1.78 + 0.46X \quad (3)$$

where X is queue length = 0, 1, 2, 3, ...

On the basis of 537 observations of inside operations, the average total time a customer spent in the service line was 3.0 min, including both waiting time and service time. Like the situation involving inside servicing at financial institutions, it was difficult to monitor customers entering and exiting the waiting line during peak periods; therefore, no attempt was made to separate waiting time and service time.

User Costs

Inside Facilities

The cost components for using a drive-through at a fast-food establishment were almost identical to those outlined earlier for financial institutions. The only difference was in the average transaction time. The average total transaction time of 3.0 min at a fast-food establishment remained constant during both off-peak and peak operations. Walking times and the time necessary to get in and out of a vehicle

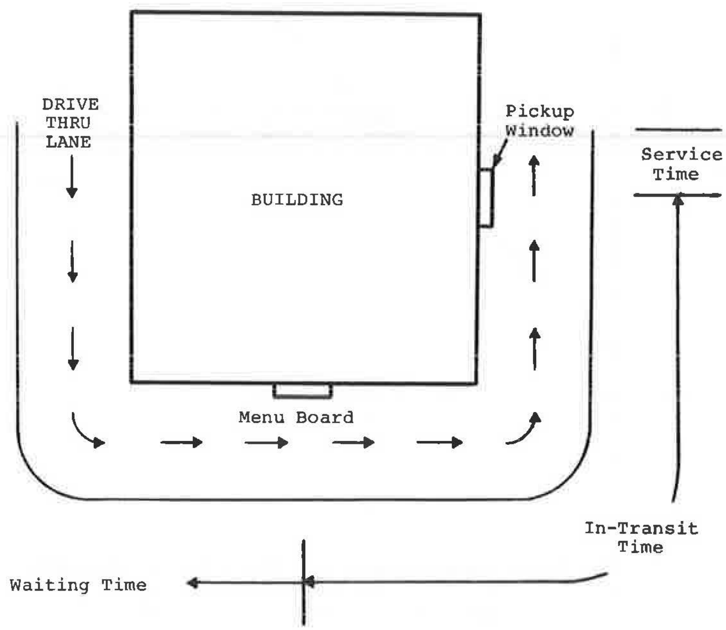

FIGURE 5 Components of system time for a typical fast-food drive-through facility.

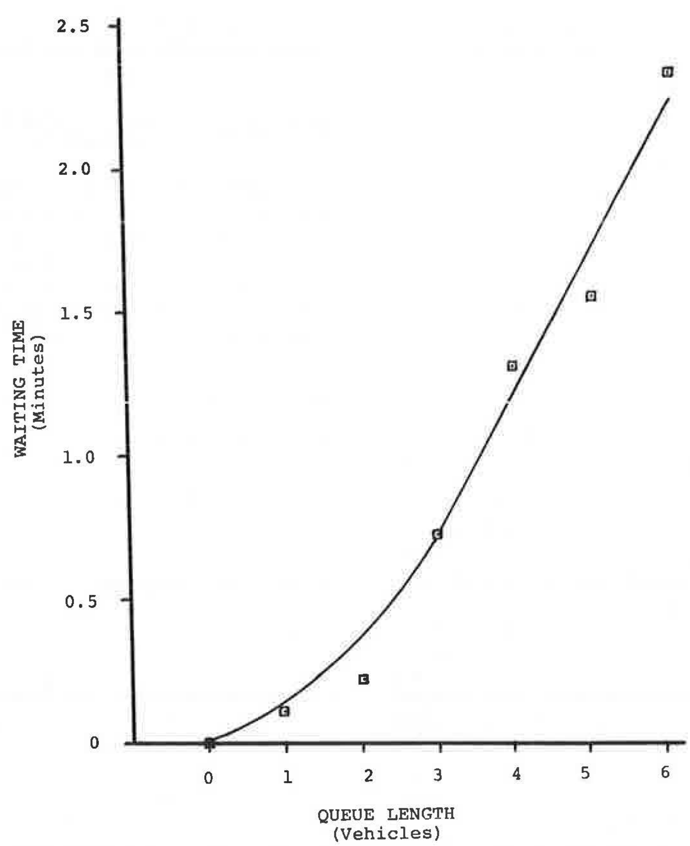

FIGURE 6 Peak period waiting time versus queue length at fast-food drive-through facilities.

