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The Fuel Economy of Light Vehicles

As domestic oil production decreases, cars with better fuel economy become more attractive. By 1995 it should be possible without major innovations to have fuel economies of more than 60 miles per gallon

by Charles L. Gray, Jr., and Frank von Hippel

The U.S. is coming out of an era in which economic growth was stimulated by an abundance of cheap petroleum and going into a difficult period in which energy, particularly in the form of liquid fuel, will be much costlier and in limited supply. That this will be a dangerous period is already clear from the anxiety expressed by U.S. officials about the security of the nation's continued access to the world's largest-known reservoirs of underground oil, those in the Persian Gulf region. Consumers are therefore being urged to conserve energy while government and industry focus on developing costly new domestic supplies. Useful as these measures may be, we believe the possibility of making a successful economic transition to the postpetroleum era depends on a much more determined effort by both government and industry to increase the efficiency with which energy is utilized in those sectors of the economy that depend on liquid fuel, starting with the single largest consumer: the automobile.

The automobile has given Americans an extraordinary degree of personal mobility. Today there are about 100 million passenger cars and 30 million light trucks (mostly privately owned pickup trucks and vans) registered in the U.S., nearly one for every adult. In 1980 this vast fleet of vehicles consumed about six million barrels of petroleum products per day, the approximate equivalent of all U.S. imports or about 60 percent of U.S. domestic production.

A few years ago such facts would have seemed only mildly interesting. In 1972, before the Arab oil embargo, there had been no gasoline shortages, and the total cost of U.S. oil imports was only $5 billion. By 1980 the cost of importing not much more oil had escalated to $80 billion, or roughly $1,000 for every American household. With the cost rising rapidly and the future availability of petroleum uncertain some people have begun to ask if Americans can continue to enjoy the luxury of the private automobile.

Where some believe the U.S. is suffering from too many private vehicles others maintain that the automobile plays an irreplaceable role in American life. They fear that the U.S. automobile industry, already hard hit by foreign competition, will soon be building too few cars to ensure a healthy domestic economy. This view was recently expressed most forcibly in a report to former President Carter by Neil Goldschmidt, the outgoing Secretary of Transportation. The production of automobiles and trucks and their subsequent servicing account for about 8.5 percent of the nation's gross national product, for more than 12 percent of personal-consumption expenditures and for about 25 percent of U.S. retail sales.

This part of the economy is currently in serious trouble because of a rapid shift in consumer preference toward smaller and more fuel-efficient vehicles in 1979. In 1980 the U.S. automobile industry lost more than $4 billion and foreign car makers captured more than 25 percent of the U.S. market. By the end of the year, according to Secretary Goldschmidt's report, 190,000 automobile workers, a fourth of the total number, were on indefinite layoff, and between 350,000 and 650,000 workers in automobile-related industries had lost their jobs. If the industry is to compete successfully in the future, stated the report, "U.S. automakers face at least one and perhaps several rounds of major capital expenditures to retool their production facilities [including] the redesign of the auto itself" for greatly increased fuel economy. The report questioned the financial ability of the U.S. automobile industry "to sustain in the latter part of the decade an investment program approaching the magnitude of the current one."

Our own analysis encourages us to conclude that if this financial limitation could be overcome, it would be possible with currently available technology to raise the average fuel economy of the entire U.S. automobile fleet built in 1995 to more than 60 miles per gallon. (Sixty m.p.g. is equivalent to 25 kilometers per liter.) With more advanced technology it might be possible to attain 90 m.p.g.

To place these goals in perspective let us briefly review the recent history of fuel economy in American automobiles. In 1974 the average car sold in the U.S. achieved an on-the-road fuel economy of a little more than 13 miles per gallon of gasoline. By 1980 the figure had risen to an estimated 19 m.p.g. By mandate of Congress the fleet of automobiles built for the 1985 model year must achieve an average of 27.5 m.p.g., as measured by dynamometer tests administered by the Environmental Protection Agency (EPA). This figure was set by Congress at almost exactly double the fuel economy of the 1974 model year (as determined by the same testing method). The Department of Transportation was also instructed to set fuel-economy standards for light trucks at the "maximum feasible level." Recently the department determined that in view of the current financial problems of the industry it could set this level no higher than 21 m.p.g. in 1985.

It appears now that as a result of the new consumer demand for fuel economy the manufacturers will probably exceed the 1985 passenger-car standards by a significant margin. The General Motors Corporation has announced that it expects its 1985-model-year fleet to achieve an average fuel economy of 31 m.p.g. as measured by the EPA test. The on-the-road fuel economies actually achieved are expected to be significantly lower, however, because of defects in the test, which was frozen by law in 1975. The Department of Energy currently estimates that in 1985 the average on-the-road fuel economy of new American light vehicles (including imports) will be 25 m.p.g. for passenger cars, 18 m.p.g. for light trucks and 23 m.p.g. overall.

The Department of Energy projects that, assuming these average efficiencies are achieved, the U.S. will still be consuming automotive fuel in 1985 at a rate of 5.5 million barrels per day, only 500,000 barrels per day below the current rate. This continued high level of consumption is partly due to a projected increase of 10 percent in the light-vehicle miles driven by a still growing population of driving age. Primarily, however, it is due to the older vehicles that will still be on the road in that year, which will pull the average fuel economy of the total 1985 light-vehicle fleet down to 18 m.p.g.

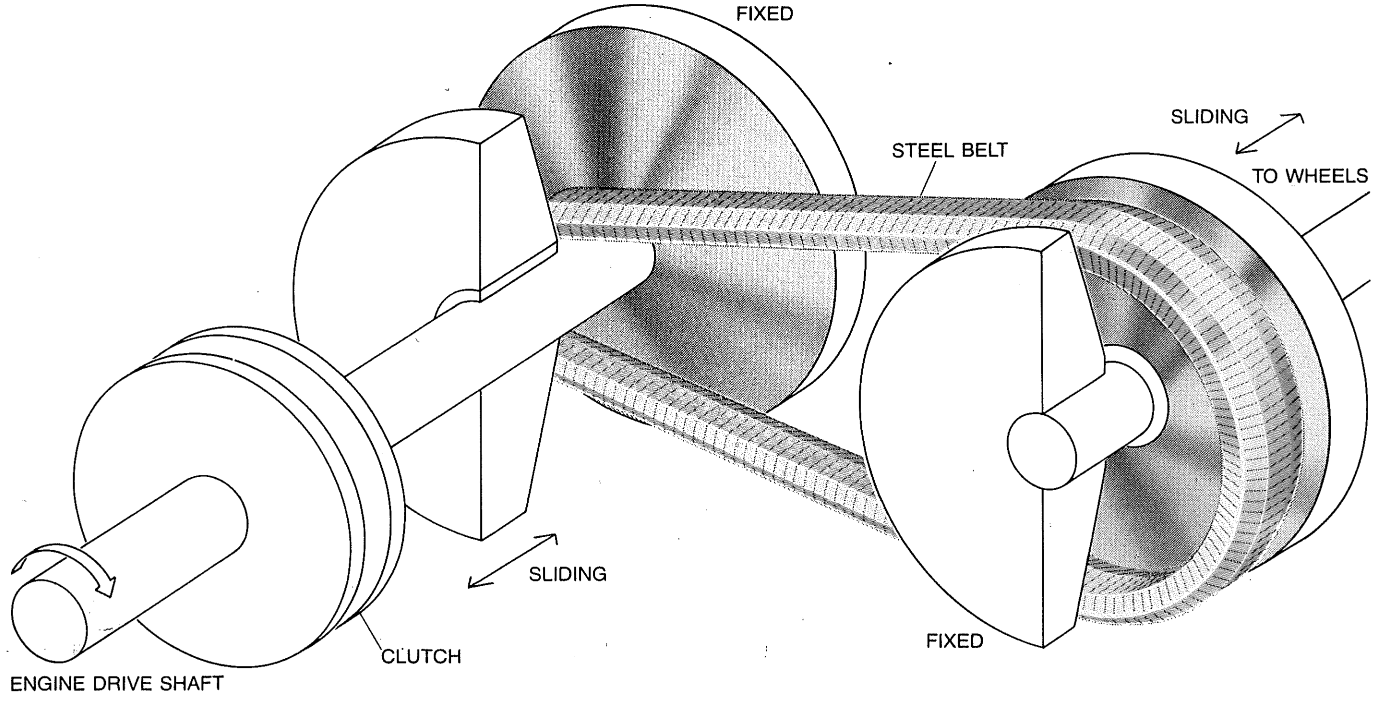
On the supply side the Exxon Corporation projects that by 1985 U.S. oil production will decrease by 20 percent, or two million barrels per day. If both projections are realized, American automobiles will consume the equivalent of all but 2.5 million barrels per day of U.S. production in 1985, leaving little for the remaining sectors of the economy, which in 1980 consumed more than 10 million barrels of oil per day. Hence it appears that even with considerable reductions in oil consumption in some of these other sectors the U.S. will still have a major need for oil imports in 1985.

It is our thesis that one of the most effective and least expensive ways to reduce U.S. dependence on foreign oil in the years beyond 1990 is to make it a matter of national policy to redesign the automobile so that it will be much more energy-efficient and to provide prudent financial aid to U.S. industry in achieving that goal. By the year 2000, we believe, it should be possible to reduce the fuel consumption of the American light-vehicle fleet by two-thirds to about two million barrels per day. The saved oil "produced" by the automobile industry in this way would be much lower in cost than an equivalent amount of oil produced synthetically from coal or shale. The environmental impact would also be much less.

