Improving Automotive Efficiency

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Batteries and fuel cells? Cleaner air and reduced oil imports can be won by redesigning conventional internal-combustion-powered vehicles

by John DeCicco and Marc Ross

Public concerns about health and safety, the environment and petroleum dependence create pressure to build a better car. Although congestion and accidents result from driving itself rather than from fuel use, much of urban air pollution, greenhouse gas emissions and the economic burden of oil imports can all be tied directly to fuel consumption. Automobile use continues to grow in the U.S. and worldwide. Fuel efficiency must increase at least as fast just to prevent fuel-related problems from worsening. Efficiency must improve even more rapidly to begin to solve these problems.

In September 1993 the U.S. auto industry and the Clinton administration announced a historic partnership to develop vehicles having three times the fuel economy of today's fleet while providing the same comfort, safety and performance. Prominent options include electric vehicles powered by batteries or fuel cells and hybrid vehicles combining an electric drivetrain with a combustion engine that might use a variety of fuels. While such alternatives are being studied and tested, however, gasoline and diesel cars and trucks will most likely dominate the roads for decades to come. They offer remarkable reliability, comfort and utility at an affordable cost. Moreover, they are sustained by an enormous economic infrastructure: factories, petroleum refineries, service stations and all the people, from auto workers to garage mechanics, trained to make the system work.

The vibrant state of automotive engineering also contributes to the longevity of cars powered by the internal-combustion engine. Although pioneers like Carl F. Benz and Rudolph C. K. Diesel envisioned almost all its potential refinements a century ago, only recently have many of them become practical, as new techniques liberate design and production engineers. Microprocessors, sensors and electronic controls now permit optimization of many operations; materials have become stronger, lighter and more adaptable. Computers enable designers to create and improve vehicle models rapidly. Many advances useful for refining conventional cars and light trucks are, in fact, essential for alternative vehicles. Radically different approaches may be needed in the long run, but breakthroughs are not necessary, because late 20th-century engineering capabilities can deliver substantial environmental and economic benefits over the next decade.

The effort to improve fuel efficiency begins by examining how and where a car uses energy [see "The Amateur Scientist," page 112]. Fuel use depends on the type of driving as well as on vehicle characteristics. For example, fuel economy is worse in congested streets because of more frequent starting and stopping. Engineers use the term "end-use load" to refer to any aspect of vehicle operation that consumes power provided by the engine. Loads include braking loss, tire resistance, aerodynamic drag and accessories, such as air conditioning and power steering. The energy needed to meet these loads is greatly multiplied by the need to overcome losses throughout the drivetrain. Consisting of the engine, transmission and associated components, the drivetrain converts fuel energy into useful mechanical energy that propels the car and runs its accessories. After the thermodynamics of combustion and the friction have been accounted for, only about one sixth of the energy available in gasoline remains for the end-use loads. Put another way, today's drivetrains are only 17 percent efficient in average driving.

