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 difficult transition might be understood 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 post-oil economy depends on a much more concerted 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 biggest consumer of its products - the automobile.

The automobile has given Americans an unprecedented degree of personal mobility. Today there are about 100 million passenger cars and 30 million light trucks (mostly privately owned) and some 30 million buses and vans registered in the U.S., nearly one for every adult. In 1980 this vast fleet of vehicles consumed about 654 billion barrels of petroleum products per year, the approximate equivalent of all U.S. imports or about 60 percent of the nation's total production.

A few years ago such facts would have seemed only mildly interesting. In 1973, before the Arab embargo, there had been no gasoline shortages, and the cost of petroleum imports was only $3.8 billion. By 1980 the price of oil was rising, and the cost of importing even more oil had escalated to $54 billion, and the dependency on foreign, mostly Persian Gulf, imports had reached 43 percent. It is not surprising that the 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 indispensable 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 rate of change in consumer preferences toward smaller and more fuel-efficient vehicles. In 1979 the U.S. automobile industry sold more than 44 million cars and trucks, and foreign car manufacturers captured more than 25 percent of the U.S. market. By the end of 1980 the market, according to Secretary Goldschmidt's report, 190,000 automo

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The General Motors Corporation has announced that it expects its 1985 model-year fleet to achieve an average fuel economy of 31 miles per gallon 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 mpg for passenger cars, 18 mpg for light trucks and 23 mpg overall.

The Department of Energy projects that, assuming these average efficiencies are achieved, the U.S. will still be consuming a substantial amount of fuel. It is estimated that 6 million passenger cars and 1.7 million light trucks will be driven by 1985. Even if the fuel consumption of the American light vehicle fleet were to decrease, there would be little more than a 5 percent reduction in the amount of oil used. The environmental impact would also be minimal. Average fuel economies of more than 60 mpg 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 driveline systems (the mechanisms for delivering the power plant's output to the wheels). Such changes could be introduced piecemeal today as carmakers begin to respond to the new market for more fuel-efficient light vehicles, but the full potential of the possible changes acting synergistically, rather than with two or more at a time, remains to be widely appreciated.

We shall therefore describe a hypothetical fleet of 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 cars 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 transmission and the peak power of the engines being optimized for fuel economy. All this 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 or five members could travel long distances and when few house

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 mpg. By mandate of Congress the fleet of cars sold in the United States would have to exceed an average of 27.5 mpg, as measured by a method determined by the Environmental Protection Agency (EPA). This figure was set by Congress and is the average fuel economy of the 1985 model year (as determined by the same testing method). The same test was also used to set a fuel economy standard for light trucks at the "maximum feasible level." The departments determined that in view of the current financial problems of the industry it could set this level no higher than 21 mpg in 1985. It appears now that as a result of the new consumer demand for fuel economical cars the industry will exceed the 1985 passenger-car standard of 1990 mpg, and the General Motors Corporation has announced two policies whose speeds can be changed continuously by changing the effective radii of the pulleys. A cone sliding along the outer rim of one pulley on the axis of the other pulley allows the belt to slip to a smaller radius.