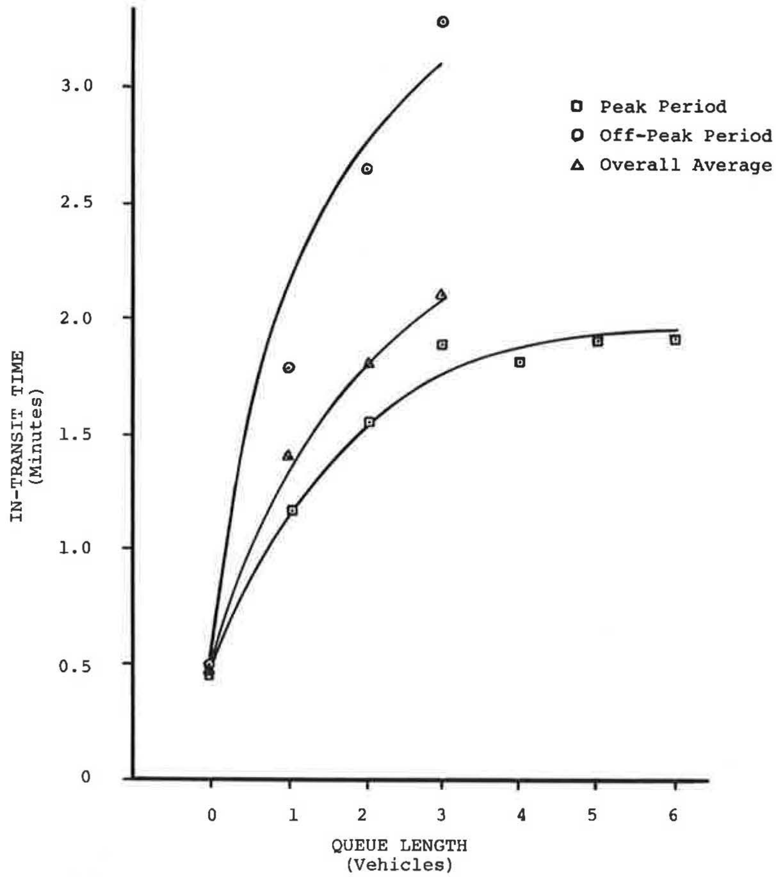

FIGURE 7 In-transit time versus queue length at fast-food drive-through facilities.

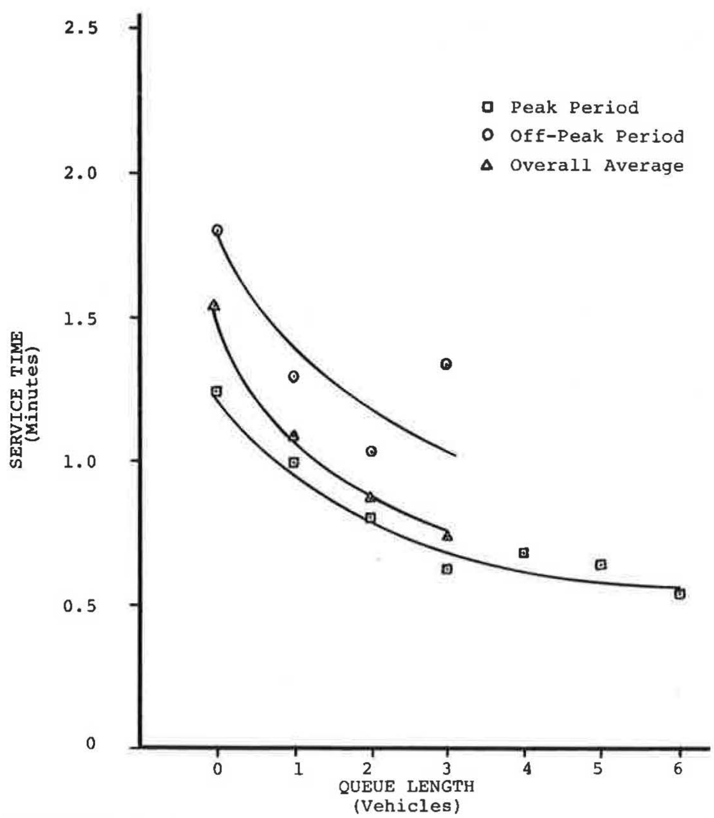

FIGURE 8 Service time versus queue length at fast-food drive-through facilities.