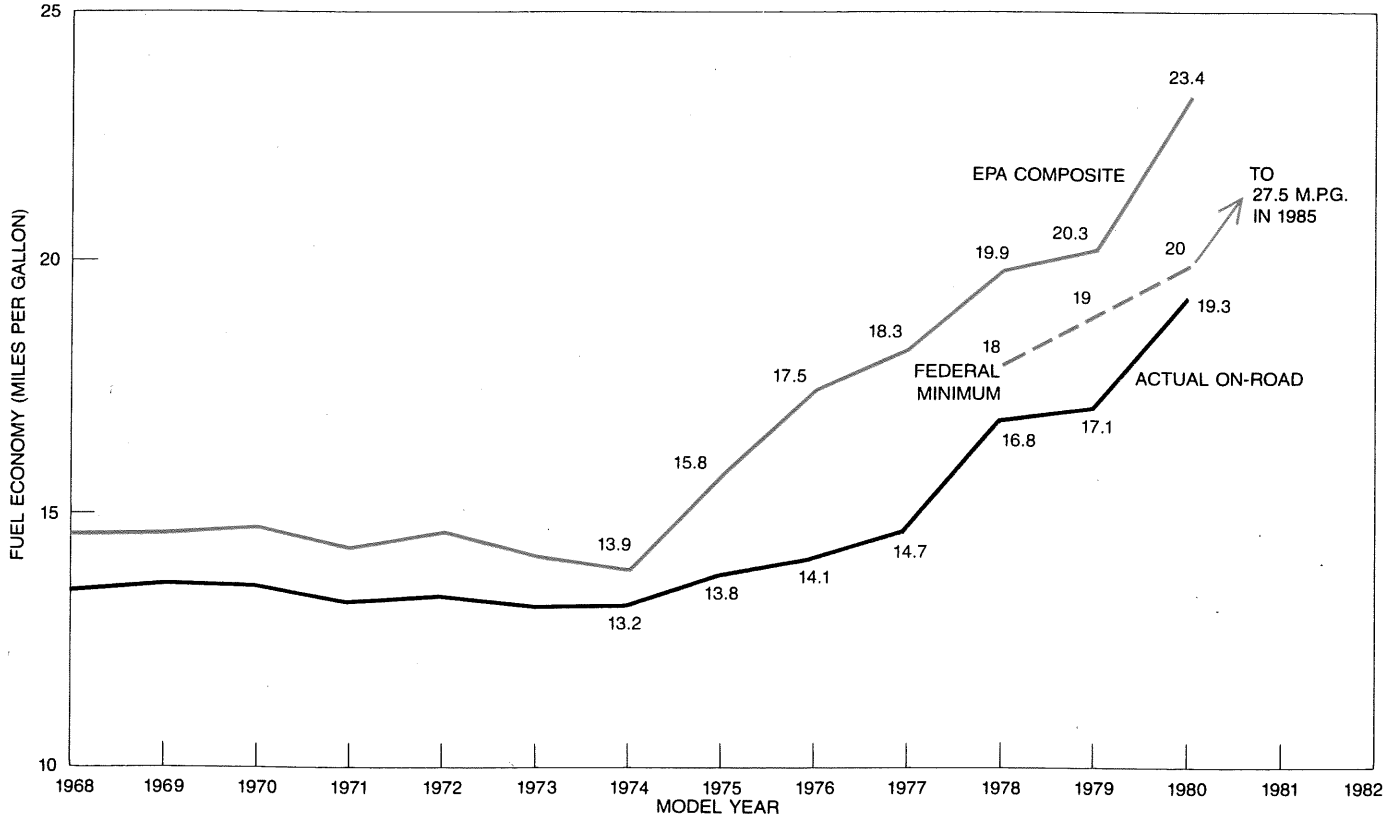
Average fuel economies of more than 60 m.p.g. may seem unrealistic, but we believe they are not. The enormous potential for efficiency improvements in today's automotive technology arises from the possibility of combining changes both in the average physical characteristics of automobiles and in the efficiency of their power plants and drive lines (the mechanisms for delivering the power plant's output to the wheels). Such changes are being introduced piecemeal today as carmakers begin to respond to the new market for efficient light vehicles, but the full potential of the possible changes acting synergistically, rather than one at a time, remains to be widely appreciated. We shall therefore describe a hypothetical fleet of light vehicles that have been redesigned to achieve much higher fuel economy.

Unlike today's fleet, in which two-thirds of the cars are designed to carry five or six passengers, more than half of the fleet we propose would be four-passenger vehicles and would include a significant fraction of two-passenger cars. The power required at the drive wheels would be less than half that of present vehicles because of reductions in weight, in aerodynamic drag and in the rolling resistance of the tires. The vehicles would be powered by significantly more efficient versions of today's internal-combustion engines, with the transmissions and the peak power of the engines being optimized for fuel economy. All the technology required for such a highly efficient fleet exists today in production vehicles or in near-commercial prototypes. We are confident that the vehicles we propose can be designed not only to achieve high fuel efficiency but also to be acceptably safe, to meet reasonable emission standards and to be only slightly costlier, if at all, to operate than current vehicles.

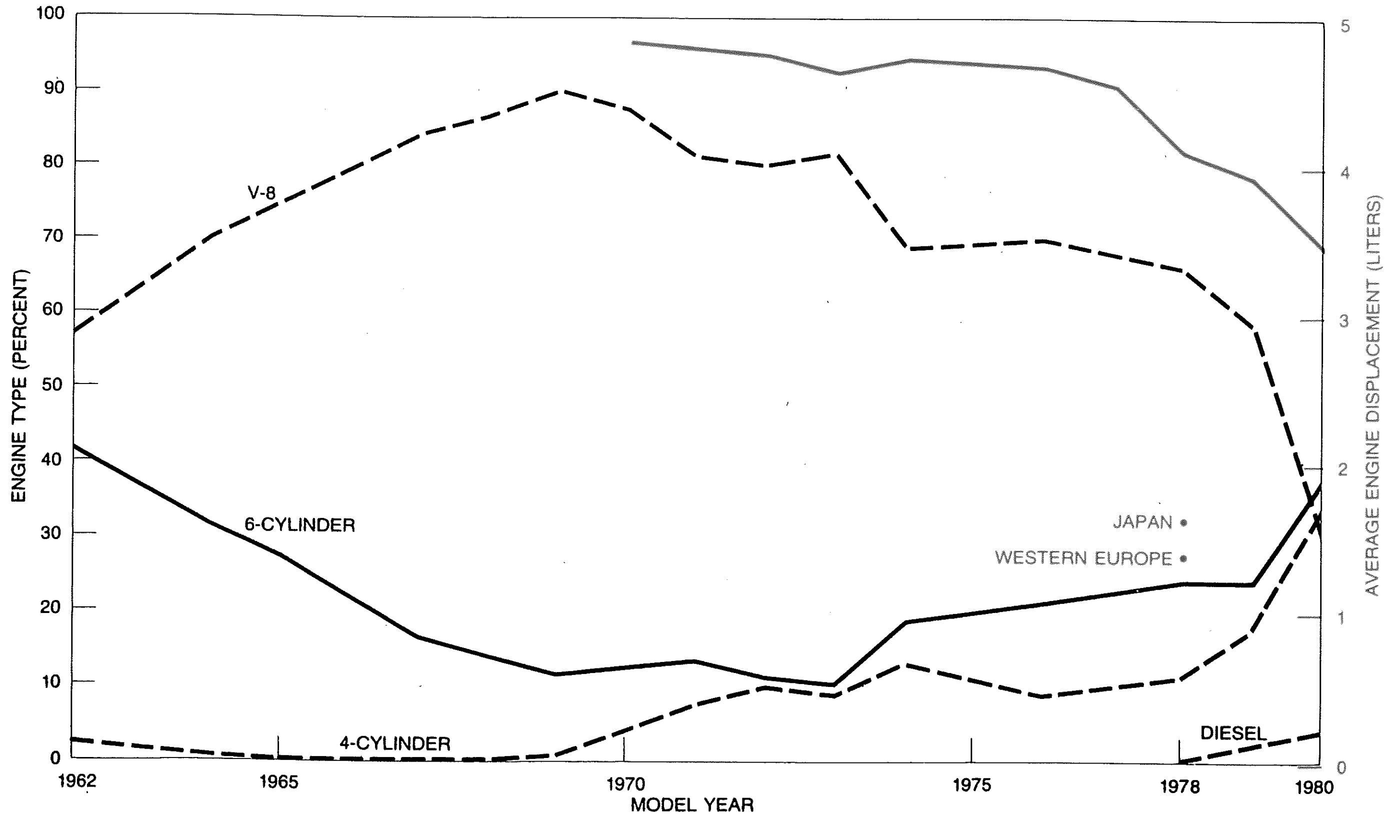
The American passenger car was developed in the era when fuel was cheap, when families with four to six members were common and when few households could afford more than one car. The standard six-passenger car made both personal and commercial sense. Similarly, light trucks were originally developed as work vehicles. Today the average household has fewer than three people, and most households with two or more own at least two cars or a car



