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AUTOMOBILE FUEL USE AND CONSERVATION[1]

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ABSTRACT

Variations in automobile fuel economy as functions of trip length and of driving conditions (urban and inter-city) are calculated for subcompact, "average," and full-size cars. Fuel economy is considerably worse for urban driving than for inter-city driving because of cold-start operations and frequent stop-and-go cycles for urban driving. Fuel economy improves markedly with increasing trip length because the adverse impact of cold start is spread over more miles. Subcompacts achieve much better fuel economy than do full-size vehicles under all conditions; this is especially so for urban driving.

A number of strategies exist that could be used to conserve fuel by discouraging short auto trips and by discouraging the use of large cars. These strategies include: shifts from automobiles to public transit, shifts from automobiles to bicycles for short trips, shifts from full-size to subcompact automobiles, increases in automobile occupancy, and reductions in the overall level of automobile travel.

As gasoline supplies shrink and prices skyrocket, we are focusing more and more attention on automobile use and fuel economy. This paper examines auto fuel economy as determined by three basic factors: vehicle design, driving conditions, and use characteristics. Vehicle design includes auto weight, transmission type, horsepower, rear axle ratio, engine design, accessories, emission control equipment, aerodynamic drag, and rolling resistance. Driving conditions include vehicle speed; road surface, gradient, and curvature; and the number of stops and speed changes per mile. Use characteristics include vehicle occupancy, purpose of trip, trip length, and personal driving habits.

To evaluate the impact of each of these factors on fuel economy would be an immense task. Therefore, the factors listed above have been "collapsed" into

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two basic variables. Variations in automobiles are accounted for by considering three different typical cars: a hypothetical "average" car whose fuel economy is equal to the national average estimated by the Federal Highway Administration (FHWA), a full-size car, and a subcompact.

Driving conditions are classified as either urban or inter-city. Within urban areas, the impact of trip length on fuel economy is included because automobiles operated under cold-start conditions exhibit poor fuel economy for the first several miles of driving. The impacts of speed, road type, and traffic density are aggregated within the urban/inter-city split.

Use factors, such as vehicle occupancy, trip length, and trip purpose are included within the urban/inter-city split. The influence of personal driving habits on fuel economy is ignored.

In 1971, automobiles travelled 950 billion miles consuming 70 billion gallons of gasoline in the process [1]. This fuel use amounted to 31% of domestic petroleum consumption [2]. Table 1 shows how automobile travel and fuel use have grown during the past two decades. In 1950, auto propulsion accounted for less than 10% of the nation's energy budget; by 1971 this figure had increased to nearly 14%.

During this 21-year period, automobile mileage increased at an average annual rate of 4.7%, fuel use per mile increased at 0.4% a year, and total auto fuel use grew at 5.1% a year. Roughly 90% of the increased fuel use was due to greater traffic, with the remainder due to declines in auto fuel economy.

The Average Auto

Urban fuel economy is considerably worse than inter-city fuel economy [3, 4] because city driving involves more speed changes and stop-and-go cycles

Table 1. Direct Fuel Use for Automobiles

	Total auto travel (billion VM)[a]	Fuel economy (mpg)	Auto fuel use[b]		
			Actual (trillion Btu)	As a percent of –	
				U.S. petroleum use	Total U.S. energy use
1950	364	15.0	3,310	24.5	9.7
1955	488	14.5	4,560	26.0	11.5
1960	588	14.3	5,600	27.9	12.6
1965	712	14.2	6,840	29.4	12.8
1970	901	13.7	8,950	30.2	13.3
1971	954	13.7	9,450	31.0	13.7

[a] VM = vehicle-miles.

[b] Gasoline converted at 136,000 Btu/gallon.

Source: References 1 and 2.

than does inter-city driving [5] and because many urban trips use cold vehicles for short distances.

