Chapter 5

Increased Automobile Fuel Efficiency

Contents

TABLES

FIGURES

Chapter 5

Increased Automobile Fuel Efficiency

STATUS AND TRENDS

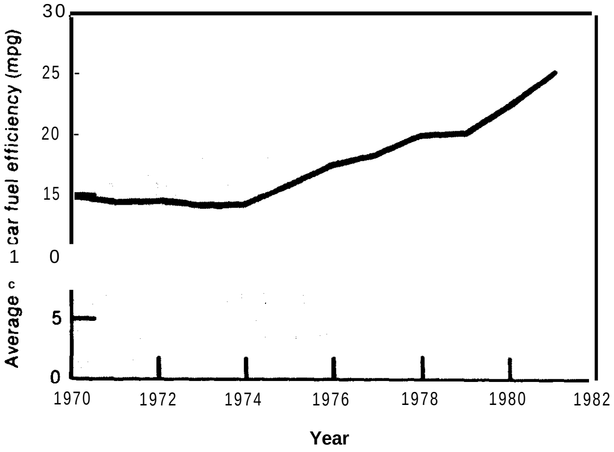
Until the 1970's, fuel economy was seldom important to American car buyers. Gasoline was cheap and plentiful, taxes on fuel and on car size low. In contrast with automobile markets in most of the rest of the world, automakers had few incentives to build small cars, or consumers to purchase them. The typical American passenger car –large, comfortable, durable–evolved in relative isolation from design trends and markets in other parts of the world. Fuel economy was a minor consideration. (This was not the case for heavy trucks, where fuel costs have always been a substantial component of operating expenses.)

In the late 1960's and early 1970's, Federal emissions control standards worked at the expense of fuel economy. But fuel economy pressures were also building—signified by gasoline shortages, the sudden rise in oil prices, and the passage of the Energy Policy and Conservation Act of 1975 (EPCA). EPCA set fleet average mileage standards for automobiles sold in the United States beginning in 1978. The combination of Corporate Average Fuel Economy (CAFE) standards and market forces stimulated rapid changes in the design of American cars, followed by a sharp swing in consumer demand during 1979 and 1980 toward small, economical imports.

A similar upsurge in small-car demand had followed the 1973-74 oil shock. Over the 1965-75 period, American-made cars averaged about 14 to 15 miles per gallon (mpg). * For model year 1980, the average for cars sold in the domestic market was up to 21 mpg, 1 mpg above the EPCA requirement. For 1981 models, domestic cars sold through January 5, 1981, averaged almost 24 mpg, or almost 2 mpg above EPCA requirements. (See also fig. 6.)

Most of the increases in fuel economy have come from downsizing—redesigning passenger cars so that they are smaller and lighter, and can use engines of lower horsepower. Other changes in vehicle designee. g., decreased aerodynamic drag and rolling resistance, improved automatic transmissions and higher rear axle ratios, electronic engine controls, greater penetration of diesels–have also helped to reduce fuel consumption.

Figure 6.—Historical Average New-Car Fuel Efficiency of Cars Sold in the United States



SOURCE: J. A. Foster, J. D. Murrell, and S. L. Loas, "Light Duty Automotive Fuel Economy. . Trends Through 1981 ," SAE Paper 810386, February 1981.

While the latest technology is used in these redesigns, technology itself is not–and has not been–a limiting factor in passenger-car fuel economy in any fundamental sense. The limiting factor is what the manufacturers decide to build based on judgments of future consumer demand. Decisions on new models may also be constrained by the costs of new capital investment. Technology does have a vital role in managing the many tradeoffs among manufacturing and investment costs, fuel economy, and the other attributes that affect consumer preferences—quality, comfort, carrying capacity, drivability, and performance. Technology is also critical in managing possible tradeoffs involving fuel economy, emissions, and safety.

American automakers are still incrementally downsizing their fleets–in the process convert-

---

*Based on EPA's combined test cycles (55 percent city and 45 percent highway cycle).

ing to front-wheel drive, which helps to preserve interior space. These redesigns have been largely paced by three interrelated factors: 1) CAFE standards, which require fleet averages of 27.5 mpg by 1985; 2) each manufacturer's estimates of future market demand in the various size classes (until 1979, market demand for smaller, more fuel-efficient cars lagged behind the CAFE standards, but it has now outstripped them—several recent projections point toward fleet averages of more than 30 mpg by 1985[1]); and, 3) the capital resources of U.S. firms, which affect both their ability to design and develop new small cars and their ability to invest in new plant and equipment for manufacturing them.

The gradual downsizing of the U.S. automobile fleet has been accompanied by an intensive developmental effort aimed at maximizing the fuel economy of cars of a given size, consistent with the need for low pollutant emission levels and occupant safety—both also matters of Government policy. Foreign manufacturers, who in 1980 accounted for about one-quarter of sales in the United States, are also improving the fuel economy of their fleets, but they can concentrate on technical improvements rather than new small-car designs because their product lines are already heavily oriented toward cars that are small in size and low in weight.

Because the U.S. automobile fleet now contains over 100 million cars, increases in new-car fuel economy take time to be felt. Typically, about half the cars of a given model year are still on the road after 10 years; it takes about 17 years before 99 percent are retired. Thus, while new-car fuel economy for the 1980 model year reached about 21 mpg, the average for the U.S. fleet in 1981 is still only about 16 to 17 mpg, a legacy of the big cars of earlier years. if new cars average 30 to 35 mpg by 1985—a target that is easily attainable from a technological standpoint–the average fuel efficiency of cars on the road would reach only about 22 mpg by 1985. While more than half the annual fuel savings associated with the 1985 CAFE standards will be achieved by 1985, the full benefit of the 30-mpg new cars of 1985—and of further improvements in later years—will not come until the end of the century.

Of course, 30-mpg CAFE standards are possible right now, and 50-mpg cars are currently being sold. Proportionately higher fuel economy figures will in principle be attainable in the future, as automotive technology progresses. But today only a portion of consumers want such vehicles—because fuel economy often comes at the expense of comfort, accommodations for passengers and luggage, performance, luxury, convenience features and accessories, and other attributes more commonly found in larger cars–and manufacturers try to plan their future product mix to appeal to a broad range of consumer tastes.

The sudden shift in market demand toward small, fuel-efficient cars in 1974-75, followed by a resurgence in large-car sales during 1976-78 and another wave of demand for fuel efficiency in 1979 and 1980, illustrates the unpredictable nature of consumer preferences. The 1979 market shift has outpaced the CAFE standards. The 27.5-mpg requirement set by EPCA for the 1985 model year remains in effect for subsequent years unless modified by Congress. If world oil prices again stabilize, and supply exceeds demand—as occurred through much of 1981 —the risks and uncertainties facing U.S. automakers could multiply, a particularly worrisome situation given their precarious financial situations and the large capital outlays necessary for redesign and retooling. Recently, American automakers have been reassessing their commitments to rapid downsizing and new small-car lines—both because of cash flow shortfalls and because of uncertainty over future market demand.[2]

The 14-mpg U.S. fleet average of 1975 is a useful baseline for estimating recent and near-term fuel savings resulting from the combination of EPCA standards and market forces. For the period 1975-85, OTA estimates that fuel economy in-

---

[1] W. G. Agnew, "Automobile Fuel Economy Improvement," General Motors Research Publication GMR-3493, November 1980; *The U.S. Automobile Industry, 1980: Report to the President From the Secretary of Transportation, DOT-P-1 O-81-O2,* January 1981. Independent estimates by OTA are similar.

[2] J. Holusha, "Detroit's Clouded Crystal Ball; Gasoline Glut Spurs Review of Small Cars," *New York Times,* July 28, 1981, p. Dl; J. Holusha, "For G. M., a Fresh Look at Spending Strategy," New *York Times,* Nov. 10, 1981, p. D1.

creases in passenger cars alone will have saved slightly **more than 0.8 MMB/DOE (million barrels per day, oil equivalent)** on the average—much less in the earlier years, and about twice as much near the end of this 10-year period, Considering only passenger cars, the cumulative saving through 1985 will be approximately 3 billion barrels (bbl) of petroleum–about 75 percent of the total U.S. crude oil imports during 1979 and 1980. For the period 1985-95, by the end of which the average efficiency of all cars on the road should be **30** mpg or more, the daily savings would be at least 3 million barrels per day (MMB/D), giving an additional cumulative saving of at least 10 billion bbl compared with a 14-mpg fleet. Thus, for the 20-year period 1975-95, the total savings from increased passenger-car fuel economy would be over 13 billion bbl—equivalent to 8 years of crude oil imports or about 7 years of net petroleum imports at the 1981 rate.

These estimated reductions in petroleum consumption could be larger if fuel-economy improvements proceed faster than assumed. Fuel-economy improvements in trucks, particularly light and medium trucks, will also save significant amounts. Nonetheless, the U.S. passenger-car fleet would still consume 3.6 MMB/D in 1985 and 3 MMB/D in 1995–compared with 4.3 MMB/D in 1980—if the passenger-car fleet grows as expected and cars continue to be driven at the historical rate of 10,000 miles per year, on the average. If automobile travel is reduced, fuel consumption would be decreased proportionately.

The savings in petroleum consumption–which represent a direct benefit to consumers as well as an indirect benefit because of the expected improvement in the U.S. balance of payments—also carry costs. These will generally take the form of higher purchase prices for new cars, even though these cars will be smaller. Costs will be higher because the redesign and retooling for a downsized U.S. fleet requires capital spending at rates significantly higher than the historical average for American manufacturers. Increased capital spending—which, along with the sales slump of 1979-81, shares responsibility for the over $4 billion lost by U.S. automakers during 1980–is passed along at least in part to purchasers. To the extent that competitive forces allow, importers will also raise prices even though their capital spending rates may not have gone up.

Many of the technological roads to improved fuel economy also carry higher direct manufacturing costs. A familiar example is the diesel engine—which, for comparable performance, can increase passenger car fuel economy, and decrease operating costs, by as much as 25 percent, but at a substantial penalty in purchase price. In this case, the higher costs stem largely from an intrinsically expensive fuel injection system, but also from the greater mechanical strength and bulk required in a diesel engine. Beyond economic costs and benefits, smaller cars cannot be designed to be as safe as larger cars (given best practice design in both) –thus, risks of death and injury in collisions could go up.

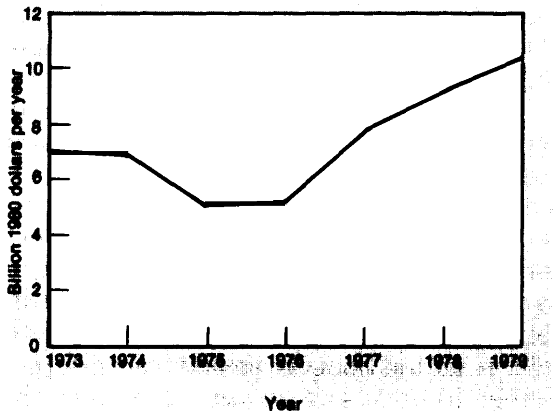
For the 10-year period 1968-77, average annual capital investment by the big three U.S. automakers in constant 1980 dollars was $6.68 billions (AMC and, in later years, Volkswagen of America add only small amounts to these averages). Over this period, production fluctuated considerably, but with only a slight upward trend; thus, the average expenditure is primarily that for normal redesign and retooling as new models are introduced and existing product lines updated, rather than for increases in production capacity. Note that the period 1968-77 includes investments associated with the introductions of several new small cars around 1970 (Pinto, Maverick, Vega), as well as later subcompact designs (Chevette, Omni/Horizon). The figures also include overseas investments by the three U.S. firms.

The 2 years with the highest investments during the 1968-77 period were 1970 ($7.67 billion) and 1977 ($7,78 billion). In 1978, investment rose to $9.21 billion, and in 1979 it reached $10.5 billion (still in 1980 dollars) –half again as much as the historical level. (See fig. 7.) Estimates of investment for the 5-year period 1980-84 reach close

---

[3] **These investment figures were tabulated from annual reports by R. A. Leone, W. J. Abernathy, S. P. Bradley, and J. A. Hunker, "Regulation and Technological Innovation in the Autombile Industry, " report to OTA under contract No. 933-3800.0, May 1980, pp. 2-92. Conversions to 1980 dollars are based on the implicit price deflator for nonresidential fixed domestic investment.**

Figure 7.—Historical Capital Expenditures by U.S. Automobile Manufacturers



SOURCE: G. Kulp, D. B Shonka, and M. C. Holcomb, "Transportation Energy Conservation Data Book: Edition 5," Oak Ridge National Laboratory, ORNL-5765, November 1981.

to $60 billion.[4,5] Such estimates have generally been based on fleet redesigns to meet EPCA requirements through 1985. While it is doubtful that they include much spending for new models to be introduced in the immediate post-1985 period, they do include substantial overseas expenditures —perhaps one-quarter or more.

The $60 billion estimate represents about $12 billion per year in 1980 dollars, nearly double the historical spending level. It is a clear indication of the market pressures (for smaller cars as well as for greater fuel economy in vehicles of all sizes, including light trucks) being placed on domestic manufacturers. Component suppliers also face higher-than-normal investments.

The remainder of this chapter treats the factors that determine automobile fuel consumption in more detail—both the technological factors and market demand—as well as the net savings in fuel consumption that may accrue from increases in automobile fuel economy. While consumer preferences—as judged by manufacturers in planning their future product lines–are dominant, technology is vital in maximizing the fuel economy that can be achieved by cars of given size and weight, as well as given levels of performance, emissions, and occupant safety.

AUTOMOBILE TECHNOLOGIES

Fuel consumed by an automobile (or truck) depends, first, on the work (or power) expended to move the vehicle (and its passengers and cargo), and second, on the efficiency with which the energy contained in the fuel (gasoline, diesel fuel) is converted to work. The power requirements depend, in essence, on: 1) the driving cycle–the pattern of acceleration, steady-state operation, coasting, and braking–which is affected by traffic and terrain, but otherwise controlled by the driver; 2) the weight and rolling resistance of the vehicle; and **3)** the aerodynamic drag, which depends on both the size and shape of the vehicle and is also a function of speed. The designer controls weight, aerodynamic drag, and to some extent the rolling resistance, but can affect the driving cycle only indirectly –e.g., through the power output and gear ratios available to the driver.

The fuel consumed in producing the power to move a vehicle of given size and weight is again a function of vehicle design, primarily engine design. The efficiency with which the engine converts the energy in the fuel to useful work depends on the type of engine as well as its detail design; diesel engines are more efficient than spark-ignition (gasoline) engines, but not all diesel engines have the same efficiency.

Furthermore, an engine's efficiency varies with load. For example, when a car is idling at a traffic light, the engine's efficiency is virtually zero

---

[4] General Accounting Office, "Producing More Fuel-Efficient Automobiles: A Costly Proposition, " CED-82-14, Jan. 19, 1982.

[5] *Fuel Economy Standards for New Passenger Cars After 1985* (Washington, D. C.: Congressional Budget Office, December 1980), p. 56. Other estimates are generally comparable but may differ as to whether development costs or only fixed investment are included.

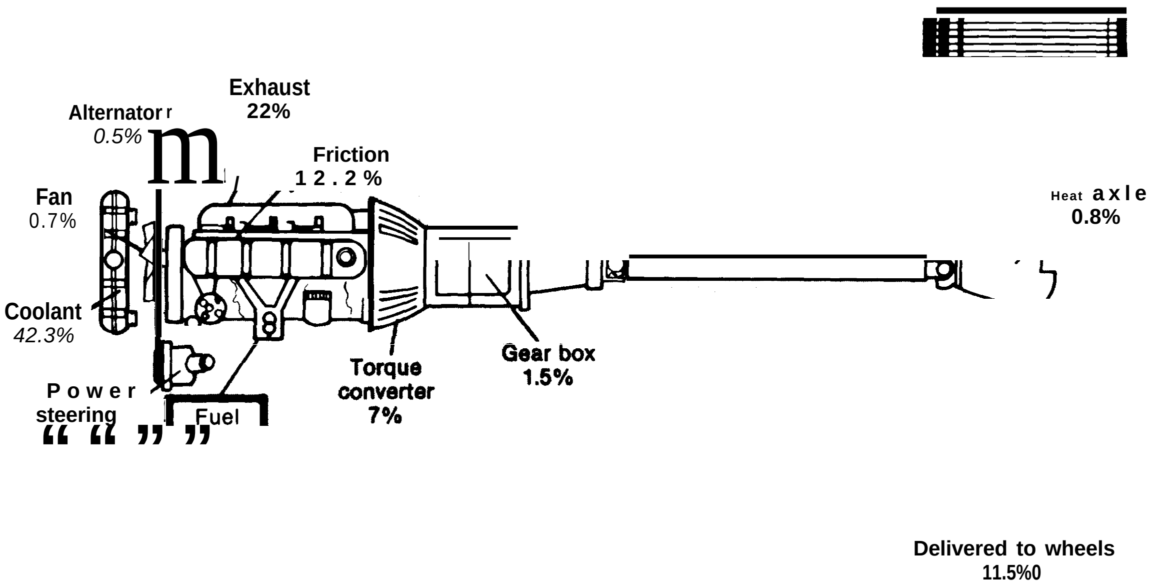
because the energy in the fuel is being used only to overcome the internal friction of the engine and to power accessories. Engines are more efficient at relatively high loads (accelerating, driving fast, or climbing hills), but such operation will still use fuel at a high rate simply because the power demands are high–hence the justification for the 55-mph speed limit as an energy-conservation measure.

Efficiency–the fraction of the fuel energy that can be converted to useful work—cannot be 100 percent in a heat engine for both theoretical and practical reasons. For a typical automobile engine, peak efficiency may exceed 30 percent, but this is attained for only a single combination of load and speed. *Average* efficiencies, characteristic of normal driving, may be only 12 or 13 percent, even lower under cold-start and warmup operation. To illustrate this point, figure 8 shows energy losses for the drivetrain in one 1977 model car in the Environmental Protection Agency's (EPA) urban cycle. This figure should not be taken too literally because losses vary considerably from car to car and numerous design changes have been implemented since 1977, but the figure does serve to illustrate approximate magnitudes.

The design of the engine affects the amount of fuel consumed during the driving cycle in two basic ways. First, the size of the engine fixes its maximum power output. In general, a smaller engine in a car of given size and weight will give better fuel economy, mainly because the smaller engine will, on the average, be operating more heavily loaded, hence in a more efficient part of its range, There are practical limits to engine downsizing, however, because a heavily loaded, underpowered engine provides poor performance and can suffer poor durability.

Second, the designer can directly affect driving-cycle fuel economy through the transmission and axle interposed between the engine and wheels. Significant gains in fuel economy over the past few years have come from decreases in rear axle

Figure 8.—Fuel Use in City Portion of EPA Fuel' Efficiency Test Cycle (2,750 lb/2.3 liter)



SOURCE Serge Gratch, Ford Motor Co., private communication, 1982.

ratios* so that engines are operating at higher efficiencies during highway operation, and from changes in transmission ratios** to better match driving needs to engine efficiency (in earlier years transmission ratios were often chosen to maximize performance rather than fuel economy). Adding more speeds to the transmission—whether manual or automatic—serves the same objective. The optimum would be a continuously variable, stepless transmission allowing the engine to operate at all times at high loads where its efficiency is greatest. (Such transmissions can be built today, but require further development for widespread use in cars.)

Changes in many other areas of automobile design can help increase fuel economy, but the primary factors are size (which is one of the factors that determines aerodynamic drag), weight (which determines the power needed for acceleration, as well as rolling resistance), and powertrain characteristics (engine plus transmission). These are discussed in more detail below, in the context of the driving cycle—itself a critical variable in fuel economy—followed by brief discussions of emissions and safety tradeoffs, methanol-fueled vehicles, and electric vehicles (EVs).

Vehicle Size and Weight

On a sales-averaged basis, the inertia weight of cars sold in the United States during 1976 (including imports) came to slightly over 4,000 lb.[6] This corresponds to an average curb weight*** of 3,700 to 3,800 lb. The average inertia weight for 1981 is expected to be about 3,100 lb, and may further decrease to around 2,750 lb by 1985. Although the lightest cars sold here still have inertia weights close to 2,000 lb–as they did in 1975—the distribution has shifted markedly toward the lower end of the range. Many heavier models have disappeared; consumers are now selecting smaller and lighter vehicles—downsized or newly designed U.S. models as well as imports.

While size is a primary determinant of weight, newer designs typically make greater use of lightweight materials such as plastics and aluminum alloys, as well as substituting higher strength steels—in thinner sections—for the traditional steels. Materials substitution for weight reduction will continue, but is constrained by the higher costs of materials with better strength-to-weight or stiffness-to-weight ratios. As production volumes go up, costs of at least some of these materials will tend to decline.