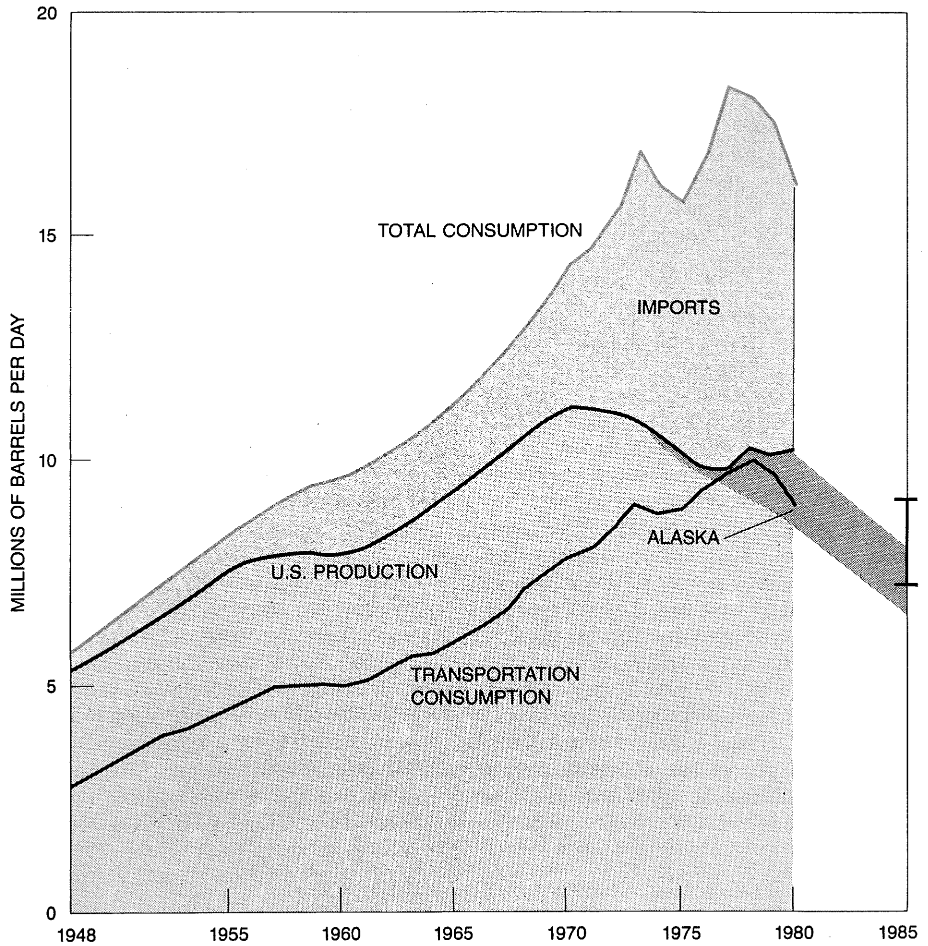
CONTINUOUSLY VARIABLE TRANSMISSION will improve fuel economy by enabling the engine to run at the most efficient speed for a given power output. This drawing depicts a variable transmission to be built by the Borg-Warner Corporation. A steel V-belt links two pulleys whose speeds can be changed continuously by changing the effective radii of the pulleys. A cone sliding toward the belt on the axis of one pulley squeezes the belt out to a larger radius; a cone on the axis of the other pulley allows the belt to slip to a smaller radius.



FUEL ECONOMY OF NEW PASSENGER CARS, domestic and foreign, sold in the U.S. has been rising partly in response to market demand and partly to meet Federally mandated standards, which became effective with the 1978 model year. The Federal standards are specified by dynamometer tests conducted by the Environmental Protection Agency (EPA) that simulate separate cycles of city and highway driving from which is derived a composite estimate of fuel economy based on 55 percent city driving and 45 percent highway driving. When the EPA standard was developed, the composite figure was only slightly higher than average on-the-road fuel economy. The two figures have since diverged. The lower of the two fuel-economy figures seen in automobile advertisements is the EPA city estimate, which is close to on-the-road performance. Federal city-highway-composite standard will reach 27.5 miles per gallon (m.p.g.) in 1985.



DECLINE OF THE V-8 ENGINE was triggered by the oil embargo of late 1973, a year when some 80 percent of new American-built cars were still powered by eight-cylinder engines. The decline finally came in the 1980 model year, when 70 percent of American cars were equipped with either smaller engines or diesel engines. In the 1980 model year the average engine size (*color*) of new passenger cars sold in the U.S. had fallen by a third but was still twice the average size of engines in 1978 cars built in western Europe and Japan. By 1985 the V-8 engine will be virtually extinct in passenger cars. By then Americans may even be able to buy cars with fewer than four cylinders.



U.S. OIL CONSUMPTION has been falling for three years. Transportation continues to take a little more than half of the total. Eighty percent of transportation fuel is consumed by road vehicles of all types, and 80 percent of road-vehicle consumption is accounted for by 130 million automobiles and light trucks used primarily as passenger vehicles. In 1980 these 130 million private vehicles consumed six million barrels of motor fuel per day. Imports of oil in 1980 averaged 6.5 million barrels per day at a cost for the year of about $80 billion. U.S. production of oil in 1980 was 10.2 million barrels per day, 15 percent of it from Alaska. The vertical bar at 1985 indicates the range of domestic production that year based on recent projections.

and a light truck. Well over half of American light trucks (vehicles with a gross weight when fully loaded of less than 10,000 pounds) have been bought for personal use and serve mainly as passenger cars. It is clear that today the American automobile fleet has a great deal of carrying capacity that is used only infrequently.

It was not until after the gasoline price rise of 1979 that the American public took advantage of the large fuel savings that could be achieved by shifting to a fleet better suited to modern patterns of usage. As a result sales of five- and six-passenger cars and the larger light trucks have dropped sharply. In the first half of 1980 four-passenger cars captured 45 percent of the passenger-car market, compared with 33 percent in 1978. Even this shift, however, leaves vehicle capacity and actual transportation requirements badly mismatched. Surveys show that on about 80 percent of all trips American cars carry no more than two people and that in a little more than half of all trips the driver is alone. Therefore it is likely that if inexpensive, fuel-efficient two-passenger cars become available in the 1980's, many will be sold. (Today the only such vehicles available are relatively expensive and energy-inefficient sports cars.)

It is hazardous, of course, to predict market behavior when complex social factors enter in, but assuming that periodic gasoline shortages and price increases will continue to occur over the next decade, a passenger-car sales mix in the mid- to late 1980's might have a breakdown something like the following: two-seaters 25 percent, four-seaters 50 percent and five- or six-seaters 25 percent. In addition the demand for light trucks might drop to a ratio of only one truck to every six cars sold instead of the current one to every four. If the U.S. automobile industry were prepared for such a shift, the industry might well benefit from it: some fuel-conscious households might choose to own an increased number of vehicles, each with a different functional design. A household that today owns two vehicles might decide, for example, to own three if they were more efficient than the present ones: two two-seaters for driving to work and for local errands and a third car with a capacity of four, five or six for family trips. Indeed, the rapid increase of three-vehicle households to about 20 percent of all households in the 1970's is already due in part to the increasing popularity of small cars.

The road to improved fuel economy combines a number of related and interacting paths: weight reduction, reduction in aerodynamic drag, reduction in rolling resistance, more efficient engines and more efficient transmissions. There has already been a substantial drop in the weight of American automobiles and in the average size and power of their engines without any significant loss of useful interior space. For example, one of the new Chrysler "K cars," the five-passenger 1981 Plymouth Reliant, weighs 1,070 pounds (30 percent) less than the 1980 Plymouth Volaré with a sacrifice of only four cubic feet (4 percent) in the volume of the passenger compartment and one cubic foot (6 percent) in the trunk space. As a result of this weight reduction the engine horsepower has been reduced from 120 to 84 and the miles per gallon has been increased from 17 to 24. A major feature of the weight-reduction program in the Reliant, as in many 1980 and 1981 models, has been a changeover to front-wheel drive with the engine mounted transversely. This has made it possible to shorten the engine compartment and to eliminate the long, heavy drive shaft that called for a large tunnel through the passenger compartment. The elimination of the rear-axle differential gear has also made possible a shorter, deeper luggage compartment.

Further major reductions in weight could be achieved by replacing steel with aluminum, fiber-reinforced plastics and foam-filled structures, an evolutionary process already under way. The ultimate weights that can be achieved by such substitutions will probably be close to 40 percent less than those that are being achieved in today's newly redesigned cars. The concern has sometimes been expressed that the savings in fuel that can be realized with lightweight materials might be offset by increases in the energy needed for their fabrication. This is not the case. Very roughly, a reduction of 1 percent in the weight of a passenger car can yield a reduction of .7 percent in the car's lifetime energy consumption. Since passenger cars today consume about 10 times their weight in fuel over a lifetime of 100,000 miles, a one-pound reduction in weight implies a fuel saving of about seven pounds. This is several times the penalty in manufacturing energy resulting from the substitution of lightweight materials.

Let us now turn to a specific hypothetical four-passenger lightweight vehicle whose aerodynamic drag and rolling resistance are reduced significantly below those of today's vehicles. Consider first the engine. The efficiency of an automobile engine is quite low when it is operating at a small fraction of its peak rated output. It is therefore important to equip vehicles with engines that are not unnecessarily powerful. The peak power requirements of an automobile engine are dictated by its ability to accelerate, climb hills and pull loads. We have chosen minimum performance requirements that reflect the importance of fuel efficiency. We assume that light vehicles must be able to accelerate from zero to 50 miles per hour in about 13 seconds. Although this acceleration capability is below the average of today's fleet (from zero to 50 m.p.h. in about 10 seconds), it is better than the performance of a number of models that are currently popular. We assume also that the car must be able to maintain a speed of 55 m.p.h. while climbing a 5 percent grade. (Only 3 percent of the driving in the U.S. is up steeper grades.) The car must also have extra power for accessories such as air conditioning and (in some vehicles) enough extra power to tow a trailer of the same weight up a 5 percent grade at 40 m.p.h.

Let us now consider the implications of these performance requirements for the engine of our hypothetical vehicle, which will have a "test weight" (the curb weight plus 300 pounds representing the average load in urban driving) of 2,200 pounds. This weight is comparable to the test weight of the lighter four-passenger cars being sold in the U.S. today. With continued effort toward weight reduction 2,200 pounds could easily become a typical test weight for future U.S. five- and six-passenger cars. (The five-passenger Reliant already has a test weight of only 2,600 pounds.) Although the frontal area of our hypothetical vehicle will be about the same as it is for current cars (two square meters, or 21.5 square feet), the coefficient of aerodynamic drag will be at the low end of today's range: .4. (Aerodynamic drag is a relative measure of the air resistance of a body with respect to that of other objects with the same frontal area.) A flat square plate has a coefficient of drag of 1.17. A value of .4 is still considerably higher than what has been achieved with aerodynamically shaped but still "practical" prototype cars. The tire-rolling resistance of the hypothetical vehicle is equivalent to 1 percent of the downward pull of gravity. This is also at the low end of the current range. Prototype high-pressure tires exist, however, that have values of rolling resistance about 20 percent lower than those of any commercial tires available today.

In order to arrive at the engine horsepower needed for the hypothetical vehicle it is necessary to consider the efficiency of the transmission that delivers power to the wheels. This is a complex technical area. In today's cars the gearing of transmissions usually provides for the selection of only two or three specific rotational speeds of the engine for a given road speed. As a result in acceleration from zero to 50 m.p.h. with a manual transmission the average engine power output is usually limited to about 80 percent of the peak output.