Continuously Variable Transmissions will improve fuel economy by enabling the engine to run at the most efficient speed for a given driving condition. The General Motors Corporation has announced
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 a market before it is evident. But what complex social factors enter into, but assuming that periodic gasoline shortages and price increases will 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 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 Volare 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 evolution away 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 one-cent reduction in fuel costs. This is several times the penalty in manufacturing energy resulting from the substitution of lightweight materials. Let us now turn to a specific hypothesis.
Four passenger lightweight vehicles whose aerodynamic drag and rolling resistance are reduced significantly below those of today's vehicles. Consider first the engine. The efficiency of an automotive 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 requirement of an automotive engine is high, which is not necessarily appropriate to today's vehicles. Consider a few models that meet the current fuel efficiency requirements that reflect the importance of fuel efficiency. We assume that light vehicles might accelerate to 60 mph in about 10 seconds, it is difficult to numerically evaluate the number of models that are currently popular. We assume also that the cars must be able to travel at a speed of 35 mph while climbing a 5 percent grade. (Only 3 percent of today's cars have such grades.) The car must also have extra power for accessories such as air conditioning, that can use up to 50 percent of the engine's capacity. To achieve this, we might have to weigh our cars extra power, enough to tow a trailer (towing 1 ton), and to lift the first 2,000 tons to 5,000 tons. We now consider the implications of these performance requirements for the engines of our hypothetical vehic- le, which will have a "test weight" (the curb weight plus 300 pounds representing the fuel quantity). For two engines, we might represent 2,200 pounds. This weight is comparable to the weight of 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 is for current cars (two square meters, or 215 square feet), the coefficient of aerodynamic drag will be at the lower end of today's range: 0.4. (Aerodynamic drag is a relative measure of the air resistance of a body with respect to that of ordinary objects with the same frontal area.) A straight line represents a coefficient of drag of 0.17. A value of 0.4 is considerably higher than what has been achieved with aerodynamically shaped but still "prac- tical" prototype cars. The tire-reeling re- sistance of the hypothetical vehicle is equivalent to 1 percent of the downward pull of gravity. This is also at the low end of today's range. Proportionate to high-pressure tires exist, however, that have valves of rolling resistance, 20 percent lower than those of any com- mercial tires available today.

In order to arrive at the engine's peak power needed for the hypothetical vehi- cule it is necessary to consider the effi- ciency of the transmission that delivers power to the wheels. This is a complex technical area. In today's cars the number of transmissions usually provides for a selection of two or three different gear ratios for the engine, with an additional gear for given road speed. As a result in the range of 50 to 100 mph, a manual transmission the average engine power output is usually limited to about 35 percent of peak output. The current inability to harness the full peak power at all road speeds should soon be remedied with the introduction of transmissions that are con- tinuously variable. Such a transmission in combination with some simple gear- ing makes it possible to choose a continu- ous range of engine speeds. As a result, most road speeds any power output up to the full rated output of the engine can be made available. Even more im- portant for achieving fuel economy is the fact that the most efficient engine speed is achieved. With this, 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 the significant amounts of energy are expended. We shall also assume that the combined power losses in the drive train are absorbed by the engi- ne alone. We shall assume further that the vehicle is the power delivered to the transmission. The loss is about the same in one of today's passenger cars equipped with manual transmission or with one of the newer fuel-efficient automatic transmis- sions. In other words, the engine power losses of peak power demand the power that is necessary to move the vehicle through the air and the road. The efficiency of vehicle power output of the engine would be limited to 50 percent.

With these assumptions our hypothet- ical vehicle has an engine power output of about 36 horse- power at sea level at 85 percent of its peak output. For higher altitudes and engine efficiency, we might assume an additional 20 percent to 30 horsepower would be available, as they are today.

We have not mentioned potential improvements in the thermal effi- ciency of the engine, in the efficiency with which the engine con- verts fuel energy into mechanical ener- gy. Today's most efficient engine for transportation is the diesel. One of the reasons for this is the long history of some other engines in which fuel is injected directly into the cylinder is that the efficiency falls more slowly than the efficiency of "carbonated" engines, in which the fuel is burned in an air-fuel mix drawn into the cylinder. Another advantage is obtained by using a two- stroke cycle, where the engine does not have to be fed fuel when they are started cold. The equivalence of diesel engines, however, is still far from being optimized. Various compromises with fuel economy have been made to obtain engines that would oper- ate 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 inject- ed and begins to burn. The prechamber makes the fuel efficiency of automobile diesel engines between 10 and 15 per- cent lower than that of large trucks, which have direct cylinder injec- tion. Engine designers have been seek- ing to eliminate the prechamber in automotive diesels without unacceptable performance or emissions. They now appear to be quite close to doing so.