Weight is a fundamental factor in fuel economy because much of the work, hence energy, needed for a typical driving cycle is expended in accelerating the vehicle. The fuel consumed in stop-and-go driving is directly related to the loaded weight of the car (including passengers and payload) and the inertia of its rotating parts. Everything else being the same, it takes twice as much energy to accelerate a 4,000-lb car as a 2,000-lb car over the same speed range. Urban driving, in particular, consists largely of repeated accelerations and decelerations; thus, weight is critical to fuel consumption. (This also points up the potential that smoothing flows of traffic offers for gasoline savings.) Lighter cars consume less fuel even at constant speeds because they have less rolling resistance.

Although the weights of cars can be reduced by making them from lightweight materials and by shifting from separate body and frame designs to unitized construction, cars can always be made lighter by making them smaller.

Small cars can also have lower aerodynamic drag, because drag depends on frontal area as well as on the shape of the vehicle. Drag can be reduced by making cars lower and narrower, as well as by streamlining the vehicle. Drag reduction has become at least as important as styling in recent years; working primarily with wind tunnel data, automakers have reduced typical drag coefficients* from 0.5 to 0.6, characteristic of the

---

***Rear axle ratio is the ratio of the drive shaft speed to the axle speed.**

****Transmission ratio is the ratio of the engine crankshaft speed to the drive shaft speed.**

[6] J. A. Foster, j. D. Murrell, and S. L. Loos, "Light Duty Automotive Fuel Economy . . . Trends Through 1981 ," Society of Automotive Engineers Paper 810386, February 1981. Inertia weight is a rep resentative loaded weight—equal to curb weight, which includes fuel but not passengers or luggage, plus about 300 lb–used by EPA for fuel economy testing.

*****Curb weight is the weight of the car with no passengers or cargo.**

***The drag coefficient is a measure of how aerodynamically "slippery" the car is. The aerodynamic drag is proportional to the drag coefficient, the frontal area and the velocity squared.**

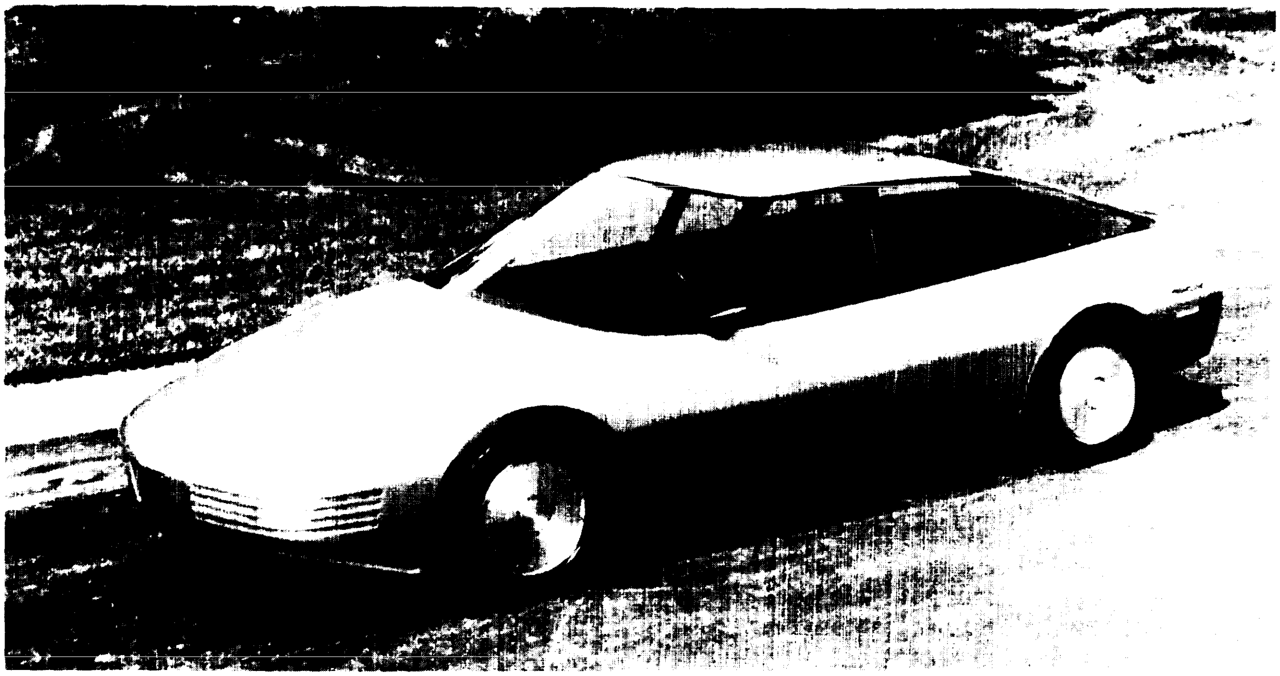


Photo credit: General Motors Corp

The shape of this experimental car is designed for low aerodynamic drag

early 1970's, **to 0.4 to 0.5 at present, with a number** of models being under 0.4. Values in the range of 0.35 will eventually be common.

It takes only 15 or 20 horsepower to propel a typical midsized car at a steady 55 mph—that is all that is needed to overcome rolling resistance and aerodynamic drag. The remainder of the engine's rated power is used for acceleration, climbing hills, and other demands. The low power requirements for constant-speed driving–typically 15 to 20 percent of the engine rating—emphasize the importance of the fuel used in start-and-stop driving (and the influence of weight) in determining driving-cycle fuel economy.

Powertrain

The engine (or other vehicle prime mover) converts the energy stored in fuel (or, for an EV, in batteries) to mechanical work for driving the wheels. The efficiency of the engine—as well as the efficiency of the transmission—determines the proportions of the energy in the fuel which are, respectively, used in moving the car and lost as waste heat. Under most operating conditions, transmissions are much more efficient than the engine.

The efficiency-work output divided by energy input—of any engine depends on both detail design and fundamental thermodynamic limitations. The temperatures at which the engine operates place practical constraints on the efficiencies of some types of engines—e.g., gas turbines—but not on others—e.g., spark-ignition (SI) (gasoline) and compression-ignition (CI) (diesel) engines where the combustion process is intermittent. The components of the latter need not withstand temperatures as high as those where combustion is continuous.

Many other factors besides efficiency enter into the choice of engine for a motor vehicle; until recently, efficiency was often of secondary importance. Cars and trucks have been powered by gasoline or diesel engines because these have favorable combinations of low cost, compact size, light weight, and acceptable fuel economy. Neither demands for improvements in exhaust em issions nor for better fuel economy have yet resulted in serious challenge to these engines—which have been dominant for 70 years. At least through the end of the century, most passenger cars are likely to be powered by reciprocating SI or diesel engines.

SI and CI or diesel engines have peak efficiencies generally in the range of **30** to **40** percent. However, their efficiency at *part-load* **can be** much less; the farther the engine operates from the load and speed for which its efficiency is greatest, the lower the efficiency. In typical urban driving, the *average* operating efficiency is less than one-third of the peak value–e.g., in the range of 10 to 15 percent.

Part-load fuel economy remains a more critical variable for an automobile engine than maximum efficiency because of the light loading typical of most driving. Such a requirement favors CI engines, for example, but works against gas turbines. CI engines have good part-load efficiency because they operate unthrottled, thereby avoiding pumping losses. They also have high compression ratios–which, up to a point, raises efficiency under all operating conditions.

Various modifications to SI engines can increase part-load efficiencies. This is one of the advantages of stratified-charge engines—which use a heterogeneous fuel-air mixture to allow overall lean operation, ideally without throttling as in a diesel—and also of SI engines that burn alternative fuels such as alcohol or hydrogen. Smaller, more heavily loaded SI engines also tend to have greater driving-cycle fuel economy because the higher loads mean the engine is running with less throttling. Among the steps that can be and are being taken to give greater fuel economy are:

- using the highest compression ratio consistent with available fuels;
- refined combustion chamber designs, particularly those optimized for rapid burning of lean mixtures, one of the routes to higher compression ratios;
- minimizing engine friction;
- optimizing spark timing consistent with emissions control;
- minimizing exhaust gas recirculation consistent with emissions control;
- precise control of fuel-air ratio, both overall and cylinder-to-cylinder, particularly under transient conditions such as cold starts and acceleration—again consistent with emissions control; and
- minimizing heat losses.

Transmission efficiencies also depend on load, but much less so than engines; transmission efficiencies are also much higher in absolute terms. For manual transmissions, more than 90 percent of the input power reaches the output shaft except at quite low loads. Because they have more sources of losses, automatic transmissions are less efficient, particularly those without a lockup torque converter or split-path feature. In these older transmissions, all the power passes through the torque converter, even at highway cruising speeds. The resulting fuel-economy penalty, compared with a properly utilized manual transmission, is typically in the range of 10 to 15 percent. By avoiding the losses from converter slippage at higher speeds, split-path or lockup designs cut this fuel-economy penalty approximately in half, four-speed transmissions offering greater improvement than those with only three forward gears.

One function of the transmission is to keep the engine operating where it is reasonably efficient. Although automatic transmissions are less efficient than manual designs, they can sometimes increase overall vehicle efficiency by being "smarter" than the driver in shifting gears. Further benefits are promised by improved electronic control systems for automatics. These microprocessor-based systems can sense a greater number of operating parameters, and are thus able to use more complex logic, perhaps in conjunction with an engine performance map stored in memory. Such control systems could also be used with manual transmissions—e.g., to tell the driver when to shift. A continuously variable transmission would be better still. As mentioned above, these can be built now, but they have not been practical because of problems such as high manufacturing cost, low efficiency, noise, and limited torque capacity and durability.

Fuel Economy—A Systems Problem

An automobile is a complex system; design improvements at many points can improve fuel economy. Even if each incremental improvement is small, the cumulative effect can be a big increase in mileage. Interactions among the elements of the system (engine, transmission, vehicle weight) and the intended use of the vehicle are among the keys to greater system efficiency. At the same time, as the state of the art improves, further increases in efficiency tend to become more difficult unless there are dramatic technical breakthroughs–and OTA thinks such breakthroughs are improbable. This is a mature technology in which, as a general rule, radical changes are few and far between.

Making cars smaller and lighter helps in many ways to reduce the power needed, hence fuel consumed. Front-wheel drive preserves interior space while allowing exterior size and weight to be reduced. Reductions in the weight of the body structure mean that a smaller engine will give equivalent performance, while also allowing lighter chassis and suspension members, smaller tires and brakes, and related secondary weight savings. Among other steps taken in recent years have been the adoption of thinner, hence lighter, window glass—and even redesigned window lift mechanisms.

Once major decisions have been made concerning overall vehicle design parameters—size, engine type, etc.—subsystem refinement and systems integration become the determining factors in the fuel economy achieved in everyday driving. Some of these refinements decrease the need for power, as by reducing friction or making accessories more efficient; others increase the efficiency of energy conversion, as by using three-way exhaust catalysts and feedback control of the fuel-air ratio to limit emissions while preserving fuel economy.

Tradeoffs With Safety and Emissions

Government policies to increase automobile fuel efficiency, reduce pollutant emission levels, and improve passenger safety involve significant tradeoffs. Measures to control auto emissions can impair fuel efficiency. Reducing the size of cars to increase fuel economy makes them intrinsically less safe. Meeting regulatory goals also affects manufacturing costs. Tradeoffs like these have not always been fully recognized in the formulation of Federal policy,[7] but will continue to be important as policy makers focus on questions of post-1985 fuel economy.

The issues include whether Government policies are to be directed at further improvements in mileage, such as by a continued increase in CAFE standards, or by a gasoline tax, and whether emissions standards are to be tightened or relaxed. The tradeoffs will involve manufacturing costs, as always—but the relationship of fuel economy to safety will perhaps be most critical.

Safety

The tradeoffs between fuel economy and occupant safety are largely functions of vehicle size—therefore of weight as well. Although many characteristics of the car are important for occupant safety, protection in serious collisions depends quite substantially on the crush space in the vehicle structure and on the room available within the passenger compartment for deceleration. Penetration resistance is also vital. Design requirements are based on a "first collision" between vehicle and obstacle, and a "second collision" between occupants and vehicle. In the "first collision," the more space available for the structure to crush—without encroaching on the passenger compartment-the slower the average rate of deceleration that the passenger compartment and the passengers experience. More crush space translates directly to lower decelerations.

Space, hence vehicle size, is also important within the passenger compartment. The more space available inside, the easier it is to preserve the basic integrity of the structure and the slower the occupants can be decelerated during the "second collision. " Seatbelts, for example, can stretch to lower the decelerations the restrained occupants experience, but only if there is nothing

---

[7] ***U.S. Industrial Competitiveness. A Comparison of Steel Electronics, and Automobiles,*** **OTA-ISC-135 (Washington, D. C.: U.S. Congress, Office of Technology Assessment, June 1981), pp. 120-122.**

rigid for the occupants to hit; deformable anchors for seatbelts are thus a further method for improving safety.

Because of their larger crush space and interior volume, big cars can *always* provide more protection for their occupants in a collision—given best *practice design.* However, not all cars embody best practice designs, and the crashworthiness of autos in the current fleet does not improve uniformly and predictably with vehicle size. Furthermore, vehicle safety depends on avoiding crashes as well as surviving them, and therefore on factors such as braking and handling as well as driver ability. These and other factors related to the potential effects on auto safety of increasing fuel efficiency are discussed in chapter 10.

Emissions Control

Fairly direct tradeoffs exist between engine efficiency and several of the measures that can be used to control the constituents of exhaust gases that contribute to air pollution. The three major contributors in the exhaust of gasoline-fueled vehicles, all regulated by the Clean Air Act and its amendments, are hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x).8 Emissions control measures have frequently worked against the fuel economy of cars sold in the United States since 1968, when manufacturers began to retard spark timing to reduce HC emissions. Although the costs of emissions control measures—as reflected in the purchase price of the vehicle—have often been disputed and remain controversial, there have also been operating cost penalties because fuel economy has been less than it would otherwise have been.

Mileage penalties were more severe in the mid-1970's than at present, but efficiency increases have come at the expense of higher first cost. Ground is periodically lost and regained, but even with best practice technology at any given time, the engineering problems of balancing emissions and fuel economy at reasonable cost have forced many compromises. One recent estimate of the net effect of emissions control through 1981 finds a 7.5-percent fuel-economy penalty.[9]

"The single change with the greatest continuing effect has been reduced compression ratios resulting from the changeover to unleaded gasoline. Cl engines *require* high compression ratios; SI engines, in contrast, suffer from a form of combustion instability termed detonation (i.e., the engine "knocks") if the compression ratio is too high for the octane rating of the fuel. Thus, decreases in the already lower compression ratios of SI engines—to values in the range of 8:1 versus ratios as high as 10:1 in the early 1970's—have led to significant decreases in fuel economy.

Lead compounds, formerly added to gasoline to raise the octane, have been removed to prevent poisoning (deactivation) of catalytic converters—themselves adopted to control, first, HC and CO, and later NO_x as well–and also because of concern over the health effects of lead compounds. While electronic engine control systems, including knock detectors, have allowed compression ratios to be increased somewhat, only a portion of the ground lost can be regained in this way.

Methanol with cosolvents can be used as an octane-boosting additive to gasoline that does not interfere with the catalytic converter. In addition, compact, fast-burn combustion chambers may help. By burning the fuel fast enough that the preflame reactions leading to detonation do not have time to occur, fast-burn combustion systems might allow compression ratios to be increased by several points. This latter approach, however, increases HC and NO_x emissions, and it is not yet clear how much compression ratios can be raised while maintaining emissions within prescribed limits.

Related measures used to control emissions—and/or to limit detonation—can also degrade engine efficiency. Retarding ignition timing—to limit detonation, and in some cases help control HC and CO emissions by promoting complete combustion of the fuel–hurts fuel economy. Other techniques adopted in the early 1970's to con-

---

[8] D. J. Patterson and N. A. Henein, ***Emissions From Combustion Engines and Their Control*** **(Ann Arbor, Mich.: Ann Arbor Science Publishers, 1972).**

'L. B. Lave, "Conflicting Objectives in Regulating the Automobile," Science, May 22, 1981, p. 893.

trol HC and CO—such as thermal reactors, which were likewise intended to drive the combustion process toward complete reaction of HC and CO —also led to increased fuel consumption.

Unfortunately, while more complete combustion decreases HC and CO pollutants, NO_x in the exhaust is increased under conditions leading to more complete combustion. Thus, not only does control of exhaust emissions conflict with fuel economy, but there are also potential conflicts between control of HC and CO on the one hand, and NO_x on the other. The NO_x standards of the mid-1 970's could be met by adding exhaust gas recirculation (EGR) to the repertoire of measures used for HC and CO control. Although EGR initially carried a substantial fuel economy penalty, and also impaired driveability, improved control systems—which recirculate exhaust only when needed—have improved both economy and driveability substantially. Still, the drawbacks of other methods of NO_x control, * together with the more stringent NO_x standards of later years, have led to the most common current control technique—the three-way catalytic converter, which reduces levels of all three pollutants. This gives fuel economy comparable to an uncontrolled engine, though at higher first cost.

Compression ratios of diesel engines are often twice those for SI engines; at these high levels small changes in compression ratio have relatively little effect on efficiency. For this reason and because of the different set of emissions standards applied, CI engines have faced fewer conflicts between emissions control and fuel economy. This advantage has helped them to compete with SI engines for passenger cars, although the situation may change in the future, as the diesel standards become tougher. Particulate (bits of unburned, charred fuel) are the most difficult of diesel emissions to control, although NO_x also poses problems. However, future regulations for particulate in diesel exhaust are not yet definite. This creates uncertainty not only about the control technologies that might be needed, but also about the future penetration of CI engines in passenger vehicles.

Nonetheless, as will be seen below, OTA remains cautiously optimistic about diesels. Their higher intrinsic efficiency at both full- and part-load makes them quite attractive in terms of fuel economy, and there is considerable scope for further improvements in their driveability and related characteristics that are more important for passenger cars than for trucks and other uses in which diesels have been more common. The long developmental history of CI engines provides a useful foundation for passenger-car applications.

Methanol-Fueled Engines

There are basically two routes to higher SI engine efficiency via alternate fuels: lean operation, which cuts pumping and other thermodynamic losses, and higher compression ratio.[10] Fuels vary in the extent to which these factors operate and there are a number of secondary effects, but alcohols and hydrogen have excellent potential for both lean burning and higher compression ratios, with possible driving-cycle economy improvements in the range of 10 to 20 percent. Further engineering development—but no breakthroughs —would be needed before alcohols or other alternate fuels could be used in U.S. cars, but the production and distribution of such fuels are more significant barriers.

Diesels, like SI engines, can operate on a variety of alternative fuels, although perhaps needing spark-assisted combustion. Powerplants such as open-chamber stratified-charge engines and continuous combustion engines can often tolerate quite broad ranges of fuels with minimal design changes.

Because methanol from coal is an attractive synthetic fuel, methanol-burning engines for passenger cars are discussed in more detail below. Unlike ethanol, which will probably be used primarily as a gasoline extender (e.g., in gasohol),

---

***It should be noted, however, that burning a very lean fuel/air mixture also reduces NO_x emissions substantially. Because methanol has considerably wider flammability limits than does gasoline, the use of methanol opens new opportunities for controlling NO_x.**

[10] J. A. Alic, "Lean-Burning Spark Ignition Engines–An Overview," *Proceedings, 2nd Annual UMR-MEC Conference on Energy,* Rolla, Me., Oct. 7-9, 1975, p. 143.

S w A w g
m g E rt g m G
E w

sufficient quantities of methanol could be produced to consider using it as the only or principal fuel for some automobiles.

If methanol-fueled engines receive intensive development aimed at maximizing fuel economy and driveability, driving-cycle fuel-efficiency improvements (on a Btu basis) of 20 percent or more should be possible, compared with a well-developed but otherwise conventional SI engine burning gasoline. Most of the improvement stems from the higher octane rating of methanol, which would permit compression ratios in the range of 11 or 12:1—perhaps even higher, depending on whether preignition is a serious limiting factor—as well as the somewhat leaner air-fuel ratios possible.

The engineering of vehicles to run on methanol —or other alchohols—is rather straightforward.[11] Indeed, a good deal of experience has already been accumulated. Despite the greater efficiency possible with methanol, vehicles fueled with it probably will require larger fuel tanks to achieve acceptable cruising ranges, because methanol has significantly less energy per gallon than gasoline or diesel fuel. Methanol corrodes some of the materials commonly used in gasoline-fuel systems, which must be replaced by more corrosion-resistant components.