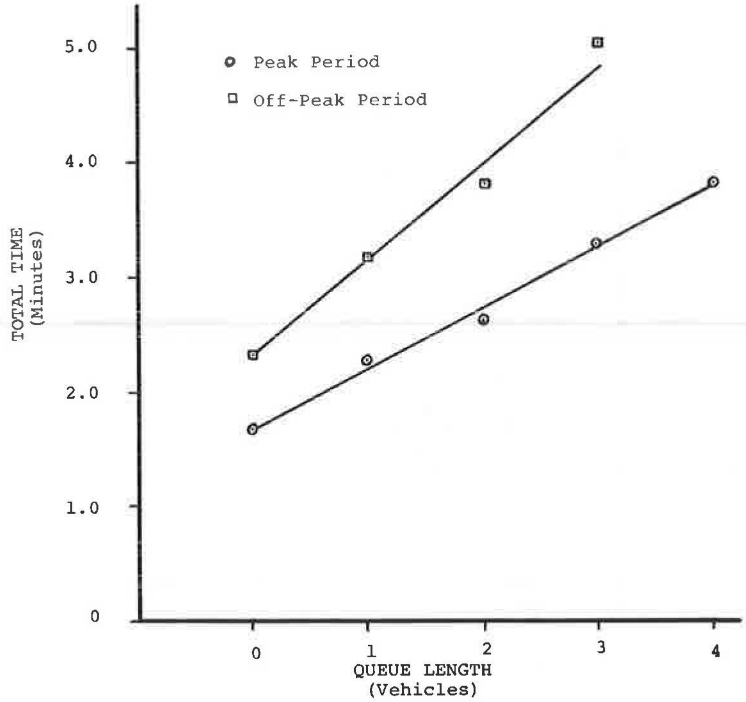

FIGURE 9 Total time in the drive-through system versus queue length for fast-food establishments.

were the same as those estimated for financial institutions (30 sec and 10 sec, respectively). Multiplying these times by the value of time of $5.00 per hour and including the cost of starting an automobile engine, the average cost of using inside facilities was $0.36 per customer. Like the situation at the financial institutions, the value of time spent at fast-food establishments ($0.357) was greater than the cost of fuel ($0.03).

Drive-Through Facilities

Costs associated with the use of drive-throughs at fast-food establishments were also similar to those at financial institutions. By relating waiting times to queue lengths, a series of user costs was developed. As described earlier, user costs for any type of drive-through were $0.965 per minute of time in the system. This cost included the value of time, fuel, engine oil, and engine wear. Multiplying this number by the time values obtained from Equations 2 and 3 that define the linear relationships in Figure 9 yields the data needed to establish a user cost relationship based on queue length. This relationship is shown in Figure 10.

Figure 10 also establishes the break-even point of cost between drive-through and inside service for peak or off-peak periods. The horizontal line represents the cost of doing business inside fast-food establishments, which was earlier reported as $0.36 per customer. For off-peak periods, the break-even point of cost occurs at a queue length of just under two vehicles. For peak periods, the break-even point of cost occurs at a queue length of just over four vehicles. In other words, if there are two or more vehicles in the drive-through line during off-peak periods or five or more vehicles in the line during peak periods, then inside service is more economical for the arriving customer. As was the case for financial institutions, the break-even point for inside versus drive-through service was not significantly affected by increasing or decreasing walking times in and out of the facility by 50 percent. This is because the walking time is short relative to the total time spent inside.

Fuel Consumption

In order to predict weekly fuel consumption for fast-food drive-through facilities, the average queue lengths for peak and off-peak periods were obtained. These figures were 1.92 and 0.73 vehicle, respectively. The average queue lengths were then weighted according to the amount of peak and off-peak traffic the fast-food establishments generated. With a weighting of 52 percent peak-period traffic, an average queue length of 1.35 vehicles was computed. Thus, the average weighted time spent at a fast-food drive-through facility was approximately 2.9 min. Using the average volume of 2,000 vehicles per week per facility, the weekly fuel consumption of each drive-through was 62 gal. If these customers were to use inside facilities instead, the fuel consumption for starting 2,000 automobile engines would be 5 gal. Thus, the average fast-food drive-through facility handling 2,000 vehicles per week causes a net amount of 57 gal of excess fuel consumption. Using the same estimate of 2,000 vehicles per week, the annual fuel consumed at the drive-through operation is 2,960 gal. Table 2 presents weekly excess fuel consumption data at fast-food drive-through facilities for various customer volumes. It can be seen that excess fuel consumption ranges from 15 to 86 gal per week per facility, depending on the number of patrons using the facility.

SUMMARY AND CONCLUSIONS

Because the drive-through facility has become a widespread phenomenon in recent years, this study's primary purpose was to examine the economics of the