To estimate the potential for raising fuel economy, we analyzed a set of low-

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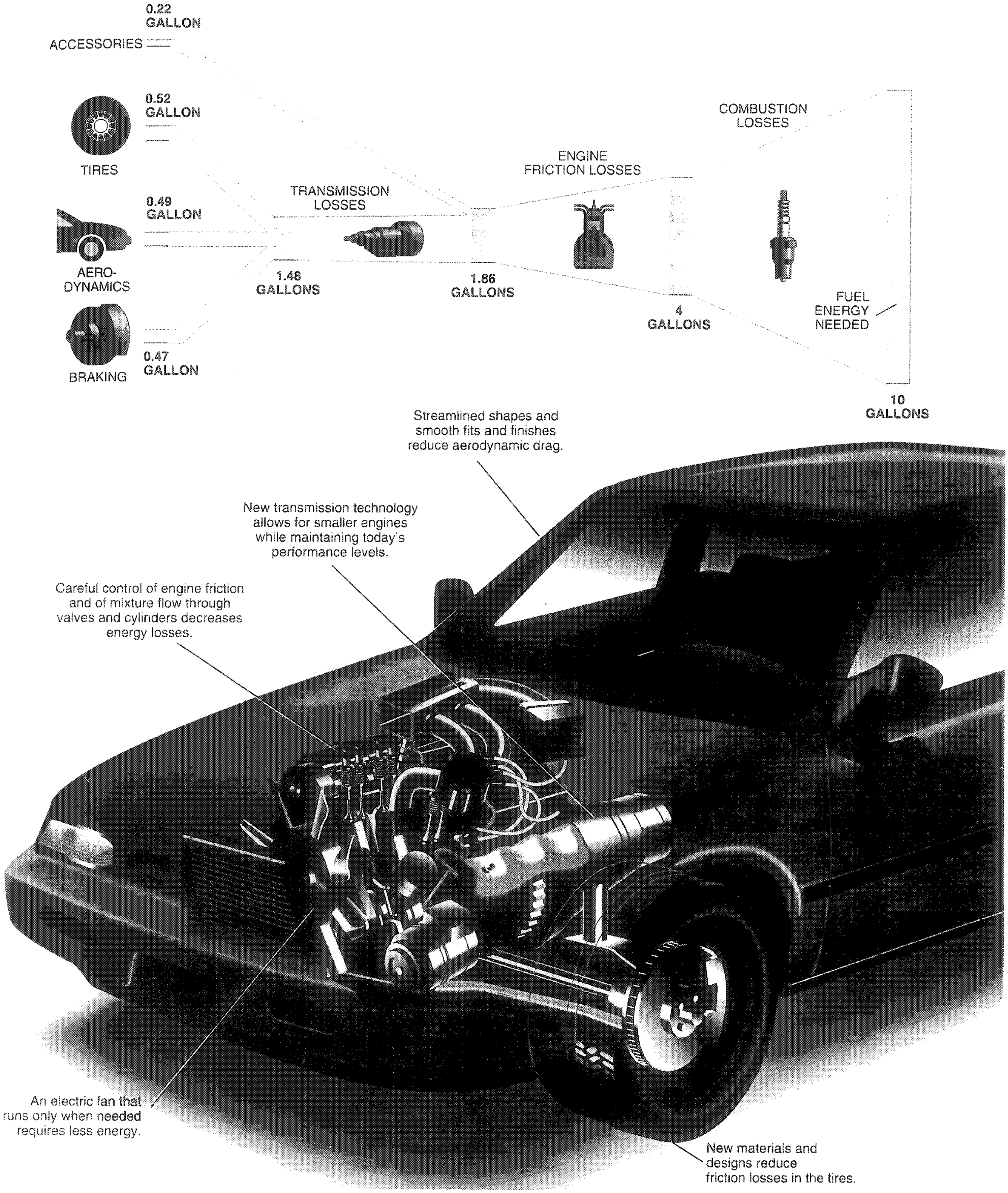
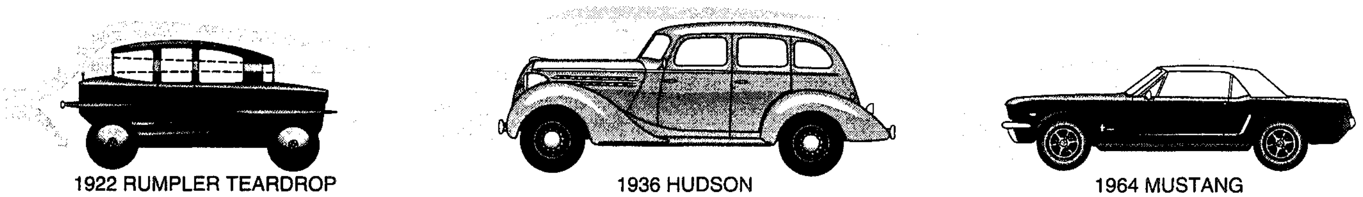


FUEL NEEDS arise in stages (*top illustration*), starting with the energy lost by tires, air drag, braking and accessories. Energy requirements are multiplied by 1.11 to overcome transmission friction and again by a factor of 2.2 to offset engine friction. Finally, combustion losses increase the energy demand by another 2.5. New materials, designs and technologies (*bottom illustration*) that minimize losses in the early stages of the multiplication process will raise fuel efficiency.


1922 RUMPLER TEARDROP

1936 HUDSON

1964 MUSTANG

STYLING IMPROVEMENTS have lowered aerodynamic drag. The Rumpler Teardrop was an early attempt at streamlining. Future designs, most likely based on ones similar to the Opel Calibra or the Impact, can lower drag by 25 percent or more.

cost design changes, most of which are found in some models already on the road. Improving the drivetrain by reducing friction offers one clear path to greater efficiency. Reducing end-use loads presents another. Even without any tinkering with the drivetrain, modifications to tires, aerodynamics and vehicle mass will trim a car's energy requirements. Each unit of energy savings achieved by lower loads yields six units of energy savings overall. Thus, load reduction is fundamental.