Because alcohols have much higher heats of vaporization than gasoline and therefore do not vaporize as easily, alcohol-fueled engines are more difficult to start in cold weather. Driveability during warmup also tends to be poor. Fuel injection is one approach to mitigating such difficulties. Another solution is to start and warm up the engine on a different fuel. In Brazil, where many cars and trucks run on 100 percent ethanol, engines are typically started on gasoline via an auxiliary fuel system. A lower cost alternative might be to blend in a small fraction–5 to 10 percent–of a hydrocarbon to aid in starting and warmup. Fuel blends could be tailored seasonally just as gasolines are.

Methanol also offers advantages in reducing heat losses and thus raising fuel efficiency. Al-

---

[11] "CH_3OH: **Fuel of the Future?"** ***Automotive Engineering,*** **December 1977, p. 48.**

though its high specific heat and high heat of vaporization can cause starting and warmup problems, these characteristics also mean that the fuel can, in principle, be used to help control internal engine temperatures and heat flows so as to reduce heat losses.

Test programs with alcohol fuels have sometimes shown abnormally high engine wear—particularly piston ring and bore wear. While the causes have not yet been fully determined, corrosion, perhaps associated with wall-washing and crankcase dilution during cold-start, are possible contributing factors.[12] If this is the case, solving the cold-start and warmup difficulties would also be expected to cut down on wear. Oil additive packages specially tailored for alcohols should be a further help.

Emissions from methanol-burning automobiles can be controlled with many of the same technologies used for gasoline engines. However, because of the differing fuel chemistries, standards developed for gasoline-burning vehicles are not necessarily appropriate for alcohols. Aldehydes, for example, may need to be controlled.

Battery-Electric and Hybrid Vehicles

The automobile powerplants considered by OTA for increased fuel efficiency are all heat engines–i.e., they convert the energy (heat) produced when a fuel burns into mechanical work. Passenger cars can also be powered from energy stored in forms other than fuel—e.g., by mechanical energy drawn from a spinning flywheel. Among these alternative storage media are rechargeable batteries that convert chemical energy into electrical energy. The electric energy can then drive a direct current (DC) (or sometimes, through an inverter, an alternating current (AC)) motor. Many of the first automobiles built, around the turn of the century, used battery-electric power.

In an extension of the battery-electric concept —called a hybrid—a conventional heat engine drives a generator (or alternator) which can then supply power to an electric motor directly, charge batteries, or both–depending on the instantaneous needs of the driving cycle. A parallel hybrid is designed so the heat engine can also power the wheels directly, through a transmission (the engine turns the generator and the drive wheels in parallel). A series hybrid, in contrast, has no direct mechanical connection between heat engine and drive wheels. Diesel-electric submarines provide examples of both series and parallel hybrid powertrains, but automobiles have never been mass produced with either arrangement.

Whether or not a battery-electric or hybrid automobile would have an overall energy conversion efficiency greater or less than a more conventional SI- or CI-powered car depends on many variables, including the sources of the electricity used to charge the batteries. In the context of this report, the potential of battery-electric or hybrid vehicles as substitutes for petroleum-based fuels is more important than the net energy conversion efficiency. If the electricity for charging the batteries comes from a coal or nuclear generating plant—or any other nonpetroleum energy source—widespread sales of such cars could help conserve liquid petroleum.

At present, however, the limitations of practical electric and hybrid vehicles far outweigh any advantages that might be gained from their petroleum-displacing effects.[13] Battery-electric cars will have very limited applications until the performance of batteries (as measured, for example, by the quantity of energy that can be stored per unit of battery weight), increases roughly fivefold—or unless petroleum availability declines much more rapidly than now expected. Hybrids share many of the disadvantages of battery-electric cars and—although they offer theoretically promising energy conversion efficiencies—are dependent on fuels. Their current prospects are even dimmer than for battery-electrics, in large part because hybrid vehicles would be expensive and complex—the duplication in the powertrain is a formidable cost barrier.

---

[12] T. W. Ryan, III, D. W. Naegeli, E. C. Owens, H. W. Marbach, and J, G. Barbee, "The Mechanism Lending to Increased Cylinder Bore and Ring Wear in Methanol-Fueled S.1. Engines, " Society of Automotive Engineers Paper 811200, 1981.

[13] R. L. Graves, C. D. West, and E. C. Fox, "The Electric Car—Is It Still the Vehicle of the Future, " Oak Ridge National Laboratory Report ORNL/TM-7904, August 1981.

Despite the widespread publicity given to battery-electric automobiles over the past 20 years—most recently, the attention garnered by General Motors' announcement of production plans for the mid-1980's—progress in EVs remains severely limited by battery performance. This is true both for battery systems that are available now and for those that appear to have possibilities for near-term production. Power and energy densities of available batteries remain too low for practical use in other than highly specialized automotive applications. Power density (watt per pound or W/lb) measures the *rate* at which the battery can supply energy. Energy density (watt hours per pound or Whr/lb) measures the total *amount* of energy that can be stored and then withdrawn from the battery. For some battery systems, to get all the energy out requires a slow rate of withdrawal, limiting the instantaneous delivery of power. Because of the transient demands of automotive driving cycles, power density is almost as important for vehicle applications as energy density, which determines the operating range before the batteries need to be recharged.

In general, battery systems that are near-term candidates for automotive applications suffer from both low power density *and low* energy density. Table 20, which includes several batteries that are still in rather early stages of development, gives typical values. Energy and power density tend to be inversely related, a particular problem for the familiar lead-acid battery; the inverse relation means that—for any given battery system—the designer can choose higher energy density only at the sacrifice of power density. Limited power density restricts the acceleration capabilities of current **EVs** to low levels—for some driving conditions, to the detriment of safety. The energy density, in contrast, limits the total amount of energy that can be carried, therefore, the range of the vehicle before the batteries must be recharged. Recharging is a time-consuming process—as much as 10 hours for some, though not all, batteries. If power density and energy density are low, then the vehicle must carry more batteries. This makes it heavier, increasing the demands for power and energy and compounding the design problems.

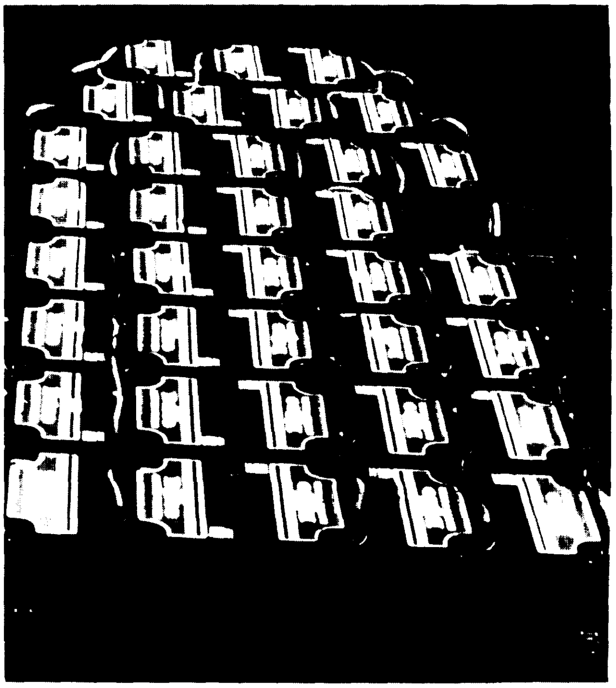


Photo credit: Electric Vehicle Council

A view of the battery-pack configuration in a demonstration electric vehicle

As a rule-of-thumb, and assuming reasonable costs, an energy density in the vicinity of 100

Table 20.-Potential Battery Systems for Electric (and Hybrid) Vehicles

Battery	Energy density (Whr/lb)	Power density (W/lb)	Status
Lead-acid	15-20	5-20	Available
Nickel-zinc	30-40	40-80	Available, but expensive
Zinc-chlorine	~35	~50	Experimental; potentially inexpensive
Aluminum-air	100-200	~80	Experimental; cannot be electrically recharged (requires periodic additions of water and aluminum)
Sodium-sulfur.	~100	~100	Prospective; high-temperature; potentially inexpensive

SOURCE: Office of Technology Assessment.

Whr/lb, along with a power density of about 100 W/lb, would suffice for a practical general-purpose vehicle. With these characteristics, 400 lb of batteries would give about 100 miles of travel between battery recharging and produce about 55 horsepower. Urban or commuter cars might get by with somewhat lower figures. Table 20 shows that currently available battery systems either cannot achieve such figures, or—as with nickel-zinc batteries-are too expensive for widespread use.

Battery-electric cars–often production vehicles converted by replacing the engine and fuel system with an electric motor and lead-acid batteries (like the storage batteries used in golf carts) -have been built in prototype or limited-production form for years. At present, a four-passenger electric car with lead-acid batteries would weigh about twice as much as a conventionally powered car, cost twice as much, and have a range of less than 50 miles before recharging. The battery pack alone would weigh 1,000 lb or more, and would have to be replaced several times during the life of the vehicle, adding to the operating costs.

In addition to the nickel-zinc batteries mentioned above, there are a number of other candidate battery systems for EVs–of which table 20 includes three as examples—the zinc-chlorine, aluminum-air, and sodium-sulfur batteries. These share the advantage of relatively inexpensive raw materials, but have other drawbacks: for example, the zinc- chlorine battery has low energy density; the aluminum-air system is "recharged," not by an inward flow of electricity, but by mechanical replacement of materials (in consuming materials to produce electricity the aluminum-air battery is like a fuel cell, but fuel cells are continuous-flow devices); the sodium-sulfur battery operates at temperatures greater than 5000 F. All of these batteries are experimental, and none has been developed as rapidly as once hoped; the same is true of many other candidate battery systems with theoretically attractive characteristics for EVs and/or hybrid vehicles.[14]

Not only are battery-electric cars severely limited in range and performance by the energy and power densities of available batteries, but production costs would also be high, at least initially. A further and serious disadvantage is the limited life of many prospective battery *systems.* Often, the batteries would need to be replaced–at high cost—before the rest of the vehicle reached the end of its useful life. Battery-electric cars also pose new and different safety problems, such as spills of corrosive chemicals in the event of an accident,

Battery-electric powertrains may have a place in local delivery trucks, and perhaps for small, specialized commuter cars. More widespread use depends on large improvements (a factor of at least 5 in battery performance, particularly energy density). Although research and development (R&D) on battery systems for EV applications will continue, there seems little likelihood of significant production—i. e., hundreds of thousands of vehicles per year—before the end of the century. "Breakthroughs" in batteries are improbable; slow incremental progress is more likely to characterize R&D on battery systems, and hence EV (and hybrid) vehicles. Moreover, by the time battery performance is improved sufficiently for practical application, progress in fuel-cell technology may make the latter a more attractive option. (Fuel cells convert a fuel, now generally hydrogen but potentially a hydrocarbon or methanol, directly to electricity.)

Hybrids also are limited by battery performance, but the on board charging capacity means that not as many batteries are needed, so the bat-

---

[14] A. R. Landgrebe, et al., **"Status of New Electrochemical Storage and Conversion Technologies for Vehicle Applications, "** *Proceedings of the 16th Intersociety Energy Conversion Engineering Conference,* **Atlanta,** Ga., **Aug. 9-14, 1981, Vol. 1 (New York: American Society of Mechanical Engineers, 1981), p. 738.**

tery **pack is lighter.** However, hybrids must carry a complete heat engine, as well as a generator or alternator, and an electric drive motor. Although the engine can be small, because it need not be capable of powering the vehicle by itself, the cost and complication of the hybrid powertrain are prohibitive, at least at present. The complication comes not only from the duplicate energy conversion and drive systems but also from the control system. While the performance requirements for the control system are not unusual, the need for a reliable, mass-produced system at reasonable cost does create a demanding set of constraints. The added weight of the batteries and duplicate drivetrain, and the efficiency losses associated with recharging the batteries, also tend to counteract the theoretical advantages of hybrids in fuel economy.

FUTURE AUTOMOBILE FUEL EFFICIENCY

Automobile technology is not a major constraint on fuel economy. Small cars can be designed today—indeed, are on the market—with mileage ratings twice the current new-car average. Technology *is* important for increasing the fuel economy of the larger, more powerful, and more luxurious cars that many Americans still desire. Evolutionary improvements will continue to increase the mileage of both large and small cars, but the pacing factor at the moment is market demand.

Because consumer demand is unpredictable, estimates of post-1985 fuel economy are uncertain; these estimates largely reflect expectations of the importance consumers will place on size and gas mileage. Projections of the fuel economy that the U.S. new-car fleet will achieve vary widely, but most now tend to be optimistic. Only 2 or 3 years ago, American automakers viewed the CAFE standards, correctly, as pushing their product lines away from the sorts of cars that most consumers still demanded. Now many of those same consumers are buying cars with average fuel economies above the CAFE requirements.

EPA statistics indicate that average domestic new-car fuel economy averaged almost 24 mpg for 1981 models sold through January 5, 1981.[15] If imports are included, the figure is about 25 mpg. A few predictions are as high as 90 mpg for 1995 or 2000, although such projections are usually exhortations rather than realistic attempts to project future trends. While the technology to achieve such efficiencies will exist, fleet averages are likely to remain well below the economy ratings that the best performers will be able to achieve.

The primary differences among the many projections of automobile fuel economy for the years ahead arise from varying assumptions of future market demand. Different assumptions for the rate of introduction of new technology are also common. A constraint for American manufacturers may be the ability to generate and attract capital for R&D and for investment in new plant and equipment, particularly if movement toward small, high-mileage cars and introductions of new technology are more rapid than domestic firms have been anticipating. Many foreign automakers already produce cars that are smaller and lighter —and get better fuel economy—than those they now sell in the United States.

Although the fuel economy achieved by the new-car fleet in future years will depend strongly on market demand and the health of the auto industry, technology is also important. Both the timing of new vehicle designs and their ultimate costs—whether routine downsizing and materials substitution, or more demanding tasks such as improved powerplants—depend on extensive programs of engineering development. These take time and talent, as well as money. Complete success can never be guaranteed. Some projects will have more satisfactory outcomes than others.

To distinguish these technological dimensions from questions of market demand, the discussion below first outlines two scenarios for future developments in automobile technology. Designated the “high-estimate scenario” and the “low-esti-

---

[15]" Light Duty Automotive Fuel Economy . . . Trends Through 1981 ,“ op. cit.

mate scenario, " they represent plausible upper and lower bounds for fleet average passenger-car fuel economy in future years. Of course, among the cars on the market in any year, some would have mileage ratings considerably below, some considerably above, the fleet averages for that year. These scenarios are independent of market demand for cars of various size classes, and are simply based, respectively, on optimistic and pessimistic expectations for rates of advance in automobile technology as these affect fuel economy. Using these scenarios, later sections of the chapter discuss the effect of market demand on the fuel economy of the U.S. auto fleet.

Technology Scenarios

Both the high- and low-estimate technology scenarios take as a baseline the new-car fuel economy now expected for 1985. This baseline includes a "number of technical advances, as well as further downsizing, compared with 1982 model cars. While the product plans of individual manufacturers for 1985 are not known in detail, the broad outlines of 1985 passenger-car technologies can be easily discerned. The scenarios then cover the period 1985-2000. The high *estimate* assumes:

- that engineering development projects aimed at improving fuel economy are generally successful;
- that these technological improvements are quickly introduced into volume production; and
- that they produce fuel economy improvements at the high end of the range that can now be anticipated.

The low *estimate* assumes, in contrast:

- that development projects are not as successful–e.g., that technical problems decrease the magnitude of fuel-economy gains, lengthen development schedules, and/or result in high production costs;
- the pace of development is slower than would result from the vigorous efforts to "push" automotive technology assumed for the high estimate scenario; and
- the resulting fuel-economy improvements are at the low end of the range that can now be anticipated.

From a technological perspective, the vehicle subsystem most critical for fuel-economy improvements is the powertrain-i.e., the engine and transmission. Here, as in other aspects of automotive technology, more-or-less continuous evolutionary development can be expected. But major changes in powertrains have also been occurring—e.g., new applications of diesel engines to passenger cars.

The pace of development may vary for other aspects of automobile technology—aerodynamics, downsizing and weight reduction, power consumption by accessories—but individual innovations with large impacts on fuel economy are unlikely. Engine developments, in contrast, depend more heavily on successful long-term R&D programs; fundamental knowledge–e.g., of combustion processes–is often lacking, and the risks as well as the rewards can be large. In contrast, development programs aimed, for instance, at friction reduction, are likely to be more straightforward–and less costly.

Table 21 presents OTA's high and low estimates for improvements in fuel economy by category of technology, based largely on informed technical judgments. * Relative to an assumed 1985 car which gets 30 mpg (EPA rating, 55 percent city, 45 percent highway driving cycle), table 21 indicates that gains of 35 percent in fuel economy may be possible from engine redesigns, but that percentage improvements in transmissions and vehicle systems are likely to be smaller. Nonetheless, the cumulative improvements in fuel economy can be quite large.

Alternative methodologies for estimating future fuel economy—e.g., the use of learning curves, or analytical modeling of the vehicle system—generally lead to comparable results. All approaches to projecting fuel economy have their limitations. The method adopted by OTA does not always do the best job of evaluating the systems effects of combining different technologies—i.e., open-chamber diesel engines combined with four-speed lockup torque converters. Learning curves, based on historical trends, do not take explicit account of new technologies. Analytical modeling is a valuable tool for comparing alternative technologies,** but models ***must **be validated by comparison with hardware results before the model can be used with confidence.**

Table 21.–Prospective Automobile Fuel-Efficiency Increases, 1986-2000

	Percentage gain in fuel efficiency					
	High estimate			Low estimate		
Technology	1986-90	1991-95	1996-2000	1986-90	1991-95	1996-2000
Engines						
Spark-ignition (SI)	10	10-15	15	5	5-10	5-10
Diesel:						
Prechamber. ,	15	15		15	15	
Open chamber	25	35	35	20	20	25
Open chamber (SI) stratified charge (SC)		15	20			
Hybrid diesel/SC			35			
Transmissions						
Automatic with lockup torque converter	5	5	5	5	5	5
Continuously variable ((XT).		10	15			10
Engine on-off		10	10			10
Vehicle system						
Weight reduction (downsizing and materials substitution)	8	13	18	4	8	10
Resistance and friction (excluding engine)						
Aerodynamics.	2	3	4	1	2	3
Rolling resistance and lubricants	1	2	3	1	1	2
Accessories	2	3	4	1	1	2

[a] improvements in fuel efficiency are expressed as percentage gain in mpg compared with an anticipated average 1985 passenger car. The 1985 average car used as a reference has an Inertia weight of about 2,500 lb, is equipped with spark-ignition engine, three-aped automatic transmission, and radial tires, and has an EPA mileage rating (55 percent city, 45 percent highway) of 30 mpg. The fuel efficiencies of the individual baseline cars, which are used to calculate future fuel efficiencies in each size class, are given In tables 23 and 24. Percentages are given on an equivalent Btu basis where appropriate—e.g., for diesels, which use fuel having higher energy content per gallon than gasoline, the percentage gain refers to miles per gallon of gasoline equivalent, which Is 10 percent less than miles per gallon of diesel fuel. The table does not include efficiency improvements from alternate fuels such as alcohol.

SOURCE: Office of Technology Assessment.

None of the figures in this table should be interpreted as predictions. Rather, they illustrate ranges in fuel-economy improvement, based on OTA's judgment of what is likely to be technically practical. The projected improvements are not directly associated with the developmental programs of specific automobile manufacturers—either domestic or foreign. As changes in automobile technology occur, older designs will coexist with new—just as, recently, older V-8 SI engines have remained in production alongside replacements such as diesels and V-6 SI engines. New engines and transmissions are typically introduced with the presumption that they will remain in production for at least 10 years. These rather slow and gradual patterns of technological change are likely to continue unless market conditions force an acceleration. For this to happen, the market pressures would have to be rather intense, if only because of the limited capital resources available at present to the domestic automakers.

Table 21 lists the net improvements in automobile components that could be expected, on the average, for the high and low estimates during each 5-year period. Note that the technologies listed in the table are not in every case compatible with one another, nor can any simple combining procedure yield net figures that have clear and direct meaning for particular hypothetical vehicles. This is because different technologies combine in different ways. For example, the poor part-load efficiencies of throttled SI engines mean that continuously variable transmissions and engine on-off will yield greater improvements than for partially throttled open-chamber stratified-charge engines or diesels. Thus, the choice of cost-effective technologies cannot be inferred from such a table alone, but must depend on more detailed analysis, and finally on testing.

The technologies listed in table 21 are discussed in more detail in appendix 5A at the end of this chapter.

Projection of Automobile Fleet Fuel Efficiency

Based on the technological scenarios in table 21 and several assumptions about the size mix of new cars, OTA has constructed a set of projections for the fuel economy of passenger cars sold in the U.S. market in future years. As emphasized earlier in this chapter, market demand—not technology—is the key factor in determining the mileage potential of the new-car fleet, Market demand is particularly critical in determining the size mix of new-car sales.

