ENERGY AND TRANSPORTATION IN THE UNITED STATES

Marc Ross

American Council for an Energy-Efficient Economy
1001 Connecticut Avenue, NW Suite 801
Washington, DC 20036

American Council for an Energy-Efficient Economy
2140 Shattuck Avenue, Suite 202
Berkeley, CA 94704

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Marc Ross

Physics Department, University of Michigan, Ann Arbor, Michigan 48109
and

American Council for an Energy Efficient Economy, 1001 Connecticut Avenue NW, Washington DC 20036

INTRODUCTION

Transportation activities accounted for 28% of all US energy use in 1987, or 21.3 quadrillion Btu (quads). More than 97% of this energy was in petroleum products. Moreover, 63% of all petroleum is used directly for transportation, and much of the petroleum used in other sectors is in the form of by-products of gasoline, diesel fuel, and jet fuel production. In addition, while energy use for transportation grew at the relatively moderate average rate of 1.2% per year in 1972–1987, all other sectors slashed their use of petroleum, so transportation's share is larger than in the past (1).

What is the story behind these numbers? The past 15 years have been tumultuous. The oil embargo of the fall of 1973 led to shortages and price controls. The Motor Vehicle Information & Cost Savings Act of 1975 introduced the Corporate Average Fuel Economy standards. The second oil shock, accompanying the Iranian revolution of 1979, led to long lines at filling stations and high fuel prices. Then, as governments, equipment manufacturers, and consumers around the world moved toward more efficient use of petroleum, and oil producers moved to increase production, oil prices fell and fuel again became plentiful. The typical price of gasoline in the United States is now about the same as in 1972, after accounting for the general inflation.

But we have hardly returned to 1972 conditions. Our capital, human knowledge, institutions, and equipment have changed forever. Our un-

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derstanding of transportation energy issues—supplies of petroleum, the efficiency of its use, the side effects of its extraction and use, and even alternatives to the present energy-using system—is far deeper today than before the adventures of the past 15 years.

In this paper, energy use in all areas of transportation is briefly analyzed. Then a coherent subset of issues facing the largest of the activities, personal passenger transportation based on petroleum fuels, is explored in depth: the reasons for past and future growth in driving, the past developments in fuel economy, and the possibilities for change in the next one to two decades. This look ahead involves (*a*) the technical potential for further improvement in fuel economy and reductions in air pollution, (*b*) the role of the market in these areas, and (*c*) the role of public policies.

This narrow focus has been adopted to enable the exploration of several perspectives on one area of transportation in some depth. Other fuel options and other transportation modes are of course important, and are very briefly discussed at the end of this paper. Nevertheless, petroleum-fueled personal passenger transportation is the largest energy user, accounting for 58% of transportation energy use, and will remain so for the period in question. Although there are alternatives of considerable interest, there will be no rush to embrace them on a national scale.

ACTIVITY AND ENERGY USE, 1972–1985

In this section, energy use in 1985 is first disaggregated. In each subsector, energy use is expressed as the product of a level of activity and an energy-intensity. For example, for automobiles the activity selected is vehicle-miles traveled and the energy-intensity is then expressed in Btu per mile. Total energy use is a sum of such products:

$$E = \sum_i A_i (EI)_i \qquad 1.$$

Using the simple but elegant Divisia technique, the change in energy use over time is then decomposed into a change due to changed activity levels and a change due to changed energy-intensities.

Transportation in 1985

There are several sources of data on energy and activity in transportation; this richness of data makes the sector more congenial for the energy analyst than any other sector except manufacturing. Using these sources, a group at Oak Ridge National Laboratory has disaggregated transportation energy use (Table 1.10 of Refs. 2 and 3).

One area of transportation that needs a more ambitious disaggregation is

trucks. The light truck has been the most rapidly growing category of transportation, more so than air travel. It is, however, primarily a categorization problem. Trucking is dominated in fuel use by light trucks (pickups, vans, and jeep-like vehicles, under five tons); about three fourths of light trucks, in turn, are now being used as cars (4). A good analysis requires disaggregation of trucking into light trucks used as personal passenger vehicles, light trucks used for freight, 5–13-ton trucks, and very heavy trucks. (In the tables in this article the last two are grouped together as heavy trucks.) Among the reasons for the shift to pickup trucks as passenger vehicles is the decreasing number of passengers in typical trips. The average household size declined from 3.14 in 1970 to 2.66 in 1987, and the average occupancy of automobiles declined from 2.2 to 1.5 or 1.6. Light trucks also appear to be more durable than cars. The average light truck is scrapped after 14 years, while the average car is scrapped after 10 (Table 2.11 of Refs. 2 and 3). Other advantages of light trucks may flow from the fact that they are more lightly regulated with respect to fuel economy, emissions, and safety than cars.

Two sources of first-hand data permit the disaggregation of trucking: the Census's Truck Inventory and Use Survey (TIUS) of 1982 (4) and the 1985 Residential Transportation Energy Consumption Survey (RTECS) of the Energy Information Administration (EIA) (5). The activities and energy use of highway vehicles are obtained from these sources (Table 1). In preparing this table, an inclusive definition of light trucks, as to types of vehicle, is used. In some other studies, light trucks comprise a more restricted group of vehicles. This difference largely explains the larger activity and energy use by light trucks (and smaller by heavy trucks) in Table 1, compared to the results of some other studies (2, 8, 9, 10).

Table 2 shows energy, activity, and energy-intensity in detail for all of transportation in 1985. The main characteristic is the dominance of personal passenger vehicles. Passenger transportation dominates freight in energy use, and personal vehicles dominate passenger transportation. Personal passenger vehicles account for 58% of all transportation energy use and for 85% of all passenger-miles (assuming a personal vehicle occupancy of 1.6 in 1985). Commercial air carriers provide 11% of the passenger-miles, while buses and trains together provide only 4%.

The personal vehicle is more energy intensive than the other forms of passenger transportation, but not by as much as many think. The average car is shown in Table 2 to have an energy-intensity of 7100 Btu per mile (an in-use fuel economy of 17.6 mpg). An urban transit bus has an energy-intensity of 3600 Btu per passenger-mile (Table 2, note e). So a car with two people, or a car with one person but twice the average fuel economy, not only goes where and when you want, but has roughly the same energy-intensity per passenger-mile as an urban bus. (The low energy-intensity for buses in Table

Table 1 Highway vehicle activity and energy use, 1985

	Vehicles[a] (millions)	Miles/vehicle (thousands)	Vehicle-miles[b] (trillions)	mpg	Energy (quads)
Automobiles					
household	104	9.7[c]	1.01	17.2[d]	7.35
fleet	10.5[e]	27	0.28	20[f]	1.78
passenger light trucks[g]	28.7[h]	9.6[c]	0.28	13.3[d]	2.60
freight light trucks[i]	9.6[h]	10.5[j]	0.10	12[j]	1.05
heavy trucks[k]	4.1	23	0.035	5.4	2.40
buses[l]	0.6	10	0.006		0.15
motorcycles			0.009		0.02
Total			1.78		15.35[m]

[a] Automobile and truck totals based on R. H. Polk data (pp. 28, 29 of Ref. 6)
[b] In approximate accord with data from the Department of Transportation (7), (p. 53 of Ref. 6)
[c] From (5), but slightly less to account for some of those vehicles used by households being fleet automobiles or freight light trucks with higher use.
[d] (5)
[e] (Table 2.35 of Refs. 2 and 3)
[f] Estimate between new-car in-use fuel economy of 22 mpg and household fuel economy of 17 mpg.
[g] Includes pickups, vans, and jeep-like vehicles.
[h] For number of light trucks, subtract heavy trucks from total. Assume 75% of light trucks are used for personal passenger transportation. This assumption is based, for example, on 1982 TIUS results that 73% of light trucks do not carry freight (4). (Freight includes craftsman's tools.)
[i] Under 10,000 lbs.
[j] Miles per vehicle adjusted is up about 10% and fuel economy down about 10% from household trucks (5).
[k] Based primarily on summary of TIUS (Table 2.39 of Refs. 2 and 3). Number of heavy trucks based on 3.58 million in 1982 (TIUS), addition of 5.4 million trucks in 1982–1985, and sales fraction of heavy trucks of 9% in the period (pp. 10, 11 of Ref. 6). 1985 miles per vehicle, vehicle-miles, and fuel economy generated assuming (*a*) that miles per vehicle-year of trucks over 26,000 lb. remained at 36.6 thousand, and those of trucks between 10,000 and 26,000 lb. remained at 9.5 thousand (TIUS), and (*b*) that 1982 fuel economies improved 2%. The results of this exercise for 1985 is 76 and 19 million vehicle-miles, and 27.5 and 19.1 thousand Btu per mile, for the heavier and less heavy groups of trucks, respectively. The resulting energy use is: diesel 1.95 and 0.08, gasoline 0.10 and 0.27 for the two groups of heavy trucks, respectively, in quads (quadrillion Btu).
[l] Tables 2.47 and 2.48 of Refs. 2 and 3
[m] This quantity (and gasoline and diesel totals) was used as a control total to make minor adjustments.

2 is due to school buses and the shaky assumption that their average passenger load is 20. The average load of the urban transit bus is 17.) The energy-intensity of certificated air carriers is also not as great as one might, at first, think.

Freight energy use is also dominated by highway vehicles, but freight activity measured in ton-miles is dominated by nonhighway modes. The nonhighway freight modes are much less energy intensive than heavy trucks. Note that gas pipelines are fairly energy intensive, however; a gas is much more difficult to pump than a liquid.

The Change from 1972 to 1985

Many of the transportation activities have been tracked in consistent or nearly consistent data series since 1970 and before. For this paper, the period

Table 2 Transportation activity and energy use, 1985[a]

Mode	Energy (quads)	Activity[b] unit	Activity (trillions)	Energy-intensity (thousand Btu per unit)
Passenger				
automobiles[c]	9.16	VM	1.29	7.1
light trucks[d]	2.60	VM	0.28	9.3
buses	0.15	PM	0.11[e]	1.4[e]
rail	0.05[f]	PM	0.015	3.5[f]
air	1.61[g]	PM	0.336	5.0[g]
subtotal	13.57			
Freight				
light trucks[d]	1.05	VM	0.10	10.4
heavy trucks	2.40	TM	0.7	3.4
rail[h]	0.45	TM	0.91	0.49
marine[i]—domestic	0.30	TM	0.89	0.34
—foreign	0.75	lbs	1.54	0.5
pipelines[j]	0.55[f]	TM	0.26	2.1[f]
subtotal	5.50			
Miscellaneous				
military	0.70			
recreational boats	0.22			
general aviation	0.14			
subtotal	1.06			
Grand total	20.12			

[a] Adapted from Table 1.10 (Refs. 2, 3) and Table 1.
[b] PM, passenger-miles; VM, vehicle-miles; lbs, pounds shipped; TM, ton-miles.
[c] Includes motorcycles
[d] Under 10,000 lbs.
[e] Assumes occupancy of 20 passengers in school buses. The energy-intensity of urban transit buses is stated to be 3.6 thousand Btu/PM.
[f] Includes losses in generating and distributing electricity.
[g] Freight-activity, responsible perhaps for 0.05 quad, is included. Energy use is purchases of domestic fuel by domestic and international carriers. The energy-intensity is based on total fuel used, roughly corrected for freight activities.
[h] Table 3.9 of Refs. 2 and 3.
[i] Tables 3.5 and 3.6 of Refs. 2 and 3.
[j] Natural gas pipelines only. Activity is based on total consumption of natural gas (1) and assumed average transportation of 620 miles.

1972–1985 is selected for an analysis of trends. Energy consumption in 1972 and 1985, and average growth rates for activity during that period, are shown in Table 3. (It will be seen that our analysis does not require activities in different subsectors to be measured in the same units. Energy use measures must be commensurate across subsectors, however.)