Cutting vehicle mass provides important leverage on efficiency because it exerts a ripple effect. A lighter vehicle requires less power, and so it can be equipped with smaller drivetrain components. Consequently, mass drops even further. The current weight of a new car with the gas tank and radiator filled but without passengers averages just under 3,000 pounds. Although downsizing is an obvious way to reduce mass, we excluded this option from our analysis. Instead we considered the use of lighter, stronger materials combined with refined design and manufacturing techniques. New materials and better use of space can reduce mass without sacrificing vehicle size and carrying capacity. We estimated the degree to which cars could be made lighter based on these approaches, adjusting for the weight added by airbags and strengthened door panels needed for safety. On balance, applying the best designs available and adopting new materials can cut as much as 25 percent from a car's weight.

Some opponents of fuel economy regulation assert that decreasing mass decreases safety. But the protective benefit of heavier automobiles comes at the expense of greater damage to people. Cars built with lightweight but strong materials can shield passengers more effectively than can many heavier vehicles of today yet pose less risk to the occupants of other cars during collision. Safety is assured largely through better restraint systems and improvements to vehicle structure and interior surfaces that minimize the crash energy transferred to people in the car. Better crashworthiness comes not from vehicle size or mass itself but from features that safeguard passengers, regardless of vehicle size.

Whether a vehicle is massive or light, drivetrain inefficiencies hurt fuel economy. The best opportunities for improving the drivetrain lie in reducing engine friction, which accounts for about one half of fuel use. In a car's motor, pistons move through the cylinders, each displacing a certain volume. Expanding gases pushing on the piston produce power. The combined volume for all the cylinders is termed engine displacement. A larger engine can deliver more power but entails greater friction.

Rubbing friction occurs among moving parts such as valves, pistons, connecting rods and the crankshaft. There are losses in ancillary parts such as the radiator fan and water pump. Pumping friction occurs when the air and fuel mixture is drawn into the cylinders and the exhaust is expelled. A particular site of pumping friction is the throttle valve that controls air intake.

Refinements in design, manufacturing technique, materials and lubrication minimize rubbing friction. Ancillary losses can be reduced through modifications such as replacing a belt-driven fan with an electric fan that runs only when needed. Pumping friction can be cut by intelligent control of intake and exhaust processes. And all these frictional losses can be lessened with a smaller engine.

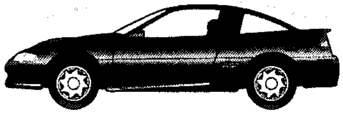
Studying how frictional work relates to engine power reveals important ways to enhance drivetrain efficiency. Power output is reduced by internal friction; it must meet the needs of the end-use loads plus the transmission. Engine friction is proportional to engine speed and displacement. Output, however, does not necessarily depend on these factors. Technologies that provide needed power while reducing average engine speed or displacement—or that even turn the engine off when power is not required—offer opportunities to cut engine friction while meeting output requirements.

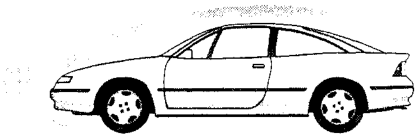
The value of many efficiency enhancements lies in their effect on specific power: the ratio of maximum power output to engine displacement. Technologies that enhance specific power permit reduced displacement while satisfying vehicle loads. Increasing the number of valves improves flow through the cylinders. For example, the specific power of four-valve engines averages 40 percent higher than that of two-valve engines. Similarly, overhead camshaft designs boost average specific power by at least 20 percent. There are trade-offs, such as increased rubbing friction with added valves. Motors with four valves per cylinder and overhead camshafts achieve peak power at high engine speeds, so that compensating changes in gearing are needed for good driveability. Successful designs take into account such considerations to yield more miles per gallon at acceptable cost.

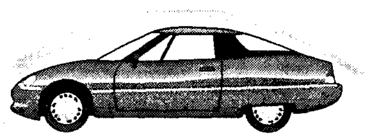
Perhaps the most profound engine refinement now being commercialized affects the control of intake and exhaust processes. Fuel ignition takes place within a motor's cylinders. Carefully manipulating the flow of the fuel mixture and exhaust products through the cylinders can boost mechanical efficiency. In conventional engines, when and how far a valve opens depends on the position of the piston, not on engine speed or load. Electronic sensing and control capabilities, together with precision manufacturing methods, have made it possible to use variable valve control. This technique optimizes cylinder flows over a broad range of conditions. Greater valve opening increases maximum power, allowing engine displacement reduction. Under low loads, reduced valve opening time can largely replace throttle operation, thereby decreasing pumping friction.