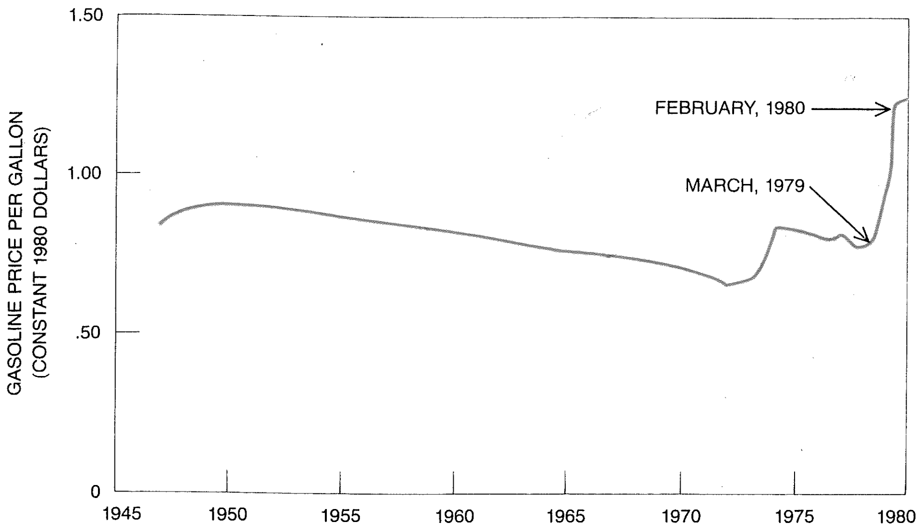
The current inability to harness the engine's peak power at all road speeds should soon be remedied with the introduction of transmissions that are continuously variable. Such a transmission in combination with some simple gearing makes it possible to choose a continuous range of engine speeds. As a result for most road speeds any power output up to the full rated output of the engine can be made available. Even more important for achieving fuel economy is the fact that the most efficient engine speed associated with a given power output can be selected automatically by a microprocessor.

We shall therefore assume that our hypothetical lightweight vehicle is equipped with a continuously variable transmission and that the engine can thus be operated at its most efficient speed over the full range of road speeds at which significant amounts of energy are expended. We shall also assume that the combined power losses in the drive line (the transmission itself, the ancillary gearing, the wheel bearings and the brakes) will be 10 percent of the engine power delivered to the transmission. The loss is about the same in one of today's passenger cars equipped with a manual transmission or with one of the newer fuel-efficient automatic transmissions. In addition we assume that in periods of peak power demand the power drawn by the car's accessories can be limited to .5 horsepower.

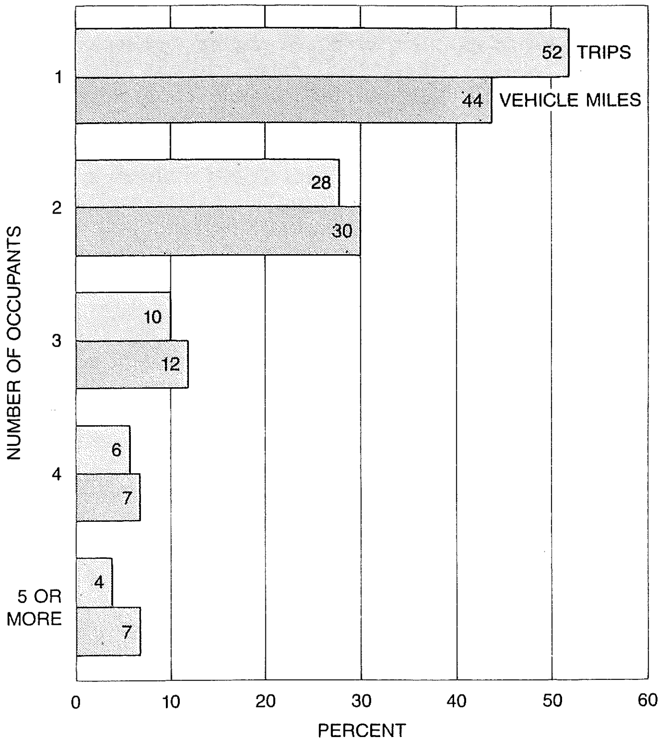
With these assumptions our hypothetical vehicle will require an engine with a peak rated output of about 36 horsepower. This is 25 percent less than the horsepower of the diesel engine in the slightly heavier 1980 Volkswagen Rabbit. The 36-horsepower engine would be much more efficient than the considerably larger engines of today in the 5- to 15-horsepower range, where it would operate most of the time in ordinary driving. For those drivers who want to pull a heavy trailer or for those who need a light truck, optional engines with an additional 20 to 30 horsepower would have to be available, as they are today.

So far we have not mentioned potential improvements in the thermal efficiency of the engine itself, that is, the efficiency with which the engine converts fuel energy into mechanical energy. Today's most efficient engine for transportation is the diesel. One of the inherent advantages of this engine and of some other engines in which fuel is injected directly into the cylinder is that the efficiency falls more slowly than the efficiency of "carbureted" engines, in which fuel and air are mixed before being drawn into the cylinder. Another advantage is that, unlike carbureted engines, they do not have to be fed extra fuel when they are started cold.

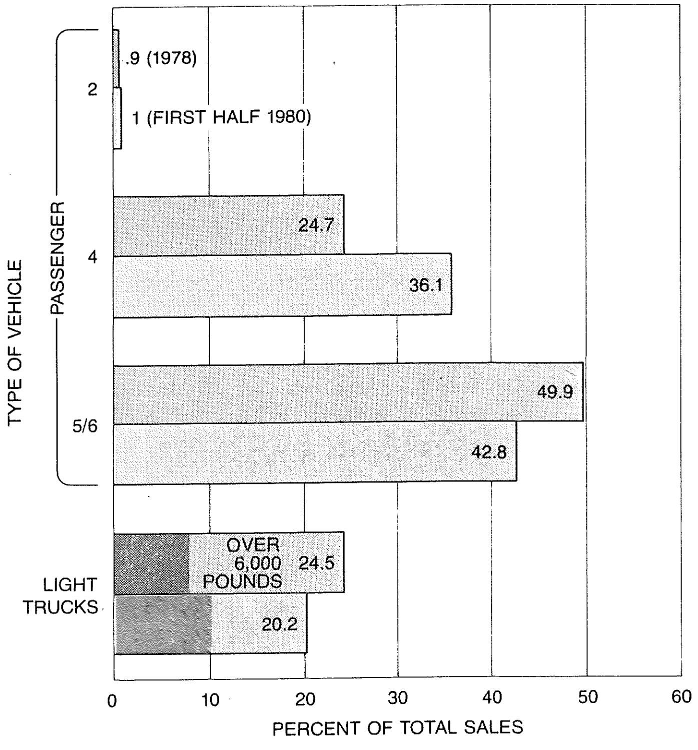
The current generation of automotive diesels, however, is still far from being optimized for fuel economy. Various compromises with fuel economy were made to obtain engines that would operate at high rotational speeds (for high peak power), would be easy to start, would make little noise and would meet mandated emission standards. The most important of the compromises was the addition to each cylinder of a small "prechamber" into which fuel is injected and begins to burn. The prechamber makes the fuel efficiency of automotive diesel engines between 10 and 15 percent lower than that of large truck diesels, which have direct cylinder injection. Engine designers have been seeking ways to eliminate the prechamber in automotive diesels without unacceptable performance or emissions. They now appear to be quite close to doing so.



U.S. GASOLINE PRICES, expressed in constant 1980 dollars, actually declined between 1950 and the winter of 1973, when the Organization of Petroleum Exporting Countries (OPEC) initiated the first of a series of sharp price increases. The era of cheap oil for Americans did not really end, however, until March, 1979, with further OPEC increases and the partial lifting of price controls on oil and gasoline. The average combined Federal and state tax on gasoline of 14 cents per gallon in 1980 was a third lower in real terms than it had been a decade earlier.



AMERICAN MOTORISTS drive without anyone else in the car on 52 percent of their trips (*top bar in color*). Such trips account for 44 percent of all vehicle miles (*top bar in gray*). The percentage of trips with more than one person in the car and the corresponding percentage of vehicle miles are given by the other pairs of bars. Eighty percent of all automobile trips are made with no more than two people in the car and account for 74 percent of the total vehicle miles. These statistics were gathered in 1977–78 by the Bureau of the Census.



SHIFT TO SMALLER VEHICLES is under way. The upper bars of each pair show the percentage distribution of light vehicles sold in the U.S. in 1978. The lower bars of each pair (*color*) show the sales mix for the first half of 1980. Sales of four-passenger cars increased nearly 50 percent at the expense of larger cars and light trucks. The mix of light trucks also shifted sharply toward smaller vehicles. The demand for two-passenger cars has changed very little, probably because most of those that have been available have been sports cars.

The average efficiency of automotive engines could also be increased by the adoption of another technology that is standard on large truck diesels: turbocharging. The turbocharger is a combination of a turbine and a compressor. The turbine is spun by the exhaust gases; the compressor, which is on the same shaft, pushes extra air into the cylinder and thereby allows additional fuel to be burned on each power stroke. Turbocharging makes it possible to raise the peak power output of an engine of given displacement or, what is equivalent, to reduce the size of the engine for a given peak power. A reduction in engine size is beneficial because smaller engines ordinarily have smaller friction losses and other losses. Turbocharging automotive diesels has made possible fuel-economy advances of between 10 and 15 percent.

In calculating the fuel economy of hypothetical future light vehicles we have assumed that the vehicles will be equipped with direct-injection turbocharged engines and with continuously variable transmissions under the control of a microprocessor capable of choosing the most efficient point on a "map" describing the engine's efficiency. In such a map the thermal efficiency of the engine is plotted as a function of the engine's rotational speed and the amount of energy delivered per revolution [*see illustration on page 44*].