Table 3 reveals the critical role of the light truck as a personal passenger vehicle. It also shows the growing importance of air travel, as well as the relatively slow growth of most freight activities. In the latter connection,

Table 3 Transportation energy use and activity, 1972–1985

	Energy (quads)		Activity	Growth rates (percent per year)	
	1972	1985	means[a]	activity	energy-intensity[b]
Passenger					
automobiles	9.18[c]	9.16	VM	2.1[d]	−2.1[e]
light trucks[f]	1.11	2.60	VM	8.9	−2.0
(combined)	(10.29)	(11.76)	VM	3.0	−2.0
buses[g]	.11	0.15	PM	2	1
rail[h]	.04	0.05	PM	0.3	1
air[i]	1.30	1.61	PM	6.3	−4.6
subtotal	11.74	13.57			
Freight					
light trucks[j]	0.99	1.05	VM	1.9	−1.4
heavy trucks[k]	1.82	2.40	GNP[k]	2.5	−0.3
rail[l]	0.57	0.45	TM	0.9	−2.7
marine[m]—domestic	0.32	0.30	TM	2.9	−3
—foreign	0.69	0.75	T	1.6	−1
pipelines[n]	0.77	0.55	quads	−1.7	−1
subtotal	5.15	5.50			
Total[o]	16.90	19.07			

[a] VM, Vehicle-miles; PM, passenger-miles; TM, ton-miles; T, tons shipped; quads, quadrillion Btu (of natural gas consumed in the United States).

[b] Independent data for cars and to a lesser extent for light trucks, but energy-intensity trends are typically calculated as difference in growth rate between energy and activity.

[c] Table 1.13 of Refs. 2 and 3.

[d] Automobiles (excluding motorcycles) were driven 986 and 1290 billion miles in 1972 and 1985, respectively (7).

[e] Consistent with change from 13.5 to 17.8 mpg.

[f] The light truck VM in 1972 is the difference between total truck VM (7) and non-light-truck VM (Table 2 of Ref. 11). Thus it equals 260 − 90 = 170 billion. The fraction of these vehicles used as passenger vehicles in 1972 (0.534 from Ref. 11) is used to apportion the VM, yielding 91 billion VM for passenger light trucks. Fuel used is determined assuming that fuel economy improved 2% per year in 1972–1985, so fuel use for passenger light trucks in 1972 = (91/275) exp (13 × ln 1.02) × 2.60 = 1.11 quads, where 275 billion VM were traveled in 1985.

[g] (Tables 2.45 and 1.18 of Refs. 2 and 3). The average occupancy of school buses is assumed to be 20.

[h] Tables 3.11 and 3.12 of Refs. 2 and 3.

[i] Table 3.1 of Refs. 2 and 3, corrected to domestic fuel purchases.

[j] Fuel use is based on assumed fuel economy of 10 mpg and VM from note f: (79/10) × 1.25 = 0.99 quads. Activity grows from 79 to 101 billion miles (Table 1).

[k] Fuel use for all trucks (Table 1.13 of Refs. 2 and 3) or 3.91 quads in 1972, from which 2.10 for light trucks (notes f and j) is subtracted. Activity is taken proportional to real GNP. An alternative would be ton-miles in intercity motor freight, which grew from 470 to 610 billion from 1972 to 1985 (p. 57 of Ref. 6).

[l] Table 3.9 of Refs. 2 and 3.

[m] (Tables 3.5 and 3.6 of Refs. 2 and 3). A universal 1% per year energy-intensity reduction is assumed for foreign.

[n] Natural gas pipelines only. No historical data is available on energy use for pipelines for petroleum or materials other than natural gas.

[o] Miscellaneous uses have been omitted from Table 1.

although value measures of trade and freight are increasing, tonnage measures are declining with respect to GNP. This reflects the growing share of consumption, in advanced industrial societies, accounted for by less materials-intensive, and therefore lighter, products (12).

The data in Table 3 has been set up to enable a Divisia decomposition. Define $G(X)$ to be the compound growth rate, measured in percent per year, of a quantity $X(T)$:

$$G(X) = (100/T)\ln[X(T)/X(0)]$$

with T in years; and define the weighted average growth rate:

The Divisia decomposition of Equation 1 is:

$$G(E) \approx < G(A) > + < G(E/A) > \qquad 2.$$

where one should note

$$< G(E/A) > = < G(E) > - <G(A) >$$

Here W_i is the time-average energy weight of the subsector:

$$W_i = 1/2[E_i(T)/E(T) + E_i(0)/E(0)]$$

[See Boyd et al (12a) for further details.] Equation 2 states that the average growth rate in energy use (approximately) equals the energy-weighted average growth in activity plus the average growth in energy-intensity. (For typical energy-use time series, the approximation is good to about 0.1% per year or better.)

The results of the analysis are summarized in Table 4. The behavior for transportation as a whole is the same as that for personal passenger vehicles alone: growth in activity at an average 3% per year, but a rapid decline in energy-intensity, so that energy use grew only 1% per year in this period.

The separate results for passenger and freight activity show what is not surprising to any observer of the US scene: travel is increasing rapidly, but so is the energy-efficiency with which it is provided. Freight activity in ton-miles has been increasing much less rapidly, a characteristic of an affluent and mature society. At the same time, it has proven more difficult to improve the

Table 4 Divisia analysis of energy used for transportation, 1972–1985
(growth rates in percent per year)

	Activity	Energy-intensity	Energy
Passenger	3.6	−2.4	1.1
Freight	1.7	−1.1	0.5
Total	3.0	−2.0	1.0

energy-efficiency of freight services. (The notes to Table 3 show that the freight data is much less complete and therefore the decomposition for freight is less reliable than that for passenger travel, but the essential picture is clear.)

If we want to understand these results, we must decompose and probe them further. What is responsible for the growth in travel? What is responsible for the decline in energy-intensity? In the next two sections these questions will be explored with respect to personal passenger vehicles.

TRENDS IN HIGHWAY TRAVEL

Vehicle travel continues to grow in spite of arguments that saturation is imminent. Figure 1 shows total vehicle-miles traveled, and Figure 2 total vehicle-miles per adult (i.e. total vehicle-miles divided by the population aged 16 and over). The data and a curve with adjusted parameters for income and fuel price effects are shown. The theoretical curve is almost proportional to real disposable income per capita, corrected by a moderate fuel price elasticity effect, representing an elasticity of −0.1 (indicating that a 10% increase in the fuel price induces a 1% decline in consumption). In a slightly different approach to these data, Werbos found a fuel price elasticity of −0.2 (14).

The decomposition of this trend in vehicle-miles will be based on information from the 1983 National Personal Transportation Survey (NPTS) on drivers and their driving (15). From our present perspective, however, 1983 was an unusual year because of the high fuel prices, with a real fuel price 42% higher than now, so in the following the amount of driving in that year will be corrected by a factor of $(1.42)^{0.15} = 1.05$ (where the average of the two elasticities mentioned in the last paragraph is adopted). That is, about 5% more driving would have occurred in 1983 had gasoline prices been like those of 1986. This correction crudely represents the effect on vehicle-miles of the fuel price excursion of the late 1970s and early 1980s.

Just because income per person provides a good statistical fit to the general growth trend for driving does not mean it is a good interpretation. De-

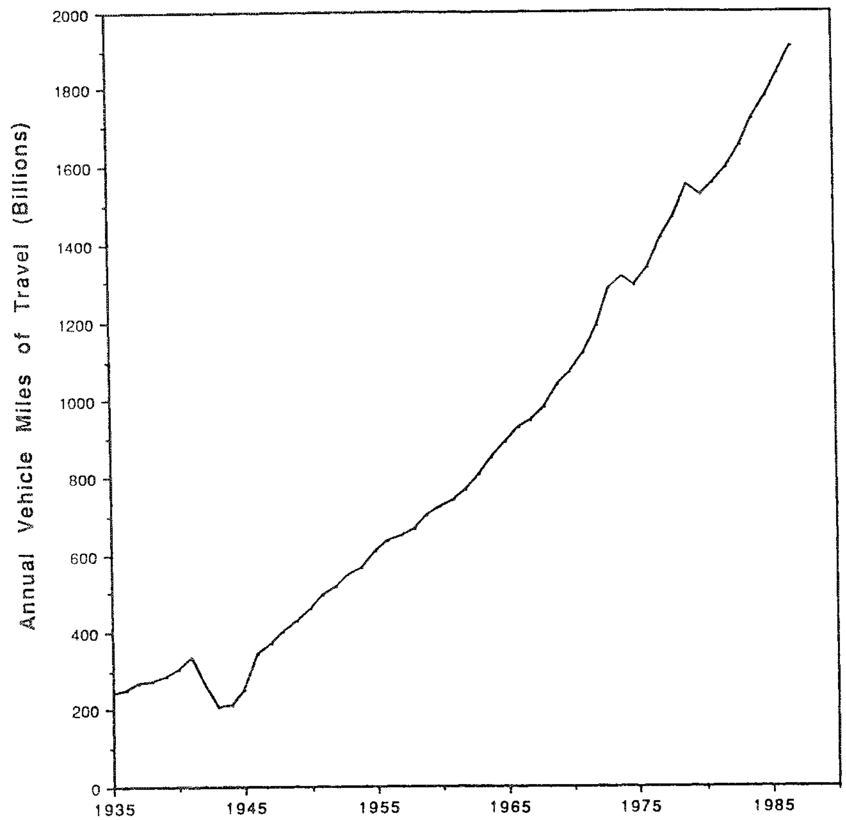

Figure 1 Total vehicle-miles traveled on highways annually (in the 12 months prior to January of the year shown). Source: (13)

mographics provide a more interesting perspective. Much of the growth in driving since the late 1960s is associated with women moving into the labor force and those women becoming drivers (Table 5). In 1969, 39% of adult women were employed; in 1983, 50% were employed. In 1969, 74% of employed women had drivers licenses; in 1983, 91% did. The relative increase in licensed drivers accounts for half the growth in driving per adult shown in Figure 2 between 1969 and 1983.

From 1969 to 1983 (corrected), personal vehicle-miles traveled grew at a rate of 3.5% per annum (p.a.). This growth can be described in terms of the 1.8% p.a. growth rate in number of adults, a growth of 0.6% p.a. due to shifts in employment and the changing role of women discussed in the previous paragraph, and the residual, a 1.1% p.a. growth in driving per licensed driver.

In the next decade growth in the number of adults will slow dramatically, as

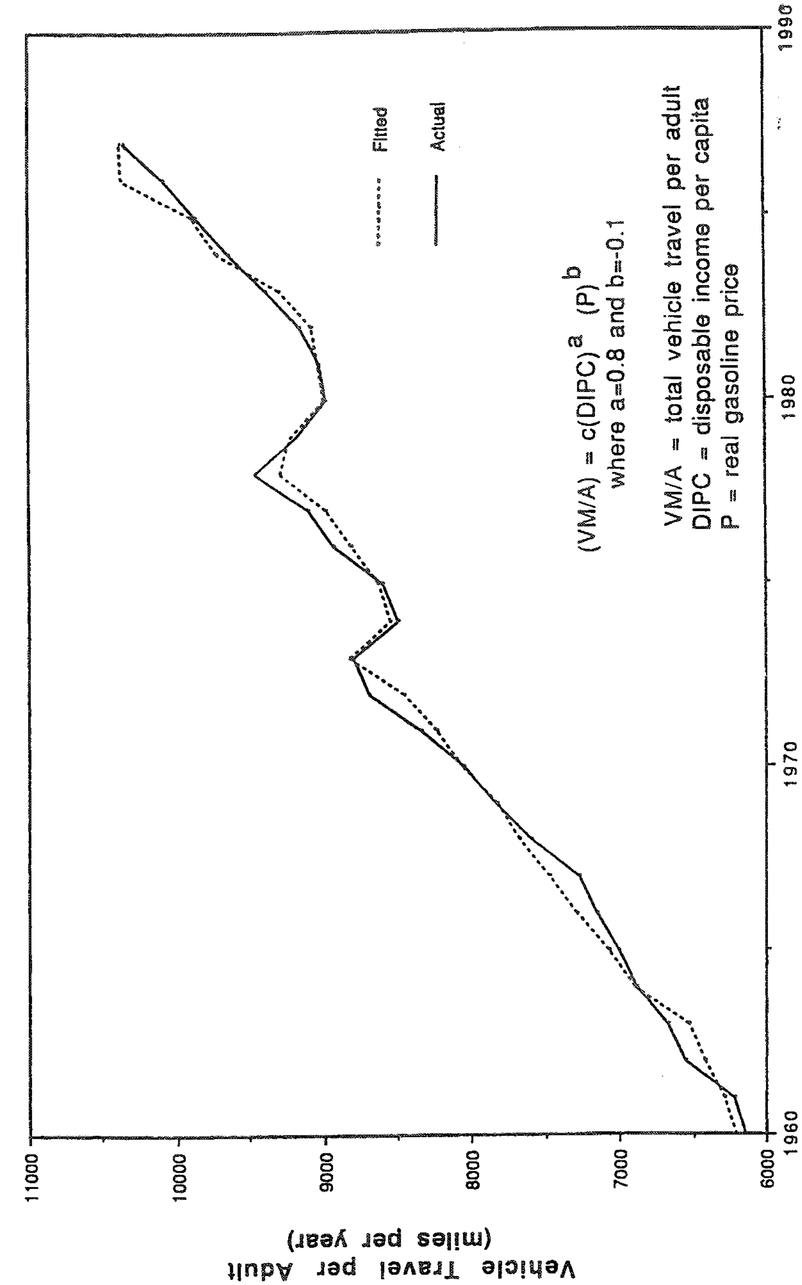

Figure 2 Elasticity analysis of total vehicle-miles traveled per adult. The analysis is similar to that of (14), but differs in details as well as including more recent data. Source of primary data: (13)