The automobile technologies listed in table 21 are more important as tools for increasing the fuel economy of the larger, more luxurious cars that many American purchasers still demand than for cars that are small and light—e.g., nearly all current imports, as well as the new generations of American-made subcompacts. Improved powertrains and the use of materials with high strength-to-weight ratios will lead to improved fuel economy in cars of all sizes. But a 10-percent increase in gas mileage for a big car—with mileage that is initially low—saves more fuel than a 10-percent improvement to a small car that is already more fuel efficient.

This is not to say, however, that a given technological development will necessarily give the same percentage improvement for cars of all sizes—or even be applicable to all types of cars. Continuously variable transmissions (CVTs) have been in limited use for many years in small cars, and would no doubt be applied widely in subcompacts before finding their way into heavier vehicles. The reason is simply that the mechanical design problems for a CVT are simpler if the levels of torque that must be transmitted are low.

On the other hand, if gas turbines become practical as automobile powerplants, they are likely to be used first–and perhaps exclusively–in big cars, because turbine engines are more efficient in larger sizes.

Any projection of fleet fuel economy will depend on the assumed weight (size) mix of new-car sales in the years ahead. For its analysis, OTA adopted a simplified description of this mix, based on three size classes–small, medium, and large. This allows possible market shifts to be analyzed in terms of the assumed proportion of new-car sales by size class—for each of which the average fuel economy has been estimated. This is a considerable abstraction from the real situation –-one in which the spectrum of curb weights from which consumers select extends from less than 2,000 lb to over 4,000 lb. For any given weight—now and in the future—there will also be a range of fuel economies, depending on vehicle design. The convenience of the description in terms of only three size classes, for which other characteristics are averaged, comes at the expense of the richness and variety that will actually exist in the marketplace.

New-Car Fuel Efficiency by Size Class

Table 22 describes the small, medium, and large size classes on which OTA's projections are based. The scheme is similar to current EPA practice for fuel-economy ratings—grouping cars of similar passenger capacity and interior volume. However, the designations of car sizes in table 22 differ from some current designations because they are intended to reflect future vehicle characteristics rather than the past; in other words, OTA prefers to call a future small car just that, not a ‘‘minicompact.“ Each class in the table encompasses a considerable range of possible vehicle designs. Under either the high or low estimate scenarios, curb weights of cars in the U.S. fleet are expected to decrease over the period 1985-2000.

Table 22.–Small, Medium, and Large Size Classes Assumed for 1985-2000

	Curb weight[a] (lb)				1981 equivalents	
Class	High estimate	Low estimate	Interior volume (ft^3)	Passenger capacity	Size class	Typical models
Small	1,300-1,600	1,400-1,700	< 85	2-4	Minicompact, two seaters	Honda Civic Toyota Starlet
Medium.	1,600-2,000	1,700-2,000	80-110	4	Subcompact, compact	VW Rabbit Chrysler K-Car
Large.	2,200-3,000	2,500-3,000	100-160	5-6	Intermediate, large, luxury	GM X-Car Ford Fairmont

[a] Curb weight is the weight of the car without passengers or cargo.

SOURCE: Office of Technology Assessment.

Tables 23 and 24 expand on the descriptions in table *22.* For these tables, OTA has **estimated weight averages, engine alternatives, and average fuel economies at 5-year intervals through 2000** for the two technology scenarios. **Again, these estimates reflect informed technical judgment but should not be viewed as predictions.** The curb weights are averages expected for each of the three size classes; rather broad ranges in actual weights are likely, especially in the medium and large classes. The fuel **economy estimates are** likewise averages with considerable spread anticipated. Fuel economy projections are given in terms of current **EPA rating practice (combined city-highway figures)—which overestimate actual over-the-road mileage by as much as 20 percent.** The EPA rating basis has been adopted for ease of comparison with fuel economy ratings for the current fleet; in later sections, to estimate actual fuel consumed, EPA ratings are adjusted downward to more realistic values.

The average fuel economy estimates in tables 23 and 24 for the high- and low-estimate technology scenarios are grouped together in table 25 so that the differences by size class and technology level can be more easily compared. Table 25 illustrates the importance of size and weight for fuel economy. By 2000, the low-estimate average efficiency for medium-size cars is the same as the high-estimate efficiency for big cars—both are 50 mpg. Large cars show the greatest percentage improvements because more can be done to improve fuel economy before diminishing returns become severe.

One way to abstract the effects of downsizing and weight reduction from other technological improvements is to examine specific fuel economy—by normalizing to ton-mpg, or the miles per gallon that would result for an otherwise similar car weighing 1 ton. Ton-mpg values have exhibited an upward trend overtime as automotive technologies have improved.[16]

Figure 9 shows the gradual increase–with considerable year-to-year fluctuations—that has characterized average fuel economy in ton-mpg for the U.S. new-car fleet over the past decade, together with estimates through 2000 based on the

---

[16] "Powerplant Efficiency Projected Via Learning Curves, " *Automotive Engineering* July 1979, p. 52.

Table 23.—Automobile Characteristics- High-Estimate Scenario

	Small				Medium				Large			
	1965	1990	1995	2000	1965	1990	1995	2000	1985	1990	1995	2000
Average curb weight (lb)	1,600	1,500	1,400	1,300	2,000	1,800	1,700	1,600	3,000	2,600	2,400	2,200
Engine type (percent):												
Spark ignition	100	95	70	60	90	70	50	30	75	30	30	25
Prechamber diesel	—	5	—	—	10	10	—	—	25	40	—	—
Open chamber diesel or open chamber stratified charge	—		30	40		20	50	70	–	30	70	75
Fuel economy[a] (mpg)	48	62	74	84	39	51	61	71	27	37	43	49

[a] Combined EPA clty/highway fuel-economy rating, baaed on 55 percent city and 45 percent highway driving.

SOURCE: Office of Technology Assessment.

Table 24.—Automobile Characteristics-Low-Estimate Scenario

	Small				Medium				Large			
	1965	1990	1995	2000	1985	1990	1995	2000	1985	1990	1995	2000
Average curb weight (lb)	1,700	1,600	1,500	1,400	2,000	1,900	1,600	1,700	3,000	2,600	2,600	2,500
Engine type (percent):												
Spark ignition	100	100	100	60	90	60	70	70	75	60	50	40
Prechamber diesel	—	—	—	—	10	20	30		25	40	20	
Open chamber diesel	—	—	—	40	—	—	—	3 0	-	–	–	3 O G
Fuel economy[a] (mpg)	*45*	*52*	*57*	*65*	*35*	*41*	*45*	*50*	*23*	*28*	*31*	*34*

[a] Combined EPA city/highway fuel-economy rating, baaed on 55 percent city and 45 percent highway driving.

SOURCE: Office of Technology Assessment.

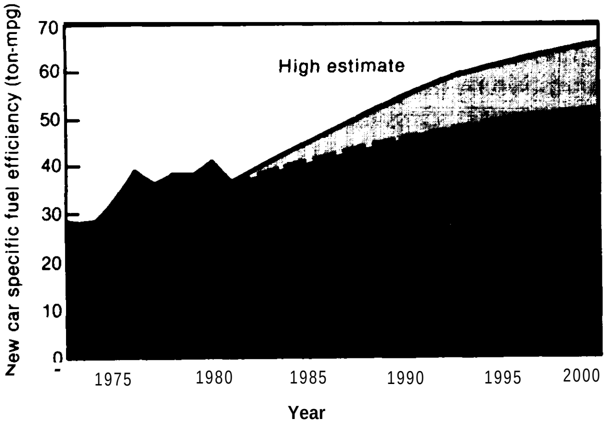
Table 25.—Estimated New-Car Fuel Economy: 1985-2000

	Average new-car fuel economy[a]			
Size class	1985	1990	1995	2000
Large:				
High estimate	27	37	43	49
Low estimate	23	28	31	34
Medium:				
High estimate	39	51	61	71
Low estimate	35	41	45	50
Small:				
High estimate	48	62	74	84
Low estimate	45	52	57	65

[a] Combined EPA city/highway fuel-economy rating, based on 55 percent city and 45 percent highway driving.

SOURCE: Office of Technology Assessment.

Figure 9.—Sales.Weighted Average New-Car Fleet Specific Fuel Efficiency



SOURCE: Off Ice of Technology Assessment.

high and low scenarios in table 21. As for the earlier tables, figure 9 aggregates both domestic automobiles and imports. Using such projections, the fuel economies of future new-car fleets of various size (weight) mixes can be estimated.

As the figure shows, average specific fuel consumption for new cars sold in the United States has increased from less than 30 ton-mpg in the early 1970's to roughly 39 ton-mpg in 1981, a 30-percent improvement. The most efficient 1981 cars sold in this country gets 50 ton-mpg. * By 1990, the average should equal the current best. By 2000, the *average* could be as high as 65 ton-mpg.

Based on the projections in tables 23-25, or alternatively those in figure 9, the effects of changes in the size mix of the new-car fleet can be estimated. In the mix of new 1981 cars sold through January 5, 1981, small cars made up only 5 percent of the market; the rest was almost evenly divided between medium cars (48 percent) and large cars (47 percent). By 1985, the share of small cars may remain at 5 percent, but the share of medium cars is expected to go up at least to 60 percent, dropping the large-car share to 35 percent or less. Even in the unlikely event that the 60:35, ratio remains unchanged beyond 1985–that medium cars show no further sales gains over large cars–the average fuel economy of the new-car fleet in 2000 would be 62 mpg in the high-estimate scenario, 43 mpg in the low-estimate scenario. * (See table 26, "no mix shift" case.) These figures represent a substantial improvement over the 25 mpg expected in 1981 and the 30 to 35 mpg expected for 1985. A further shift in consumer preference toward smaller and lighter cars would increase the expected fleet-average fuel economy even more.

To illustrate the effects of a continuing shift towards smaller and lighter cars, table 26 also gives average fuel economies at 5-year intervals for a "moderate" mix shift-leading to 35 percent small cars, 50 percent medium cars, and 15 percent large cars by 2000-and for a "large-scale" mix shift. The latter assumes 70 percent small cars, 25 percent medium cars, and only 5 percent large cars in 2000. **As** the table shows, the large-scale mix shift could give a new-car fleet average fuel economy of 60 to 80 mpg by 2000. Whether market demand will lead to such a mix shift depends on factors such as price differentials between large and small cars, and the compromises in other vehicle characteristics that accompany smaller cars, as well as the pricing and availability of fuel.

---

*These are diesels, for which the ton-mpg rating has been expressed on a gasoline-equivalent basis; the value based on diesel fuel would be about 55 ton-mpg. The best current SI engine models sold in the United States have ton-mpg ratings about 10 percent lower, or roughly 45 ton-mpg.

*The corresponding numbers for the 1981 mix are 59 mpg in the high estimate and 41 mpg in the low estimate.

Table 26.—Effect on Size Mix on Estimated Fuel Economy of the New-Car Sales in the United States

	Estimated average new-car fuel economy[a] (mpg)											
	No mix shift[b]				Moderate mix shift[c]				Large-scale mix shift[d]			
Technology scenario	1985	1990	1995	2000	1985	1990	1995	2000	1985	1990	1995	2000
High estimate	34	45	54	62	34	48	59	70	37	53	65	78
Low estimate	30	36	39	43	30	38	43	51	33	43	49	58

[a] 55 percent city, 45 percent highway EPA rating.

[b] The no mix shift case assumes:

Size class	*Sales mix (percent) for all years*
Small	5
Medium	60
Large	35

[c] The moderate mix shift assumption is as follows:

	Sales *mix (percent)*			
Size class	*1985*	*1990*	*1995*	*2000*
Small	5	15	25	35
Medium	60	60	55	50
Large	35	25	20	15

[d] The large-scale mix shift assumption is:

	Sales mix (percent)			
Size class	*1985*	*1990*	*1995*	*2000*
Small	10	30	50	70
Medium	75	65	45	25
Large	15	5	5	5

SOURCE: Office of Technology Assessment.

ESTIMATED FUEL CONSUMPTION, 1985–2000

In this section estimates of the fuel consumed by the U.S. passenger-car fleet are based on the various assumptions and projections of car size mix and efficiency discussed above, but assume that gasoline and diesel fuel continue to power passenger vehicles, with no significant penetration of alternative fuels such as methanol.

In 1975, when Federal fuel economy standards were enacted, passenger cars consumed an average of about 4.3 MMB/D of fuel. (Trucks are omitted from the calculations in this chapter, but many light trucks and vans are used interchangeably with passenger cars and add about 1.1 MMB/D to average consumption). Passenger-car fuel consumption rose to 4.8 MMB/D in 1978, but has since declined to 4.3 MMB/D–about the 1975 level.[17] OTA projects that passenger-car fuel consumption will continue to decline—to about 3.6 MMB/D in 1985, as the automobile fleet becomes more fuel-efficient. This estimate assumes that the fleet will grow from about 107 million cars in 1980 to 110 million in 1985, and that the average car will continue to accumulate about 10,000 miles per year.

Projected Passenger-Car Fuel Consumption

The baseline chosen for discussing fuel consumption by passenger cars past 1985 is outlined in table 27. Growth in the automobile fleet—which depends on both sales levels for new cars, and the rates at which older cars are scrapped—is

Table 27.—Baseline Assumptions for Projections of Automobile Fuel Consumption

	1980	1985	1990	1995	2000	2005	2010
Vehicle miles of travel: Trillion miles/yr	1.14	1.17	1.20	1.23	1.26	1.28	1.31

Also assumes 47 percent of fleet vehicle miles traveled (VMT) by cars less than 5 years old, 38 percent of VMT by cars 5 to 10 years old, and 15 percent of VMT by cars older than 10 years.

New-car fuel economy (combined EPA ratings; 55 percent city, 45 percent highway)

1985 base case (low-high estimate)

Small cars:	45-48 mpg
Medium cars:	35-39 mpg
Large cars:	23-27 mpg

Fleet baseline average efficiency
30 mpg, 1985-2010

High- and low-estimate scenarios
See table 25

On-the-road fuel efficiency:
10 percent less than EPA rated fuel efficiency

Size *mix:*
See table 26

SOURCE: Office of Technology Assessment.

---

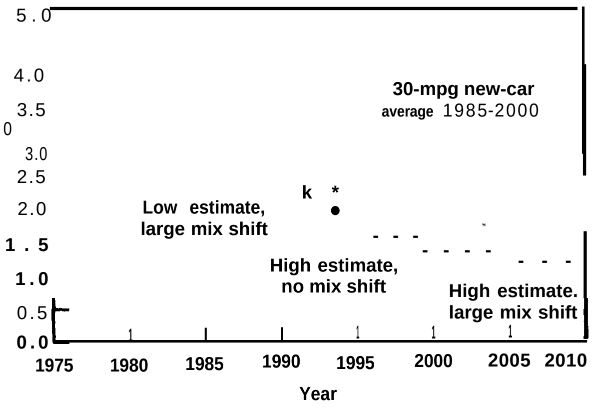
[17] Derived from J. K. Pollard, et al., "Transportation Energy Outlook: 1985-2000," Transportation Systems Center, U.S. Department of Transportation, DOT-TSC-RS-1 12-55-81-6, September 1981, pp. 4-21; and "Monthly Energy Review, " Energy Information Agency, U.S. Department of Energy, DOE/EIA-0035 (81/10), October 1981.

projected to average less than 2 percent per year.[18] Cars are assumed to be driven an average of 10,000 miles per year, with newer cars driven more and older cars driven less, on the average (see table **27).** The projections for new-car fuel economy and future size mix are taken from the tables in earlier sections. Because those fuel-economy projections were based on EPA ratings, which overestimate actual on-the-road mileage, fuel economy has been adjusted downward 10 percent to compensate.

If neither fuel economy nor size mix were to advance past a 1985 baseline average of 30 mpg, fuel consumption by passenger cars would still decline slowly for 10 years, reflecting the larger fraction of cars in the fleet with fuel economies at this baseline value, Between 1985 and 1995, passenger-car fuel consumption would decline–even with a status quo in fuel economy and size mix—from about 3.6 MMB/D in 1985 to 2.7 MMB/D in 1995. Thereafter, the upward trend would resume because of increases in the total size of the fleet.

But of course, automobile technology will continue to improve (table 21), and a continuing shift toward smaller cars is also probable (table 26). Therefore, under almost any realistic set of assumptions, passenger-car fuel consumption will continue to decrease during the post-1995 period. At some point it may still turn upward because of increases in fleet size, this turning point depending on both technology and size mix. In any case, as figure 10 shows, the decline in passenger-car fuel consumption will level off by about 2005 (unless growth in the fleet is slower than projected in table 27 or cars are driven fewer miles per year).

Figure 10.—Projected Passenger-Car Fuel Consumption



SOURCE: Off Ice of Technology Assessment.

Figure 10 gives fuel-consumption projections to 2010 based on these assumptions. The influence of technological improvements is striking. For example, even without a mix shift toward cars smaller than in the 1985 baseline mix, the high estimate gives fuel savings greater than those for the low estimate with a large-scale shift towards smaller cars. But such a mix shift would also create substantial fuel savings. For the cases plotted in this figure, passenger-car fuel consumption stays well below 2.5 MMB/D during the early years of the next century. The figure also shows the potential benefits if technical success is accompanied by a strong shift to smaller cars. The difference in 2010 between the low estimate with no mix shift (about 2.0 MM B/D), and the high estimate with a large mix shift toward smaller cars (1.1 MMB/D), is nearly a factor of 2. The lower end of this range is about one-fourth the current level of fuel consumption. Where within this range the actual fuel consumption would fall is likely to depend–as emphasized earlier–on market demand for fuel-efficient vehicles, and/or continuing Government policies designed to encourage the manufacture and purchase* of fuel-efficient cars. Changes in vehicle miles traveled would also change the fuel consumption proportionately.

---

[18] *U.S. Industrial* ***Competitiveness: A Comparison of*** *Steel, Electronics,* **and Automobiles,** op. cit., pp. 140-141.

An illustration of the importance of new-car sales can be derived as follows: In 1980, 47 percent of the vehicle-miles traveled (VMT) were by cars 0 to 4 years old, 38 percent by 5 to 9 year old cars, and 15 percent by cars 10 years old and older. Call this the base case. A persistent 20 percent depression in new car sales could change the VMT distribution by 1995 to: 40 percent by cars O to 4 years old, 35 percent by cars 5 to 9 years old, and 25 percent by cars 10 years old and older. Call this the "low" car sales case. If VMT are held constant at the 1980 level, fuel consumption under the base case would be up to 0.3 MMB/D (or nearly 20 Percent)** ***lower **than fuel consumption in the "low" car sales case in 1990, everything else being equal. And cumulative oil savings could be over 1 billion bbl during the period 1981-2000. The base case, however, probably would be accompanied by higher VMT than the "low" sales case, and much of this savings could be lost.**

Total projected oil savings are bracketed by the curves in figure 11. These show the fuel conserved relative to the 1985 baseline case of new-car efficiencies of 30 mpg between 1985 and 2010. Clearly, the high-estimate technology scenario, accompanied by a continuing shift toward smaller cars, leads to large fuel savings. By 2010–when virtually the full benefit of fuel savings from **cars sold in the period 1985-2000** would be realized–the cumulative savings (relative to **a 30-mpg fleet) could be as high as 10 billion bbl of oil equivalent. This is equivalent to 6 years sup**ply of passenger-car fuel at the 1980 rate of consumption. The fuel **economy increases expected between now and 1985 would add about** 14 billion bbl to this cumulative savings between now and 2010 (relative to 1980 fuel consumption). Thus, between now and 2010, the total savings possible is about 24 billion bbl relative to 1980 passenger-car fuel consumption–an amount about equal to proven U.S. oil reserves, which were 26.5 billion bbl as of 1980.[19]

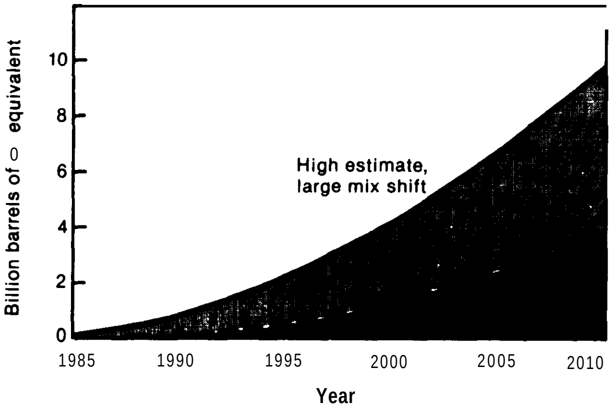
Substitution of Electric Vehicles

The estimates above are based on a passenger-car fleet for which energy comes from a fuel carried onboard—e.g., gasoline or diesel fuel. In the "Battery-Electric and Hybrid Vehicles" section, the prospects for EVs were briefly discussed, with the conclusion that major improvements in battery performance were necessary before EVs (or hybrids) would be practical in any but very specialized applications. If, however, these improvements are achieved—or if acute shortages of transportation fuels occur in the future—EVs might be sold in sufficiently large numbers to affect petroleum consumption.