The efficiency is low when little energy is delivered per revolution because most of the work done by the expanding gases of combustion goes to overcoming internal engine friction. Power output is proportional to the product of energy delivered per revolution times revolutions per minute (r.p.m.), so that the curves of constant power output on the efficiency map take the form of hyperbolas. Inspection of the efficiency map shows that when only a small fraction of the engine's peak output is needed, maximum efficiency is achieved by holding the engine revolutions constant at the lowest practical level (1,000 r.p.m.) and adjusting the energy delivered per revolution as it is needed. When more than a certain fraction of the peak engine output is needed (more than 20 percent in the example in the illustration), additional power can be obtained at maximum efficiency by holding the energy delivered per revolution constant at a high level and increasing the engine's rotational speed.

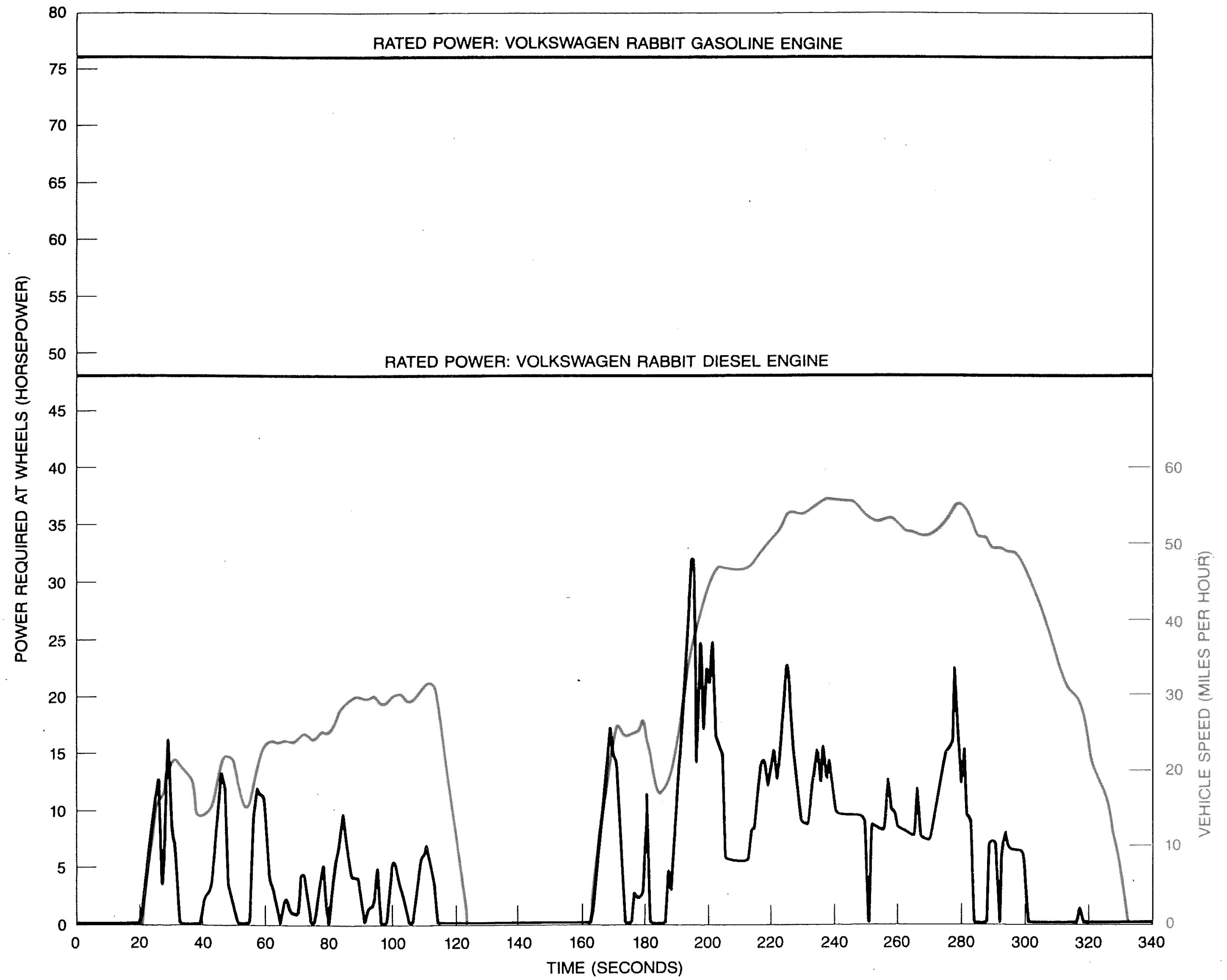
Once the weight, the aerodynamic drag, the tire-rolling resistance, the accessory power requirements, the driveline losses, the transmission characteristics, the engine size and the operating map of an automobile have been specified it is not too difficult to calculate the vehicle's fuel economy on any specific driving cycle. In our computations we have used the EPA's city-and-highway driving cycles and have expressed the results in terms of the standard "composite" weighted average consisting of 55 percent city driving and 45 percent highway driving.

In order to arrive at a hypothetical fleet of vehicles attainable by 1995 we have extrapolated from the specifications of average and "best" vehicles of different models available in the 1980 model year. The extrapolations involve vehicle weight, frontal area, coefficient of aerodynamic drag, tire-rolling resistance, type of transmission and drive-train thermal efficiency. Two sets of values were projected for 1995: those attainable with the current "best" technology and those we believe could reasonably be attained with the advanced technology available by 1995 [*see illustration on page 46*].

Here are a few examples of what we believe can be done. In 1980 the average and the lightest four-passenger cars sold had respective weights of about 2,700 and 2,000 pounds. In 1995 an average test weight of 2,000 pounds should be achievable for these vehicles with the current best technology. With advanced technology an average test weight as low as 1,400 pounds (1,100 pounds curb weight) might be practical. At the upper end of the weight range personal light trucks that in 1980 weighed 4,200 pounds (the average) and about 2,400 pounds (the lightest) could be reduced by 1995 to an average of 2,500 pounds and perhaps to as little as 1,750 pounds. The weight of five- and six-passenger cars could be similarly reduced. We believe that two-passenger cars averaging 1,500 pounds could be made available by 1995 and that weights as low as 1,050 pounds (750 pounds curb weight) might be practical for such vehicles with advanced technology.

Although the frontal area of the vehicles might not be much smaller in 1995 than it was in 1980, we project possible reductions of from 20 to 40 percent in the average coefficient of aerodynamic drag from today's value of about .5. The rolling resistance of tires can also be reduced significantly. Reductions in weight, aerodynamic drag and tire-rolling resistance are all important because braking, air resistance and tire losses account for about equal amounts of fuel consumption in average driving. With the advanced engine and transmission described above, we calculate that it should be possible to approximately double the drive-train thermal efficiency (the percentage of the energy in the fuel that is delivered to the wheels as driving power) from the 1980 average of about 12 percent to 25 percent.

In calculating the fuel economies of these possible future vehicles we have assumed that they would meet the performance specifications we listed that led to a 36-horsepower engine in a hypothetical four-passenger car. We have also assumed that on the average .5 horsepower is required from the engine to operate the accessories. On the basis of all the foregoing assumptions we calculate that with the current best technology the entire 1995 fleet of light vehicles should be able to achieve a fuel economy of more than 58 m.p.g. Given a plausible mix of sizes, for example 20 percent two-passenger cars (at 81 m.p.g.), 40 percent four-passenger cars (at 70 m.p.g.) and 40 percent larger cars and light trucks (at 58 m.p.g.), the average fuel economy of the light-vehicle fleet would be about 65 m.p.g. Increasing the average horsepower of the fleet by 15 percent would reduce the average fuel economy by 1 m.p.g. Such an increase would give 20 percent of the fleet a towing capability or alternatively would give the entire fleet an average zero-to-50-m.p.h. acceleration time of less than 12 seconds. With advanced technology a fleet of the same composition could conceivably attain a fuel economy of 90 m.p.g. [*see illustration on page 47*].



POWER NEEDED AT THE WHEELS of a typical vehicle, here a 1980 Volkswagen Rabbit, is ordinarily much lower than the rated horsepower of the engine. The diesel-model Rabbit is a third less powerful than the gasoline model. The colored curve represents the speed in the first 5.5 minutes of the 23-minute driving cycle devised by the EPA for establishing the fuel economy of cars in city driving. The jagged black curve represents the actual power requirement at the wheels of the car over the 5.5-minute period. The power requirement at the wheels decreases to zero when the car is decelerating or idling. The peak power requirement of 32 horsepower is reached at 196 seconds into the driving cycle, when the car is traveling at 36 m.p.h. and is increasing its speed at the rate of 3 m.p.h. per second.

REQUIREMENT	PERFORMANCE SPECIFICATIONS	POWER REQUIRED AT WHEELS (HORSEPOWER)
ACCELERATION	0-TO-50 M.P.H. IN 13 SECONDS	32
HILL CLIMBING AT CONSTANT SPEED	5 PERCENT GRADE AT 55 M.P.H.	29
ACCESSORIES	LIGHTS, FANS, AIR CONDITIONING, ETC.	+3 (AT ENGINE)
TOWING	TOW VEHICLE OF EQUAL WEIGHT UP 5 PERCENT GRADE AT 40 M.P.H.	+20

POWER REQUIREMENTS at the wheels of a hypothetical four-passenger vehicle capable of meeting certain performance specifications have been calculated by the authors. They believe the specifications are reasonable for a fleet of fuel-efficient vehicles. Thirty-two horsepower at the wheels should be adequate for a vehicle with a test weight of 2,200 pounds (curb weight plus 300 pounds), a frontal area of two square meters (21.5 square feet), a coefficient of aerodynamic drag of .4 and tires with low rolling resistance (1 percent of vehicle weight). If the vehicle is used for towing a trailer of comparable weight, another 20 horsepower is needed.