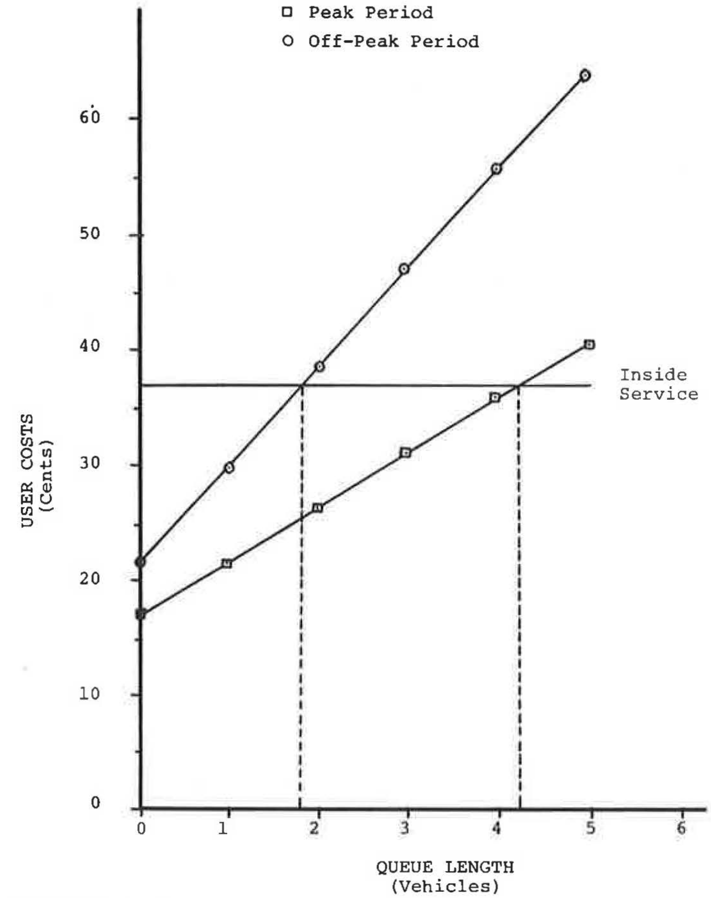

FIGURE 10 User costs of inside service and drive-through service at fast-food establishments.

TABLE 2 Weekly Fuel Consumption at Fast-Food Drive-Through Facilities for Various Levels of Weekly Customer Volume

Vehicles per Week	Fuel Consumed in Drive-Through (gal)	Fuel to Start Engine (gal)	Excess Amount of Fuel Consumed (gal)
500	16	1	15
1,000	31	3	28
1,500	47	4	43
2,000	62	5	57
2,500	78	7	71
3,000	94	8	86

drive-through system from the standpoint of the customer and to determine how much excess fuel automobiles consume when customers use these facilities.

The time that a customer spent at a drive-through facility was related to the customer's position in line. The data obtained reveal that the average drive-through service time for financial institutions was 2.0 min. Thus, the linear equation total time (TT) = 2.00 + 2.00X was developed to predict the total time spent in the system as a function of the customer's position in the queue.

For fast-food establishments, service times varied greatly and depended on peak or off-peak operations and queue position. Linear relationships were also developed to compute total time spent in the system. For off-peak periods, the equation TT = 2.20 + 0.89X was used. For peak periods, the equation TT = 1.78 + 0.46X was used to estimate total time as a function of queue position.

The average total time of 3.0 min was determined for inside service at fast-food establishments. This value represented both peak and off-peak operations. At financial institutions, the average total time was 2.6 min for inside service during off-peak periods. This value increased to 3.4 min during peak-period operations.

User costs were computed for drive-through and inside service. These costs included the value of time and fuel costs, oil costs, and engine wear costs for idling vehicle engines. These costs indicated that for financial institutions inside service was more economical to the customer when one or more vehicles per lane were in the drive-through during off-peak periods and two or more vehicles per lane were in the drive-through during peak periods. For fast-food drive-through facilities, inside service was more economical during off-peak periods when two or more vehicles were in the drive-through system and during peak periods when five or more vehicles were in the system.

Fuel consumption at drive-through facilities was also computed. For the average financial institution handling 2,000 vehicles per week through a two-channel drive-through system, 62 gal of excess fuel were consumed per week, or 3,210 gal annually. For the average fast-food establishment handling 2,000 vehicles per week through the drive-through system, an excess of 57 gal of fuel was consumed per week, or 2,960 gal annually.

A number of significant conclusions can be drawn from the data that were collected and analyzed. First of all, customers using the drive-through may not always be served as quickly as customers using inside facilities. In other words, drive-through facilities are not always the fastest means of doing business. An economic guideline was established in this study to help the customer decide which type of facility to use.

It can also be concluded that many of the service-time and waiting-time characteristics found in this study can be of use in determining adequate storage design characteristics for drive-through facilities. Developing a proper design for the expected number of drive-through patrons is essential to the effectiveness of the drive-through system. Inadequate design can lead to traffic problems that can contribute to congestion on the surrounding street network and to inefficient operation that discourages business.

Based on observations of customer preference, another conclusion of the study is that the drive-through is certainly a convenience for which Americans are willing to pay a premium in user costs. Whether the reason is the desire of customers to remain in the comfort of their automobile or the convenience the drive-through provides of conducting business in more casual attire, the drive-through has made its mark on our society and will continue to provide service for many years in the future.