The result would be to replace some of the petroleum consumed in the transportation sector by electric power generation. To the extent that this electricity was produced from nonpetroleum fuels–e.g., natural gas, coal, nuclear–the cumulative oil savings shown in figure 10 would increase (see app. 56). Table 28 illustrates the results for a highly optimistic level of EV substitution. Note that this again is *not* a prediction; substantial penetration by electric and/or hybrid vehicles **(EHVs) before the** end of the century is unlikely, and doubtful even thereafter. The table simply shows what might happen if battery improvements occur more rapidly than OTA ex**pects, or** if other factors combine to increase the attractiveness of **EHVs. Table 28 assumes that EHVs represent 5 percent of the total U.S. passenger-car fleet by 2000, and 20 percent by 2010. This** would require **EHV production and sales at** levels of several million per year during the last few years of the century.

Table 28 shows that penetration of EHVs at high enough rates could begin to replace meaningful volumes (14 percent) of transportation fuels dur-

Figure II.—Cumulative Oil Savings From Increased Automobile Fuel Efficiency Relative to 30 MPG in 1985, No Change Thereafter



SOURCE: Office of Technology Assessment.

Table 28.—Effects of Substituting Electric Vehicles[a]

	Composition of passenger-car fleet (million)		Passenger-car fuel consumed or replaced (MMBID)	
	2000	2010	2000	2010
Conventional cars	133	124	1.7	1.4
EVs	7	31	0.04	0.2
Percent EVs	5	20	—	—
Percent fuel consumption replaced.	—	—	2	14

[a] If battery Improvements occur more rapidly than OTA expects, or if other factors combine to increase the attractiveness of electric vehicles.

SOURCE: Office of Technology Assessment.

---

[19] *World Petroleum Availability 1980-2000— Technical Memorandum, OTA-TM-5* **(Washington, D. C.: U.S. Congress, Office of Technology Assessment, October 1980.)**

ing the first decade of the next century. Nonetheless, the savings in petroleum would be relatively small in absolute terms–because EHVs are best suited as replacements for small cars which already get good mileage.

Comparing the estimated fuel savings in table 28–only **0.2** MM B/D even for optimistic assumptions of EHV penetration—with the fuel-consumption trends projected in figure 9, demonstrates that improvements in automobile technology, particularly if combined with more rapid mix shifts toward smaller cars, offer much greater potential. Thus, the primary apparent advantage of EVs during the next 30 years is that they would not depend on petroleum supplies—an important factor if severe absolute shortages develop–rather than any potential for *saving* petroleum.

Fuel Use by Other Transportation Modes

Thus far, the discussion of fuel consumption has been restricted to passenger cars, although, as pointed out earlier, many light trucks—i.e., vans and pickups—are used primarily for passenger travel. In addition, medium and heavy trucks, buses, motorcycles, and airplanes–plus rail and marine transportation and military operations—consume petroleum-based fuels. All of these transportation modes depend predominately on heat engines for power, although SI engines are not so widely used as in passenger cars. Diesels have already replaced SI engines in almost all heavy trucks, and rates of installation in medium-duty trucks are going up rapidly. Diesels are also common in rail and marine applications, although some large ships rely on gas turbines or steam power. Commercial aircraft are generally powered by turbine engines.

Table 29 summarizes the projected oil consumption for transportation between 1980 and 2000. The projections for automobiles are derived in this chapter, while those for other transportation modes are taken from the "market trend" base case in a recent Department of Transportation study.[20] The projections for fuel consumption by trucks in table 29 assume that many of the technological improvements discussed above for passenger cars will also be applicable to light trucks. However, the specific technologies discussed elsewhere in this chapter are more generally appropriate to pickup trucks and vans than to medium and heavy trucks.

---

[20] **J. K. Pollard, et al., "Transportation Energy Outlook: 1985-2000," Transportation Systems Center, U.S. Department of Transportation; DOT-TSC-RS-1 12-55-81-6, September 1981.**

Table 29.-Projected Petroleum-Based Fuel Use for Transportation

	1980[a]		1990[a]		2000[a]	
Mode	MMB/D[b]	Percent	MMB/D[b]	Percent	MMB/D[b]	Percent
Passenger car	4.3	49	2.4-2.9	35	1.3-2.1	23
Light trucks	1.1	13	0.9	12	0.8	11
Other trucks	1.1	13	1.2	16	1.4	19
Other highway (buses, motorcycles, etc.)	0.1	1	0.2	3	0.2	3
Total highway	6.6	75[c]	4.7-5.2	65[c]	3.7-4.5	55[c]
Air	0.8	9	1.1	14	1.5	20
Marine	0.7	8	0.8	10	0.9	12
Rail	0.3	3	0.4	5	0.4	5
Pipelines [d]	0.1		0.1	1	0.1	1
Military Operation	0.3	3	0.3	4	0.4	5
Total nonhighway	2.2	25[c]	2.7	35[c]	3.3	45[c]
Total	8.8	100	7.4-7.9	100	7.0-7.8	100

[a] All fuel consumption numbers, except for passenger cars, from J. K. Pollard, C. T. Phillips, R. C. Ricci, and N. Rosenberg, "Transportation Energy Outlook: 1985-2000," U.S. Department of Transportation, Transportation Systems Center, Cambridge, Mass., DOT-TSC-RS-112-55-81-6, September 1981. Passenger-car fuel consumption from this study.
[b] 1B -5.9 MMBtu.
[c] Sums may not agree due to round-off errors.
[d] Does not include natural gas.

SOURCE: Office of Technology Assessment.

Some of the fuel economy gains for other transportation modes—as for passenger cars—will be offset by growth in miles traveled. Annual growth rates of 1 to 3 percent per year are expected for most modes of transport, although sales of light trucks have recently dropped to such an extent that mileage traveled by such vehicles may decrease in the years ahead. **In** total, fuel consumed for transportation is projected to decline from 8.8 MMB/D in 1980 to the range of 7 to 8 MMB/D by 2000, and then to rise slowly as diminishing returns set in.

Because of the differing growth rates for the various transportation modes and the differing magnitudes of the fuel economy improvements expected, the distribution of fuel use by mode will change. Passenger cars now account for half of all the fuel used in transportation. Their share will decrease to about 25 percent by the early part of the next century. Medium and heavy trucks currently consume 12 percent of all transportation fuel, a figure that could rise to 20 **percent** by 2000. Likewise, the percentage of transport fuels used by aircraft could nearly double.

COSTS OF INCREASED FUEL EFFICIENCY

Overview

Automobile manufacturers spend for many purposes–R&D, investment in plant and equipment, labor, materials, marketing, and administration. How much a particular manufacturer spends depends on the firm's financial capabilities, the rate of technology change, initial characteristics of the product line, and the state of existing manufacturing facilities.

R&D on vehicle designs and manufacturing processes is an important spending area. Development—on which most R&D money is spent, research expenditures being small by comparison —creates new product designs and production methods. Growth in R&D activity, required to support rapid changes in vehicle design, will raise both the total costs of automobile production and the proportion of development and other preproduction expenses.

In 1980, the four major domestic manufacturers spent almost $4.25 billion (1980 dollars) on R&D. For individual firms, this spending amounted to 2 to 5 percent of sales revenues. in addition, major parts and equipment suppliers spent about $293 million on automotive R&Din 1980. Together, major automobile manufacturers and suppliers spent over $4.5 billion on R&D for automobiles and other vehicles.[21]

Capital investment levels are even greater. These expenditures, which go hand-in-hand with design and development activities, are the largest single category of spending in automobile manufacturing. Major categories of capital goods include factory structures, production equipment such as machine tools and transfer lines, and a wide variety of special tools such as dies, jigs, and fixtures.

Manufacturers today are making investments to improve product quality, as well as increase productivity and cut costs. Flexible manufacturing is also becoming an increasingly attractive investment. Such sophisticated facilities are relative**ly** expensive but may yield low operating costs and other long-term benefits. General Motors (GM), **Ford,** and Chrysler spent $10.8 billion (1980 dollars) on property, plant, equipment, and special tooling in 1980.22

Financing is an important aspect of capital investment. Historically, the automobile industry has financed capital programs with retained earnings, except during recessions when low sales generated inadequate revenues. Several current, and possibly enduring, factors—declining profitability, high inflation, slow market growth, market volatility, and consumer resistance to real price increases—have eroded manufacturers' ability to finance major capital programs from earnings (or by issuing stock), leading them to borrow funds

---

[21]" R&D Scoreboard: 1979," Business Week, July 7, 1980; "R&D Scoreboard: 1980, " Business Week, July 6, 1981.

[22]Annual Reports for 1980.

and therefore to face potentially higher costs of capital. GM and Ford each borrowed over $1 billion during 1980; they may together borrow as much as $5 billion by the mid-1980's.[23]

Although domestic manufacturers have recently borrowed from foreign and other nontraditional sources, they are able to borrow only a limited portion of their capital needs (at acceptable interest rates). Borrowing in the United States has recently become more costly to automobile manufacturers because their bond ratings have been lowered, in recognition of the low profitability, high spending levels, and high risks that characterize today's auto market. Consequently, they are obtaining cash by restructuring their physical and financial operations (e.g., by selling assets and changing the handling of accounts receivable), engaging in joint ventures, and selling tax credits (under Economic Recovery Tax Act of 1981 leasing rules).

Automotive fuel economy improvement affects other costs as well, although not to the same extent that it affects R&D and capital investment, Costs for labor and materials depend on vehicle design and on production volumes and processes. For example, automated equipment reduces labor content; small cars require less material; and lighter body parts and more efficient engines may require new, relatively expensive materials (high-strength steels, aluminum alloys) and processes (heat treatments, longer weld cycles, a greater number of forming operations, slower machining). Reductions in the amounts of labor and materials used per car help offset inflationary and real increases in their costs. Labor costs, however, are slow to change in the short term because they are subject to union negotiations, and because contractual provisions constrain layoffs and require compensation payments.

Finally, spending on marketing and administration is not directly related to technological change or to production; although these expenses may be cut back to facilitate spending in other areas. During 1980, for example, auto manufacturers made large cuts in white collar staffs to lower administrative costs. However, marketing activities may increase because of heightened competition or the introduction of new products.

The remainder of this chapter focuses on capital costs, because they are the critical component of the overall costs of changing automobile designs. On **a per car basis,** however, labor and materials costs will remain higher than capital costs because of the ways different types of costs are allocated. The costs of capital goods (including financing) are recovered throughout their service life in vehicle prices. Since capital goods are used to produce many vehicles over many years (at least 30 years for plants, 12 years for much production equipment, and 3 to 5 years for special tooling), each vehicle bears a relatively small percentage of the costs of capital to produce it. In contrast, labor services and materials are effectively bought to manufacture each car.

Relative to other manufacturing costs, capital costs are expected **to** undergo the greatest percentage increase as manufacturers increase their output of fuel-efficient vehicles. Moreover, capital costs are becoming proportionately greater because capital goods are being purchased at faster rates and at higher real prices than historically, and because automotive production is becoming more capital-intensive as automation proceeds—i.e., more capital equipment is being used to produce automobiles relative to labor, materials, and other inputs. Consequently, capital costs will have an especially pronounced influence on the financial health of automobile manufacturers over the next two decades.

Investments to Raise Fuel Economy Technology-Specific Costs

Table 30 presents capital cost estimates prepared by OTA for the technologies described earlier in this chapter, based on discussions with industry analysts and the most recently published analyses. However, they draw on the experience and expectations of the mid and late 1970's, when limited consumer demand for fuel economy led manufacturers to make conservative projections of vehicle design changes and high projections of costs. Because of recent surges in the demand for fuel economy and small cars, manufacturers now expect to make substantial im-

---

[23] Also see "Producing More **Fuel-Efficient Automobiles:** A Costly **Proposition, " op. cit.**

Table 30.—Post-1985 Automotive Capital Cost Estimates

	$M/500,000 units	Associated costs
Platform change		
Weight reduction, redesign	500-1,000	R&D[a], redesign
Material substitution	100-400	R&Da, materials, labor
Engine change		
Improved Sib, diesel	50-250	R&D[a], redesign
New Sib, diesel, DISC[c]	400-700	
Transmission change		
Improve contemporary drivetrains	100-400	R&D[a], redesign
New drivetrains—CVT[d], energy storage, engine on-off	500-700	R&D[a], redesign

[a] Capital costs for accessory and lubricant Improvements and aerodynamic and rolling resistance reductions are not Included separately. They may in total cost about $50M/500,000, an amount within the range of error implied by the above estimates. Note: aerodynamic improvements will be carried out with weight-reducing design changes; lubricant end tire changes are already being made by suppliers and may continue as a regular aspect of their businesses; and some accessory Improvements . are made regularly and as accompaniments to engine redesigns.

[b] Spark ignition.

[c] Direct injection stratified charge.

[d] Continuously variable transmission.

SOURCE: Office of Technology Assessment.

provements in fuel economy by the mid-1980's by accelerating technological change schedules and by increasing the proportion of small cars in the sales mix.

Note that increasing production volume for existing models is much cheaper than introducing new models; U.S. manufacturers could probably double their output of many existing models. The costs of design changes in the post-1985 period now seem even more uncertain, because earlier achievements will leave fewer and generally more costly options available.

Projecting costs for specific design changes is difficult, for several reasons. First, the redesign of any one vehicle component or subsystem often necessitates related changes elsewhere. Second, such changes may require new production processes. Third, actual costs to individual manufacturers are technology-specific and sensitive to several factors—technological development, production volume, vertical integration, the rate at which changes penetrate the fleet, and available manufacturing facilities. These factors are discussed below.

Technological Development.–Many technologies are inherently expensive due to materials requirements or complexity of design or manufacture. The diesel engine for passenger cars is a good example. Over time, experience with a new technology may lead to some cost reduction.

Production Volume.–Costs vary with production volume because equipment and processes are designed such that average product cost is lowest once a threshold production volume is achieved.[24] Because this minimum volume or scale grows as the production process becomes more highly automated, the rising capital intensiveness of automobile production increases the sensitivity of unit costs to production volume. Operating costs (comprised of labor, materials, and allocated marketing and administration costs) per unit are sensitive to production volume in the short term. For example, Ford's operating costs per dollar of sales were estimated to be under $0.90 in the first quarter of 1979, but subsequent sales declines brought them close to $1.05 by the fourth quarter of 1980.[25]

The cost estimates in table 30 assume uniform 500,000-unit capacities. * Cost estimates for uniform or optimal capacity levels provide a better measure for spending levels for the industry as a whole than for individual manufacturers because individual firms acquire different levels of capacity at different costs according to their finan-

---

[24] See K. Bhasker, ''The Future of the World Motor Industry" (New York: Nichols Publishing Co., 1980.) The optimum production volumes may change with manufacturing technology, however.

[25] " Ford's Financial Hurdle: Finding Money is Harder and Harder," *Business Week,* February 1981.

*This procedure was aiso employed in the Mellon Institute study (Ref. 32) which drew on data provided by automobile manufacturers.

cial ability, sales volume, and technological options. The costs of acquiring more or less than optimal capacity, however, are not linearly related to the level of capacity.

Vertical Integration.—Vertical integration refers to the degree to which a manufacturer is self-sufficient in production or distribution. integration can reduce costs in two ways: 1) by eliminating activities and costs associated with the transfer of goods between suppliers and distributors (dealers), and the automakers themselves; and 2) by enabling manufacturers to optimize the flow of production and distribution. Major U.S. automobile manufacturers are highly integrated compared with firms in many other industries, although they are much less integrated than oil companies. Various U.S. automobile firms make steel, glass, electronic components, and robots, but overall they buy about ha lf of their materials and other supplies. GM's greater vertical integration relative to other U.S. automobile manufacturers is one reason for its lower manufacturing costs. The high effective degree of vertical integration among Japanese auto manufacturers (over 80 percent for some firms) helps to make auto production in Japan cheaper than in the United States. *

Rate of Change.–The rate at which new technology is incorporated in automobiles influences cost in three important ways. First, the faster a design is implemented, the shorter are the product development, product and process engineering schedules, and the less likely is production to be at minimum cost, given scale. Second, increasing the rate of technological change raises the number and magnitude of purchases from suppliers. Third, a faster rate of change can make facilities and processes technologically obsolete, necessitating investments in replacements before original investments are recovered.

Available Facilities.—Opportunities for manufacturers to redesign their product lines are shaped by the characteristics of their base vehicles and existing production facilities. The technological scenarios described at the beginning of this chapter illustrate how paths of change may differ.

Estimates of manufacturing costs require evaluation of the requirements for implementing each combination of new technologies. Investment by different manufacturers to produce the same vehicle will differ because their initial facilities and vehicle designs provide different bases for change, and because manufacturers have choices in the timing and extent of major facility renovations, in balancing plant renovation and new construction, and the selection of new production equipment—e.g., degree of automation. Different production bases make rapid change more costly for some manufacturers than for others.

The variability in actual facilities costs is illustrated by recent projects associated with new vehicle designs. Chrysler spent over $50 million to renovate its Newark assembly plant to produce 1,120 K-cars per day. * Chrysler made similar alterations to its Jefferson Avenue (Detroit) assembly plant to enable K-car production at the same rate as at the Newark plant, but at a cost of$100 million. GM plans to spend $300 million to $500 million to build a new Cadillac assembly plant (replacing two old ones) on the Chrysler Dodge Main site in Michigan. The differences in these spending levels reflect different starting points and differing objectives. Since automation, quality control, and nonproduction aspects of the above projects contribute to other goals in addition to higher fuel economy, these examples illustrate how difficult it is to infer the specific costs of investments *to* raise fuel economy.

New Car and Fleet Investments

The incremental investments manufacturers make to raise automobile fuel efficiency **will affect the costs of producing new cars and new-car fleets.** To gage **the effect of changing automotive technology on industry investment requirements, the costs of capacity associated with the high- and low-estimate scenarios were estimated**

***These conditions reflect peculiarly close relationships between Japanese manufacturer and supplier firms, even in the absence of formal linkages.**

***The project entailed new plant layout; body shop *renovation;* conveyor system replacement and rearrangement; assembly tooling replacement; installation of automatic and computerized machine welding, transfer, and framing equipment; installation of new painting, front-end alignment, trim and cushion assembly equipment and additional quality control systems.**

by weighting and adding the costs of specific changes. This procedure produces crude estimates of the investments necessary to produce cars at fuel efficiencies projected in the scenarios. * Table 31 presents investment projections by scenario and by 5-year periods, and tables 32-34 present the derivation of table 31 in somewhat more detail.

Adding the costs of specific technologies taken separately—for which cost data are available—is an imprecise way of estimating the costs of technology combinations embodied in new automobiles and fleets, because it does not capture the costs of implementing changes together. Very accurate investment estimates can be made by evaluating for specific new automobile designs the plant-by-plant changes in costs (for everything from property and construction to engineering and equipment to taxes), accounting for various economies (concurrent and sequentially introduced technologies may share plant, equipment, even special tooling) and extra costs for minor changes to the car during production.

---

*Assuming that each technology is applied across the fleet at efficient volume, the calculations can be performed on a per-500,000 unit basis and scaled up or down to determine overall or implied per unit investments. The average investment to produce each size class in each period with projected technological characteristics may be calculated by weighing the cost of each technology (table 30) by its proportion of application and summing the weighted investments.

Table 31.—Summary of Investment Requirements Associated With Increased Fuel Efficiency

		High estimate[a]			Low estimate[a]		
Year	Units	Large	Medium	Small	Large	Medium	Small
1985-90	$Mil./5OO,OOO	900-1,740	820-1,660	780-1,600	490-1,000	480-1,000	450-1,000
	$/car	180-350	160-330	150-320	100-200	100-200	90-200
1990-95	$Mil./5OO,OOO	570-1,100	570-1,100	610-1,200	520-940	520-930	500-900
	$/car	110-230	110-230	120-240	100-190	100-190	100-180
1995-2000	$Mil./5OO,OOO	350-950	370-980	350-050	480-860	520-930	500-900
	$/car	70-190	70-200	70-190	100-170	100-190	100-180

[a] See table 23 and 24 for definitions of these scenarios.

SOURCE: Office of Technology Assessment.