The gap between these projections for the 1995 fleet of vehicles and the estimated fuel economy of 18 m.p.g. for the 1980 U.S. fleet (if light trucks are included) may well prompt the reader to ask: Is the gap understandable, and are the projected numbers believable? Perhaps the simplest way to understand the large factor of potential improvement we project is to recognize that reductions in the propulsion energy required at the wheels of a vehicle and improvements in the average thermal efficiency of its drive train have multiplicative effects. Therefore if the average thermal efficiency of the drive train were to be kept constant at the 1980 value of about 12 percent, the combined effect of all the other improvements in weight, aerodynamic drag and tire-rolling resistance would increase the fuel economy of the 1995 fleet based on the best current technology to only 31 m.p.g. and of the fleet based on advanced technology to only 43 m.p.g. Such numbers would not seem unreasonable in view of the fact that the lightweight (1,950 pounds test weight) 1981 Toyota Starlet, which is equipped with a conventional engine, already achieves 39 m.p.g. on the EPA city cycle and 54 on the highway cycle, or 44 m.p.g. on the composite cycle we have adopted for our projections.

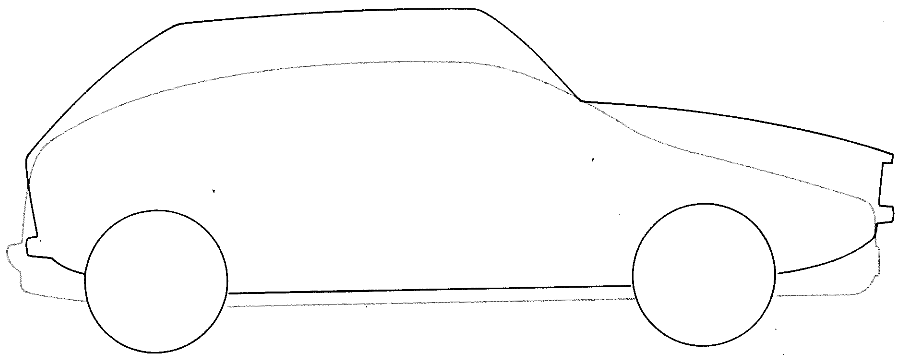
Alternatively, if the average test weight (3,300 pounds), aerodynamic drag and tire-rolling resistance of the 1980 fleet were held constant and the average thermal efficiency of the drive train were simply doubled from 12 to 25 percent, the average fuel economy of the fleet would rise only from 18 m.p.g. to about 37, again a number that does not seem intuitively unreasonable. It is only when the effects of decreased power requirements and increased drive-train efficiency are compounded that we arrive at the initially surprising fuel-economy projections in the range of 65 to 90 m.p.g.

The best demonstration of the validity of our projection would involve a prototype vehicle with the features we have described. Although no publicly disclosed prototype includes all these proposed features, two recent experimental cars incorporate enough of them to validate our calculations. The first is a Volkswagen Rabbit with a turbocharged diesel engine built in 1976 for the U.S. Department of Transportation. The vehicle, which has a test weight of 2,400 pounds, achieved a composite fuel-economy score of 60 miles per gallon of diesel fuel. Since diesel fuel holds 10 percent more energy per gallon than gasoline, the prototype's 60 m.p.g. is equivalent to 54 m.p.g. for a gasoline-fueled vehicle.

The second prototype is a more recent experimental vehicle for four passengers also built by Volkswagen. Powered by a direct-injection diesel, the vehicle has reportedly achieved a gasoline-equivalent composite city-highway fuel economy of about 70 m.p.g. If the report is correct, the prototype has already equaled the fuel economy we have projected for a hypothetical four-passenger car to be marketed in 1995 and has done so without either a continuously variable transmission or a low-drag body. The prototype also lacks a fuel-saving feature that we have not included in our projected fleet but that is in the advanced development stage: a flywheel that can be disengaged from the engine. This makes it possible to have the engine stop automatically when the vehicle is stopped or decelerating and then restart automatically and instantly with the energy stored in the flywheel when the accelerator is pressed again.

In our projections we have not ignored the fact, well known to many buyers of recent-model cars, that the EPA testing procedure yields estimates of composite city-highway fuel economy considerably higher (by 15 to 20 percent) than most cars have actually delivered on the road. Fortunately for the purposes of this discussion, however, the vehicles whose characteristics come closest to those we have been describing, namely front-wheel-drive diesel-powered vehicles, achieve on-the-road fuel economies that are much closer to the EPA ratings than vehicles of conventional design.

So much for the technological potential. The discussion cannot, however, end here. Before the nation can select a fuel-economy goal it must understand the relation between fuel economy on the one hand and safety, clean



COEFFICIENT OF AERODYNAMIC DRAG of the Volkswagen Rabbit (*black silhouette*) is about .4, somewhat below the average of about .5 for current American light vehicles. The coefficient for a perpendicular flat plate is 1.17. Color outline shows the profile of a new Volkswagen prototype that offers more interior space than the Rabbit but has a drag of only .3.

air and cost on the other. We shall therefore explore these issues briefly.

A frequently expressed concern is that passengers in smaller, lighter vehicles are exposed to greater risk of serious injury or death in an accident. Statistics collected for the National Highway Traffic Safety Administration in the mid-1970's show that this is indeed the case. The risk of serious injury or death in an accident increased with decreasing vehicle weight. At the extreme, occupants of the lightest cars were at almost exactly twice the risk of those in the heaviest cars. The study also showed that use of seat belts reduced the risk in all vehicles by more than half. As a result occupants of the lightest cars who fastened their seat belts were at lower risk than those in the heaviest cars who forfeited such protection. (Today Americans fasten their seat belts only about 10 percent of the time.)

The increased injury risk in light cars is partly offset by the statistical fact that mile for mile the drivers of subcompact cars appear to have between 10 and 30 percent fewer accidents than the drivers of larger cars. Moreover, one of the major sources of the increased hazard associated with driving small cars, namely collisions with heavy cars, is steadily being reduced as large cars get lighter. The shift toward lighter cars nonetheless makes it imperative that automobile makers improve the crashworthiness of their products at the same time that they redesign them for better fuel economy.

Currently new passenger cars sold in the U.S. are expected to be able to meet the 30-mile-per-hour crash-test standard for all models planned through 1985. Work done by the National Highway Traffic Safety Administration has indicated, however, that there is still much room for improvement in the crashworthiness of light four-passenger cars. The safety of lightweight two-seat city cars may present a special challenge, one that is only partly diminished by the fact that such cars are meant to be driven predominantly in city traffic, where the average vehicle speed is only about 30 m.p.h. We would urge that an international cooperative program be undertaken to demonstrate safe designs for such vehicles.

A second area of major concern in redesigning the automobile for high fuel economy is air pollution, particularly from the increasingly popular diesel engine. Diesel emissions are high in two troublesome pollutants: nitrogen oxides (which contribute to respiratory ailments and to the formation of smog and acid rain) and small particulates that lodge deep in the lungs and carry chemicals that are known to be mutagenic and may prove to be carcinogenic. For equal power output current diesel engines emit more of these two pollutants than gasoline engines.

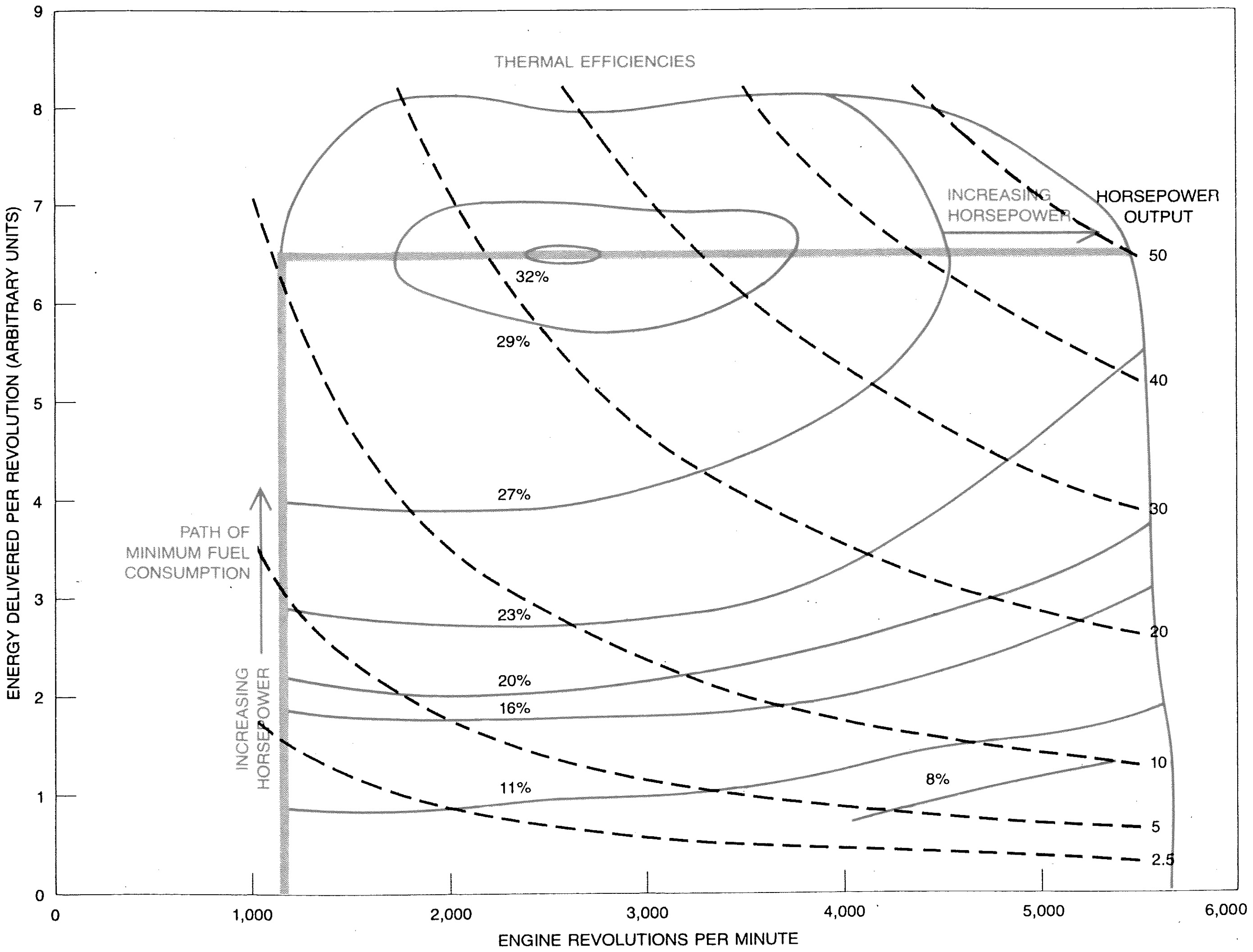
It appears that by 1983 cars powered by prechamber diesel engines, particularly in the smaller sizes, will be able to meet the Federal limit on nitrogen oxide emissions (one gram per mile) that has been applied to gasoline-powered vehicles starting in the current model year. It is expected, but it is less certain, that the more efficient direct-injection diesels will eventually be able to meet the same standards.