It has been documented in this study that drive-through facilities consume thousands of gallons of excess fuel on an annual basis. In the event of another serious fuel shortage, the use of drive-through facilities in areas where adequate parking is available should be discouraged as a public policy in an effort to conserve fuel that would otherwise be consumed in an unproductive and wasteful manner.

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Utility Industry Progress Toward Implementing Electric Vehicle Introduction

GERALD MADER and ORESTE BEVILACQUA

ABSTRACT

The work of the Electric Vehicle Development Corporation (EVDC) is summarized. Founded in 1983, EVDC is charting and pursuing a realistic course for electric vehicle (EV) commercialization in the United States. The corporation's first objective is to support the development of an EV for use in commercial fleets. EVDC plans to demonstrate a market-acceptable commercial EV that uses near-term battery and drivetrain technology in the late 1980s. To accomplish this, five interrelated elements are being addressed: market identification, electric van specification, organization participation, electric van development, and financing and promotion. An advanced EV is expected to be introduced in the early 1990s. EVDC is moving from a technology-driven toward a market-driven approach to EV promotion that emphasizes the vehicle's advantages to the end user or consumer. EVDC hopes to accelerate EV promotion through coordinated vehicle design efforts, performance testing, and EV demonstrations, and by inducing special electric utility incentives such as lower off-peak rates. The coordinated participation of various EV stakeholders (the U.S. Department of Energy, the EV User Task Force, manufacturers, and the Electric Power Research Institute) is required to ensure that EVDC's planned EV introduction strategy is successful. Drawing these diverse organizations together is an arena in which EVDC can play an important leadership role.

The Electric Vehicle Development Corporation (EVDC) is a nonprofit organization formed in November 1983 to advance the development and introduction of electric vehicles (EVs). The corporation's nucleus consists of 30 U.S. utilities that serve a collective population of over 70 million consumers. By the end of 1985, EVDC membership is expected to include more than 50 utility companies as well as business and industrial organizations with EV interest.

EVDC's most important role is to chart and pursue a realistic course for EV commercialization in the United States. EVDC has developed a step-by-step approach to accomplish this commercialization and is working with and through other organizations toward effective, rapid attainment of commercialization. The approach is identified, the steps are delineated, and the progress made thus far is summarized.

APPROACH AND OBJECTIVES

EVDC's approach to EV commercialization, together with an implementation strategy, are outlined in the following paragraphs. The first commercialization objective is to develop an EV and support system for use within commercial fleets. This vehicle will utilize near-term battery and drivetrain technology. EVDC plans to demonstrate a market-acceptable commercial EV in the late 1980s. Introduction of EVs into the broader personal transportation market--the second commercialization objective--is tied to the availability of advanced battery and drivetrain technology that can satisfy the more demanding performance requirements of this market segment. The time frame for the introduction of an advanced EV is expected to be the early 1990s.

INTRODUCTION STRATEGY

To accomplish the first objective (fleet EV), the following five interrelated strategy elements are required:

1. Market identification,
2. Electric van specification,
3. Organization participation,
4. Electric van development, and
5. Financing and promotion.

Market Identification

A review of the EV literature in 1982 concluded that appropriate information needed to justify further EV market development or demonstration activities was seriously lacking. Prior research and demonstration results had produced mixed conclusions with respect to EV market potential. More important, they lacked the methodological rigor and detail needed for planning and investment decisions. This was especially the case with respect to commercial-sector EV applications, which may hold the most promise for quantity EV adoption during the next decade.

In light of this, the Institute for Social Research of the University of Michigan was commissioned by Electric Power Research Institute (EPRI) and the Detroit Edison Company to perform a pilot study on market prospects. This pilot study, conducted in early 1983, had two distinct components:

- A pilot survey of commercial fleet operators in the Detroit Edison service area. This survey provided both an initial estimate of potential EV market size and a methodology through which the size and characteristics of the national market and submarkets could be evaluated in future studies.
- An analysis of ongoing EV field test and demonstration programs. This analysis provided information needed to proceed with a new round of carefully designed commercial-sector demonstrations that would avoid past mistakes and maximize opportunities for success.

Following this pilot study, it was decided to proceed with a full-scale study. An appropriate statistical sample of establishments was drawn from a comprehensive list compiled by Dun and Bradstreet. Fleet managers in establishments throughout the United States (representing 13 million vehicles) were contacted by telephone, and nearly 600 interviews were conducted during 2 months of the fall of 1983. The overall response rate for these interviews was 92 percent. Because scientific sampling procedures were used, it was possible to translate the sample data into estimates for the entire nation with known degrees of precision.

There are an estimated 6 million automobiles and 7 million light-duty trucks and vans in commercial fleets in the United States. As shown in Table 1, almost 20 percent of these vehicles are typically driven less than 30 mi per day (mpd), and almost 50 percent are typically driven less than 60 mpd. In general, light-duty trucks and vans tend to be driven fewer miles per day than automobiles in commercial fleets. Trucks and especially vans thus appear to be the most promising initial target for EV production in quantity.