In the past, high cost limited installation of variable valve control mechanisms. Advanced design and assembly techniques now permit widespread application. Since the late 1980s Japanese automakers have increased their use of variable valve control in both Japan and the U.S. In 1992 Honda introduced a notable improvement in valve control that brought a lean-burn engine to the U.S. market.

Most contemporary gasoline motors


1992 TALON


FUTURE MODEL BASED ON 1990 OPEL CALIBRA


FUTURE MODEL BASED ON 1994 IMPACT

normally operate with precisely the amount of oxygen needed for complete combustion. Lean-burn engines run on mixtures containing excess air. Advantages include reduced pumping losses and better thermal efficiency. But the emission of nitrogen oxides (NO_x) from such engines creates a problem: catalytic reduction of NO_x compounds is difficult under lean conditions. Development of an appropriate catalyst is an active area of research, because success would lead to more general use of lean-burn technology.

Another possible refinement, the advanced two-stroke engine, is also capturing industry attention. Two-strokes accomplish compression and ignition of the fuel and air mixture in fewer strokes than do the more conventional four-stroke engines. Fewer piston strokes lead to less frictional loss. Lighter and potentially less expensive than four-strokes, two-strokes also burn lean air-fuel mixtures.

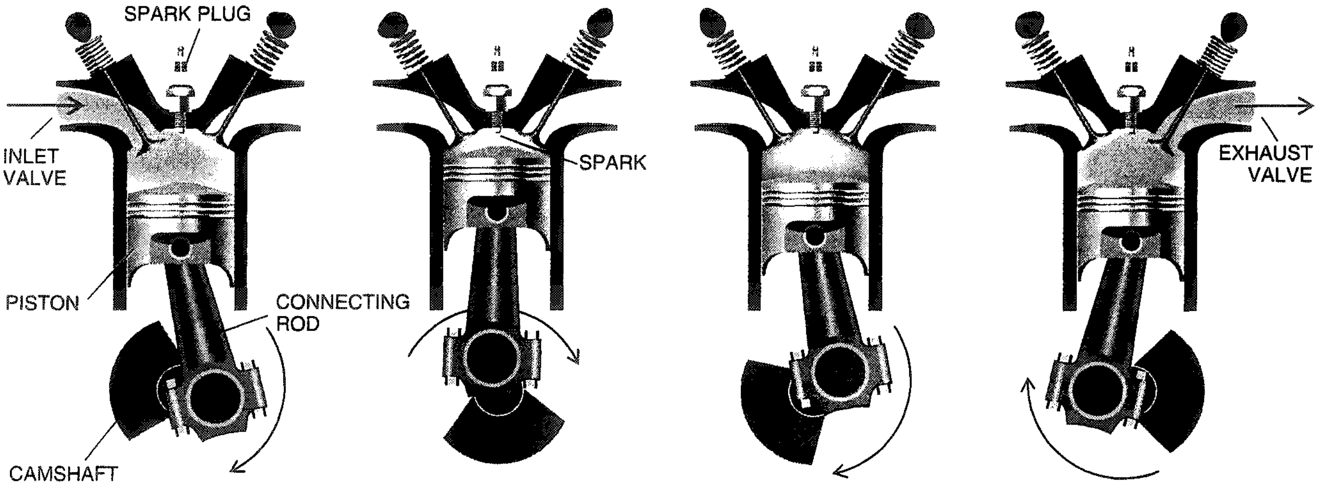
Modifications to the transmission along with the engine can bring impressive energy savings. Although a car's wheels must cover a wide range of road speeds, the engine operates most quietly and efficiently in a relatively narrow range of revolutions per minute. The transmission has a range of gear ratios to couple the motor to the wheels so that the motor can run effectively at all road speeds. To take full advantage of the benefits of engine downsizing, one must design the transmission to maximize the amount of time the motor operates at high efficiency.