As for the particulate emissions, it seems probable that small diesel engines will be able to meet the limit of .2 gram per mile the EPA has established for 1985 vehicles. Even if they do, an emission of .2 gram per mile will be about 20 times higher than the quantity of particulates emitted by a comparable gasoline-fueled vehicle. The consequences for human health of the mutagenic material carried by diesel particulates remains an unresolved issue. A rising fraction of diesel-powered cars in American cities, however, will add to the quantity of diesel fumes that most people find objectionable and will generally reduce visibility in these areas. Although the pollution problems of the diesel may not be insuperable, they should motivate a continuing search for efficient automotive power plants that are inherently cleaner.

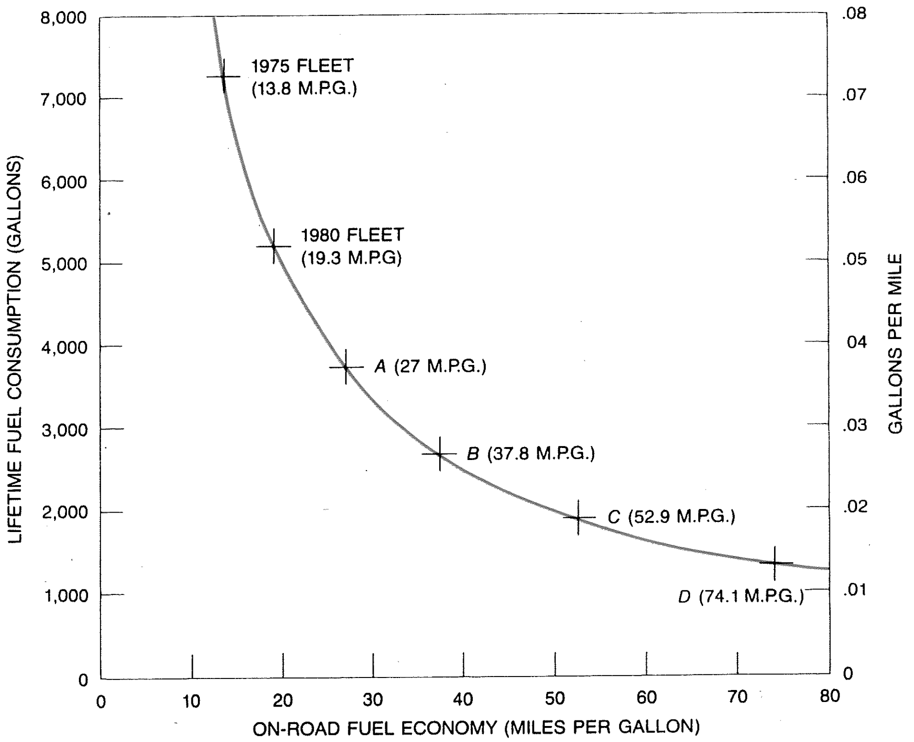
It is worth noting in this connection that there is one variant of the gasoline-fueled engine that is both efficient and relatively clean and would not require a major break with traditional automotive technology. This is the direct-injection stratified-charge engine. The distinctive feature of such engines is that the charge, or fuel-air mixture, in their combustion chambers is stratified, or made inhomogeneous, at the instant combustion is initiated. As a result the formation of nitrogen oxides is sharply suppressed. The stratification also makes it possible to burn fuel-air mixtures so lean in fuel that they would not burn if the fuel were uniformly mixed with the air. As a result direct-injection stratified-charge engines have efficiency advantages comparable to those of the diesel.

Stratified-charge engines are also capable of burning fuels other than gasoline, of which perhaps the most important is methanol. Because methanol can be produced both from coal and from plant material it is a promising liquid fuel for the postpetroleum era. A fully optimized methanol-fueled engine could combine extremely low emission of pollutants with high thermal efficiency (probably higher, in fact, than that of a comparable diesel engine). It is our own hope that the technology of methanol-fueled engines will be vigorously pursued.

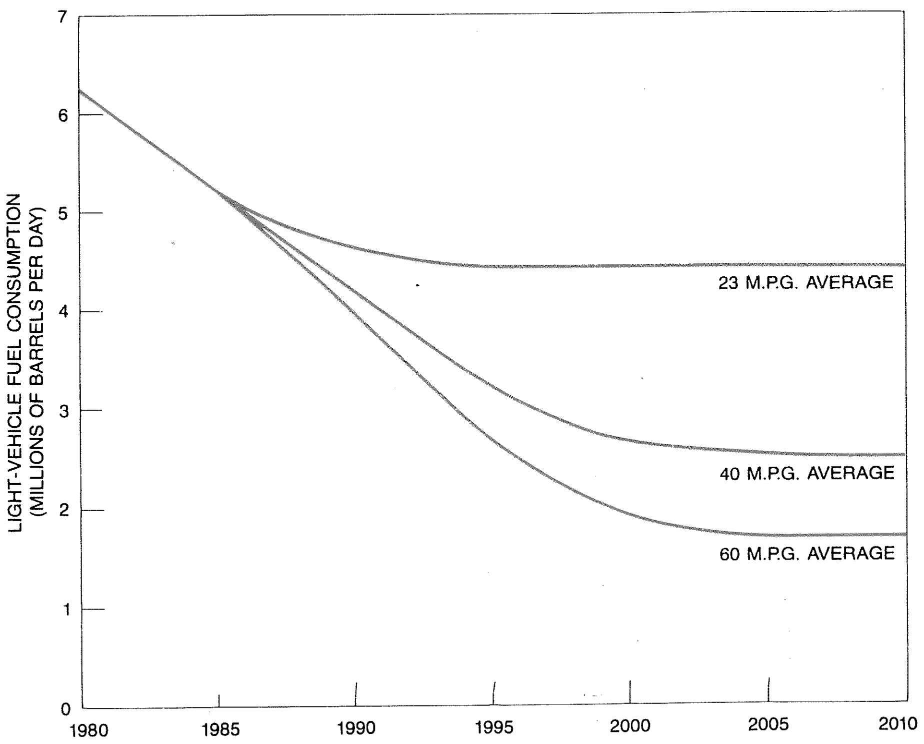
Another possible alternative to today's internal-combustion engines is the battery-driven electric motor. Because of the limitations of present storage batteries electric cars are now primarily of interest for short trips. Today the driv-



EFFICIENCY "MAP" FOR DIESEL ENGINE in a Volkswagen Rabbit relates revolutions per minute (r.p.m.), energy delivered per revolution, power output and thermal efficiency (*contour lines in color*). Power output is proportional to the product of energy delivered per revolution times r.p.m., so that the contours of constant power output are hyperbolas (*black broken lines*). In a car with a continuously variable transmission a microprocessor could select for any power output the point along one of the hyperbolas where the engine is most efficient. Broad line in color is the locus of points of maximum efficiency. Below 10 horsepower a constant 1,000 r.p.m. is best.



SETTING A FUEL-ECONOMY GOAL for the 1990's involves recognition of diminishing returns; equal percentage increments in fuel economy save progressively less fuel. The 40 percent increase in on-the-road fuel economy from 13.8 m.p.g. in 1975 to 19.3 m.p.g. in 1980 represents a saving of 2,000 gallons over the typical life of a car (100,000 miles). Another improvement of 40 percent to 27 m.p.g. (*A*) will save an additional 1,500 gallons. Still further improvements of 40 percent to 37.8 m.p.g. (*B*), 52.9 m.p.g. (*C*) and 74.1 m.p.g. (*D*) would yield progressively smaller savings: respectively about 1,100, 750 and 550 gallons. The authors nonetheless believe the cost of improvements can be justified until the average fuel economy is at least 60 m.p.g.



POTENTIAL FUEL SAVINGS are projected for three hypothetical fuel-economy targets for light vehicles reaching the market in the 1995 model year. The Federal Government has already set a target of 27.5 m.p.g. for 1985 cars as measured by the EPA composite city-highway driving cycle. Because of the recent increased demand for fuel-efficient vehicles this goal will probably be exceeded by several m.p.g. Actual on-the-road fuel economy of the 1985 light-vehicle fleet will probably average only about 23 m.p.g. Top curve shows the projected fuel consumption to the year 2010 for a constant yearly number of vehicle miles if no further improvements in fuel economy are mandated or achieved. Middle and bottom curves depict fuel consumption if on-the-road fuel economy climbs to 40 and 60 m.p.g. between 1985 and 1995.

ing of electric vehicles has the effect of conserving petroleum and natural gas because only about a fourth of the nation's electricity is generated from these premium fuels. In developing an automotive strategy for the postpetroleum era, however, one will want to compare the overall cost of converting coal or plant material into methanol for internal-combustion engines with the cost of converting the same materials into electricity for charging the batteries of electric vehicles. With current technology it appears that the methanol route would be the more efficient utilization of the primary fuel.