Table 32.—Average Capital Investments Associated With Increased Fuel Efficiency by Car Size and by Scenario (1985=90)

	Percent of production facilities that incorporate new technologies or are redesigned					
	High estimate			Low estimate		
	Large	Medium	Small	Large	Medium	Small
Engines						
SIE[a] $50-250M/500,000	30	70	95	60	80	100
Prechambe[b] $400-700 M/500,000.	15	—	5	15	10	—
Open chamber[c] $400-700M/500,000	30	20	—			
Transmissions						
Four-speed auto and TCLU[d] $300-500M/500,00	70	70	70	50	50	50
Platform						
Various[e] $500-1,000 M/500,000	100	100	100	50	50	50
Capital costs for technology changes weighted average)						
Total $M/500,000.	$905-1,740	$825-1,665	$778-1,623	$490-1,005	$480-1,020	$450-1,000
Per car (total÷500,000÷10)f	$181-348	$165-333	$156-325	$98-201	$96-204	$90-200

%ark-ignition engine.

[b] Prechamber diesel.

[c] Open chamber diesel or open chamber stratified charge.

[d] Four-speed automatic with torque converter lockup.

[e] Weight reduction, material substitution, aerodynamic and rolling resistance reductions, improved lubricants end assessories.

[f] Vehicle change investments are divided by 10 to approximate amortization practices. Forty percent of capital spending goes for plant (30 year) and equipment (12 years), which may together be summarized as "facilities" and amortized over 15 years (Ford Motor Co. interview) 0.4x3+0.6x 15 = 10.2 or about 10 years.

SOURCE: Office of Technology Assessment.

Table 33.—Average Capital Investments Associated With Increased Fuel Efficiency by Car Size and by Scenario (1990-95)

	Percent of production facilities that incorporate new technologies or are redesigned					
	High estimate			Low estimate		
	Large	Medium	Small	Large	Medium	Small
Engines						
SIE $400-700 M/500,000	15	25	35	25	35	50
Prechamber $400-700 M/500,000	–	—	—	30	20	—
Open chamber $400-700 M/500,000	40	30	30			
Transmissions						
CVT, four-speed auto and TCLU $500 -700 M/500,00	35	35	35	50	50	50
Engine on-off $500-700 M/500,000 ... ,	15	15	15			
Platform						
Various $100-400 M/500,000	100	100	100	50	50	50
Capital costs for technology changes						
Total $M/500,000	$570-1,135	$570-1,135	$610-1,205	$520-935	$520-935	$500-900
Per car(total =500,000 +10).	$114-227 -			$104-187	$104-187	$100-180

SOURCE: Office of Technology Assessment.

Table 34.—Average Capital Investments Associated With Increased Fuel Efficiency by Car Size and by Scenario (1995.2000)

	Percent of production facilities that incorporate new technologies or are redesigned					
	High estimate			Low estimate		
	Large	Medium	Small	Large	Medium	Small
Engines						
SIE $400-700 M/500,000	15	15	35	15	25	10
Open chamber $400-700 M/500,000	35	40	15	30	30	40
Transmissions						
CVT improved $100-400 M/500,00	50	50	50			
CVT $500-700 M/500,000	—	—	—	35	35	35
Engine on-off $500-700M/500,000	—	—	—	15	15	15
Platform						
Various $100-400 M/500,000	100	100	100	*50*	50	50
Capita/ costs for technology changes						
Total $M/500,000	$350-950	$375-985	$350-950	$480-865	$520-935	$500-900
Per car (total÷500,000÷ 10).	$70-190	$74-197	$70-190	$96-173	$104-187	$100-180

SOURCE: Office of Technology Assessment.

The Transportation Systems Center of the U.S. Department of Transportation, for example, has developed a "surrogate plant" methodology to do this. The accuracy of this approach is based on detailed consideration of vehicle designs and the corresponding equipment and plant needs. The methodology requires specific projections of engineering changes that are beyond the scope of this report, and speculative for the 1990's.

Note that investment figures presented here apply only to investments required to raise the fuel economy of cars sold in the United States. Total capital spending reported by U.S. manufacturers also includes investment in nonautomobile projects (such as truck and military equipment production), investments in foreign subsidiaries, and spending for normal replacement of worn-out capital and for capacity improvement and expansion.

Note also that not all of a given investment may be associated with fuel economy improvement. For example, engines, transmissions, and car bodies are redesigned periodically. Changes of this sort cannot always be distinguished from those made for increased fuel efficiency, so the full cost of the investments shown in table 31 should not be allocated solely to fuel economy improvements.

The difficulty of allocating costs when a single investment produces several distinct results is a well-known problem of accounting,[26] and there is no fully satisfactory method for making the allocations. For the purposes of the fuel savings cost analysis in the next sections, it is assumed that the percentages shown in table 35 represent the share of investment costs attributable to increases in fuel economy. Engine and body redesigns are made for many reasons other than fuel efficiency. **On** the other hand, most of the advanced materials substitution (to plastics and aluminum) assumed in the scenarios, or automatic engine cutoff, probably would not be incorporated into cars by 2000 without the impetus **for increased fuel efficiency. Advanced transmissions represent an intermediate case between these extremes.**

The total capital investment associated with the production of fleets of given size mix is calculated by taking an appropriately weighted sum of investments by size class. Assuming that U.S. new-car sales average 11.5 million units in 1985-90, 11.7 million units in 1990-95, and 12.1 million units in 1995-2000 (conforming to growth rates projected earlier in this chapter); and assuming that imports throughout the 1985-2000 period average 25 percent of all sales (near recent levels), following the high-estimate scenario for the 15-year period may require $30 billion to $70 billion in investments and R&D expenditures. Following the low-estimate scenario may require about $25 billion to $50 billion (see table 36). if new-car sales are lower due to continued recession and consumers' stagnant real disposable income, then the investments would be proportionately smaller. For example, if domestic sales remain at 8 million vehicles per year (6 million domestically produced) between 1985 and 2000, then capital investments would be about two-thirds as large as shown in table 36 (but R&D costs could remain

Table 35.—Percentage of Capital Investments Allocated to Fuel Efficiency

Category	Percentage of investment allocated to fuel efficiency
Engine.	**50**
Transmission:	
CVT, four- and five-speed auto and TCLV	**75**
Energy storage and engine on-off	**100**
Platform:	
Weight reduction (body redesign)	**50**
Materials substitution	**100**
Composite of all efficiency related investments:	
1985-90	**55-85**
1990-95	**70-80**
1995-2000	**65-75**

SOURCE: **Office of Technology Assessment.**

Table 36—Total Domestic Capital investments for Changes Associated With Increased Fuel Efficiency[a] (billion 1980 dollars)

Time of investment	High estimate[b]	Low estimate[b]
High car sales[a]		
1985-90	**14-29**	**8-17**
1990-95	**10-20**	**9-16**
1995-2000	**7-18**	**916**
Total.	31-67	**26-49**
Low car sales		
1985-90	10-20	**6-12**
1990-95	7-14	**6-11**
1995-2000	4-12	**6-11**
Total	**21-46**	**18-34**

assumptions about car sales:

	High car sales
1985-90 . . .	**11.5 million cars/yr**
1990-05	**11.7 million cars/yr**
1995-2000. . . .	**12.1 million cars/yr**
	Low car sales
1985-2000. . . .	**8 million cars/yr**

Estimates also assume that imports average 25 percent of total car sales between 1985 and 2000.

[b] Within the uncertainties, the Investment requirements are the same for all three sales-mix scenarios.

SOURCE: Office of Technology Assessment.

---

[26] A L. Thomas, "The Allocation **Problem in Financial Accounting Theory" (Sarasota,** Fla.: **American Accounting Association, 1969), pp. 41-57, and A. L. Thomas, "The Allocation Problem:** Part **Two"** (Sarasoto, Fla.: **American Accounting Association, 1974.)**

the same). If this happens, total investments plus R&D would be reduced by about 25 percent below those for the high car sales case.

The greater investments (per vehicle) associated with the high-estimate scenario reflect the fact that the scenario contains more extensive changes more often than the low-estimate scenario. In either case, however, there is no significant difference in the total investment for increased fuel efficiency for the different size-mix scenarios, since the rate of capital turnover for increased fuel efficiency is probably adequate to accommodate the mix shifts. *

OTA estimates of cumulative investments imply that manufacturers would make capital investments of $2 billion to $5 billion per year (1980 dollars) over about 15 years to implement the high-estimate scenario and about $2 billion to $3 billion per year to implement the low-estimate scenario in the case of high car sales. The corresponding figures would be about $1.5 billion to $3 billion and $1billion to $2 billion, respectively, for low car sales.

Actual added capital spending levels by manufacturers are likely to be lower than indicated because some investments in technologies to raise fuel economy will take the place of investments in more conventional technologies that would normally be made as plant and equipment wear out. In fact, deducting the cost of changes that would have been made under normal circumstances,** but are obviated by or could be incorporated in the investments shown in tables **32-34,** could reduce the added investment cost of implementing the scenarios by two-thirds in the high estimate and by about 80 percent in the low estimate, leading to capital investments averaging $0.3 billion to $0.7 billion per year for the low estimate (high car sales) and **$0.6** billion to $1.5 billion per year for the high estimate (high car sales) above "normal. "

Spending by the automakers will be reduced to the extent that they buy rather than make various items; to the extent that U.S. suppliers provide purchased items, the total investment levels can be viewed as spending estimates for U.S. automakers and suppliers together. However, joint ventures with foreign firms, erection of foreign plants with foreign government aid and relatively labor-intensive designs, and purchases of parts and knocked-down vehicle kits from overseas would all lower investment costs to U.S. firms. So would an increase in import penetration. Finally, note that future levels of normal capital spending, however they are determined, may be higher than past levels if competition from foreign manufacturers makes it "normal" frequently spend to improve fuel economy and to modernize facilities.

Fuel Savings Costs

To compare the costs and gains of saving fuel by raising automobile fuel economy with the costs and gains through other means, it is useful to express costs in terms of a common measure such as dollars per quantity of oil (gallons or barrels-per-day) saved. To measure the total dollars per quantity of oil saved implied by raising fuel efficiency requires estimating changes in variable (labor and materials), fixed capital and R&D costs.

OTA was unable to obtain or develop reliable variable cost figures for technologies discussed in this report, because information about variable costs, which vary considerably between companies, is proprietary and speculative for the 1990's. Four general observations about variable costs of raising fuel **economy can be made:** First, implementing some new technologies, including certain weight-reduction measures (e.g., smaller engines and body frames), will lower variable costs by reducing labor and materials requirements. Second, automation will lower labor requirements. Third, using some new technologies, such as four- and five-speed transmissions and alternative engines, will raise variable costs because they are inherently more complex than conventional technologies. Fourth, use of new materials will raise variable costs. The net change in variable costs is uncertain and will depend heavily on basic materials costs and the success

---

***On the average, over 50 percent of engines, transmissions, and bodies are being redesigned during each 5-year period for increased fuel efficiency, whereas the mix shift requires 10 to 20 percent change during each 5-year period.**

****Assuming "normal" capital turnover is: engines improved after 6 years, on average, redesigned after 12 years; transmissions same as engines; body redesigned every 7.5 years; no advanced materials substitution.**

of **adapting the new designs to mass production. Note that variable** costs have been about three times the level of fixed costs for the average car or light truck.

Based on the percentages shown **in table 35,** however, table 37 shows the capital investment attributable to increased fuel efficiency per gallon of gasoline equivalent saved, assuming the average car is driven 100,000 miles and the average service life of the investment is 10 years. In all cases, the investment cost is less than $1.00 per gallon saved. If, however, accelerated capital turnover reduces the useful service life of the investment to 5 years, the costs would be twice those shown in table 37. Conversely, if automobiles are kept longer and driven further in the future, then the cost per gallon is reduced. For example, if cars are driven 130,000 miles over their lifetime, on the average, the costs would be 75 percent of those shown in table 37.

The final cost category considered here is the product development cost. Although it is difficult to make detailed predictions of the costs of development, U.S. automobile manufacturers spent from **40** to 60 percent as much on R&D (mostly development) during the 1970's as they spent on capital investments.[27] During 1978 and 1979, R&D averaged about **40** percent of capital investments.

In order to compare the investments for increased fuel efficiency in automobiles with those for synfuels, it is convenient to express them as the investment cost attributable to fuel efficiency plus the associated R&D expenditures per barrel per day oil equivalent saved by these investments. Assuming that development expenditures are 40 percent of capital investment, the costs in table 37 can be converted to the investments shown in table 38 for individual cars and fleet averages between 1985 and 2000. The combined R&D and capital costs appear to increase somewhat from the 1985-90 period to the 1990-95 period. However, technical advances by the early 1990's could prevent further increases during the late 1990's.

---

[27] G. Kulp, D. B. Shonka, and M. C. Halcomb, **"Transportation Energy Conservation Data** Book: **Edition 5,"** Oak **Ridge National Laboratory, ORNL-5765, November 1981.**

Table 37.—Estimated Capital Investment Allocated to Fuel Efficiency per Gallon of Fuel Saved

	High estimate			Low estimate		
	Car size:			Car size:		
	Large	Medium	Small	Large	Medium	Small
1985						
Mpg	27	39	48	23	35	45
1990						
Mpg	37	51	62	28		52
Gallons saved/yr[a]	910	550	430	705	380	270
Investment ($/car)[b]	100-190	90-180	90-180	60-110	60-110	50-110
Dollars per gallon[c]	0.11-0.21	0.17-0.34	0,21-0.42	0.084,16	0.15-0.30	0.19-0.41
1895						
Mpg	43	61		31	45	57
Gallons saved/yr[a]	340		240	310	200	150
Investment ($/car)[b]	80-180	80-180	90-180	70-130	70-130	70-130
Dollars per gallon[c]	0.24-0.51	0.29-0.60	0.37-0.77	0.22-0.42	0,35-0.67	0.44-0.83
2000						
Mpg	50		85	35	50	65
Gallons saved/yr[a]	260	210	150	260	200	190
Investment ($/car)[b]	50-150	50-150	50-150	70-130	70-140	70-140
Dollars per gallon[c]	0.18-0.56	0.24-0.71	0.33-0.99	0.27-0.50	0.36-0.68	0.36-0.68

[a] Fuel consumption of car relative to fuel consumption of comparable car 5 years earlier. Assumes 100,000 miles driven over life of car and on-the-road fuel efficiency 10 percent less than the EPA rated mpg shown.
[b] The investment attributed to fuel efficiency assuming an average life of 10 yeara for the investment. Also assumes production at rated plant capacity during the 10 years. Does not include R&D costs, which would add about 40 percent to the cost.
[c] The investment per car divided by the fuel saved over the life of the car.

SOURCE: Office of Technology Assessment.

Table 36.-Capital Investment Attributed to Increased Fuel Efficiency Plus Associated Development Costs per Barrel/Day of Fuel Saved

Car size	New-car fuel efficiency at end of time period[a] (mpg)	Capital investment plus associated development costs (thousand 1980$ per B/D oil equivalent fuel saved)[b]
1985-90		
Large.	28-37	19-51
Medium	41-51	35-81
Small.	52-62	47-1oo
Average A[c]. . . .	38-48	21-57[d]
Averge B[c].	43-53	21-60[d]
1990-95		
Large.	31-43	53-120
Medium	45-61	69-160
Small.	57-74	89-200
Average A[c]. . . .	43-59	58-120[d]
Average B[c]. . . .	49-65	64-140[d]
1995-2000		
Large.	34-49	44-130
Medium	50-71	57-170
Small	65-84	78-240
Average A[c]. . . .	51-70	48-150d
Average B[c]. . . .	58-78	50-150[d]

[a] EPA rated 55/45 city/highway fuel efficiency of average car in each size class.

[b] Assumes development costs total 40 percent of capital investments and that a car is driven 10,000 miles per year on averge. A barrel of oil equivalent contains 5.9 MMBtu.

[c] Averages A and B are based on the moderate and large mix shift scenarios, respectively.

[d] Averages are calculated by dividing average investment fOr technological improvements by fuel savings for average carat end of time period relative to average car at beginning of time period. The resultant average cost per barrel par day is lower than a straight average of the investments for each car size because of mathematical differences in the methodology (I.e., average of ratios v. ratio of averages) and because extra fuel is saved due to demand shift to smaller cars. The averaging methodology used is more appropriated for comparisons with synfuels because it relates aggregate investments to aggregate fuel savings. It should be noted that the cost of adjusting to the shift in demand to smaller sized cars is not Included. Only those investments which increase the fuel efficiency of a given-size car are included. However, given the rate of capltal turnover assumed for the scenarios, adjustments to the shift In demand probably can be accommodated within the investment costs shown.

SOURCE: Office of Technology Assessment.

Note that the costs and fuel savings benefit of improving fuel economy are incurred at different times by different parties. Manufacturer (and supplier) investments are made prior to production: 30 percent of capital spending occurs 12 to **24** months before first production, 65 percent occurs within the 12 months preceding production, and 5 percent occurs after production begins.[28] R&D costs may occur 5 to 7 years before first production. Fuel savings begin only after a vehicle is purchased, and they accrue over several years. Fuel savings benefit the consumer directly and the industry only indirectly.

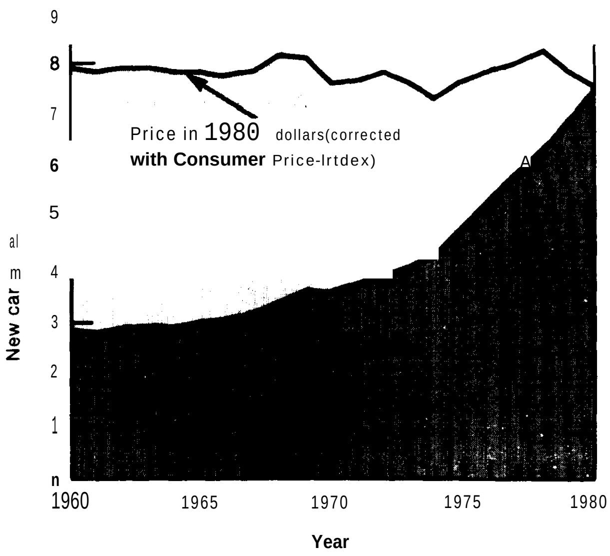
Consumer Costs

Automotive fuel economy improvements can affect costs to consumers through changes in real car purchase prices and changes in real costs of maintaining and servicing cars.

Prices

Trends in average car prices are easier to predict than trends in prices for specific car classes or models, because manufacturers have flexibility in pricing models and optional equipment. Real car prices (on which consumers base their expectations) have been relatively stable over the last 20 years (see fig. 12), although nominal car prices have risen steadily since the mid-1960's, because of general inflation. Labor and materials cost increases are not necessarily passed on to consumers. For example, the General Manufacturing Manager of GM's Fisher Body Division observed in a recent interview that although raw materials and labor costs have been rising about 11 to 12 percent annually, only 7 to 8 percent of those increases have been recovered through price, with improvements in productivity helping to control costs.

Figure 12.— Real and Nominal U.S. Car Prices, 1960-80



SOURCE: Bob Clukas, Bureau of Economic Analysis, U.S. Department of Commerce, private communication, 1981.

---

[28] Harbridge House, **Inc.**, ***Energy Conservation and*** *the Passenger* **Car:** *An* ***Assessment*** *of Existing Public Policy,* **Boston, July 1979.**

W/here expenses increase faster than prices, manufacturers can still make profits by charging higher prices for those options or car models for which consumer demand is relatively insensitive to price. This flexibility is eroded when large proportions of automotive costs increase due to rapid and extensive change. Some industry analysts expect that through the mid-1980's, large capital spending programs and real increases in labor and materials costs will lead to increases in real car prices of up to 2 percent per year (approximately half of which reflects capital costs); more rapid automotive change might lead to even greater increases.[29]

Two percent of today's average car price (about **$8,000)** is about $160, although prices of individual cars will rise by greater and lesser amounts. OTA's scenario analysis suggests that investment costs alone for 5-year periods could range fro-m $50 to $350 per car (assuming 10-year amortization periods for plant and equipment). The Congressional Budget Office (CBO), for comparison, concluded that average automobile production costs may increase by about $560 between 1985-95 because new technologies will cost that much (per car, on average) to implement.[30] These analyses may overstate the average amount of capital cost increase, because when new technologies replace old ones, the capital costs charged to old "technologies" should drop out of the vehicle cost calculation (unless old equipment is made obsolete prematurely). Actual cost increases will also depend on changes in variable costs, as illustrated below.

Table 39 shows two plausible estimates of consumer costs (per gallon of fuel saved) for increased fuel efficiency, based on the analysis in this chapter. The lower costs are calculated assuming that labor and material (variable) costs are no higher for more fuel-efficient cars than for cars being produced in 1985.[31] The higher costs include variable cost increases that are twice as large as the capital charges associated with increasing fuel efficiency .[32]

Although the range varies from costs that are easily competitive with today's gasoline prices to levels much above those prices, OTA does not believe that future variable costs can be predicted with sufficient accuracy to warrant more detailed estimates of variable costs. Table 39 should therefore be viewed as illustrative; actual consumer costs will depend on many factors, including the success of new production technologies.