The lower curve in Figure 1 gives fuel economy (as a per cent of mpg for fully warmed-up vehicles) as a function of trip length for cars started cold [6]. For short trips, fuel economy for cars started cold is poor relative to that for fully warmed-up cars. For longer trips, this effect is much less significant because the poor performance during the first few miles is averaged with the much better performance during the remaining miles when the car is warmed-up. After about 10 miles, the typical car is fully warmed-up. For example, a 1.5-mile trip in a cold car will consume twice as much fuel as the same trip in a fully warmed-up car.

The upper curve in Figure 1 is derived by assuming that two-thirds of all urban trips use cars that are started cold and that the remainder use cars started fully warmed-up [7]. This is based on the assumption that all work trips and half of all other trips are made with cars started cold [8, 9].

Table 2 and Figure 2 present fuel use estimates [7] for 1971 using the upper curve of Figure 1 and data from the FHWA [1, 5-9]. Figure 2 shows the considerable variation in fuel use as a function of trip length. For example, a two-mile urban trip requires 80% more fuel than two miles of inter-city driving.

Because of poor fuel economy in urban areas, urban driving accounts for 63% of automobile fuel use while contributing only 55% of vehicle mileage. Similarly, auto trips of five miles or less account for 16% of total mileage, but consume 22% of total auto fuel use.

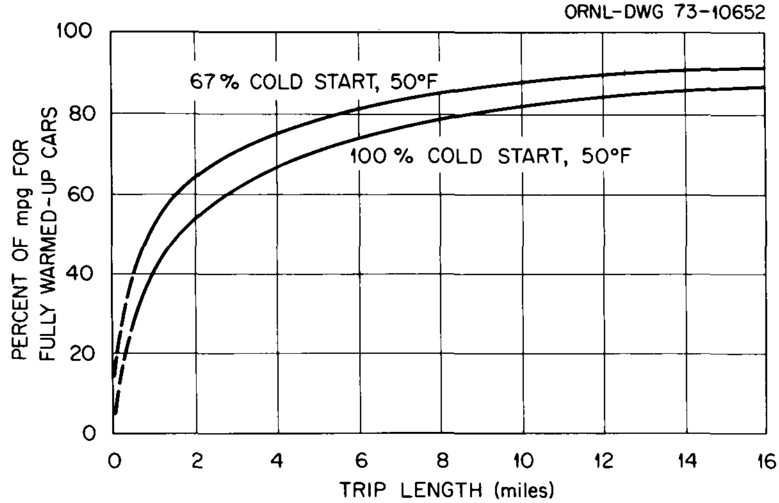

Figure 1. Urban automobile fuel economy as a function of trip length due to cold start. (Note that the curves show integrated mpg for given trip lengths, not instantaneous mpg for given distances from cold start.)

Table 2. Fuel Use for the Average Auto in 1971[a]

Trip length (miles)	Fuel use (Btu/VM)	Occupancy (PM/VM)	Fuel use (Btu/PM)	Percent of total auto[b]		
				VM	PM	Fuel use
			Urban			
1	18,000	1.9	9,500	1.8	1.6	3
2	14,600	2.0	7,300	3.0	2.8	4
3	13,400	1.9	7,100	3.3	2.9	5
4	12,500	1.9	6,600	2.9	2.6	4
5	12,000	2.0	6,000	4.7	4.4	6
6-10	11,000	1.9	5,800	15.4	13.5	17
11-15	10,400	1.9	5,500	12.4	10.9	13
16-20	9,900	1.9	5,200	9.1	8.0	9
21-30	9,400	2.1	4,500	2.4	2.3	2
Average	11,400	1.9	5,900	55.0	49.0	63
			Inter-City			
21-30	8,100	2.1	3,900	9.4	9.1	8
31-40	8,100	2.3	3,500	6.6	7.0	5
41+	8,100	2.6	3,100	29.0	34.9	24
Average	8,100	2.4	3,300	45.0	51.0	37
U.S. Average	9,900	2.2	4,600	100.0	100.0	100

[a] VM = vehicle-miles, PM = passenger-miles.

[b] In 1971, total auto VM was 954 billion, PM was 2060 billion, and fuel use was 9,450 trillion Btu.