Table 5 Drivers licenses and driving, by sex and employment

	1969		1983		
	% of adults	% with license	% of adults	% with license	Annual miles per driver (1000s)
Employed full time or part time					
Male	36.3	93.5	34.4	95.8	15.9
Female	20.8	74.1	26.0	91.1	7.7
Not employed					
Male	10.5	64.8	13.2	76.0	7.7
Female	32.4	54.9	26.4	64.2	4.5
Total	100	75.1	100	83.6	10.3

Source: (15)

will the effect of increasing employment and licensing of women (because they have already moved so far toward matching men in this respect). If men and women in 2000 have the employment-licensing characteristics of men in 1983 (in the various age groups) and if the average growth rate of driving per licensed driver remains the same as for 1969–1983, then vehicle-miles traveled will grow an average of 2.4% per year from 1983 to 2000. This slower growth should be felt soon, after the response to the fuel price reductions of the mid-1980s is complete—if the analysis is accurate.

The projection of slower growth in road travel is supported by two other facts. The distance driven per driver is unlikely to increase much further for the predominant cohort, employed men in their prime years (25–54). This group already drives an average of 18,000 miles per year or about 1 1/2 hours per day. Moreover, as shown in Figure 3 for all employed men, this driving pattern is essentially independent of income (unpublished analysis of the NPTS data by Anant Vyas). (In the past, evidence has been offered for a fairly strong income dependence of vehicle-miles per household, but that is of less interest than the weak dependence shown, which is for vehicle-miles per driver.)

On the other hand, there is no hint that the information revolution will reduce the amount of travel. If anything, just as more information seems to lead to more use of paper, better information and communication may lead to increased travel. The cellular phone may, for example, lead some people to spend more time in their vehicles. More important, the growth in part-time work and business services is leading people to spend more time on the road. These developments are abetted by the information revolution, but are also partly due to a relative decline in full-time work with good pay.

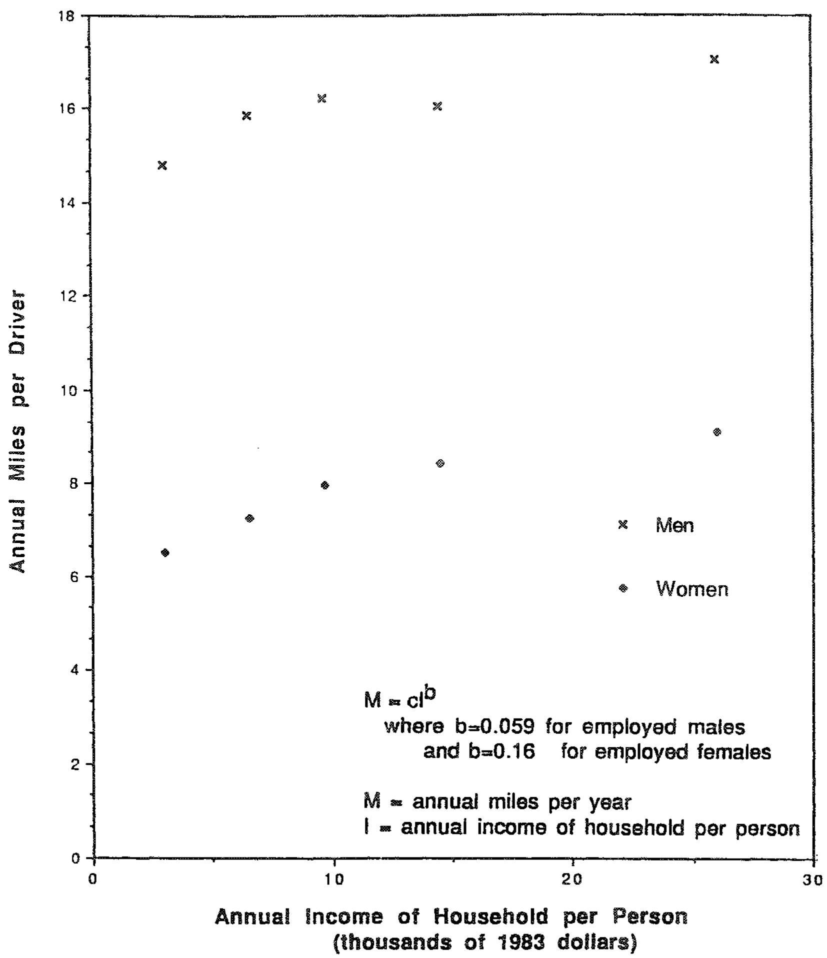

Figure 3 Distance driven per driver (in thousands of miles) vs household income per person, showing the small income elasticity of driving in the United States. Data is for 1983 from (15)

The description of vehicle-miles traveled on the basis of the number of drivers, just presented, is in contrast to one based on the vehicles in use—an approach that has been widely used in forecasting. The trouble with using miles per vehicle for forecasting is that, in the United States, a fundamental shift in the use of private vehicles is now beginning to take place. The number of households with more vehicles than drivers is becoming large. This trend toward extra, probably special-use, vehicles may well continue strongly as vehicles are kept in service longer and the adult population grows more

slowly. (For example, the median age of cars in use has increased two years since the early 1970s.) The growth in the number of vehicles and, especially, their use is thus difficult to forecast accurately.

In conclusion, recent growth in vehicle-miles has been fueled by the baby boom cohort entering adulthood and the changing role of women. Those sources of growth are saturating, so total vehicle-miles should start to grow more slowly. Nevertheless, there is still considerable room for growth in vehicle-miles.

RECENT TRENDS IN FUEL ECONOMY

The Mix of Vehicles Purchased

Since its nadir of about 14 mpg in 1973, the fuel economy of new cars has approximately doubled to 28 mpg. (These new-vehicle fuel economies are nominal, i.e. laboratory measurements. Their relation to in-use fuel economy is discussed below.) The average fuel economy of new light-duty vehicles (both cars and light trucks) has, however, only increased one mpg since 1981 (Figure 4). One important reason for slower growth in fuel economy compared to the previous period is that consumers are switching to light trucks, and their fuel economy is lagging.

The early 1970s saw a shift to smaller cars. In spite of frequent remarks to the contrary, however, consumers are not switching back to larger cars (Figure 5), although they did, to a small extent, in the early 1980s. If the size of cars is specified in terms of interior volume, then one finds that the sales-weighted average volume has hardly changed in the past decade. The Environmental Protection Agency (EPA) interior volume averaged 109 ft^3 in 1978, fell to a low of 104 ft^3 in 1980, and is now steady at 108 ft^3.

In addition, while there is considerable variation in fuel economy within each automobile size class, especially in the small classes, the average fuel economies for each class vary only 30% from the smallest to the largest size class (Figure 6). This is in part due to the low fuel economies of some heavy high-powered cars that are styled as sport cars and so have low interior volume, with the result that the average fuel economy in the smaller classes is held down. In other words, while the very highest-fuel-economy cars are indeed small, buying the average small car does not ensure getting a high fuel economy.

With these observations in mind, it is not surprising that a Divisia analysis of automobiles by size class shows that only one-tenth of the fuel-economy improvement in new cars from 1976 to 1988 was due to consumers' shifting to smaller cars, while the lion's share came from fuel-economy improvements within each size class (Figure 7). This analysis is, however, somewhat sensitive to how the size classes are defined.

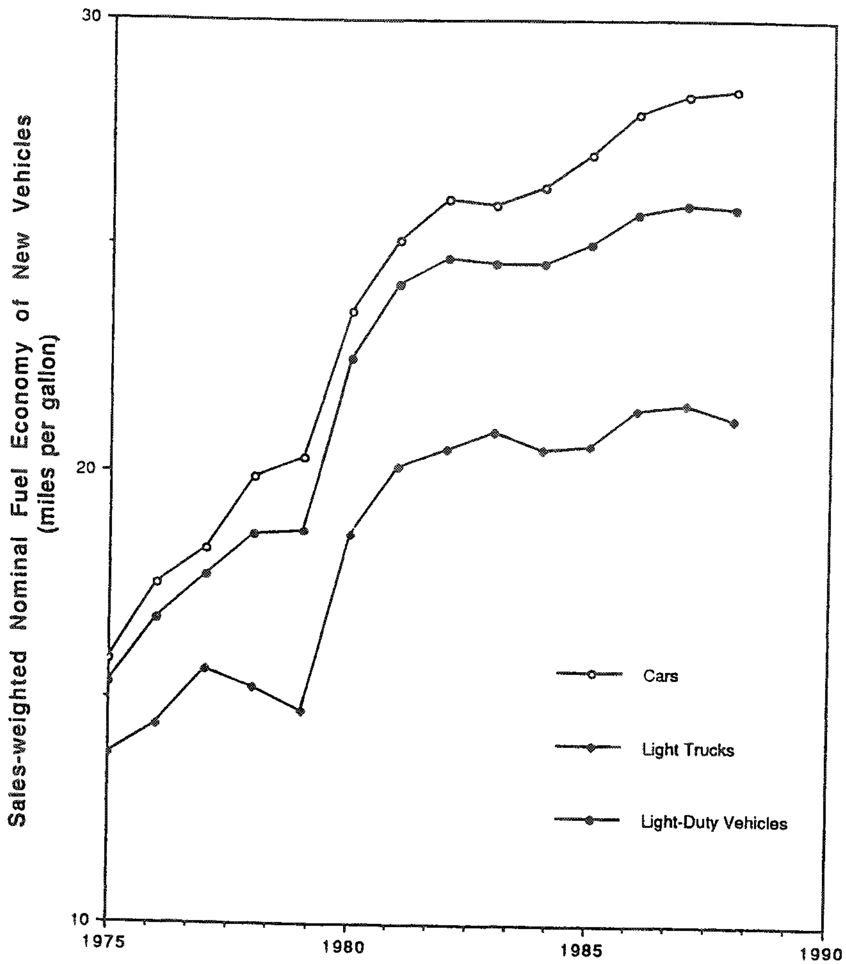

Figure 4 Sales-weighted fuel economy of new automobiles and light trucks (domestic and foreign) and the composite fuel economy of both. The nominal 55%/45% city-highway fuel economy is shown. Source: (16, 17)

What happened within each size class is that new models with higher fuel economy were introduced, replacing or taking market share from old models. In recent years, this process has weakened in the compact and subcompact classes, especially for foreign cars. This weakening explains the slowed progress in fuel-economy improvement for cars since 1982, shown in Figure 7. The introduction of models with higher fuel economy has continued in the intermediate and large classes, explaining the recent improvement.