---

[29] Maryann N. Keller, ***Status Report: Automobile Monthly Vehic/e Market Review,*** **Paine Webber Mitchell Hutchins, Inc., New York, February 1981.**

[30] Congressional Budget **Office**, *Fuel Economy Standards for* **Passenger Cars** *After1985,* **1980.**

[31] **Richard L, Strom botne, Director, Office of Automotive Fuel Economy Standards, National Highway Traffic Safey Administration, U.S. Department of Transportation, private communication, 1981.**

[32] Richard **H.** Shackson **and H. James Leach, "Maintaining Automotive Mobility: Using Fuel Economy and Synthetic Fuels to Compete With OPEC Oil," Energy Productivity Center, Mellon Institute, Arlington, Va., Interim Report, Aug. 18, 1980. Variable cost changes were deduced from the estimates of capital investment and changes in consumer costs by assuming an annual capital charge of 15 percent of the investment and deducting this capital charge from the consumer cost estimate.**

Table 39.—Plausible Consumer Costs for Increased Automobile Fuel Efficiency Using Alternative Assumptions About Variable Cost Increase

			Consumer cost[a] **($/gal** gasoline saved)	
Time period	**Mix shift**	**Average fuel efficiency at end of time period (mpg)**	**Assuming no variable cost increase relative to 1985 variable costs of production**	**Assuming variable cost increase equal to twice the capital charges**
1985-90	**Moderate**	**38-48**		
	Large	**43-53**	0.15-0.40[a]	0.40-1 lob
1990-95	**Moderate**	**43-59**		
	Large	**49-65**	**0.35-0.85[b]**	**1.10-2.60[b]**
1995-2000. . . .	**Moderate**	**51-70**		
	Large	**58-78**	**0.30-0.95[b]**	**0.90-2.80[b]**

[a] **Assumes annual capital charges of 0.15 times capital investment allocated to fuel efficiency, no discount of future savings, and car driven 100,000 miles during its lifetime.**
[b] **Within the uncertainties the costs are the same for each mix shift.**

SOURCE: Office of Technology Assessment.

Individual car prices will not necessarily change in proportion to their costs, in any case. Specifically, there are three reasons why it is difficult for U.S. manufacturers to finance automotive changes through price increases: competition from lower cost imports, the relationship between new and used car prices, and limited consumer willingness to tradeoff high car prices against lower gasoline bills. First, because high fuel-economy imports from Japan cost about $1,000 (1980 dollars) less than American-made cars,[33] U.S manufacturers have little freedom to raise prices without losing sales volume to imports (all things equal). International cost differences may narrow in the future, however, as foreign labor costs rise and if U.S. productivity increases.

Second, the effective price of new cars for most buyers includes a trade-in credit on an older car. Decline in demand for used cars, which might occur if older cars were significantly less fuel efficient than new ones and if maximum fuel economy were in demand, would effectively raise the price of new cars. This phenomenon would hinder a rapid mix shift.

Third, consumers may resist high prices for fuel-efficient cars because they tend to discount such future events as energy cost savings rather heavily, by perhaps 25 percent or more,[34] Discounting at high rates would cause consumers to demand relatively large amounts of fuel savings in return for a given increase in price. Each gallon saved seems to cost more if consumers discount at high rates, because discounting reduces the perceived number of gallons saved over the life of the car.

This phenomenon can be illustrated as follows: The undiscounted lifetime fuel savings from raising a car's fuel economy from 45 to 60 mpg is 557 gal; at a 25 percent discount rate the discounted savings is 227 gal (using a declining schedule of yearly fuel consumption) or about 40 percent of the actual savings. If it costs $150 to $350 per car to raise the fuel economy from 45 to 60 mpg, the cost per gallon saved would be $0.27 to $0.63 without discounting but about 2.5 times as much, $0.66 to $1.54, if fuel savings are discounted at 25 percent. Consumer behavior may be at odds with the national interest, because future savings of oil have a relatively low "social" discount rate for the Nation.

Maintenance

Automotive maintenance and service costs may increase with vehicle design change but the amount of increase depends on institutional as well as technological change. Manufacturers are modifying car designs to make servicing less frequent and less expensive, but—with more complex and expensive components in cars—there is a definite potential for increased repair costs. Also, use of new equipment, including electronic diagnostic units, may lead to higher real costs for service. For smaller shops, in particular, lack of familiarity with new technologies and problems with multiple parts inventories (necessary for servicing new- and old-technology cars) could add to consumer service costs. Because dealerships and larger service firms are in a better position to adjust to changing technology, they are likely to gain larger shares of the service market.

Available estimates of service cost changes for future cars are very speculative. For instance, CBO has estimated that maintenance and service costs associated with transmission improvements, adding turbochargers, and altering lubricants could raise discounted lifetime maintenance costs of new cars by $40 to $90 on average (assuming a 10 percent discount rate). The actual changes in maintenance costs, however, will depend heavily on the success of development work aimed at maintaining automobile durability with changing technology.

Electric and Hybrid Vehicles

Costs of producing electric (EV) and hybrid vehicles (EHV) will differ from those of producing conventional vehicles. EVs substitute batteries, motors, and controllers for fuel-burning engines and fuel tanks. Hybrid vehicles include most or

---

[33] *U.S. Industrial* Competitiveness: A Comparison of *Steel, Electronics,* and Automobiles, op. cit.

[34] Evidence of high consumer discount rates for energy-efficient durable goods is presented in an article by J. A. Hausman, "Individual Discount Rates and the Purchase and Utilization of Energy-Using Durables," *Bell Journal* of Economics, vol. 10, No. 1 (spring 1979), and in a "Comment" article by Dermot Gately in the same journal, vol. 11, No. 1 (Spring 1980).

all of the components of conventional vehicles as well as EVs, but in modified forms. The components required for electric propulsion, which contribute directly to vehicle cost, further add indirectly to cost because they change the structural requirements of the vehicle. The size and weight of batteries, in particular, increase the need for space and structural strength,[35] necessitating changes in vehicle design and weight increases.

Batteries are a major source of both direct and indirect cost. They may comprise 25 percent of total cost, depending on type, size, and capacity. * Batteries available for electric vehicles by 1990 may be priced (1980 dollars) at $1,700 to $2,700 (corresponding to production cost of $1,300 to $2,100) while advanced batteries available by 2000 may be priced below $2,000 (with production cost around $1,500).36

Electric motors are smaller, lighter, and simpler than internal combustion engines. Motor controllers, however, are relatively bulky and may be more expensive than the motors themselves, depending on their design. Motor-controller combinations likely to be available by 1990 may cost around $1 ,000. *

Estimates given in the report cited in footnote 36 suggest that near-term EVs and EHVs would cost at least sO percent more than comparable conventional vehicles. Technological advances in battery development could reduce electric and hybrid vehicle costs, however. Note that manufacturers may initially set the prices of EVs close to those of conventional cars to enhance their appeal to consumers.

Methanol Engines

Production of automobiles designed to run on methanol entails only minor modifications of the engine and fuel system. Consequently, the cost increase for engines designed to use methanol are minor. However, the cost of modifying an engine to operate efficiently on a fuel for which it was not designed can be more significant. One estimate is that retrofitting a gasoline-fueled vehicle for methanol use would cost $600 to $900, and redesigning an engine for methanol combustion would cost $50 to $100 per vehicle.[37] Ford, which is converting several Escorts to methanol combustion for the Los Angeles County Energy Commission, estimates that necessary modifications cost about $2,000 per vehicle, although they would cost less if larger numbers of cars were converted.[38]

---

[35] CBO, op. cit.

*Batteries may comprise about 25 to 30 percent of the weight of an electric vehicle and about 20 to 25 percent of the weight of a hybrid vehicle. The electric motor and controller may comprise about 10 percent of an electric or hybrid vehicle's weight.

[36] W. M. Carriere, W. F. Hamilton, and L. M. Morecraft, General Research Corp., Santa Barbara, Calif., "The Future Potential of Electric and Hybrid Vehicles," contractor report to OTA, August 1980.

*Battery size is a function of the number and size of constituent cells. Battery capacity—and therefore vehicle driving range—is a function of the amount of energy deliverable by each pound of battery.

[37] William Agnew, G.M. Research Laboratories, private communication.

[38] "Ford Converts 1.6L Escorts for Methanol," *Ward's Engine Update*, Feb. 15, 1981.

APPENDIX A.–PROSPECTIVE AUTOMOBILE FUEL EFFICIENCIES

Table 5A-1 summarizes the prospective automobile fuel-efficiency increases used in OTA's analysis. The technologies involved are described in more detail below. In addition, alternative heat engines are discussed and the reasons for not including them in the projections to 2000 are explained.

More or Less Conventional Engines

There is more diversity among the engine technologies listed in table 5A-1 than in any other category. The table indicates increases in fuel economy of 15 percent at most for vehicles using improved S1 engines compared with the baseline 1985 car—everything else remaining the same. Sources of such improvements include:

- smaller engines, because lighter cars will not require as much power and because the engines themselves will also continue to decrease in weight;
- decreases in engine friction–e. g., from new piston ring designs, smaller journal bearing diame-

Table 5A-1.– Prospective Automobile Fuel= Efficiency Increases, 1986.2000

	Percentage gain in fuel efficiency					
	High estimate			Low estimate		
Technology	1986-90	1991-95	1996-20000	1986-90	1991-95	1996-2000
Engines						
Spark-ignition (S1)	10	10-15	15	5	5-1o	5-1o
Diesel:						
Prechamber	15	15		15	15	
Open chamber	25	35	35	20	20	25
Open chamber (S1) stratified charge (SC)		15	20			
Hybrid diesel/SC			35			
Transmissions						
Automatic with lockup torque converter	5	5	5	5	5	5
Continuously variable (CVT)		10	15			10
Engine on-off		10	10			10
Vehicle system						
Weight reduction (downsizing and materials substitution)	8	13	18	4	8	10
Resistance and friction (excluding engine)						
Aerodynamics	2	3	4	1	2	3
Rolling resistance and lubricants		2	3	1	1	2
Accessories	2	3	4	1	1	2

[a] Improvements in fuel efficiency are expressed as percentage gain in mpg compared with an anticipated average 1985 passenger car. The 1985 average car used as a reference has an inertia weight of about 2,500 lb, is equipped with spark-ignition engine, three-speed automatic transmission, and radial tires, and has an EPA mileage rating (55 percent city, 45 percent highway) of 30 mpg. The fuel efficiencies of the individual baseline cars, which are used to calculate future fuel efficiencies in each size class, are given in tables 23 and 24. Percentages are given on an equivalent Btu basis where appropriate—e.g., for diesels, which use fuel having higher energy content per gallon than gasoline, the percentage gain refers to miles per gallon of gasoline equivalent, which is 10 percent less than miles per gallon of diesel fuel. The table does not include efficiency improvements from alternate fuels such as alcohol.

SOURCE: Office of Technology Assessment

ters, increases in stroke-to-bore ratios, improved engine oils;

- new combustion chamber designs, particularly fast-burn chamber geometries that permit lean operation at higher compression ratios;
- further refinements to electronic engine control systems (although most of the possible gains will have been achieved by 1985); and
- decreases in heat losses, consistent with allowable thermal loadings of internal engine parts and the octane ratings of available fuels.

Friction, which goes up with displacement, is a major source of losses in piston engines. Smaller engines cut friction losses, and also operate with less throttling—another source of losses—under normal driving conditions. Turbocharging is one way to make the engine smaller, improving fuel economy without sacrificing performance-albeit at rather high cost. Adding a turbocharger can help a small engine meet transient peak power demands and improve the driving-cycle fuel economy of both S1 and CI engines by perhaps 5 to 10 percent—provided economy and not performance is the goal. Further applications are possible if the benefits perceived by consumers outweigh the price increases.

Bigger gains over the 1985 baseline S1 powered car are possible with CI engines (table 5A-1). In the past, most efforts on diesels have been directed at heavy-duty applications such as trucks. Although the efficiency advantage of CI engines relative to S1 engines decreases as engines become smaller, considerable scope remains for improving the driving-cycle efficiency of passenger-car diesels. In particular, all diesel engines now used in passenger cars are based on a "prechamber" design (also termed indirect injection). The combustion chambers in such engines consist of two adjoining cavities, with fuel injected into the smaller prechamber. At present, prechamber engines have several advantages for passenger vehicles. They are quieter than open-chamber (or direct injection) diesels, have wider ranges of operating speeds, and lower-cost fuel injection systems; in addition, emissions control is easier and smoke limitations are not as serious.[39]

As development of open-chamber diesels for passenger cars continues, substantial fuel-economy improvements can be expected–perhaps 15 percent above the levels that might be achieved with prechamber diesels, themselves of course considerably better than S1 engines (table 5A-1)—assuming NO_x and particulate emissions can be controlled, and noise held to acceptable levels. The efficiency advantages of the open chamber engine stem largely from higher volumetric efficiency, lower heat losses, and more rapid

---

[39] " Future Passenger Car Diesels May Be Direct injection, " Automotive Engineering, June 1981, p. 51.

combustion. Estimates[40] indicate that a 1.2-liter open chamber diesel in an automobile with an inertia weight of 2,000 lb should be able to achieve a 55/45 EPA fuel-economy rating of 60 to 65 mpg (with a manual transmission). Such estimates assume emissions standards for Cl engines that do not severely compromise efficiency. Standards for NO_x and for particulates—which, besides making diesel exhaust smoky, are health hazards—are the most difficult to meet. In general, measures that reduce NO_x increase particulate emissions, and vice versa. To some extent, diesel engines will probably face continuing sacrifices in fuel economy to meet emissions standards.

To emphasize efficiency gains rather than differences in the energy content of various fuels, the diesel engine improvements listed in table 5A-1 are all based on miles per gallon of gasoline equivalent. Because diesel fuel contains more energy (Btu) per gallon than gasoline, miles per gallon of diesel fuel would be 10 percent greater than miles per gallon of gasoline equivalent. For example, a 1990 prechamber diesel is expected to be about 10 percent more efficient than an S1 engine in the low estimate, but about 20 percent better in terms of miles traveled per gallon of fuel.

Stratified-charge (SC) engines (table 5A-1) are S1 engines that have some of the advantageous features of diesels–such as potentially higher efficiency and potentially easier control of emissions, although low emissions levels have been difficult to achieve in practice—as well as the disadvantages of diesels, such as higher production costs.[41] SC engines, like diesels, operate with a heterogeneous distribution of fuel and air in the combustion chamber. But unlike diesels, the SC engines now in production burn gasoline and use spark plugs. SC engines, again like diesels, come in two varieties–prechamber, such as the Honda CVCC engine that has been sold in the United States since 1975, and open-chamber (also called direct injection). Prechamber engines have shown little if any fuel economy advantage, while open chamber SC engines promise good efficiencies in theory but have not yet been successfully reduced to practice. As with open-chamber diesels, it has proven difficult to achieve good response and smooth operation over the relatively wide range of loads and speeds needed for passenger cars. Moreover, open-chamber SC engines have the most potential in larger engine sizes; for a smaller engine operating at a higher load level—a situation now more prevalent—one of the major advantages of the SC engine, its lower throttling requirement, is less of a factor. Such an engine would be more costly to produce than a conventional S1 engine, though less expensive than a diesel.

Another potential advantage of open-chamber SC engines is their tolerance for a wide range of fuels—including both gasoline and diesel, as well as alcohols and other energy carriers not necessarily based on petroleum. The broad fuel-tolerance of SC engines has led to a good deal of work directed at military applications. Further, the low-emissions potential of SC engines provided early stimulus for R&D directed at automotive applications. Open-chamber SC engines could find a place in passenger cars during the 1990's if the remaining problems are overcome.

Another possible path leads to a merging of diesel and SC engine technologies (table 5A-1). This might be visualized as a diesel with spark-assisted ignition. Spark-ignition would increase the tolerance of the engine to fuels with poor ignition quality (i.e., to fuels with a low cetane numbers such as gasoline or alcohols), but the combustion process would be more nearly a constant pressure event, as in a diesel.

Gas Turbine, Brayton, and Stirling Engines

Prospects for other "alternate engines" remain dim; in particular, most alternatives to S1 and Cl engines are poorly suited to small cars. Candidates include gas turbines (i.e., those operating on a Brayton cycle), or the Stirling cycle powerplants that have also been widely discussed for automotive applications. At present, such alternatives to S1 and Cl engines suffer many drawbacks. Gas turbines, for example, would need ceramic components to achieve high efficiencies at low cost–most critically in the power turbine, because high turbine inlet temperatures are needed to raise the efficiency. Ceramics are inherently brittle, and a great deal of work remains to be done before durable and reliable engine parts can be mass-produced from materials such as silicon nitride. The technical problems are more severe for highly stressed moving parts such as turbine rotors than for the applications such as combustor heads envisioned for Stirling engines. While the problems of developing tough ceramics for high-temperature applications in energy conversion devices are receiving considerable R&D support, success cannot be guaranteed. Even if the ceramics can be developed successfully this will not necessarily suffice to make gas turbines (or Stirling-cycle powerplants) practical for use in passenger cars.

With or without ceramic components, automotive gas turbines would, at least initially, be high in cost; and beyond high costs, they suffer a number of other disadvantages as automobile engines. Although gas

---

[40] Ibid.

[41] J. A. Alic, op. cit.

turbines are highly developed powerplants in the large sizes used for stationary power or for marine and aircraft applications (500 hp and above) and ceramic components would allow higher operating temperatures and theoretically high efficiencies, turbine engines do not scale down in size as well as reciprocating engines. Both compressors and power turbines lose efficiency rapidly as their diameters decrease toward the sizes needed for smaller cars (75 hp and below). Brayton-cycle powerplants also have generally poor part-load fuel economy–which is a severe disadvantage in an automobile, where low-load operation is the rule. Furthermore, they need complex transmissions because the power turbine runs at speeds much higher than those of reciprocating engines. Fixed-shaft turbines, in particular, pose difficult problems in matching engine operating characteristics to automobile driving demands. But the most critical drawback of gas turbine powerplants is finally that they are unlikely to achieve competitive efficiencies when sized for small cars—those in the vicinity of 2,000 lb. As these size classes become a larger fraction of the market, the prospects for automotive gas turbines grow dimmer.

Stirling-cycle engines are at much earlier stages of development. High efficiency in small sizes is a more realistic possibility for a Stirling engine than for a gas turbine, but the costs of Stirling engines are likely to be even higher than those for gas turbines [42]–and both engines will probably always be more expensive to manufacture than S1 engines. Like turbines, ceramic components will be needed to achieve the best possible efficiencies in Stirling-cycle powerplants–here the most immediate needs are probably in the heater head and preheater. Seals have also been a persistent block to practical Stirling-cycle powerplants.

Both gas turbine and Stirling engines–because combustion is continuous–have intrinsic advantages in emissions control, and can burn a wide range of fuels. But intermittent-combustion engines (e.g., S1 and Cl) have thus far demonstrated levels of emissions control adequate to meet regulations. Broad fuel tolerance is again not unique to gas turbine and Stirling engines. These advantages are probably not enough to overcome the drawbacks of such engines, at least over the next 20 years.

Transmissions

Table 5A-1 lists a pair of developmental paths for automatic transmissions. (Manual transmissions are not explicitly included in the table; although more American purchasers are now choosing manual transmissions as small cars take a greater share of the market, automatics still predominate.) Geared automatic transmissions with lockup torque converters are already available in some cars; these are straightforward extensions of current technology, in contrast to continuously variable transmissions (CVTs). In principle, an engine on-off feature—in which the powerplant can be automatically shut off when not needed–could be implemented with either system (or with manual transmissions). Placing the engine drive shaft parallel to wheel axles would also yield a small improvement in fuel economy–because crossed axis gears could be replaced by more efficient parallel axis gears, or chains.

Geared automatic transmissions with either three or four speeds and a lockup torque converter-or with a split power path, an alternate method for m minimizing converter slip and the consequent losses—are already on the market. A fourth gear ratio gives a better match between engine operating characteristics and road load demands. The fourth speed, for example, may function as an "overdrive" to keep engine load and efficiency high at highway driving speeds. Neither development—bypassing the torque converter when possible, or adding a fourth speed to an automatic transmission—is new, but the added costs of such designs are now more likely to be judged worthwhile. Many manual transmissions incorporate five rather than four speeds for similar reasons—the added gear benefiting fuel economy, as well as performance at low power-to-weight ratios.