TABLE 1 Mileage Attributes of Light-Duty Commercial Automobiles and Trucks

	Typical Daily Mileage		
Attribute	<30	30–59	60–89
Estimated number of vehicles (millions)	2.5	3.3	2.3
Percent of all vehicles in commercial fleets	20	26	18
Average miles per day traveled	17	44	72
Percent occasionally driven >30 mpd	56	100	100
Percent occasionally driven >60 mpd	38	59	100
Percent occasionally driven >90 mpd	na	41	60
Average miles driven at >40 mph	na	4.5	9.3

Note: na = data not available.

To evaluate the constraints that future EV range decisions could have on the size of the potential EV market, four substitution criteria were developed to correspond to different levels of potential EV performance. Each existing fleet vehicle whose trip requirements matched a criterion was then considered to have a high substitution potential for the type of EV defined by that criterion. The four criteria were defined as follows:

1. Only vehicles typically traveling less than 30 mpd,
2. All vehicles typically traveling less than 30 mpd plus those traveling between 30 and 60 mpd that are parked for 2 or more hours during the day and that also travel less than 8 mpd at speeds greater than 40 mph,
3. Only vehicles typically traveling less than 60 mpd, and
4. All vehicles typically traveling less than 60 mpd plus those traveling between 60 and 90 mpd that are parked for 2 or more hours during the day and that also travel less than 8 mpd at speeds greater than 40 mph.

Depending on which of the four performance criteria is used, between one-fourth and three-fourths of all vehicles in today's average commercial fleet could be replaced by EVs (see Figure 1). (The number of vehicles falling within each of the substitution criteria increases substantially with the percentage of trucks and vans in the fleet.) In terms of absolute number of vehicles, this translates to between 2.5 and 7 million commercial vehicles.

Light-duty trucks and vans appear to be the most promising initial market for EV substitution. Overall, trucks and vans represent approximately 80 percent of all vehicles with high substitution potential as defined by the four criteria. These results prompted EVDC to begin an important related future investigation to determine the number of such vehi-

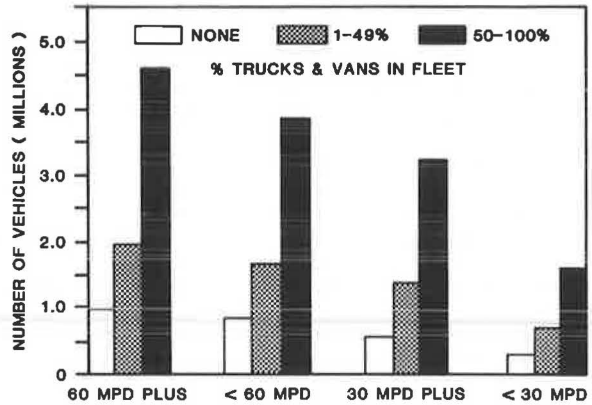

FIGURE 1 EV substitution potential under alternative substitution criteria.

cles that could be used by large fleets (e.g., those of electric utilities, telephone companies, delivery services, and local governments). After it determines the EV market needs of local territories, EVDC can then work toward actually placing the required EVs.

Electric Van Specification

Market identification is linked to the issue of cost competitiveness. The market may exist, but the cost may not be competitive. Therefore, as a preliminary step in product specification, a cost analysis was performed, the results of which are summarized in Figure 2. Under the assumed cost, use, and technology conditions, the total life-cycle costs for conventional and electric vans in the year 1990 are projected to be

- Conventional van--43.1 cents/mi;
- Improved electric van--44.0 cents/mi; and
- Advanced electric van--41.8 cents/mi.

Although these differences should not be considered significant given the number of assumptions incorporated in the analysis, it appears that the improved electric van is projected to cost only slightly more (approximately 2 percent) to own and operate than a comparable conventional van. On the other hand, the advanced electric van is projected to be somewhat less expensive to own and operate than the conventional van.

The total costs in Figure 2 are broken down into four parts. "Amortization" includes depreciation plus interest payments for capital invested in the vehicles and batteries. "Energy" includes fuel and lubricants, or electricity. "Maintenance" includes all maintenance expenses. "Other" includes tires, titling, parking, tolls, and other expenses.