Source: References 1, 5-9.

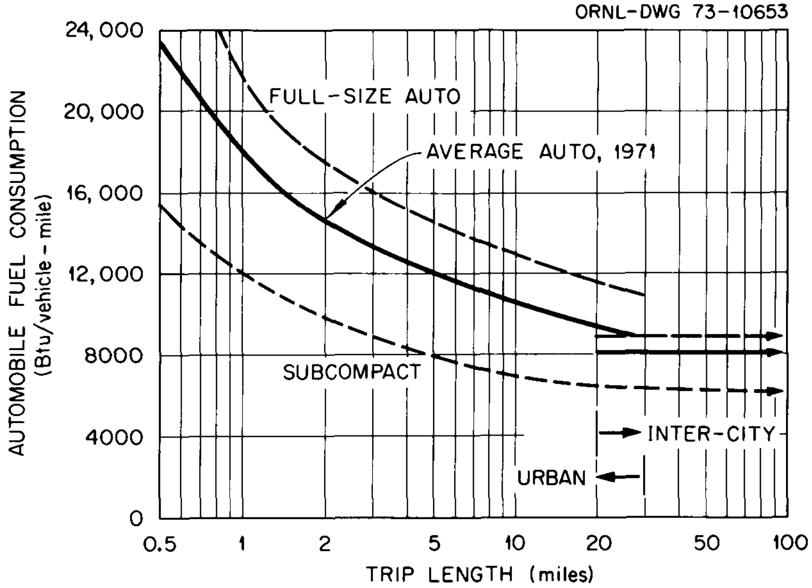

Figure 2. Automobile fuel use per VM as a function of trip length, 1971.

Combining the above results, which give fuel use per vehicle-mile (VM), with automobile occupancy data [8, 9] yields fuel use estimates per passenger-mile (PM). These results are presented in Table 2 and Figure 3. Because urban auto occupancy is lower than rural occupancy by 20%, fuel use is even higher in cities than when evaluated on the basis of vehicle-miles.

From the results given above, fuel use for a two-mile urban trip is more than double the fuel use per passenger-mile for two miles of a typical inter-city trip. Trips of five miles or less account for 14% of auto passenger-miles, but (as noted above) consume 22% of total fuel.

Full-Size and Subcompact Autos

Table 2 gives fuel use for an average auto based on the 1971 FHWA national average fuel economy figure [1]. Analogous results are presented here for two types of widely-used autos—full-size and subcompact.

The hypothetical full-size car weighs 4,200 pounds, has a 350-cubic-inch/160-horsepower engine and a rear-axle ratio of 2.7, and is equipped with automatic transmission, air conditioning, and power steering.

The hypothetical subcompact weighs 2,400 pounds, has a 140-cubic-inch/90 horsepower engine, a rear-axle ratio of 3.4, standard transmission, manual steering, and no air conditioning.