Microprocessors permit engineers to program a transmission to optimally match engine speed to power requirements. Adding gears to the transmission accommodates more gear ratios, so that a narrow band of engine speeds can better cover the driving range. With a smaller engine, more frequent gear shifting will be required, and driving in traffic might feel different. Alternatively, a continuously variable transmission can replace discrete gears with a device for smoothly varying the gear ratio. In either case, careful attention to design and electronic control will help smooth shift transitions and avoid compromising driveability.

Using the 1990 new-car fleet as a base, we developed a range of estimates for the feasibility of increasing miles per gallon. The analysis examined the extent to which available technology can be applied to reach this goal. Our mid-range projections do not include lean-burn or two-stroke engines, as common use of them is less certain because of emissions constraints. After screening technologies for their cost-effectiveness, we estimate that by 2005 average new-car fuel economy can be raised by 65 percent, from 28 to 46 miles per gallon. A comparable increase can be made for light trucks, because their energy losses are similar to those of cars.

Raising gas mileage to 46 miles per gallon would add about $800 to the retail price of a car. Compared with today's new-car average of 28 miles per gallon, the higher fuel economy would save 2,100 gallons of fuel over a typical 12-year vehicle lifetime, worth $2,500 even if fuel prices do not go up. Phasing these improvements into U.S. cars and light trucks over the next 10 years would save 2.8 million barrels a day of gasoline by 2010. The yearly fuel cost savings to all consumers would be $71 billion, far exceeding the estimated $12 billion added annually for the technology refinements.

Because we import a growing fraction of our oil, the 2.8 million barrels a day of gasoline conserved imply that U.S. oil imports could be cut by at least



1
INTAKE
AIR-FUEL MIXTURE FLOWS INTO CYLINDER

2
COMPRESSION
MIXTURE IS COMPRESSED

3
POWER
MIXTURE IGNITES, AND GAS EXPANDS

4
EXHAUST
EXHAUST GASES ARE EXPELLED

FOUR-STROKE CYCLE powers most of today's cars. Advanced designs enable control of air and fuel that flow into the cylinder. Decreasing the work to pump gases in and out of the cylinder provides further opportunity to conserve energy.

two million barrels a day in 2010. These savings are much larger than the supplies that might be obtained by exploiting reserves offshore or in the Arctic National Wildlife Refuge. Moreover, such oil savings would be achieved with reduced rather than increased environmental damage.

Reduced fuel consumption brings additional environmental benefits. Carbon dioxide emissions are proportional to fuel consumption, so higher fuel economy means lower greenhouse gas emissions. The amount of hydrocarbon vapors released into the air is also tied to gasoline use, so increased efficiency reduces their impact as well. Hydrocarbons react with nitrogen oxides to form ground-level ozone, a major air pollutant that aggravates asthma and causes other respiratory problems. Because higher efficiency pays for itself through fuel savings, there is no added cost for the associated reductions in carbon dioxide and hydrocarbon releases.

Better emissions-control technology, apart from advances in fuel economy, can lead to further large reductions in air pollution. Extensive industry and regulatory efforts are under way in this area. Unfortunately, progress has been much slower than expected because of a lack of real-world data analysis. We would be more optimistic if pollution-control efforts were more solidly based on fundamental science and well-designed observations.

Higher fuel economy for cars and trucks yields broad economic benefits as well. Money spent on oil imports is mostly lost to the U.S. economy, and gasoline purchases provide relatively few jobs per dollar spent. Because enhanced fuel economy produces savings for consumers, they have more money to spend on goods and services other than gasoline. That stimulates domestic industries, including auto production, resulting in employment gains. During congressional deliberations, U.S. auto manufacturers claimed that raising mileage standards would lead to employment loss. Although that might be conceivable if higher fuel economy were obtained by rapidly mandating smaller vehicles, it is not true for a phased-in, technology-based approach. For a scenario similar to that described here, our economic modeling shows a net increase of 100,000 to 250,000 U.S. jobs by 2010.