The progress in each size class (sales-weighted average) is shown in Figure 8 for four car sizes and all six truck sizes. The failure of most of the truck classes to improve as much as the cars is evident. Much more of the improvement in the overall fuel economy of trucks was due to the shift in sales to smaller vehicles, a shift that accompanied the boom in passenger light trucks, than was the case for cars.

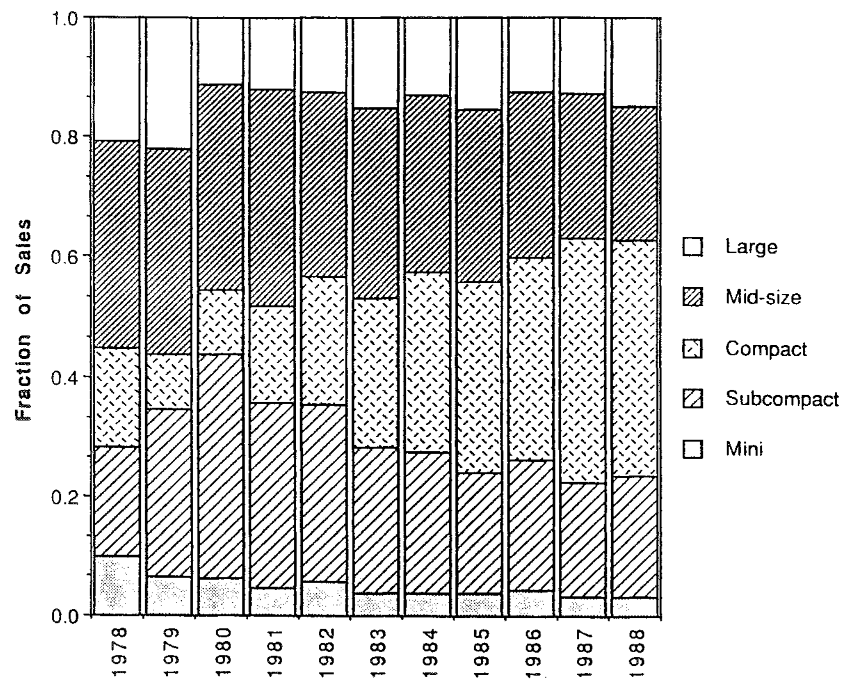

Figure 5 Fraction of sales per automotive size class (EPA interior volume basis). Figure inspired by (18), data from (19, 20)

Design, Engineering, and Trade-offs

The major fuel-economy improvements in the past decade can be grouped into three components: propulsion-system engineering, other elements of vehicle design, and trade-offs.

Engineering improvements are exemplified by the remarkable 36% increase in power per unit of engine size, or displacement (Table 6). Engine displacement has long been used as a surrogate indicator of power, but engineers have found many ways to loosen the connection.

Through improved design and use of new materials, the ratio of weight to interior volume of cars has been reduced an average of 16% over the past

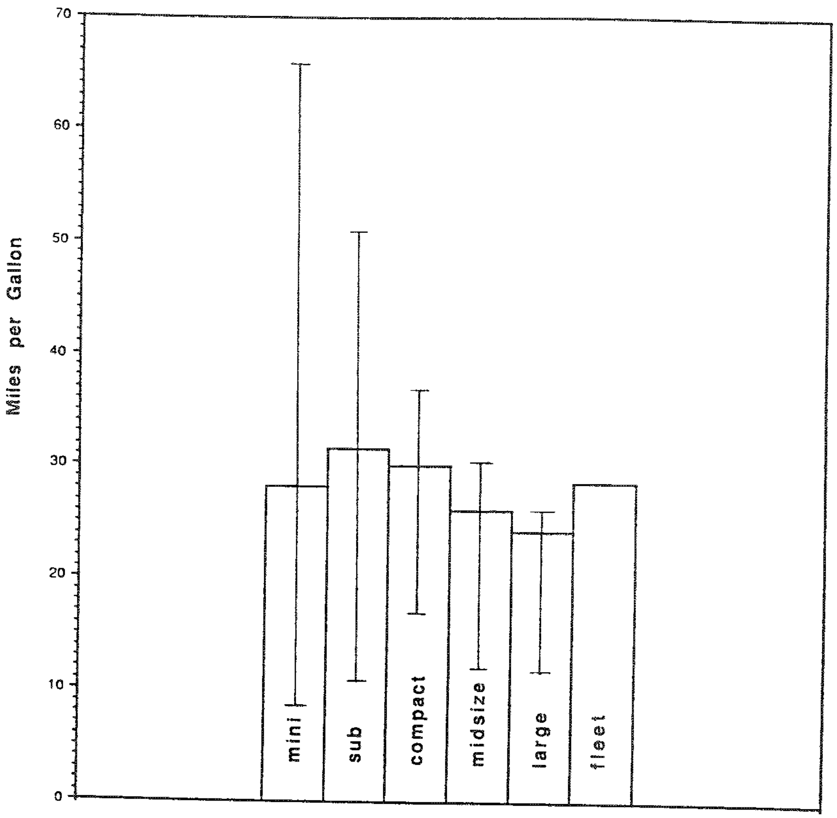

Figure 6 Sales-weighted fuel economy of cars by size class (nominal fuel economy, EPA interior volume classes). Bars show the highest- and lowest-fuel-economy models in each class. Source: (16, 17)

decade (Table 6). Weight reduction has, of course, been a major element in fuel-economy improvement.

Trade-offs among performance, emissions, cost, safety, and fuel economy have also been used by manufacturers in meeting their goals and by buyers in meeting theirs. The significant reduction in acceleration time since 1982, shown in Table 6, is such a trade-off. Cars with higher acceleration performance are attracting buyers.

To estimate the importance of the trade-off between acceleration performance and fuel economy in recent cars, several popular cars were selected and the performance data for different models of each car were studied (models with different or modified engines but the same body) to obtain a statistical relationship between fuel economy and 0–60 mph acceleration

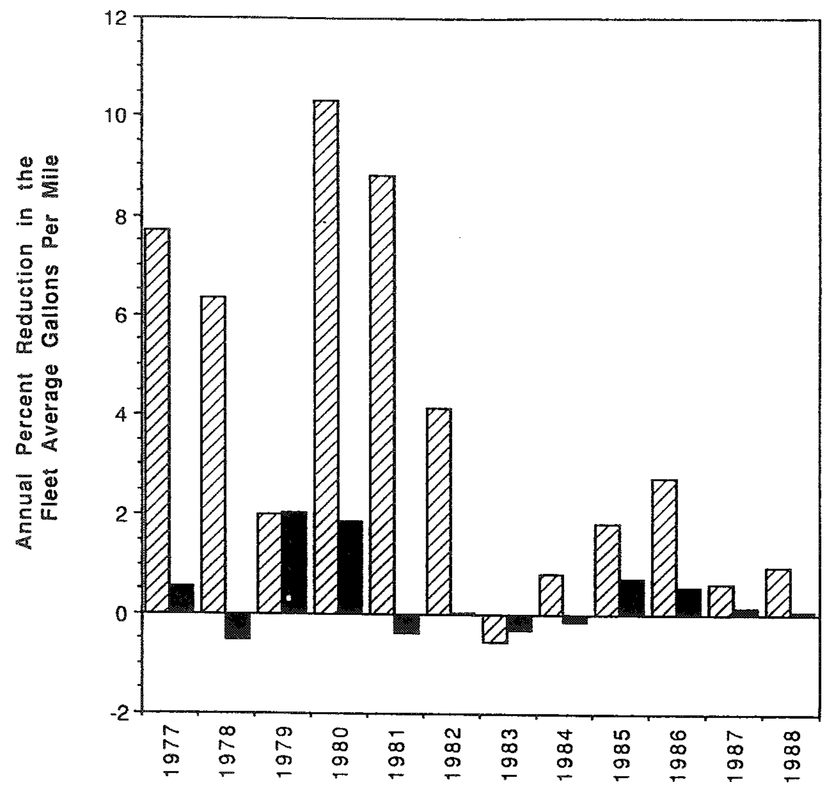

Figure 7 Divisia decomposition of the change in the sales-weighted fuel economy of all new automobiles. The decomposition is of the annual reduction in gallons per mile into the part due to fuel-economy improvement in each size class (hatched bars) and the part due to increased market shares for the smaller size classes (dark bars). Data from (20)

time. The relationship found is that fuel economy is roughly proportional to the square-root of acceleration time. Thus, other things being equal, the reduction in average (sales-weighted) acceleration time from 14.4 s in 1982 to 12.9 s in 1987 caused a decline in the fuel economy of new 1987 cars from a hypothetical 29.6 mpg to the actual 28.0 mpg (a 5% decline).

This analysis underestimates the fuel-economy benefit of designing vehicles with smaller engines. The fuel consumption in idling is roughly proportional to engine displacement, and idling and low-power output dominate urban driving. Through transmission management one can enable a smaller engine to provide good acceleration at low to moderate vehicle speeds, but manufacturers are designing vehicles with extraordinary acceleration capability as a marketing strategy.

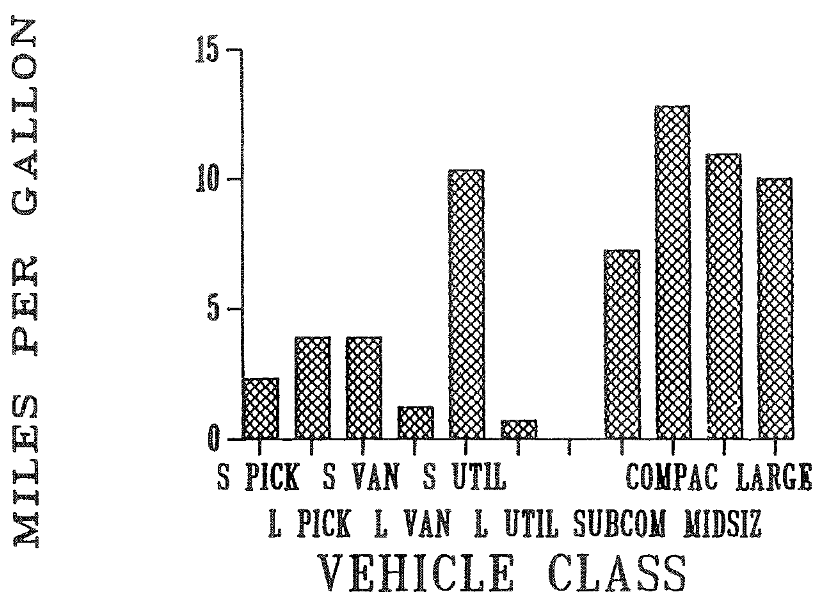

Figure 8 Change in light truck and automobile fuel economies from 1976 to 1987 by vehicle class, with six light truck classes shown at left and four automobile classes shown at right. See (2) for definitions of the classes. Source: (21)

The trade-off between fuel economy and cost in the context of contemporary vehicles cannot be reliably determined from the prices of vehicles, because typical production models with higher fuel economy are cheaper rather than more costly. There are two related reasons: (*a*) Marketing concepts dictate that high fuel economy be coupled with the stripped-down model; the customer interested in fuel economy is also believed to be interested in a low-cost vehicle. (*b*) In many current applications, technology that can improve energy-efficiency (such as weight reduction at a given size, an increased engine power-to-size ratio, and improved part-load performance with a turbocharger) is being adopted in ways that increase acceleration performance rather than fuel economy.