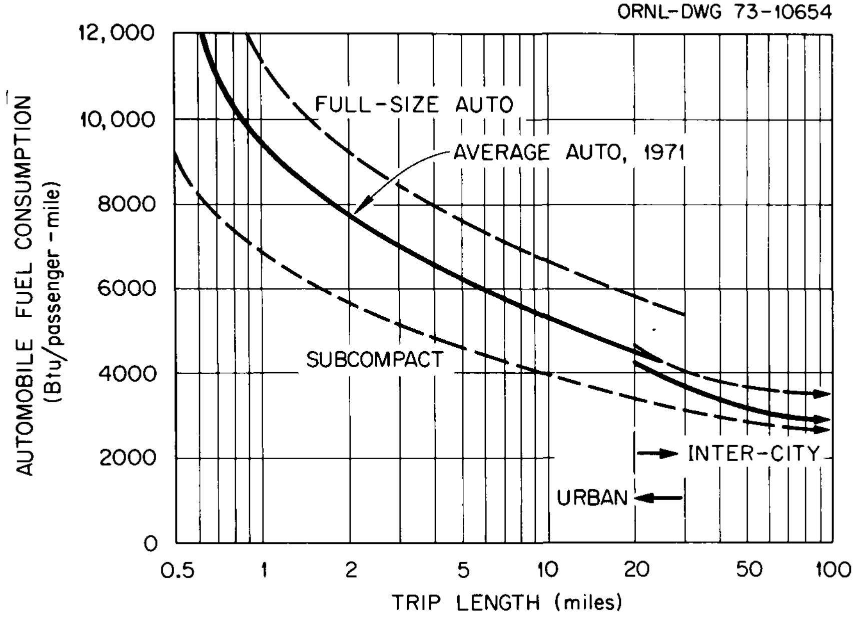

Figure 3. Automobile fuel use per PM as a function of trip length, 1971.

Based on test results in References 10 and 11, the full-size car is assumed to average 15 mpg in inter-city driving. Urban fuel economy [5, 6, 12] for a fully warmed-up car is 12 mpg, and the urban average [6, 9] is then 9.85 mpg. Since 55% of auto VM is urban [1], this car has an overall fuel economy of 11.6 mpg.

Inter-city fuel economy for the subcompact is taken [10, 11] as 22 mpg. Urban fuel economy for a fully warmed-up subcompact is the same as for inter-city driving [5, 12]. Then the urban average [6, 9] is 18.1 mpg, and the overall fuel economy for the subcompact is 19.7 mpg.

From the numbers given above and Figure 1, fuel economy as a function of trip length can be derived; these results [7] are presented in Figures 2 and 3. Figure 2 shows that the subcompact yields considerably better fuel economy than does the full-size. In urban areas, the subcompact is particularly fuel-efficient, outdoing the full-size car by 83%. On the other hand, the fuel economy advantage of the subcompact is diminished somewhat in inter-city driving, where its fuel economy is 47% better than that for the full-size.

In cities, the full-size auto is severely hampered by its weight: additional fuel is consumed to accelerate the vehicle after each stop and each speed change. The large engine (generally operating at a small fraction of its rated power) and the automatic transmission further degrade fuel economy. In inter-city driving, where there are few speed changes and stops, weight has less impact on fuel economy. The engine operates at a higher fraction of its rated power and is therefore more efficient than in cities. Finally, automatic transmission losses are reduced because of the steady speed operation.

The results of Figure 2 are combined with occupancy values [8] to yield the fuel use estimates per passenger-mile shown in Figure 3. Because the subcompact has an assumed seating capacity of only four, compared with six for the full-size auto, the occupancy figures from Reference 8 are reduced by 9% for the subcompact [7].

Policy Implications

The results presented here show that:

1. Automobiles consume major fractions of the United States transportation energy budget and total domestic petroleum budget.
2. Fuel economy is considerably worse for urban driving than for inter-city driving because of cold-start operations and frequent stop-and-go cycles in urban driving.
3. Fuel economy improves markedly with increasing trip length, because the impact of cold-start is spread over more miles.
4. Subcompact cars achieve much better fuel economy than do full-size cars especially under urban driving conditions.

These results suggest two basic energy-conserving tactics:

1. Discourage the use of automobiles for short urban trips. Either eliminate such trips or make these trips by energy-efficient modes, e.g., foot, bicycle, or mass transit.
2. Discourage the use of full-size cars, especially in urban areas.

To some extent, rising fuel prices and other auto-related costs, increasing congestion, and air pollution requirements will encourage adoption of these two measures. In addition, a number of policy options specifically addressed to urban passenger transportation could be invoked to hasten adoption of these measures. Such policies (stated in general terms) include:

1. Increase consumer costs for operating cars in urban areas, e.g., increase tolls on bridges and highways entering cities, charges for urban parking, gasoline taxes, and annual license fees related to fuel use.
2. Discourage the purchase of fuel-intensive automobiles, e.g., relate new car excise taxes to fuel consumption, horsepower, or weight.
3. Make urban auto travel less convenient, e.g., increase use of auto-free zones, abolish some urban parking areas, and create specific lanes for buses and bicycles (this reduces the capacity of roadways for autos).
4. Encourage car pools and consolidation of short trips to increase load factors, e.g., provide preferential parking spots and prices, reduce bridge tolls, and set up computer matching.
5. Construct bikeways in urban areas.
6. Improve the quality and quantity of mass transit services, e.g., provide more frequent schedules and better coverage of the urban area, purchase new equipment to increase comfort and safety, lower fares, and establish exclusive lanes for buses.
7. Conduct public education programs to inform consumers of the dollar and energy costs associated with short auto trips and the use of full-size autos in urban areas.
8. Reduce the need for transportation by encouraging changes in urban design so that people can work and shop near home.

Each of these policies would slow urban passenger transportation energy growth. However, these policies will surely have other effects on the economy, employment, the environment, land-use, health, poverty, and so on. The following discussion focuses on the energy-use implications of these policies but does not deal with other potential consequences.

SHIFT FROM AUTOS TO MASS TRANSIT

Policies that increase costs of purchasing and operating autos, restrict auto use, educate the public concerning auto costs, and provide a viable system of mass transit will induce a shift from autos to mass transit. In addition to saving energy, such a shift will reduce transportation-related deaths and injuries, urban congestion, noise pollution, and air pollution. On the other hand, travel times are likely to be longer with mass transit than with autos. (However, travel time differentials could be reduced both by improving mass transit services and by restricting auto use.)

Capital costs raise another problem since the present system of financing urban transportation systems heavily favors highway construction. However, the cost of new buses is small relative to highway costs; electric transit construction costs are much higher than the cost of buses. Finally, while the time required to manufacture and buy new buses is only a few years, the time needed to build a new electric transit system is about 20 years.

Thus buses provide a more flexible, less expensive, and easier-to-implement alternative to cars than do electric transit systems. On the other hand, electric transit operates on exclusive right-of-ways and can therefore offer higher speeds than can buses.

As Table 3 shows, a shift of 1% of urban passenger traffic in 1971 would have saved 0.3% of urban passenger traffic energy use (almost four million barrels of oil).

Table 3. Potential Energy Savings for Urban Passenger Travel

Strategy	Energy Savings[a]	
	(10^{12} Btu)	Percent of total urban passenger energy use[b]
Shift from autos to mass transit	20	0.3
Shift from autos to bicycles for trips ≤ 5 miles long	62	1.0
Shift to subcompact autos	16	0.3
Increase urban auto load factors from 1.9 to 2.4 PM/VM	12	0.2
Reduce level of auto travel	59	1.0

[a] Energy savings are computed on the basis of a 10-billion PM effect, equal to 1.0% of total 1971 urban passenger traffic.

[b] Fuel use for urban passenger traffic in 1971 totaled 6,030 trillion Btu, 35.3% of total transportation direct energy use.

Source: References 3, 7.

SHIFT FROM AUTOS TO BICYCLES

Encouraging the use of bicycles for some urban transportation requires policies similar to those needed to induce greater use of mass transit: discouraging the use of autos. In addition, policies that encourage safe bicycling (e.g., construction of bikeways and development of programs to educate both motorists and cyclists concerning traffic safety) are needed. It is likely that the danger associated with bicycling is currently a major barrier to greater use of bicycles, although psychological and social factors may also be important.

Shifting some traffic from autos to bicycles for short trips would reduce energy use (Table 3), air and noise pollution, congestion, and parking problems and save money; for trips less than or equal to five miles in length, total door-to-door travel time would increase by an average of six minutes. On the other hand, during periods of bad weather and darkness most bicyclists are likely to use autos (or mass transit); thus the advantage of bicycles are, in some sense, impermanent.

The time required to construct bikeways and thereby encourage greater bicycle traffic is probably on the order of a few years, comparable to the time needed to buy new buses, but considerably less than the time required to construct new electric transit systems.