Let us now address the matter of cost. How large an expenditure on development and retooling is justified in order to achieve a particular level of fuel economy? Here the principle of diminishing returns enters in. One can draw a simple curve relating fuel economy, in miles per gallon, to the consumption of fuel over the typical automobile lifetime of 100,000 miles [*see top illustration on preceding page*]. Such a curve shows that increasing the fuel economy of a 15-m.p.g. vehicle by 10 percent to 16.5 will save 600 gallons of fuel over the vehicle's lifetime whereas increasing the fuel economy of a 70-m.p.g. vehicle by 10 percent to 77 will save only 130 gallons.

Strictly speaking, the difference between the purchase price of the 77-m.p.g. vehicle (for example) and that of the 70-m.p.g. vehicle should not exceed the value of the 130 gallons of fuel saved. At some point, defined in the short run by the importance to international stability of reducing U.S. oil imports and perhaps in the long run by the cost of alternative nonpetroleum-based fuels, the cost of the saved energy will become so high that it will no longer be cost-effective to invest in further fuel-economy improvements.

Many cost-benefit analyses have been made, and there seems to be fairly general agreement that the value of fuel savings will exceed their cost at least until the industry is tooled up to build vehicles with a fleet average of 40 m.p.g. The analysts have not yet reached a consensus, however, on the economic value of going much beyond 40 m.p.g. Our own belief is that most cost-benefit analyses tend to overstate the cost of making fuel-economy improvements because they do not adequately take into account synergistic effects such as those between the reduction of the power needed at the wheels and the consequent reduction in the size of the engine needed. We have calculated that as a result of such effects the cost to new-car buyers of each additional fuel-economy improvement should be less than $1 per gallon of fuel saved until average fuel economies in the range of about 60 m.p.g. have been achieved.

This does not necessarily mean, however, that Americans will be adequately motivated by rising fuel costs to buy the kinds of fuel-efficient vehicles we have described. For example, the difference in fuel consumption between a 40-m.p.g. car and a 60-m.p.g. one is .0083 gallon per mile, which even for fuel costing $2 per gallon amounts to a saving of only 1.6 cents per mile (compared with the total cost of about 25 cents per mile to own and operate one of today's light vehicles). Even if the 60-m.p.g. car cost no more than the 40-m.p.g. one, it is easy to imagine that a new-car buyer would be willing to forgo such a small saving (about $170 per year) for the pleasures of having, for example, a much more powerful engine. If the 60-m.p.g. car cost a few hundred dollars more, the temptation would be greater still, even though the fuel savings would pay back the extra cost in about two years. This, of course, is what has happened historically. Even in Europe, where in the mid-1970's gasoline prices were already close to $2 per gallon in 1980 dollars, average passenger-car fuel economy did not exceed 25 m.p.g.

The automobile industry for its part should not be expected to move to the production and promotion of more fuel-efficient vehicles unless the "invisible hand" of the market forces it to. Although ultimately it may not cost any more to produce a light, fuel-efficient vehicle than it does a heavy, powerful fuel waster, retooling to manufacture a new generation of cars will cost tens of billions of dollars beyond routine refurbishing costs. It is not surprising that the U.S. automobile industry, which is already having financial problems as it retools to turn out a fleet of 20-to-30-m.p.g. passenger cars for the mid- to late 1980's, is reluctant even to consider another round of such investments any time soon. Indeed, the report by former Secretary of Transportation Goldschmidt suggests that if there were "any demand for a radically higher efficiency in the North American fleet, be it induced by market or nonmarket forces [in this period], and if the climate for investment has not improved, the attractiveness of overseas production will increase dramatically."

FACTOR	APPROXIMATE VALUES IN U.S. FOR 1980 MODEL YEAR		PROJECTED FEASIBLE AVERAGE BY 1995	
	AVERAGE	BEST	CURRENT BEST TECHNOLOGY	ADVANCED TECHNOLOGY
TEST WEIGHT (POUNDS)				
2-PASSENGER	2,900	2,250	1,500	1,050
4-PASSENGER	2,700	2,000	2,000	1,400
5/6-PASSENGER	3,700	2,500	2,500	1,750
LIGHT TRUCKS	4,200 (ALL)	2,500	2,500 (PERSONAL)	1,750 (PERSONAL)
FRONTAL AREA (SQUARE METERS)	2.0	1.8	1.8	1.8
AERODYNAMIC-DRAG COEFFICIENT	0.5	0.4	0.4	0.3
TIRE-ROLLING RESISTANCE (POUNDS RESISTIVE FORCE PER 1,000 POUNDS WEIGHT)	14	10	8	7
TRANSMISSIONS	3-SPEED	5-SPEED	CONTINUOUSLY VARIABLE	
AVERAGE DRIVE-TRAIN THERMAL EFFICIENCY (PERCENT)	12	20	25	25

ATTRIBUTES OF 1995 VEHICLES have been projected by the authors on the basis of the current best technology and of advanced technology that might reasonably become available. The "average" and "best" values for vehicles built in the 1980 model year are shown for comparison. The main difference between the two projections for 1995 is in weight and aerodynamic drag: vehicles incorporating advanced technology could have curb weight and aerodynamic drag reduced by about a third. This would yield a large gain in fuel economy.

VEHICLE CLASS	FRONTAL AREA (SQUARE METERS)		ENGINE SIZE (HORSEPOWER)		FUEL ECONOMY (MILES PER GALLON GASOLINE EQUIVALENT)	
	CURRENT BEST TECHNOLOGY	ADVANCED TECHNOLOGY	CURRENT BEST TECHNOLOGY	ADVANCED TECHNOLOGY	CURRENT BEST TECHNOLOGY	ADVANCED TECHNOLOGY
2-PASSENGER	1.7	1.6	25	18	81	113
4-PASSENGER	1.7	1.7	31	23	70	96
5/6 PASSENGER AND PERSONAL LIGHT TRUCKS	2.0	1.9	38	28	58	82

FUEL-ECONOMY ESTIMATES have been calculated by the authors for hypothetical 1995 vehicles with continuously variable transmissions and advanced diesel engines. The body and tires incorporate either the current best technology or advanced technology. The lower weight of advanced-technology vehicles allows a reduction of 27 percent in engine size. Because of reduced weight and improved aerodynamics and tires, advanced-technology vehicles are 40 percent more fuel-efficient than those built with the current best technology. Fuel-economy estimates are adjusted downward by 10 percent because diesel fuel holds 10 percent more energy per gallon than gasoline.

Unfortunately it takes some 15 years to replace substantially all the cars on the road with a new fleet: five years to retool and 10 years to replace the existing fleet. If it is in the national interest of the U.S. to reduce its dependence on imported oil, and if it is recognized that a drastic improvement in the fuel economy of the national automobile fleet is crucial to achieving that goal, then the task is too important to leave to unpredictable market forces alone. We believe, therefore, that it is necessary for the Government to set before the industry long-term goals for improving automobile fuel economy in the post-1985 period.

We believe the Government should also assure the automobile industry that market forces will support the mandated fuel-economy improvements that are desired by committing itself to two measures. First, it should establish a corporate average "gas guzzler" tax, which would specify that when the average fuel economy of the fleet of cars manufactured by a company falls below the established goal, the company will be obliged to pay a tax proportional to the shortfall and to the number of cars it produced. The threat of such a tax would ultimately be reflected in the form of higher prices (to cover the tax) for the least fuel-efficient models. (In other words, the company could cater to a small number of consumers with expensive tastes if it could find them.) Second, the Government should impose a stiff tax on motor-vehicle fuel, following the example of virtually all other petroleum-importing nations. If he is given adequate notice, the average consumer could easily offset both these taxes by buying the most fuel-efficient vehicle consistent with his needs. We would hope that the current antiregulatory mood in Washington would not be allowed to stand in the way of establishing an assured market for a new generation of highly fuel-efficient vehicles.

In order to indicate the potential savings in fuel that are at stake, we shall describe three projections based on three different fuel-economy goals for the fleet of cars that will reach the market in 1995. In each case we assume for the sake of simplicity a constant population of 150 million passenger cars and light trucks that are driven an average of 10,000 miles a year, weighted so that the newer vehicles are driven more than that and the older vehicles less. We consider three possibilities: the average on-the-road fuel economy for new light vehicles stays at the 1985 level of 23 m.p.g. projected by the Department of Energy, it increases to 40 m.p.g. or it increases to 60 m.p.g. between 1985 and 1995 and then levels off.

According to the first scenario, the consumption of fuel by the 150 million cars and light trucks continues to decline beyond 1985 as older, less efficient vehicles are retired, finally leveling off at 85 percent of the 1985 demand, or about 4.4 million barrels per day. According to the second scenario, the consumption of fuel by the year 2005 falls to half of the 1985 demand, or to about 2.5 million barrels per day. And according to the third projection, the consumption in 2005 falls to about 1.7 million barrels per day. The difference between the first scenario and the second would be equivalent to more than the capacity of the Alaska pipeline. Unlike the flow of oil from Alaska or anywhere else, of course, the "flow" of saved fuel could continue indefinitely. If the U.S. light-vehicle population increases much beyond 150 million or if the average number of miles driven per vehicle year increases significantly, these projected figures would be modified accordingly.

Given the prospect that the U.S. supply of domestic petroleum will probably shrink considerably below the present level of 10 million barrels per day in the 1980's and that supplementing the declining supply with synthetics will be extremely costly, we believe the first scenario, which projects an ultimate reduction in light-vehicle fuel consumption of only 1.5 million barrels per day below the current level, makes for a dangerous national policy. We would argue that it is essential to set much more ambitious fuel-economy goals than those currently mandated (27.5 m.p.g. by the EPA's composite fuel-economy test) for the years beyond 1985, rising as rapidly as feasible to a level in the neighborhood of 60 m.p.g. As part and parcel of the higher goals it would be in the national interest to make certain that the domestic automobile industry is not prevented from achieving the desired targets by lack of capital. Over at least the next two decades the flow of saved oil that could be "produced" by the automobile industry is no less great than the flow of liquid fuel that is likely to be produced by the still unborn U.S. synthetic-fuels industry. Not only the capital costs would be less; so too would be the environmental costs. Finally, taking leadership in the international fuel-economy race may be just the prescription needed to revitalize the U.S. automobile industry.