The In-Use Fuel Economy of the Entire Fleet

The Environmental Protection Agency determined in the early 1980s that vehicles in use achieve 10% lower fuel economy in actual urban driving than in the urban cycle test for new vehicles, and 22% lower fuel economy in actual highway driving than in the highway test (22). Regardless of age, well-maintained vehicles achieve about 15% lower fuel economy in use than the new nominal vehicle rating: New-Vehicle Composite Fuel Economy =

Table 6 Some average characteristics of new cars[a]

	volume / weight (cu. ft./ton)	power / displacement (hp/cu. in.)	acceleration 0–60 mph (seconds)	power / curb weight (hp/lb)
1987	70.4	.731	12.9	0.037
1986	70.5	.694	13.2	0.036
1985	69.8	.672	13.3	0.036
1984	69.7	.637	13.8	0.034
1983	70.1	.615	14.0	0.033
1982	69.4	.609	14.4	0.032
1981	68.9	.594	14.4	0.032
1980	67.1	.583	14.3	0.032
1979	62.6	.545	13.8	0.034
1978	60.8	.538	13.7	0.034

[a] domestic and imported, sales weighted
Source: (16)

$[.55/\text{urban} + .45/\text{highway}]^{-1}$, where urban and highway here refer to the corresponding laboratory fuel economies. This composite fuel economy is the new-vehicle fuel economy quoted throughout this report, except where specified otherwise.

It is now believed, although without solid statistical evidence, that the discrepancy between the typical new-vehicle in-use fuel economy and the nominal rating has increased to as much as 25%. Reasons for an increasing disparity are: increasing urban congestion, increasing share of urban driving, higher speeds on open highways, and higher levels of acceleration. In connection with the latter, some powerful vehicles are being described as cycle busters. Their high power enables them to be driven far outside the test cycle regimes, probably with poor fuel economy, but they incorporate features enabling them to obtain a satisfactory rating.

The other consideration in linking a history of new-vehicle fuel economies (FE_i, where i is the year) to the in-use fuel economy of the entire fleet, is the miles of travel of older vehicles. For this a simple approach is to use 1982 survey data (6). Analysis of these data yields the fraction VM_i of total vehicle-miles traveled by vehicles in each age group (i being the age of the vehicle). The in-use fuel economy of the fleet in 1987 is thus:

$$0.85 \times \left(\sum_i VM_i\right)\left(\sum_i VM_i/FE_i\right)^{-1}$$

The analysis of the connection between the nominal new-vehicle fuel economy and that of the entire US fleet shows that the in-use fuel economy of all automobiles in 1987 was about 18 mpg, far below 28.3 mpg, the 1987 nominal new-car fuel economy; 24.1 mpg, the in-use fuel economy of new cars (using a correction factor of 0.85); or 22.0 mpg, the in-use fuel economy of new light-duty vehicles (16, 17). The rapid advances in new-vehicle fuel economy made in the late 1970s and early 1980s are still working their way through the system. Many old low-fuel-economy vehicles are still being driven.

Let us turn from this record of past progress to consider the possibilities for further increases in fuel economy.

TECHNOLOGY FOR FURTHER FUEL-ECONOMY IMPROVEMENT

There are many options for improving fuel economy. Moreover, many of the options are alternatives to each other. There is not a single path to high fuel economy at this time. In addition, some technologies for improving fuel economy can also reduce emissions. Others can increase them. Many of the technologies also provide performance benefits. The potential for combined benefits has become critically important.

The energy-efficiency of vehicles can be improved in many ways, because energy uses and losses occur in many ways (Figure 9). Energy use can be analyzed in terms of *the energy loads* that arise in operating the vehicle, i.e. what the drive wheels must accomplish, and *the efficiency of the engine-transmission system,* which converts fuel and provides energy to the drive wheels as it is needed. The term efficiency can be applied to the engine and transmission, given the load, but not to the loads.

The lower half of Figure 9 shows that air resistance, tire resistance, and braking loads are comparable in urban driving. In high-speed driving, air resistance dominates. The upper half of Figure 9 shows that only about 12% of the fuel energy in the tank reaches the drive wheels. There are many losses. One of them is not usually acknowledged in discussions of this kind: According to fundamental principles, the process of combustion in itself decreases the quantity of work that can be obtained from fuel energy by about 30% (23). This is due to the irreversibility of combustion, the degradation of energy, reducing its availability to do work. Perhaps this surprising result will seem more reasonable if one considers the extreme case of low-temperature combustion; in low-temperature combustion very little work (such as rotational energy) could be extracted from all the heat generated. If instead of burning the fuel, the fuel energy were converted into electricity, in a fuel cell, this loss of available work could be avoided in principle.

The Efficiency of the Engine-Transmission System

Although the fuel economy and power-to-weight ratios of engines have been much improved in the past 15 years, much more can and is being achieved.

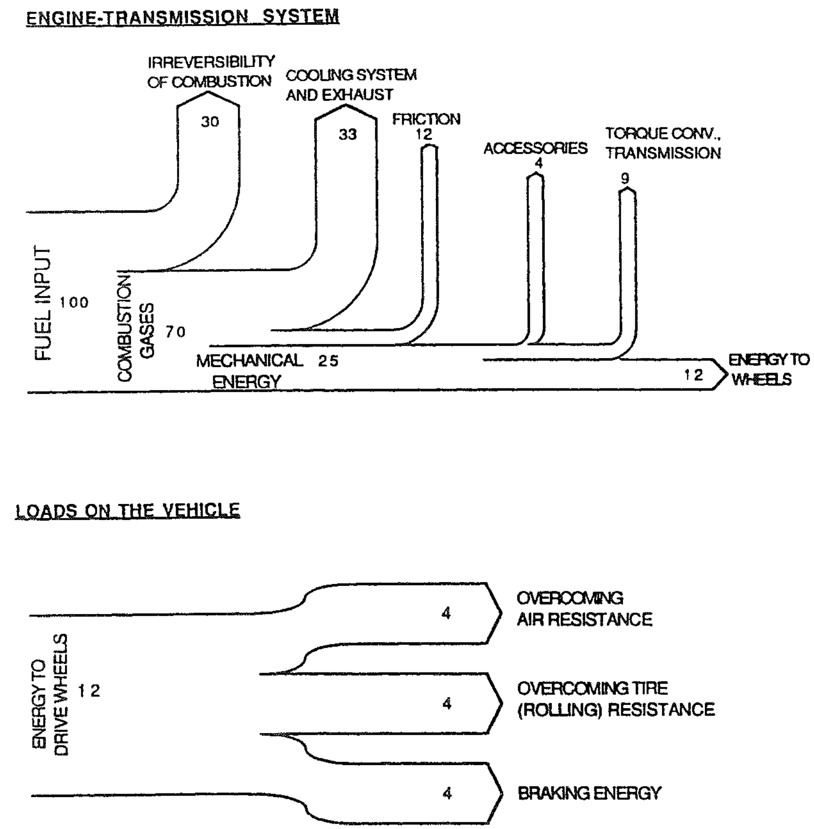

Figure 9 Flows of available energy in operating a typical car in the federal test procedure (urban driving cycle). Available energy is the capacity of the energy in question to do work. Source: (23, 24)

In today's engines about half or more of the calculated power output of the corresponding idealized engine is lost because of cycle losses, friction, and pumping losses (24). Cycle losses are due to heat loss, to the finite time for combustion, and to the finite times for filling and exhausting the chamber. These losses distort the ideal thermodynamic cycle. With the advent of powerful microprocessors and sensors, it is becoming possible to optimize the timing of the spark and the air-to-fuel ratio to reduce these losses. Electronic controls of the current generation typically respond to measurement of state variables like average air intake, temperature, and engine speed and send out signals for modifying the air-to-fuel ratio and spark timing based on encoded tables describing how a typical engine should operate. A new generation of controls involves feedback. Control is based on the sensing of state variables plus output characteristics like exhaust composition, the timing of peak pressure in each cylinder, irregularities in speed, and knock (25). The feedback capability enables optimization of performance even if sensors or actuators have drifted in calibration, and even if the particular engine differs from the standard. Early versions of such closed-loop controls are now being installed in some production models (26).

The pumping loss is the energy to pull the air-fuel mixture into the cylinder and push out the exhaust. Unless a vehicle is being accelerated rapidly, relatively little power compared to the engine's capacity is needed (27). When power requirements are low, unless gears are shifted so the engine speed can be reduced, less cylinder pressure needs to be generated with each power stroke. This is achieved by burning less fuel. But, for the typical spark-ignition engine the air-to-fuel ratio must be kept within narrow bounds for proper combustion, so less fuel means that less air can be admitted. This is achieved by restricting the air flow, i.e. by throttling. At full load, i.e. with wide-open throttle, pumping losses are relatively small. At moderate load, such as steady highway driving, they are 30% to 40% as large as the engine power output (24).

There are a multitude of proposals and prototypes for reducing throttling losses. One approach is to manage gear ratios so that when the engine delivers low power then its speed is low, so it operates as near wide-open throttle as possible. Such transmission management could be achieved with continuously variable transmissions, for example. A similar result can be achieved by not fueling and firing some of the cylinders at low load. Another possibility is to use a smaller engine, that in normal operation delivers relatively little power, but that can, by delivering the charge under pressure (e.g. through supercharging), provide a lot of power. Such an engine is optimized for typical rather than maximum power requirements. Yet another option is variable control of the intake valves such that at low load the air intake occurs for only a suitable fraction of the intake stroke (28). Throttling is thus largely avoided.

The type of engine that has been in use for many decades is already highly refined and so is more difficult to improve than those in a low state of development. While significant improvements in controls, friction reduction, and part-load strategy are still possible with the typical gasoline engine, really large improvements may require substantial departures. Paradoxically, however, any radical departures will have to compete with the highly developed engines we already have—implying that a great deal of careful development will be needed before any substantially different engine could become competitive.

Among the alternative engine concepts is the direct-injection diesel, in use in some production models and prototypes in Europe. In R&D is the more radical ceramic-coated diesel, with some ceramic parts, which would be

operated at much higher temperatures, with the extra energy in the exhaust gas captured to achieve high efficiency.

An exciting spark-ignition engine initiative is the lean-burn (high air-to-fuel ratio) two-stroke engine. The two-stroke is currently used in small engines, such as for lawn mowers, and in many marine applications. As noted above, the power output of standard automobile engines has been increased in the last decade for a given displacement, while emissions have been sharply reduced. These benefits have been achieved through many refinements and complications, as anyone over 30 knows who looks under the hood. Such refinements have not yet been incorporated in the two-stroke engine.

The two-stroke engine has twice as many power strokes in a given number of revolutions as the four-stroke and in its basic version has no valves, only ports, which are uncovered as the piston moves. A three-cylinder engine could have almost the same output as a six-cylinder four-stroke engine (of twice the displacement). Saab used such an engine (in unmodernized form) in the 1960s, and cars with them are manufactured in East Germany. This two-stroke engine would be light enough to be carried by a strong person; and it would be relatively cheap and easy to maintain.

But would it be possible to achieve low emissions and high fuel economy by refining the two-stroke engine? Development work is now under way by engine manufacturers around the world. Extraordinary improvements in the fuel economy, emissions, and misfire performance have already been achieved, compared to two-stroke engines of the past, with modern fuel injection systems (29–31). It is not clear where this development work will lead. For application as a small automotive engine, will supercharging be essential? What level of catalytic clean up of the exhaust will be necessary? How simple, light, and cheap will the resulting engine be?

Fuel-Economy Emissions Interactions

In the context of 1988 markets and political climate, the most important possibility for much higher fuel economy may be technology that couples fuel economy with emissions reductions. Many people have the misconception that emissions reduction and fuel economy are antithetical, because, given a vehicle design, if you would reduce emissions you must add equipment or make adjustments that will decrease fuel economy. In designing a new vehicle, the opposite relationship can occur. New technology or fundamental redesign often offer opportunities to both improve energy-efficiency and reduce emissions.

A major fuel-economy tie to emissions reduction arises from the nature of the mass regulatory-standards for emissions, i.e. the limits on grams of emissions per mile (32). A vehicle that consumes relatively little fuel per mile has an easier-to-meet standard in percentage terms (concentration of pollutants in the combustion gases). Emissions decrease less than a simple proportion of fuel use would suggest, however, with, e.g. a smaller engine.