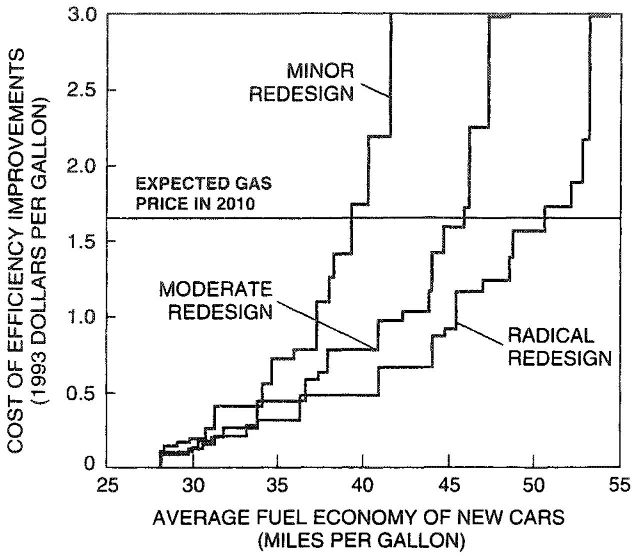
Most of the technologies we have considered appear in cars already on the road. Although higher fuel economy is clearly cost-effective in the long run, there is little market interest in applying better technologies for cutting energy consumption. Gasoline prices are at an all-time low. So manufacturers instead concentrate on applying engineering advances to enhance vehicle performance or luxury, through increased size and weight, rather than to provide better mileage. High-performance and luxury models dominate the more profitable segments of the market. Among the models offered for sale in a given year, the more fuel-efficient ones tend to be the smaller, slower, bottom-of-the-line vehicles.

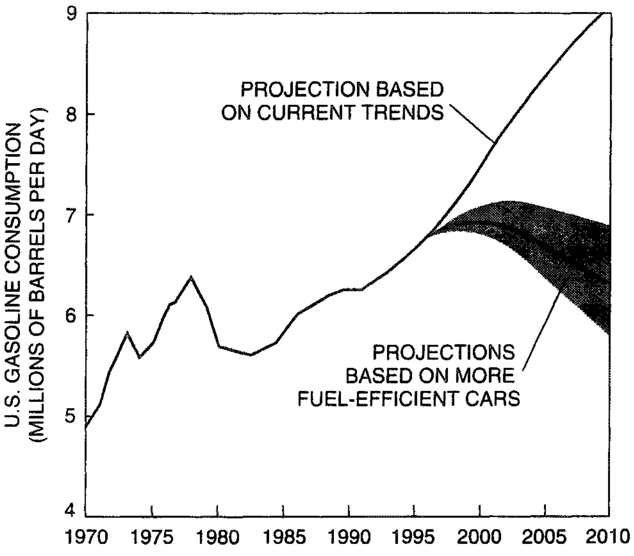
More fuel-efficient cars and trucks would sell well under different conditions, which could be brought about by such factors as national policies (fuel economy regulation, vehicle-pricing incentives or dramatically higher fuel taxes) or international events (wars or cartel decisions to limit the oil supply). The widespread benefits of reducing gasoline consumption justify public policies designed to put more efficient vehicles on the road.