The overall conclusion is that electric vans used in local service fleet applications have the potential to be cost-effective and competitive with conventional vans. Whether and when electric vans become cost-competitive will depend on achieving anticipated technological improvements--primarily in the battery--while simultaneously increasing the reliability of the propulsion system and reducing its maintenance. Cost-competitiveness also critically depends on achieving quantity electric van production to reduce vehicle and component costs. A caveat to keep in mind: if electric vans are to be cost-competitive with commercial vans, their energy and maintenance costs must be less than those for conventional vans. A reduction in operating costs (relative to conventional vans) is necessary to compensate for the additional capital costs associated with the EV and battery. Given the generally higher efficiency, smoother operation, and greater reliability of electric motors and controls compared with the internal combustion engine, the assumption of lower operating cost is realistic. Experience with commercial electric vans in Great Britain has indicated that the service maintenance cost is half that of the internal-combustion engine vans.

Building from the information gained through these initial fleet vehicle market and cost studies, an analysis was made of the relationship of electric van cost and market share to van performance. In this analysis, van performance was described in terms of range, acceleration, top speed, gradeability, and payload. Figure 3 shows an example of the results of this analysis: the relationship between vehicle range and life-cycle cost for a small electric van with a 1,200-lb payload and a large electric van with a 2,200-lb payload is shown. Separate curves are given corresponding to different 0- to 30-mph acceleration capabilities. The relationships shown in Figure 3 correspond to one specific battery type; a total of six alternative batteries were investigated in this analysis.

The results of this analysis were used to establish a performance specification for cost-competi-

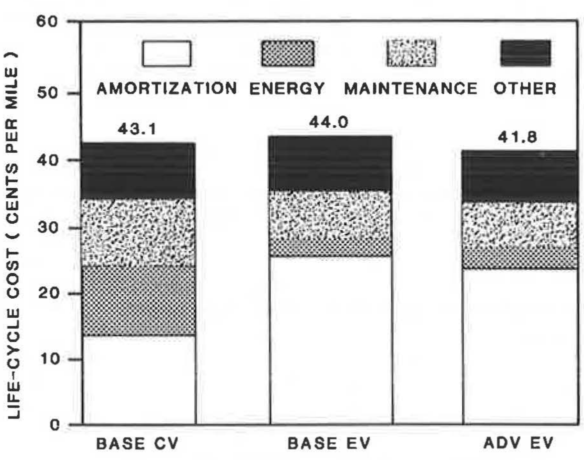

FIGURE 2 Conventional (CV) and electric (EV) fleet van total life-cycle cost comparison.

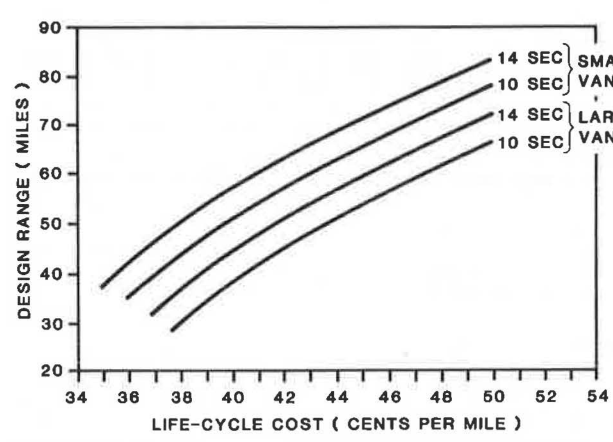

FIGURE 3 Electric van cost and acceleration trade-offs with Chloride EV5T lead-acid battery.

tive, market-compatible electric vans that could be produced in quantity by the late 1980s. The following is a summary of recommended van characteristics.

	Small Van	Large Van
Range (J227aC)	45 mi	60 mi
Payload	1,200 lb	2,000 lb
Acceleration (0 to 30 mph)	10 sec	12 sec
Top speed	55 mph	55 mph

The EVDC Technical Committee, which comprises utilities, governments, the U.S. Postal Service, and other organizations with EV operating experience, played a key role in evaluating the results of the analysis and developing the performance specification. This specification will find immediate application in the joint effort of EPRI and the U.S. Department of Energy (DOE) to develop prototype near-term, market-compatible electric vans for fleet use. The specification will also be used to expand EVDC's efforts to guide the development of EV technology, and to build support for that technology's introduction into practical use.

Organization Participation

The cooperative and coordinated participation of the various EV stakeholders is required if the EV introduction strategy is to be successful. The key stakeholders are EPRI, utilities and trade organizations, DOE, manufacturers, commercial fleets, and infrastructure support organizations.

Drawing these diverse organizations together is a critical challenge; the fact that this had not been done before was a major motivation behind the formation of EVDC. As a first step in this participation process, EVDC has formed a technical advisory committee composed of leaders in EV technology development and application. This committee will provide guidance for future technological activities and will ensure a "right-track" confidence level. More recently, EVDC has established a marketing advisory committee to assist in the effort to commercialize EVs.

Electric Van Development

In response to indications from EV users, and with the results of market and technology assessments, increased emphasis is now being placed on the development of electric vans for fleet applications. EVDC has established a two-phase plan for introducing EVs into commercial fleets.