In addition, some fundamental approaches to fuel-economy improvement also enable percentage emissions reductions. As an example, consider a lean-burn engine. With lean-burn, the combustion temperature is lower, reducing NO_x formation, as shown in Figure 10. The fuel-efficiency is nevertheless improved, because air is a better thermodynamic medium than (evaporated) gasoline. The increase in unburnt hydrocarbon with air-to-fuel ratio, which begins at the right of Figure 10, is a major challenge. It can be prevented, in principle, by improving ignition, e.g. through a higher-energy ignition mechanism, and it can be mitigated by improved exhaust after-treatment.

It is possible that a lean-burn engine can be developed with relatively low emissions, with little or no after-treatment, e.g. without a catalytic converter.

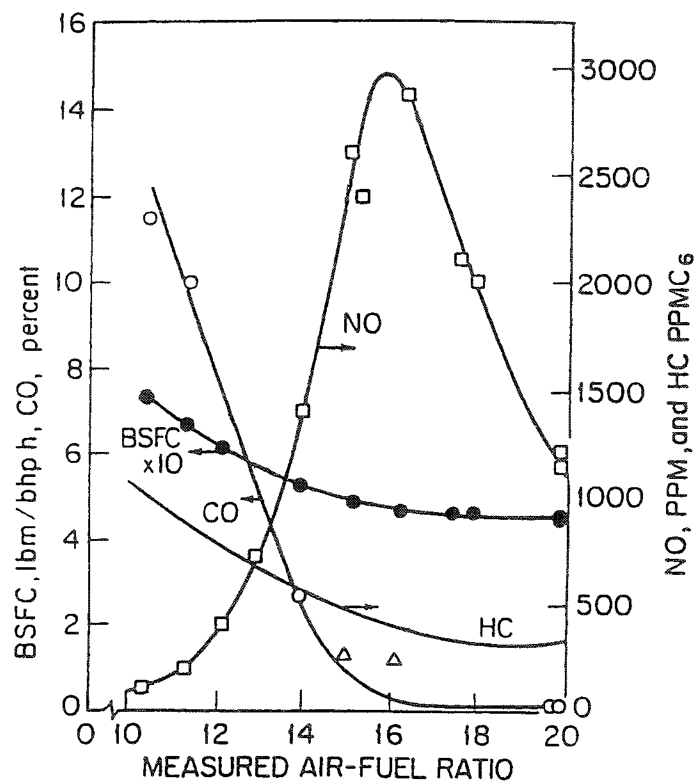

Figure 10 Exhaust gas composition and specific fuel consumption of a sample automotive engine, vs air-to-fuel ratio. The stoichiometric ratio is 14.6. Courtesy of Donald J. Patterson.

In a very high fuel-economy vehicle, such a system might be able to meet strict emissions standards. One disadvantage of this approach is that there is no practical after-treatment to reduce NO_x in an oxygen-rich environment, so that the control of NO_x would have to be achieved entirely in the engine.

Reduction of the Vehicle Load

The load has three components: energy that goes into braking, air resistance, and the tire, or rolling, resistance. A general approach to reducing braking and rolling resistance is weight reduction. Improvements in design and increasing use of lighter and stronger materials (plastics, composites, high-strength steels, and aluminum) are continuing. To recover energy that would otherwise go to the brakes requires an energy storage scheme, such as braking through a motor-generator that charges batteries, or braking by transferring energy to a flywheel. At present, these appear to be costly options for a small vehicle. Dramatic reductions of air drag are now going on as designers learn how to create the appropriate smooth surfaces and integrate them into the vehicle (26). Where the average coefficient of aerodynamic drag of 1979 model US cars was 0.48, the Taurus/Sable has a drag coefficient of 0.30 and prototype vehicles have coefficients of less than 0.2. Rolling resistance was sharply reduced with the introduction of radial tires. Further improvements are in development (26), but are limited by the primary need for tires to hold the road.

In this brief summary, many important measures that could be (or already are being) used to improve fuel economy have not been discussed, or have been mentioned only in passing. The point is that there is an extraordinary ferment in automotive technology at this time. It is due to the conjunction of new capabilities in materials, information, and control, which affect design and manufacturing as well as the vehicle itself. What will be the impact on fuel economy? Let us briefly examine the influence of the marketplace.

ECONOMICS AND FUEL ECONOMY

Through improved design and technological innovation, the loads on a vehicle can be reduced and the energy-efficiency of the propulsion system increased without necessary detriment to vehicle size, performance (e.g. acceleration), safety, and emissions. In addition, trade-offs can be made among fuel economy, size, acceleration performance, cost, safety, and other characteristics. In today's market conditions, two kinds of change in the fuel economies of new vehicles can be expected: (*a*) modifications to existing or planned production models and (*b*) creation of substantially different vehicles.

Modifications to Current Models

Technologies to improve fuel economy, which are already developed or whose development is of low risk, and were, in 1985, considered likely to be incorporated by domestic automobile manufacturers into existing and planned models, are the basis for a cost estimate by Energy and Environmental Analysis, Inc. (33). As shown in Table 7, a $48 per vehicle price increase is typical for each one mpg improvement in the fuel economy of a current compact car. The modifications considered are listed in Table 8. The corresponding cost of saving gasoline, starting with today's typical new vehicle, is less than 50 cents per gallon saved—decidedly less than the price of gasoline. (A 10% real discount rate, a vehicle lifetime of 10 years, and an average of 11,600 miles per year of driving are assumed.)

Appropriate combinations of the cost-effective technologies considered in Tables 7 and 8 are capable of changing the current compact cars, with fuel economy of about 30 mpg, into cars with fuel economy in the mid-40s or higher.

These costs are based on estimates of the manufacturing costs (materials and labor) multiplied by the average long-term ratio of vehicle retail price to manufacturing cost. This ratio is four to five. It accounts for all other costs: R&D, plant and equipment, tooling, administration, and all distribution and sales costs, as well as earnings.

The reader has to be careful in interpreting these numbers. As discussed above, the price of typical vehicles declines with increasing fuel economy, because in a high-fuel-economy model the engine system is simpler than one souped up for high acceleration performance and the design is less luxurious. In contrast, incremental costs are shown in Table 7, the average cost of modifying given vehicle models to increase their fuel economies. Typically these improvements do not require loss of acceleration-performance or reduction of interior volume, although there is weight reduction. (Some loss of acceleration performance would, however, probably characterize diesel engines, if adopted.)

Finally, and of great importance, the incremental cost of these technologies, as calculated here, does not mean that the preferred fuel-economy technologies will ultimately cost as much. Fuel-economy technologies have been costed here as add-ons, additional parts, and fabrication steps in the manufacture of existing automobile models. When the technologies are

Table 7 The cost of near-term technology to improve automotive fuel economy[a]

Typical fuel economy for application (mpg)[b]	Retail price increase per vehicle for one mpg improvement in fuel economy (1986 $)	Total cost per gallon saved[c] ($/gal.)
30	48	$0.46
40	46	$0.77
50	37	$0.98

[a] Adapted from Energy and Environmental Analysis, Inc., "Analysis of the Capabilities of Domestic Auto Manufacturers to Improve Corporate Average Fuel Economy," Appendix A (compact cars), Ref. 32.

[b] The 30, 40, and 50 mpg descriptions are nominal; they correspond to technologies listed by EEA as being incorporated in 1986–1988, 1989–1991, and 1992–1995, respectively. See Table 8.

[c] Value of the incremental retail price of the vehicle at the time of gasoline saving, per gallon. For application at 30 mpg, the cost is $0.85 \times 48 \times 1.4/[((1/30) - (1/31)) \times 116{,}000]$, where 85% is the in-use fuel economy compared to nominal, 1.4 is the appreciation of the incremental cost of the vehicle using a 10% real discount rate, and 116,000 the expected mileage in the first 10 years of automobile life.

Table 8 Sample technologies considered in the cost estimate[a]

	Increased fuel economy (percent)
Technologies introduced 1986	
weight reduction at constant size (materials substitution)	7
rolling resistance reduction (improved tires)	4
reduced aerodynamic drag	3
engine-efficiency improvement	
friction reduction (especially piston and rings)	4
improved lubricants	2
multi-point fuel injection	7
new engine designs—fast-burn cylinder	4
four valves per cylinder	8
roller cam followers (reduced friction in moving valves)	3
accessory efficiency improvement	2
front wheel drive	12
Technologies introduced 1989–1991	
optimization of transmission	
electronic transmission control	3
automatic overdrive	8
Technologies introduced 1992–1995	
engine-efficiency improvement	
diesel	45
intake valve control (variable valve timing)	8
optimization of transmission	
continuously variable transmission	12

[a] Some technologies, although briefly named, represent a complex of design changes. The timing for introduction of technologies in specific models is that forecast by Energy and Environmental Analysis. This is not a complete listing. Moreover, some technologies can be improved with time. On the other hand, some are mutually exclusive, have limited applicability, or have already been partially applied. One cannot simply combine the percent improvements. See the original references for many of the details.

Source: (32, 33)

integrated into the design and manufacture of new vehicles, it is likely that the incremental cost of the fuel-economy benefits will be much less.

Altogether New Vehicles

The highest-fuel-economy vehicles already in production have impressively high mpg ratings, but tend to be rather small vehicles with low acceleration performance. Some more ambitious prototype vehicles are shown in Table 9. Many incorporate radical innovations, such as aluminum bodies and engines (GM), direct-injection diesels that stop when the vehicle coasts or stops, and start as needed (VW & Renault), and direct-injection diesels with continuously variable transmissions (Toyota). Extensive use of plastics and light metals characterizes all these prototypes. The potential improvement suggested by prototypes is difficult to evaluate because they are often single-purpose projects. A practical, marketable vehicle may involve many compromises. The cost and performance that cars like these would have if designed for the market and mass produced remain to be determined. There is, however, every expectation that cars with very high fuel economy and good space and performance characteristics can be built, perhaps without a substantial cost penalty beyond the manufacturer's initial tooling investment (27, 35).

Table 9 High-fuel-economy prototype vehicles[a]

	Curb weight (lbs.)	Power/curb wt. (hp/lb.)	Fuel economy[b] (mpg)	Prototype status
2–4-passenger				
GM TPC	1040	0.037	66	complete
Volvo LCP 2000 diesel	1555	0.033	70	complete
Renault Vesta	1047	0.026	89	complete
4-passenger				
Volkswagen E80 diesel	1540	0.033	83	development
Peugeot ECO 2000	990	0.028	79	development
4–5-passenger				
Volkswagen Auto 2000 diesel	1716	0.031	66	complete
Renault EVE+ diesel	1880	0.027	70	complete
Peugeot VERA+ diesel	1740	0.029	66	development
Toyota AXV diesel	1430-target	0.039	97	development

[a] Ref. 26
[b] For gasoline vehicles measured with a standard test, adjusted as per Ref. 22. For diesel vehicles, unadjusted.

The Market and Fuel-Economy Improvements

How likely is the implementation of major fuel-economy increases in the next decade or so? There is technological momentum for incorporating some of the modifications listed in Table 8, at the typical costs shown in Table 7. On the basis of the cost advantages to consumers, Energy and Environmental Analysis projected in 1985 that many of these improvements will be made by domestic manufacturers by 1995. But with today's fuel prices and fuel-price expectations, these projections appear overoptimistic.

Two principal reasons for lack of urgency on the parts of manufacturers and car buyers are evident from the "von Hippel-Levi effect," Figure 11: (*a*) The contribution of fuel purchases to the cost of driving is, at present, relatively small—it is less than the cost of insurance. (*b*) The curve representing total cost vs fuel economy varies only slowly with fuel economy; the vehicle buyer can be expected to be indifferent over a broad range of fuel economy (36). For example, if a person drives 12,000 miles per year and his/her car is improved from 30 to 40 mpg (nominal), then 120 gallons of fuel are saved annually. If the cost of saved energy is 60 cents per gallon (between 46 and 77 cents, Table 7) and the cost of fuel is $1.00 per gallon, the net value of the saving is about $50 per year, a small motivation. Moreover, the simple payback on the increased price of the vehicle is about four years, somewhat long in terms of consumer behavior. (The annual operating savings are 120 gallons or $120, while the increase in the up-front cost is, from Table 7, about $470.) In other words, while the nation may have a great interest in reducing total petroleum use and some geographical regions may be very concerned with reducing fuel use by vehicles in order to reduce air pollution, the individual has very little interest, in simple economic terms, in the fuel economy of the vehicle he or she buys.