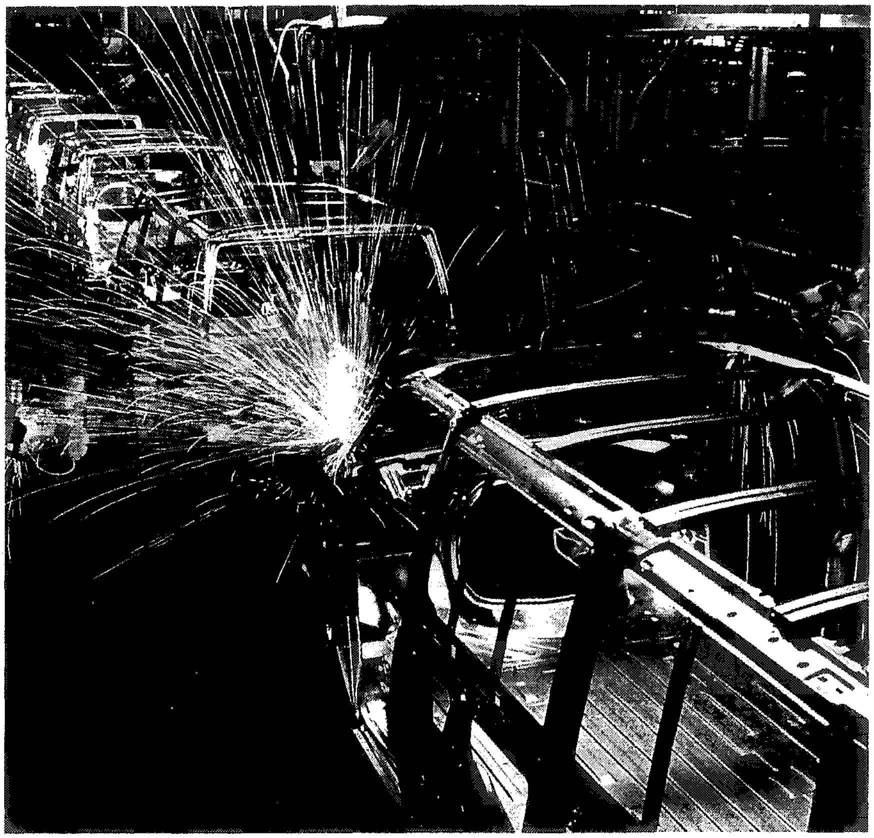
The Cost of Improving Fuel Economy

Estimating the cost of higher fuel economy is difficult because information on manufacturing is not generally made public. The authors developed an economic model using published reports that examined prices of available and useful technology. Assessing how extensively each potential refinement could be used in new cars and light trucks, the researchers ranked the technologies according to their costs as amortized over the average vehicle lifetime of 12 years. Although this treatment does not apply to any particular car, it provides a reasonable idea of the average expense of improving cars in general. The mid-range, or moderate, cost-effective level of 46 miles per gallon (*left*) was estimated by determining the curve's intersection with expected gas prices in 2010.

Without a change in U.S. policy, auto fuel use is forecasted to rise along the projection shown in the graph at the right (*light brown*). The shaded band predicts gas use if the technologies for increased fuel economy are phased in over the next 10 years. The moderate estimate (*dark brown*) corresponds to 46 miles per gallon.







AUTOMATED WELDING SYSTEMS are crucial to the assembly of vehicle bodies. Innovations in the manufacturing process, such as use of laser welding that leaves joints smooth, will help raise energy efficiency of new models.

Consumers and automakers both face a dilemma when it comes to increasing mileage. In today's market, individual customers have little interest in forgoing better performance or luxury for higher fuel economy because their direct fuel savings are not compelling. As concerned citizens, however, many want to see energy and environmental problems solved. Approaches in which everyone participates, rather than those that rely only on the choices of individual new-car buyers, can effectively respond to public concerns despite market disinterest.

Similarly, a manufacturer that applies engineering advances to increase mileage might risk losing customers, whereas another that uses the same refinements to boost performance would probably fare better in today's market. Regulations that give all automakers an incentive to raise fuel economy can overcome the risk faced by an individual manufacturer acting alone. Strengthening the fleet-average fuel economy standards would give such an incentive while also offering design flexibility. The industry can use different approaches for each vehicle line and ensure that the overall goal of reducing fuel consumption is met.

To enhance market interest, standards can be usefully complemented by special incentives, such as an expanded gas-guzzler tax and rebates on vehicles that are more efficient than average. Standards and incentives must apply equitably to manufacturers, so that all face similar pressures to increase fuel economy. The risk to any one firm would then be minimized.

Some economists point out adverse side effects of fuel economy regulation. Higher efficiency lowers the cost of driving, so people drive more and partly offset the savings. Some therefore conclude that raising gasoline taxes is a preferred approach for reducing gasoline consumption. Empirical evidence indicates, however, that such effects only fractionally offset the benefits of regulation. The price of gasoline affects the amount of driving far less than might be expected. Parking prices—or lack thereof—and road building have much more influence. Thus, a higher gasoline tax can be helpful and may be justified for a number of reasons (current taxes do not even fully cover highway costs), but taxation alone is a weak lever for controlling fuel consumption.

The time may come when conventional gasoline cars and light trucks will have to be replaced by fundamentally new designs. This eventuality justifies research and development efforts today. But more efficient conventional vehicles offer—sooner rather than later—large, tangible benefits. Many of these advancements, especially load-reduction measures, are essential steps on the way to the next generation of vehicles that will use electric drivetrains and fuel cells.

The average mileage of new light vehicles has been stagnant for a dozen years. Lack of market interest, not lack of technology, is the most serious obstacle to tackling automotive fuel use. Enacting stronger standards and other incentives for higher fuel economy calls for public policy leadership. Compared with today's new cars, refined autos would be the same size, with the same carrying capacity and acceleration ability; they would be lighter, more aerodynamic and have greater crashworthiness. They would also have lower emissions and better mileage. The benefits—direct consumer savings, lower oil imports, reduced hydrocarbon and greenhouse gas emissions and higher employment—indicate that increasing fuel economy is one of the best investments the country can make.

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