Table 3 shows that a shift of 1% of urban passenger traffic from cars to bicycles (equivalent to a 3.4% shift for all auto trips less than or equal to five miles) would, in 1971, have reduced fuel use by 62 trillion Btu (11 million barrels of oil), a 1% reduction in urban passenger traffic energy use.

SHIFT TO SUBCOMPACT AUTOS

Relating new car taxes and annual license fees to fuel use, increasing gasoline taxes, and expanding public education concerning auto fuel costs are policies that would encourage a greater shift to subcompact cars. (During the past few years subcompacts and compacts have accounted for rising shares of total new car sales in the U.S.)

Shifting new car purchases from full-size autos to subcompacts would reduce energy use (Table 3), make automotive air pollution emissions easier to control, save money for motorists, and cause essentially no loss in transportation convenience and flexibility. On the other hand, the auto industry might experience a loss of profits, at least during the transition period as they change plant and equipment to meet the rising demand for small cars. This transition is likely to have impacts on employment, both in the auto industry and among the supplier industries. Also, because of the times required to construct new auto assembly plants or modify existing plants, and to retool for production of parts and engines for smaller cars, shifting to smaller cars is likely to require several years before significant changes in auto fuel economy are observed.

A shift of 1% of urban passenger traffic from "average" cars to subcompacts would, in 1971, have reduced fuel requirements by 16 trillion Btu (3 million barrels of oil), 0.3% of total urban passenger energy use.

INCREASE AUTO LOAD FACTORS

Policies that increase automobile operating costs and that specifically promote car pooling (computer arranged car pools by employers and municipalities, reduced bridge tolls and parking charges for autos with high occupancy, preferential treatment in parking and highway lanes) could increase auto occupancy in cities from its present value of 1.9 PM/VM. Occupancy for urban commuting is even lower, only about 1.4 PM/VM; this presents a major opportunity for improving load factors since one-third of all auto VM is for trips to work and back.

Increased auto occupancy would save energy (Table 3) and reduce costs to travelers, air pollution, noise, and urban congestion. On the other hand, travel times are likely to be increased somewhat, and there are social and psychological barriers (e.g., independence, sex, race, privacy) to be overcome before more people will car pool. The time required to increase occupancy and save energy is probably only a year or two.

The energy savings given in Table 3 assume that urban auto occupancy is increased from 1.9 to 2.4 PM/VM. The latter figure is the occupancy for inter-city driving and represents a 25% improvement in urban occupancy. Energy savings per 10 billion PM amount to 12 trillion Btu for 1971 (2 million barrels of oil), 0.2% of urban passenger transportation energy use.

REDUCE LEVEL OF AUTO TRAVEL

Policies that increase the costs of purchasing and operating automobiles and that discourage the use of autos will decrease auto travel. If transportation alternatives (mass transit, bicycles) are not improved, the result will be a decline in total transportation demand. Such a change would have impacts extending far beyond those related to energy use: access to jobs, income, employment, plus the beneficial impacts of reduced air and noise pollution, etc. The energy savings of a reduction in urban auto travel are shown in Table 3.

Summary

A number of parameters that affect automobile fuel economy were examined: trip length, type of driving (urban versus inter-city), and type of car. Technical results are summarized in the preceding section and in Figures 2 and 3. Fuel economy is considerably worse in cities than under inter-city driving conditions. In particular, fuel economy declines sharply with decreasing trip length. Subcompact cars achieve much better fuel economy than do full-size cars, particularly under urban driving conditions.

A number of measures could be adopted, the major results of which would be significant reductions in energy use for urban passenger transport. Historical trends indicate a rising demand for urban passenger transport energy use, but these trends are changing because of oil scarcities, rising oil prices, increasing dependence on oil imports, environmental considerations (particularly air quality), and the problems associated with the present system of urban travel. There are no major technological barriers to improved energy efficiency of the urban transportation system; rather the problems are institutional. A variety of policy options exist that would improve vehicle fuel economy, increase auto load factors, and shift some traffic to more efficient modes.

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