Without a stimulus other than fuel saving, the manufacturer would be even less inclined to make high-fuel-economy vehicles than the consumer to buy them in today's market. A manufacturer would incur a significant technological risk and substantial opportunity costs in introducing new fuel-efficient technology. He is very unlikely to do this if his prospective buyer is likely to be indifferent about the new product.

Events, however, could alter this pattern of inertia. There are three important kinds of possible events: (*a*) new technology with multiple benefits, one of which is fuel economy, (*b*) much higher fuel prices and/or fuel shortages, or (*c*) strengthened fuel-economy regulations or other changes in public policy with strong fuel-economy implications.

Technology with multiple benefits may become part of the program of manufacturers for whom innovation is a major competitive strategy. Consider one fuel-economy innovation, the continuously variable transmission. The

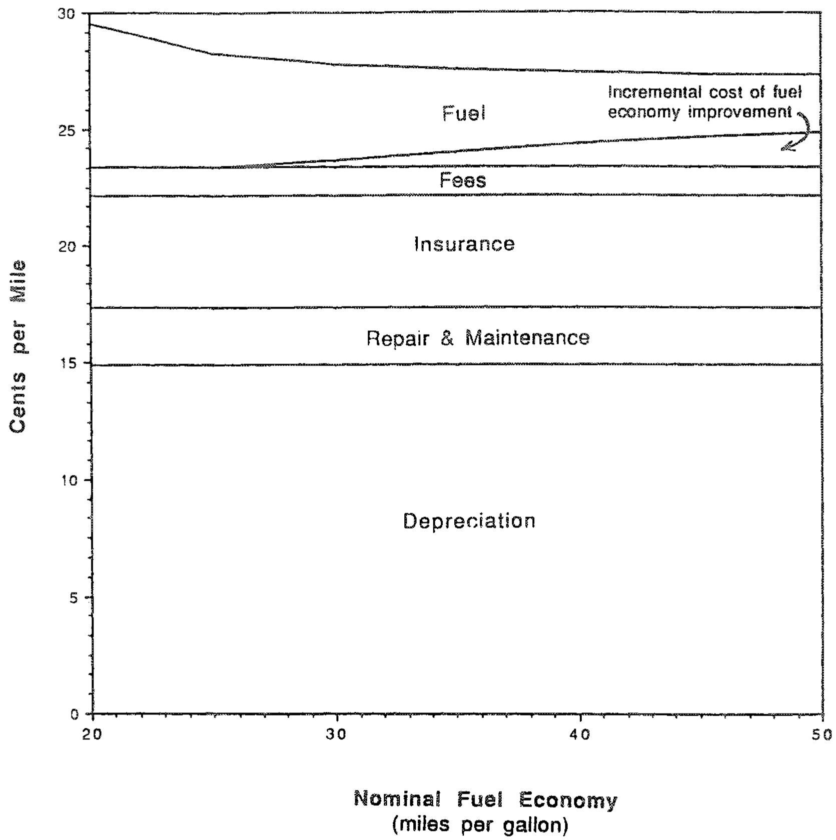

Figure 11 The cost of owning and operating a midsize car vs fuel economy. The data at left are for 1988 midsize cars (where average in-use fuel economy is 23 mpg) from the American Automobile Association (6). The incremental cost is taken from Table 7. The depiction of several costs as independent of the fuel economy of modified vehicles is somewhat arbitrary. Some argue that costs will fall, e.g. that lighter plastic components will be more durable and thus decrease depreciation; others argue that costs will rise, e.g. that the vehicle will require more maintenance because it is more finely tuned.

driver gets a different feel during acceleration. Such a technology could establish new standards of performance, creating demand for cars that also have high fuel economy.

A different kind of technical change would be creation and wide adoption of a narrow two-passenger vehicle as an extra vehicle for use in commuting and errands. A relatively safe, high-performance vehicle could probably be manufactured. Two factors make wide adoption of such a vehicle conceivable: (*a*) Rising incomes in many households and rapidly increasing vehicle

life are encouraging purchase of "excess" vehicles, often special-purpose vehicles. In 1983, 13% of all vehicles were already in excess of the number of drivers in the household (15). (*b*) A small high-performance vehicle, if afforded special parking privileges, might have appeal. There is a tremendous fashion for pickup trucks as passenger vehicles; and many of these are two-passenger vehicles. Of course, even though a very small two-passenger vehicle might have a social rationale, it might not appeal to buyers.

Fuel price increases would also motivate fuel-economy increases, but the effect is not thought to be strong (37, 38). It has been estimated that the price elasticity is −0.5 for the fuel economy of new car purchases. That is, for every 10% increase in fuel price, the average buyer would opt for a vehicle with 5% higher fuel economy. But this analysis probably overestimates the impact fuel price increases would have in the United States, because the present level of fuel economy is primarily due to the regulatory standards. A major increase in fuel economy would require fuel price increases of a factor of two or more, fuel shortages, or major changes in public policy.

PUBLIC POLICY AND FUEL ECONOMY

A Review of Recent Initiatives

Before addressing future policies that could lead to major fuel-economy improvements, the policy experience gained in the past dozen years is briefly reviewed.

INFORMATION The federal government systematically determines the fuel economy of each vehicle model every year, publishes the information in the Gas Mileage Guide, and has a window sticker put on each new vehicle. Although the in-use fuel economy varies considerably among individual vehicles of the same model (as maintained and driven), this information is reliable enough for buyers and has removed the extensive confusion that characterized fuel economy before the age of a standardized laboratory test.

PERFORMANCE REGULATIONS The mandated improvement of corporate average fuel economy (CAFE) was probably largely responsible for the approximate doubling of the new car fuel economy from 1974 to 1986, although some argue that fuel price increases alone would have driven a similar increase. The history of the sales-weighted fuel economy of new cars, when compared with the history of CAFE regulations and the price of gasoline (Figure 12), leaves little doubt as to the engine that drove the improvements. In examining the figure, note that the 1970 gasoline price was a little higher than that in 1973, that the CAFE standards were legislated in 1975, calling for an increase to 27.5 mpg by 1985, and that fuel price

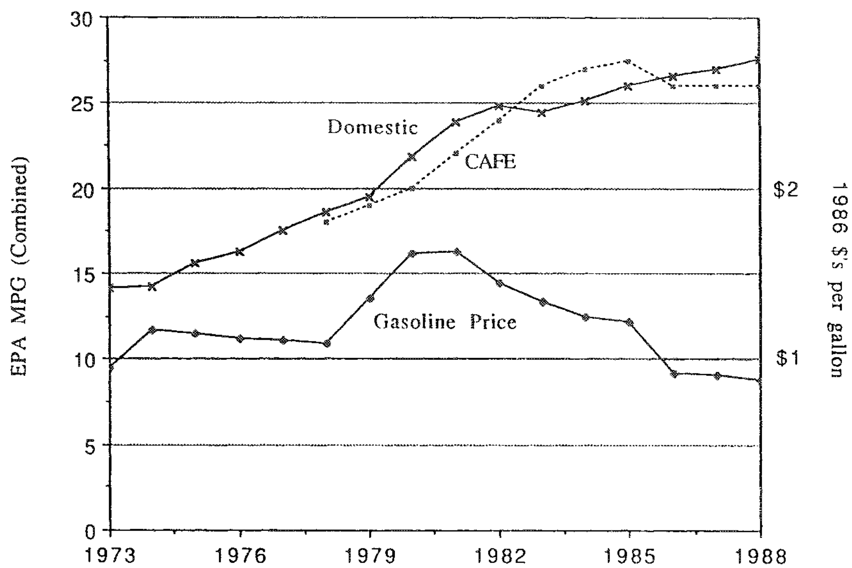

Figure 12 Fuel price, automotive fuel economy, and the CAFE standards 1973–1988. In the period before 1973 the real fuel price declined gradually. Source: (39)

elasticity studies suggest an elasticity substantially less than one, rather than greater than one.

No further increases in fuel economy are mandated, although the 27.5 mpg standard for cars remains. The 27.5 mpg standard has not yet been fully imposed, however, reductions being granted on petitions from Ford and General Motors. There are also standards for trucks, but these are not set by the legislation as such; they have been set largely in conformity with manufacturers' wishes.

Of the arguments now offered against further increases in the CAFE standards, one is especially powerful: that CAFE standards discriminate against corporations offering a full line of vehicles (including large ones). Modifications that have been suggested are: mandating a percentage improvement for each corporation and mandating a certain improvement for size-weighted fuel economy (40).

THE GAS-GUZZLER TAX The average fuel economy of vehicles purchased can be improved by a carrot or stick at the time of purchase. The gas-guzzler tax has this purpose. It kicks in at $500 for cars with fuel economy below 22.5 mpg and grows to more than $3000 for a fuel economy below 12.5 mpg. In 1986 the US Treasury collected $148 million, as the program came into its final form.

FUEL TAXES In the United States, motor fuel taxes average 23 cents per gallon and have little impact on which vehicles are purchased and relatively little impact on how much vehicles are driven. Modestly higher fuel taxes might influence owners of inefficient cars to trade them in earlier. Unfortunately, this process might not hasten the time when inefficent cars were scrapped. What would be likely to happen is what happened in the late 1970s: The prices of used cars with low fuel economy were depressed so they were bought and used by people for whom the low first cost was a strong attraction.

Fuel taxes in the United States have not been conceived as influencing purchases of light-duty vehicles. In many other countries, however, gasoline taxes are several times higher than the 23 cents per gallon average here (41). The $2 to $4 per gallon price of fuel in Europe does have a major impact on vehicle purchases and use. A definitive study of the European experience, however, would also have to take into account the much higher population density and geographical structure, which discourages the long-distance commuting by personal vehicles that is common in the United States.

RESEARCH AND DEMONSTRATION The Department of Energy has an ongoing R & D program in Transportation Energy Conservation. The 1987 appropriation was $56 million. The program is limited to work on radical propulsion systems, especially ceramic diesels, gas turbines, and electric vehicles, and in advanced materials, especially for engines. There is a general sense about this program that, although important transportation product goals, such as an electric vehicle, have not been achieved, some basic yet practical work has been done, especially on ceramics and batteries, which may have considerable economic value. The existing program is much smaller than the Cooperative Automotive Research Program, an R & D program including substantial basic research, proposed during the Carter administration, but not implemented.

The Rationale for Public Policies to Increase Fuel Economies

Concerns for national security relative to petroleum supply and for the well-being of the economy in the face of increasing energy prices, have justified public policies aimed at energy-efficiency. Concerns for metropolitan air quality, and to a lesser extent regional air quality, have justified the emissions standards.

The petroleum-supply issues remain important in spite of the current low price because of our rapidly increasing dependence on imports (caused by the low price). Net imports of petroleum are rising toward 40% of consumption, a higher level than that of 1973, before the first oil shock, and close to the 45% level of 1978, before the second oil shock.

Air quality concerns are increasing because (*a*) metropolitan air quality continues to be unsatisfactory in many areas, and the public is clearly interested in making progress; (*b*) regional air quality impacts, especially acidification of lakes and forest death, are increasingly troubling; and (*c*) the greenhouse effect will affect the global climate, as a result of increasing atmospheric concentrations of infrared-absorbing gases, such as carbon dioxide, NO_x, methane, and chlorofluorocarbons. The production of carbon dioxide by gasoline-fueled vehicles is inversely proportional to their fuel economy. The joining of these strengthened environmental concerns with those for petroleum supply gives impetus to consideration of stronger fuel economy and emissions policies.