The average efficiency of automotive engines could also be increased by the adoption of turbocharging. Turbocharging is standard on large truck diesels. The turbocharger is a com- bination of a turbine and a compressor, with the compressor drawing in air and the turbine powered by the exhaust gas. When the engine is run at high speeds, the exhaust gasses can drive the turbine, which drives the compressor. The compressor raises the pressure and temperature of the incoming air, which increases the engine's efficiency. Turbocharging can make it possible to raise the peak power output of an engine given displaced 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 ordi-

U.S. GASOLINE PRICES, expressed in constant 1990 dollars, actually declined between 1965 and the winter of 1973, when the Organization of Petroleum Exporting Countries (OPEC) ini- tiated the first of a series of sharp price increases. The era of cheap oil for Americans did not recover until the mid-1980s. In the meantime, with further increases in fuel prices, auto sales began to mimic the price controls on oil and gasoline. The average combined Federal and state tax on gasoline of 44 cents per gallon in 1980 was a third lower in real terms than it had been a decade earlier.

American motors drive without anyone else in the car. 72 percent of their trips (top bar in circle) such trips account for 44 percent of all vehicle miles (top bar in pie). The percentage of trips with more than one person in the car and the corresponding percentage of vehicle miles by such trips are given by the middle bar of each figure. Eighty percent of all automobile trips are made within about 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 (below) show the sales mix for just half of 1980. Sales of four-passenger cars increased nearly 50 percent at the expense of larger cars and light trucks. The mix of rides for two-person cars has changed very little, probably because most of those that have been available have been sport cars.
train thermal efficiency. Two sets of values were projected for 1995: those attainable with the current "best" technology and those we believe could 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 car 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 achieved. At the upper end of the weight range personal light trucks that in 1980 weighed 4,200 pounds (the average) and about 4,200 pounds (the lightest) could be reduced by 1995 to an average of 2,500 pounds and perhaps as little as 1,750 pounds. The weight of live- and 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 1,350 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, 3.5 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 38 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 the driver of a large car a towing capability or alternatively would give the entire fleet an average zero to 50-m.p.h. acceleration time of 60 seconds. With advanced technology a fleet of vehicles with the performance specifications 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 of 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 51 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 (1,930 pounds test weight) 1981 Toyota Starlet, which is equipped with a carbureted 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 (1,350 pounds), aerodynamic drag and tire-rolling resistance of the 1980 fleet were held constant and the average thermal efficiency 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. Later in this paper when the effects of decreased power requirements and increased drive-train efficiency are considered we will arrive at the initially surprising fuel-economy projections in this range.

The best demonstration of the validity of our projections will involve a prototype vehicle with the features we have described. Although no publicly disclosed prototypes exist yet, other prototypes, 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 about 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-passenger cars 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 flywheel, if the drive train stops automatically when the vehicle is stopped or decelerating and then reengages instantaneously 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 are actually delivering. Fortuitously 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.

Such a select-a-fuel economy goal must understand the relation between fuel economy on the one hand and safety, clean...
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 automakers 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 United States 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 prevent 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 as it relates to 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 not 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 in weight and storage capacity, electric cars are now primarily of interest for short trips. Today the driv-
ing of electric vehicles has the effect of conserving petroleum and natural gas because, as has been pointed out, about 90 percent of the na-
tion's electricity is generated from these prime energy sources. In developing a moti-
active strategy for the postpetroleum era, however, one will want to compare the
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tional coal-conversion engines with the long run
by the cost of alternative nonpetroleum-based
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However, we believe that
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car has not yet reached a consensus, however, on the economic value of
gain beyond 25 m.p.g. Our own belief
is that most cost-benefit analyses
tend to overstate the cost of making
economy improvements because they
do not adequately take into ac-
count ancillary effects such as those
the reduction of the power needed at the wheels and the consequent
reductions in the size of the engine needed.
We have calculated that as a result of
these effects the cost per new-car buyers of
each additional fuel-economy im-
provement should be less than 1 per
cent and 1.5 percent of fuel saved until an average
in the range of about 60 m.p.g. have been
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