In Phase 1, EVDC is initiating the Electric Van Market Application Assessment Project that involves the operation of the General Motors CF vans (produced by Bedford with the reliable Lucas/Chloride electric propulsion system and battery) within selected utility companies and service fleets (see Figure 4). This project will provide the experience necessary to establish EV service and support systems that are vital to the commercial introduction of EVs into fleet operations. The project will also seek to overcome negative perceptions of current EV technology and of the technology's near-term outlook by providing utilities with an opportunity to gain operating experience with a proven and reliable EV.

Phase 2 involves the collaboration of DOE and EPRI in a multiyear joint project to develop an improved prototype fleet EV with a fully integrated powertrain/battery system that could satisfy the market-responsive performance and design specifications developed by EVDC and summarized earlier in this paper. On the basis of emerging near-term technology in the United States and abroad, plans are being followed to develop and fabricate prototypes of fleet market-compatible electric vans that could be field tested in 1986 and 1987. These electric vans would serve as prototypes of commercial fleet EVs that could be produced in quantity in the 1987-to-1988 time frame. Van development is scheduled to start in mid-1985. The following is an outline of related emerging technology.

FIGURE 4 Electric CF van.

United States

- Development of the sealed lead-acid battery, perhaps available in 3 to 4 years, into an inexpensive, long-lived, and dependable battery for EVs.
- Verified performance of the Ni-Fe battery as an alternative battery system for fleet applications.
- Evolution of power electronics technology that will reduce cost, weight, and size; increase efficiency; and make developments such as the ac-drivetrain marketable.
- Modifications of the Eaton Corporation ac-drivetrain system to allow it to be integrated into the Chrysler T-115 minivan.
- Advent of a microprocessor that provides the attendant cost benefits that result from the combined functions of the motor, electronic controller, battery, charger, and other auxiliary components.
- Development by Ford Motor Company of an integrated ac-drivetrain for passenger cars in the 1990s.

Overseas

- Bedford (General Motors subsidiary) CF electric vans are currently being produced using assembly-line methods.
- Lucas/Chloride EV Systems is producing a standardized battery and drive system that will be assembled into light-duty commercial vehicles, including the Bedford CF van.
- Gesellschaft für Elektrischen Strabenverkehr (GES) is producing the CitySTROMer (Volkswagen Golf conversion) with an advanced, integrated propulsion system and improved thermal and electrolyte management systems for the lead-acid battery.
- Lucas/Chloride and Brown-Boveri are each developing a sodium-sulfur battery that is expected

to provide much higher performance and range capabilities than those currently available.

Financing and Promotion

Because organizations such as EPRI and DOE are under certain institutional constraints in these activities, this is an arena in which EVDC could play an important leadership role. Most financing has heretofore gone into research and development rather than the actual production of vehicles. In order to have production financing, specific market needs must be demonstrated, as discussed under the "Market Identification" section in this paper. With such market needs and opportunities identified, EVDC can then proceed with an investigation into various alternative financing mechanisms. These include limited partnerships; participation by manufacturers, government, and/or electric utilities; tax incentives; and so forth; and also identifying high-value markets suitable for initial entry.

The promotion of EVs has generally been technology driven. It is important that EV promotion also become market driven. To this end, information must be disseminated regarding specific EV advantages to the consumer or potential user. EVDC can influence and accelerate this process through coordinated vehicle design efforts, performance testing, and EV demonstrations, as well as by inducing special electric utility incentives such as lower off-peak rates. These market-driven promotional activities will in turn enhance prospects for suitable financing.

SUMMARY

EVDC has adopted an overall strategy to accomplish two EV commercialization objectives: the introduction of electric vans into commercial fleets in the late 1980s, and the introduction of advanced EVs into the personal transportation market in the early 1990s. During its first year of operation, EVDC concentrated its efforts on characterizing the commercial fleet vehicle market and developing specifications for an EV that could capture the largest market segment, as well as expanding its membership base. Contact with and coordination of key stakeholders have been strengthened through the establishment of the Technical and Marketing Committee and the initiation of a joint EPRI-DOE electric van development project. EVDC plans to initiate market and infrastructure support development activities in 1985 and to create the technical and financial plans required to implement a large-scale demonstration as the first stage in vehicle commercialization.

EVDC's objectives can be attained only through close cooperation with DOE, the EV User Task Force, manufacturers, and EPRI. EVDC is uniquely structured to accomplish this coordinative role. The EV User Task Force and EPRI senior management have members on the EVDC Board of Directors, and the EVDC Technical and Marketing Committee membership includes DOE, national laboratory staff, and manufacturers. EVDC is committed to work together with all of these organizations to move the technology closer to meeting market needs so that successful commercialization of EVs can be accomplished in the earliest possible time.

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