Major Policy Options for the Near Future

INDUCED MOTOR-FUEL PRICE INCREASE Other industrial countries impose high motor fuel taxes with the result that fuel economy is of economic importance to the vehicle purchaser. In the second quarter of 1988, taxes constituted 31% of the price of gasoline in the United States, but 47% in Japan and 63 to 79% in the major countries of Western Europe (41). The higher fuel prices in Japan and Europe may be responsible for the relatively rapid introductions there of fuel-economy innovations.

Under US conditions, a motor fuel tax that might generate a great deal of fuel-economy innovation, on the scale of $2.00 per gallon, is not feasible in the foreseeable future. The strong dependence of rural areas on cars and light trucks, and the importance of commercial trucking in our economy, suggest that it would be inappropriate to approach fuel-economy improvement primarily through use of a stick that strongly penalizes those who drive a great deal.

A moderate fuel price increase might, however, be a part of a effective package of policies aimed at improved fuel economy. (At this time it seems we could have a moderate motor fuel tax increase for revenue purposes.) Such a package could emphasize technology policies and strengthened standards for new-vehicle fuel economies, but include induced fuel price increases of 25 to 50 cents to provide a balance of motivations. The concept is that the entire cast of players (manufacturers, vehicle buyers, drivers, and those responsible for other components of the system), will be able to respond more effectively if all are motivated. In contrast, if, for example, manufacturers are pressured to bring out higher-fuel-economy vehicles but buyers are wholly indifferent, there would be a dissonance, which might lead people to look for loopholes instead of increased fuel economy.

STRENGTHENED FUEL ECONOMY REGULATIONS The tool of minimum standards for the fuel economy of new vehicles, standards that are periodically strengthened, has worked and would probably work in the future (especially if used in concert with other policies). Properly designed, it would put all manufacturers on an essentially equal competitive footing. As discussed above, there is good evidence that the overall cost of improvements would be more than matched by savings on fuel, in the fuel-economy range that is likely to be considered and over a time period that allows manufacturers to retool and change models at a typical pace.

A critical component in strengthened standards would be closure of the light-truck loophole. Light-truck performance standards would have to be developed and written into the legislation, instead of being left to the discretion of an agency.

The second half of the 1980s is, however, a time of low oil prices. Under these conditions the political will to adopt a controversial policy of strengthened fuel-economy regulations will probably be lacking. And yet it would be a straightforward, economic, and equitable way to push petroleum-supply problems off into the distant future.

STRENGTHENED AIR POLLUTION STANDARDS Local and regional air pollution problems remain serious a quarter century after the first Clean Air Act (1963). Progress has been made in cleaning up particular sources. For example, measurements of light-duty vehicles in use by the Environmental Protection Agency show that emissions per vehicle have been greatly reduced. The typical model 1988 car in normal use emits roughly one fifth of the hydrocarbons and carbon monoxide and one-third of the NO_x that an early 1970s car emitted per mile (42). Extraordinary progress has been made through the combined efforts of government and the manufacturers. In typical use our light-duty vehicles are very clean.

On the other hand, vehicle-miles traveled have increased about 80% since 1970. In addition, the standards are not completely definitive because nonstandard situations may create most of the pollution. EPA is conducting more careful studies of (*a*) emissions, especially evaporation of fuel rather than tail pipe emissions, in very hot and sunny weather, (*b*) emissions, especially carbon monoxide, in very cold weather, (*c*) emissions in high-power (wide-open throttle) operations, (*d*) emissions in heavy congestion situations, and (*e*) emissions from vehicles whose emissions control systems have failed. (For the last group inspection and maintenance programs have been introduced in regions not meeting air quality standards. Such programs can work, but are difficult to implement so as to detect and correct most of the gross emitters.)

To develop and exploit the technological opportunities to further reduce vehicle emissions, it would be valuable to strengthen technology policies (such as R&D programs) as well as to enact still more effective air pollution standards. In designing more effective standards more attention to (*a*) fuel economy–emissions interactions and (*b*) nonstandard situations seems called for. It may be that a regulatory focus on further tightening of the grams per mile limitations is not the most effective way to improve air quality. For example, taxes and rebates based on emissions performance might be more effective.

RESEARCH The body of new ideas, systematic knowledge, trained personnel, and instrumentation associated with research activity is the context in which invention and development take place. The strength of the United States in basic science research has persuaded many that our arrangements for research are in good shape, but that is not accurate. As suggested by the recent spate of engineering activity at the National Science Foundation, research in basic engineering or basic technology is very uneven in the United States. The tendency of the private sector to underinvest in research (compared to development) is well established. One of the large holes is research relating to technologies for land vehicles and their manufacture. For example, only recently has research relating to basic properties of combustion begun to be at all adequate. Many issues relating to engines and transmission management need thorough and fundamental examination. In vehicle manufacturing, the forming of metals, plastics, and ceramics is still largely an art rather than a science. It is not enough for manufacturers to apply the new information technology in a general manner; research on problems specific to vehicle design and manufacture must be carried out.

DEVELOPMENT AND DEMONSTRATION The stages of technical change that precede innovation are invention, development, and prototype demonstration. The context for development activity in the United States would be quite different than it is today if there were more active innovation in vehicles.

The federal government should be cautious (in the author's view) about directly supporting development and demonstration of commercial products. The nation has had bad experience with programs like the breeder reactor, synfuels, the electric vehicle, the Transbus, and Operation Breakthrough (manufactured housing). In these cases the project goals and management were far too inflexible for the creation of a commercial product. At present another major demonstration program is under way: clean coal technology. The jury is out in that case.

The pattern is not all one of failure, however. For example, major successes were achieved with partial federal support for demonstration of lighting and window technologies (43). The experience tentatively suggests two criteria for partially federally supported development and demonstration programs: (*a*) Federal participation in development and demonstration is more likely to be effective if the technology in question is small (with a low cost per installation) so that different attempts can be made and some failures are expected from the start. (*b*) Federal participation is more likely to be effective if the technology is generic, i.e. may have a variety of applications.

INNOVATION These days the United States is known for its prowess in basic science research, while Japan is famous for taking research concepts and applying them. The first concern of technology policy must be the vitality of the private sector in adoption of new technology. The technology pull of manufacturers who want or need to innovate is required as well as the technology push of research.

While innovation in motor vehicles is needed, the nation's manufacturers are all large and cautious. The industry has matured to the point that there are no small vehicle manufacturers left. (And the barriers against a new firm entering the business, except from a foreign base, are very high.) Until the threat of innovative Japanese manufacturers became intense, the industry was largely not competing with respect to product or manufacturing innovation (44).

One reason for the manufacturers to be cautious about new technology is the scale of risks that are involved. A typical production line produces 200,000 vehicles per year. Engine lines involve more of a commitment. The tooling costs are large. The manufacturer needs to feel confident that the new product will be successful.

A second reason for caution is that US manufacturers have made several major innovations in the past couple of decades, but have been badly stung several times by poor technological performance. The Japanese may be better at innovating and avoiding the flawed product than we are. As a result they more frequently use innovation as a competitive strategy.

In the face of this problem, a policy to directly encourage innovation is called for. One possibility is government-funded consumer rebates. The rebate could simply be based on fuel economy (45). Another possibility is contests for creation of prototype vehicles meeting certain goals. Over the past century contests for new technological achievements have provoked very interesting creations. This approach could be invigorated with major government-funded contests.

A more refined policy incorporating features of both these approaches would be federal rebates applying to the initial production runs of vehicles meeting specified goals. Different goals could apply to different sizes of both cars and trucks.

It would probably be desirable to carry out such policies in combination: both to encourage consumers to buy early versions of vehicles incorporating new technology and to prepare manufacturers to carry out such technological change (46). In the late 1970s the government presciently helped manufacturers prepare for the second oil shock with the 1975 CAFE legislation (47), but sales of the new vehicles were poor. Would rebates to smooth the way for the new technology have helped? Might the associated economic dislocation have been moderated? One does not know. There has been little evaluation of past policies to guide the formulation of new policies.

OTHER PASSENGER TRANSPORTATION ISSUES

Alternative Fuels

Alternative fuels for personal passenger vehicles is currently a hot topic. With the decline in oil prices and the difficulties of synfuels programs, interest in a synthetic gasoline has declined in the United States, but metropolitan-region air pollution has sharpened interest in fuels composed of simpler molecules, whose products are less reactive in the atmosphere. There are major efforts elsewhere with ethanol, natural gas, and LPG as motor vehicle fuels. At a more theoretical level, interest in hydrogen and electricity continues. (Much developmental work on electric vehicles has gone on in the United States, but there is as yet no hint of practical vehicles for other than small niche markets.)

Methanol enjoys the most attention in the United States at present. Some of this attention is due to the fact that modified vehicles can burn (without attention by the driver) widely varying mixtures of methanol and gasoline, thus potentially easing aspects of a transition to methanol. For example, methanol could be favored in certain air-quality regions and gasoline elsewhere. A disadvantage of this approach is that such flexible-fuel vehicles would not be designed to take advantage of the specific properties of the methanol, a substantial sacrifice. Another approach to flexible fuel capability is presented in the paper by Mellde et al (48) in this volume.

Congestion

Metropolitan area transportation is burdened by congestion. Moreover, street and highway mileage continues to grow more slowly than vehicle-miles. Only a small fraction of passenger-miles can be diverted to mass transit in the foreseeable future. Moreover, the energy-intensity of mass transit per passenger-mile may not be much less than that of the private car. Mass transit can, however, relieve congestion and can influence real-estate development so as to reduce dependence on personal vehicles. Some evidence of this is that motor vehicle-miles per adult is two thirds as great in New York and Illinois as it is in Texas. (Another response to congestion, information and control systems for highways, is not discussed.)

Intercity passenger travel faces even more severe congestion. Traveling in three dimensions is, paradoxically, much more affected by crowding than traveling in two. There is a technologically exciting opportunity: high-speed ground transportation. The concept is to replace short-haul heavily traveled air routes with high-speed ground vehicles. The main focus would be substitution for air travel, including longer-distance travel where a ground trip, e.g. between Detroit and Chicago airports, would be combined with a flight (private communication, Larry R. Johnson). An energy-efficient lightweight vehicle and guideway might be enabled by magnetic levitation. Such vehicles might be able to operate along expressway rights of way.

The energy implications of such developments are of course quite uncertain. Nevertheless, we know that the technological ferment of our times is counterbalanced by the capital-intensity of transportation, including not only the equipment directly involved, but the equipment of suppliers including, especially, energy suppliers. Moreover, inertia is created not only by physical capital but also by human capital, our organizations, modes of operation, and knowledge. This suggests that although modifications of existing systems can be achieved in relatively short times (such as the improvement of in-use automotive fuel economy and the increase of the average passenger capacity per airplane of commercial airlines since the early 1970s), more profound changes will take longer. They will take longer especially if they are motivated by concerns other than improvement in the service provided.

CONCLUSIONS

This wide-ranging discussion was intended as an antidote to the concept of autonomous energy demand, i.e. the concept that demand is not subject to ordinary policy making the way supply is. Even without considering modal switching or alternative fuels, there is great uncertainty in the energy requirements for transportation. Moreover, that uncertainty is not only associated with hard-to-control factors such as the world oil price and consumer tastes, it also depends sensitively on the energy-efficiencies of the technologies used. These technologies will, in turn, depend on what the manufacturers choose to develop and market and on public policies. There are public policies, with which we already have experience, that (in the author's opinion) are not economically severe and that do not severely intrude on private decision-making, that would probably have powerful impacts on transportation technologies and energy use during the first decade of the next century.

An exercise by the author to quantify the uncertainty in personal-passenger-vehicle energy use in 2010 yielded high and low scenarios, with energy use in the high scenario twice as high as in the low scenario. These diverse outcomes are the result of moderate, unsurprising developments and choices. The point is that energy demand is, to a critical degree, a matter for rational decisionmaking, rather than simply being an act of God or the consequence of a particular fuel-price elasticity—if one looks ahead far enough in the future so that there is time to make decisions (at normal replacement times) about the capital equipment involved.

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