Although the efficiencies of manual transmissions are greater than for automatics—that is, less of the power passing through the transmission is dissipated–the fuel economy achieved by many drivers may be as high or higher in cars equipped with an automatic transmission. By relying on the logic designed into the transmission to chose the appropriate gear ratio for given conditions, wasteful driving habits–e.g., using high engine speeds in intermediate gears–can often be avoided.

Further improvements in the control systems for automatic transmissions, as well as other changes such as variable displacement hydraulic pumps, will help to counterbalance their inherently lower efficiencies. In the past, automatic transmissions have depended on hydromechanical control systems—just as engines have. Hydromechanical control–although well developed and effective— limits the number of parameters that can be sensed, as well as the logic that can be employed. In the past, automatic transmissions have generally decided when to shift by measuring engine speed, road speed, and throttle position. By moving to fully electronic control systems, a greater number

---

[42] "Alternate Powerplants Revisited," Automotive Engineering, February 1980, p. 55.

of engine parameters can be measured, and more sophisticated control algorithms implemented—enabling the transmission to be "smarter" in selecting among the available speeds. Electronics might also be used with manual or semiautomatic transmissions to help the driver be "smarter."

As pointed out above, increasing the number of speeds in an automatic or manual transmission—from three to four or five–can help fuel economy. Although trucks often have many more speeds (for reasons beyond fuel economy), mechanical complexity (in automatics) and the demands on the driver (for manual transmissions)—as well as rapidly diminishing returns when still more speeds are added—will probably continue to limit the number of discrete gear ratios in passenger-car transmissions to four or five. if, however, discrete gearing steps can be replaced by a stepless CVT, then the engine could operate at the speed and throttle opening (or fuel flow for a diesel) that would maximize its efficiency for any road-load demand—i.e., engine speed would be largely independent of vehicle speed.[43] If otherwise practical, such a transmission could give markedly better fuel economy than other automatic transmissions–provided the CVT itself was reasonably efficient. Smooth, shiftless operation is another potential advantage of CVTs.

Continuously variable speed ratios can be accomplished in a variety of ways—e.g., the hydrostatic transmissions sometimes used in farm and construction equipment. A series hybrid electric vehicle—in which the engine drives a generator, with the wheels powered by an electric motor, typically drawing from batteries as well as the generator–in effect uses the motor-generator set as a CVT. Hydrostatic or electric CVTs are expensive and inefficient. CVTs used in past applications to passenger cars have generally been all-mechanical—e.g., based on friction drives, or belts. Typically, such designs have been limited in power capacity and life by wear and other durability/reliability problems.

At present, the most promising CVT designs are those based on chains or belts. Continuing development may well overcome or reduce the significance of their drawbacks relative to the fuel savings possible. These fuel economy improvements could be of the order of 10 percent compared with a conventional automatic transmission—again, depending on the efficiency of the CVT. Fuel economy better than that of a properly driven car with a manual transmission would be more difficult to achieve. Although the CVT would permit the engine to operate more efficiently, poorer transmission efficiency would counterbalance at least some of the savings. One reason that CVTs are expected to have lower efficiencies is the need for a startup device, such as a torque converter, in addition to the CVT mechanism itself. Given that the production costs of a CVT would also be higher than those of a manual design—in part because of the startup device—CVTs appear most likely to find a place as replacements for conventional automatic transmissions.

The third transmission technology listed in table 5A-1, engine on-off, has been placed in this section only for convenience—it could just as well appear in the engine category. "Engine on-off" systems, by which the powerplant can be automatically shut off during coasting or when stopped at signal lights or in traffic, are in principle easy to implement. Indeed, when current engines are equipped with electronic fuel injection the fuel flow is sometimes cut off when coasting above a predetermined speed. For an engine on-off design to be practical (and safe), the engine must restart quickly and reliably, and the operation of the system should not otherwise affect driveability—i.e., it should be operator-invisible, primarily a matter of control system design. Engine on-off systems are under development, and presumably will be implemented if the production costs prove reasonable compared with the expected fuel savings.

Vehicle Weight

The final group of technologies in table 5A-1–vehicle systems—includes several means of reducing power demand, hence the fuel consumed in moving the car. As discussed in the body of this chapter, the single most important means of reducing fuel consumption is by reducing the weight of the vehicle; a 1 -percent decrease in weight typically cuts fuel consumption by 0.7 to 0.8 percent, provided engine size is reduced proportionately. Fuel consumption can also be lessened by reducing air drag, frictional, and parasitic losses–such as accessory demands.

The easiest way to decrease the weight of an automobile is to make it smaller. In most newly designed cars, front-wheel drive is adopted to preserve interior volume, while considerable attention has been given to maximizing space utilization and removing unneeded weight. For cars of a given size, materials with higher strength-to-weight ratios can be used where cost effective, provided they meet requirements for corrosion resistance and stiffness. Progress has also been made by specifying less conservative margins of safety for structural design. Many of the steps taken to reduce vehicle weight interact—i.e., taking weight

---

[43] B.C.Christenson, A. A. Frank, and N. H. Beachley, "The Fuel-Saving Potential of Cars With Continuously Variable Transmissions and an Optimal Control Algorithm, " American Society of Mechanical Engineers Paper 75-WA/Aut-20, 1975.

out of one part of the car, perhaps by replacing 5-mph bumpers with 2-mph bumpers, allows secondary weight savings elsewhere in the body and chassis.

In the future, big gains will be harder to achieve. Most of the waste space has already been taken out of newly designed American cars. Overhangs for styling purposes are being reduced or eliminated, door thicknesses decreased, space utilization in passenger compartments and trunks more carefully planned. Considerable progress can still be made through careful detail design, but the easiest steps are being taken. In the future, tradeoffs between space for passengers and luggage and the weight of the vehicle will be more difficult to manage.

The two basic approaches to reducing weight are: 1) to use materials which provide comparable performance characteristics but weigh less; and 2) to design each component and subsystem with minimum weight as a primary objective—the latter more important now than in the past, when the costs associated with extra testing and analysis were harder to justify through savings in materials and fuel. The first path also tends to raise the manufacturer's costs because substitute materials usually cost more.

Material characteristics most critical in automobile structures are cost, strength, stiffness, and corrosion resistance. Costs—of the material itself, and of the fabrication processes that the choice of material entails—are in the end the controlling factors, as for most mass produced products. Nonstructural parts carry different demands but often less opportunity for saving weight (e.g., upholstery and trim, typically already plastics).

Iron and steel have been the materials of choice for building cars and trucks–as for other mechanical systems—because of their combination of good mechanical properties and low cost. Iron castings have been widely used in engines and powertrain components, steel stampings and forgings in chassis members, bodies, and frames (now often unitized). Highly loaded parts are generally made from heat treated alloy steels–e.g., some internal engine components, as well as gears, bearings, shafts. But elsewhere mild steel has been chosen because it is cheap and easy to fabricate; it can be easily formed and spot welded, gives a good surface finish, and takes paint well. Greater quantities of high-strength, low-alloy steels are now being specified–particularly for bumpers and more critical structural applications such as door guard beams; some new cars contain 200 lb of high-strength steel, triple the amounts of a decade ago.[44] Thinner body parts with good corrosion resistance can be made from galvanized or aluminized sheet steel.

The strength-to-weight ratio of inexpensive, low-strength steels can also be equaled or exceeded by alloys of aluminum and magnesium, as well as by nonmetallic materials such as reinforced plastics. Aluminum usage, now 115 to 120 lb per car, is expected to reach 200 lb per car by 1990—mostly in the form of castings.[45] Aluminum can substitute for iron and steel in engines and transmissions—cylinder heads as well as simpler, less critical components such as housings, covers, and brackets. Magnesium and reinforced plastics are other candidates for some of these applications (use of magnesium is currently limited by high costs, but these may come down in the future). However, aluminum sheet for body parts and structural members has been limited not only by high costs but by difficulty in spot welding–a problem that new alloy compositions are helping overcome.

A variety of plastics and fiber-reinforced composites –ABS, glass-reinforced polyester sheet molding compound, reaction-injection molded polymers with or without reinforcement—are being specified for production parts; some have been used for years. While more of these materials will be used in the future, GM's Corvette–a high-priced specialty vehicle made in quantities small compared with most other domestic vehicles—remains the only mass-produced American car with a glass-reinforced plastic body. Introduced nearly 30 years ago but never emulated, this illustrates the continuing advantages of metals, particularly at high production levels.

In the past, plastics have generally been applied to nonstructural parts. Polymer-matrix composites are now candidates for some structural applications—one 1981 car had a fiberglass rear spring weighing 8 lb, compared with 41 lb for the steel spring it replaced.[46] Examples of related applications, none yet in production, are driveshafts and wheels. Other types of composites—i,e., laminates consisting of two metal layers, probably steel, sandwiching a plastic such as polypropylene–may have potential as body materials. The thickness of the laminate makes it more rigid in bending for a given weight, and the plastic dampens noise and vibration; such laminates, like many other composite materials, are now too costly for widespread use.[47]

---

[44] H. E. Chandler, "Useage Update: Light, Longer Lasting Sheet Steels for Autos," *Metal* Progress, October 1981, p. 24.

[45] H E Chandler, "A Look Ahead at Auto Materials and f% ocesses in the 80's," *Metal* Progress, May 1980, p. 24.

[46] Ibid,

[47] H. S. Hsia, "Weight Reduction for Light Duty Vehicles, 1980 Summary Source Document" (draft), Department of Transportation, Transportation Systems Center, March 1981, p. 8-31.

Improvements in steels and their applications still offer the greatest scope for near-term weight savings in passenger cars—one reason is that the designer's job becomes more difficult when materials are changed. But the manufacturing problems mentioned above for aluminum as a body material—difficulty in spot welding, forming characteristics that call for changes in die design—at least remain within the realm of conventional, mass production metalworking techniques. Plastics and composites demand processing quite different from that used for metals—and high volume production of structural parts made from such materials is new, not only for the automakers, but for virtually all industries. Furthermore, unconventional materials may need additional engineering analysis and testing–e.g., they are often susceptible to different failure modes (such as environment-induced embrittlement, or discoloring). In fact, the second avenue for weight reduction is precisely an improvement in design methods.

With better methods for analyzing and controlling the stress and deflection in the vehicle structure, weight can be reduced without sacrificing structural integrity. Through better understanding of the failure modes of the materials used, as well as service loadings, margins of safety can be reduced. Both analysis and testing are important to these objectives. The greatest strides have come from widespread adoption by the automobile industry of finite-element methods for structural analysis, Not only can body and chassis structures be designed with more precise control over stresses and deflections—eliminating unnecessary material—but finite-element techniques can also help reduce the weights of engines and other powertrain components; section sizes of engine blocks can be decreased, for example.

The weight reductions, hence fuel economy gains, that are possible through materials substitution are limited primarily by costs–both material cost and manufacturing cost. Graphite reinforcements for polymers perform better than glass, for example, but are considerably more expensive; at the highest strength levels, aluminum alloys, in addition to being expensive and difficult to form, cannot be welded. If the costs justify the benefits in terms of fuel economy and other performance advantages—e.g., corrosion resistance—then automobile designers will choose new materials. In some cases, costs will come down as production volume increases, but there will always be a point of diminishing returns. Nonetheless, continued attention to detail design with conventional materials —with which the automakers have engineering and production experience–and improved methods of structural analysis, can give substantial reductions in weight, as table 5A-1 indicates. Even though downsizing and weight reduction will have proceeded considerably by 1985, improvements will continue—often rather gradually, as manufacturers gain confidence in, and experience with, new materials and improved design methods.

Safety poses a further constraint on the selection of structural materials for automobiles. The tradeoffs between vehicle size and occupant safety are discussed in chapters 5 and 10. For a vehicle of a given size, the mechanical properties of the structural materials are one of the factors on which passenger protection depends. Because the structure needs to be able to absorb large amounts of energy in a collision, the materials should be capable of extensive plastic deformation, or else able to absorb energy by some alternative process such as microfracturing while being crushed. This may limit applications of higher strength materials—both metals and nonmetals—because capacity for plastic deformation is inversely proportional to strength; it may also pose difficult design problems for some composite materials.

Aerodynamic Drag

A lighter automobile needs less power for acceleration and for constant speed travel and therefore consumes less fuel. A car with less aerodynamic drag burns less fuel at any given speed, but the power needed for acceleration is not directly affected. Because drag caused by air resistance is proportional to frontal area and to speed squared, drag reduction helps most at higher speeds–i.e., during highway driving.

Smaller cars have less frontal area, hence less drag. But drag can also be reduced by making a car more “streamlined. ” This characteristic is quantified by the drag coefficient-which has a value of 1.2 for a flat plate pushed through the air, but only 0.1 for a teardrop shape. For complex geometries such as airplanes or automobiles, drag coefficients can be precisely determined only by experiment. Extensive–and expensive—wind tunnel testing is the basic technique for minimizing the drag coefficient of an automobile.

Theoretical aspects of the aerodynamics of ground vehicles are poorly understood, particularly for shapes as complex as automobile bodies. Interactions between the stationary roadway and the moving car are a particular problem. Drag reductions are sensitive not only to overall vehicle shape—e.g., the sloped front-ends now common on passenger cars—but to relatively subtle details–such as integration of the bumpers into the front-end design, and the flow of air through the radiator. Testing and experiment are required before the final form can be chosen.

While typical cars of the early 1970’s had drag coefficients in the range of 0.50 to 0.60, many current models have values closer to 0.45, or less; the 1982 Pontiac 6000 has a claimed drag coefficient of 0.37.[48] Reductions to values of less than 0.35 are possible, but eventually limited by practical compromises involving the utility of the vehicle (passenger and luggage space can suffer, as well as accessibility for repairs), safety (a streamlined design may compromise visibility for the driver), and manufacturing costs (curved side glass can cut drag but is more expensive).’ Even so, by 1990 drag coefficients may average 0.35 or less.[49]

Nonetheless, as table 5A-1 indicates, improvements in fuel economy in the years past 1985 from continuing reductions in aerodynamic drag will be relatively small. The reasons are, first, that considerable progress has already been made, and more can be expected between now and 1985–and the returns from drag reduction rapidly diminish (frontal areas are constrained by the need to fit people into the car; no practical vehicle could approach the lower limit drag coefficient of the teardrop shape) —and, second, that drag reduction has the greatest benefits at high speeds, whereas most driving is done at lower speeds. In general, a 10-percent reduction in drag will yield an improvement in driving-cycle fuel economy of perhaps 2 percent.[50]

Rolling Resistance

Even in the absence of air resistance, some fuel would be burned in pushing a car at a constant speed. This rolling resistance depends on tire characteristics, and on friction and drag in moving parts such as axle bearings. It also depends on the road surface (concrete offers slightly less rolling resistance than asphalt). Most of the resistance is caused by deformation in the tires. Carcass design, tread pattern, and inflation pressure all affect resistance. Radial tires decrease resistance compared with bias-ply carcasses, with fuel-economy improvements of 2 to 5 percent possible;[51] more aggressive tread patterns—e.g., snow tires—increase resistance; higher inflation pressures decrease resistance.

Improved lubricants and bearing designs can also cut resistance slightly, as can brakes with minimal drag. However, more scope for fuel-economy improvements through better lubricants exists elsewhere in the vehicle—particularly in engines, but also in transmissions and rear axles—where more “slippery” oils, as well as design changes that minimize churning and oil spray, can reduce viscous drag. Although decreases in friction and rolling resistance benefit fuel economy at low speeds almost as much as at high, many of the possible gains have already been achieved, or are in sight—thus, further improvements after 1985 will be small (table 5A-1).

Accessories

Some of the power produced by the engine is used, not to move the car or to overcome the engine’s internal friction, but in driving pumps, fans, and accessories. To produce this power, fuel must be burned. Among the specific parasitic losses that automobile designers strive to minimize are those associated with cooling fans, air-conditioning compressors, power-steering pumps, and electrical loads supplied by the alternator. Decreases are possible in many of these, as table 5A-1 indicates, though often at somewhat greater cost. In some cases, downsizing the vehicle helps to reduce or eliminate parasitic losses–e.g., power steering may not be needed.

---

[48] J. Burton, “82 Pontiac 6000: A Step Further, ” Autoweek, Nov. 30, 1981, p. 10.

[49] D. Scott, ‘‘Double Loop Cuts Wind Tunnel Size and Cost, ” Automotive Engineering, May 1981, p. 69.

[50] *Automotive Fuel Economy Program: Fifth Annual Report to the Congress* (Washington, D. C.: Department of Transportation, January 1981), p. 119.

[51] Ibid.

APPENDIX B.–OIL DISPLACEMENT POTENTIAL OF ELECTRIC VEHICLES

Electric Vehicles and Electric Utilities

The extent to which electric vehicle (EV) technology can contribute to the national goal of reducing oil imports will depend on the availability and use of non-petroleum-based electricity for vehicle recharging and the fuel consumption of the car the EV replaces. Because of the limited performance of EVs, they would most likely be substitutes for relatively fuel-efficient small cars. Also, because of the limited range and hauling capacity of EVs, it is assumed that they can replace only 80 percent of the (10,000 miles per year) normal travel in a gasoline car. The remaining 2,000 miles per year would have to be accomplished with a possibly rented gasoline-fueled car, which might be less fuel efficient than the small car that the EV replaced. This latter complication was ignored, however, so the results shown here are slightly more favorable in terms of net oil displacement than might be the case in practice.

Figure 59-1 shows the consequences of introducing EVs in terms of either increased petroleum use, or net petroleum savings, for alternative assumptions about automotive fuel economy. For example, referring to the figure, if the fuel economy of the car replaced by an EV is 60 mpg (case A), then one could save as much as 133 gal per year or increase petroleum consumption by 123 gal (of gasoline equivalent) per year depending on whether, respectively, all or none of the recharge electricity is petroleum-based. * As long as the fraction of petroleum used for generating recharge energy for EVs in this case is less than about 50 percent, the introduction of EVs will result in net petroleum savings. In case B, where a car that achieves 40 mpg is replaced by an EV, the fraction of petroleum used for generating recharge energy must be less than about 80 percent to result in net petroleum savings.

Utilities plan their capacity and operations to ensure that the maximum instantaneous demand on the system, typically occurring at midday, can be met. This implies that peakloads are satisfied with generating capacity that is idle at other times. A utility will thus respond to demand fluctuations by using the most efficient (“baseload” as well as “intermediate”) plants as much as possible and progressively adding other “peaking” plants as loads increase. Baseload plants, which often cannot be adjusted rapidly (i.e., under 2 hours) to respond to demand fluctuations, are either nuclear, hydro, geothermal, or steam (oil, coal, or gas). Peaking plants can be operated for short-term response and are gas turbines fueled by oil or natural gas and pumped-storage hydro. The ability of utilities to handle the additional load created by EVs will depend on such factors as total generation potential, the equipment and fuel mix, and the time pattern of demands. These characteristics generally vary by region (fig. 59-2) as illustrated in table 59-1,

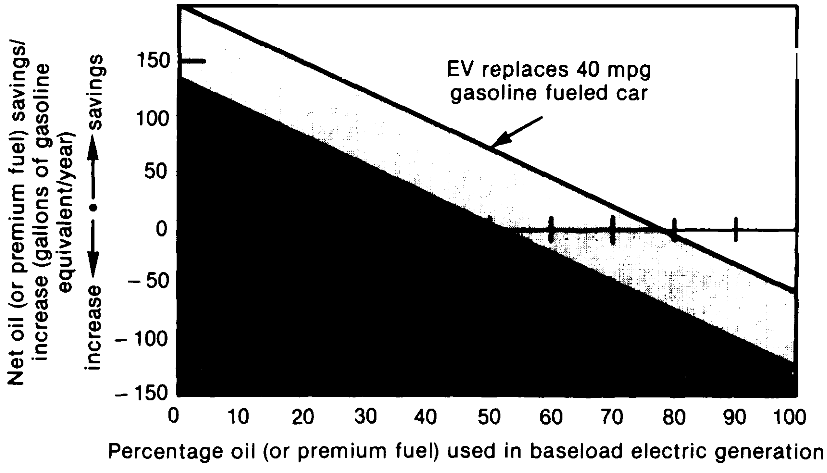
Figure 59-3 shows a peak summer demand curve and equipment mix for an individual, representative utility. Also shown are the likely changes in the load profile that would occur with the addition of EV loads under the following conditions: 1) recharging occurs over 12 hours during the night when demands on the system are the smallest, 2) recharging occurs uniformly during the day, and 3) recharging occurs during 2 hours at midday. As long as the additional EV load occurs either at night or evenly throughout the day, this load could be accommodated by increasing baseload output. Recharging over 2 hours during the day would be satisfied with peaking plants.

Assuming that the available oil-fueled baseload capacity used for recharging EVs is proportional to the amount of oil-fueled baseload in the system, figure

---

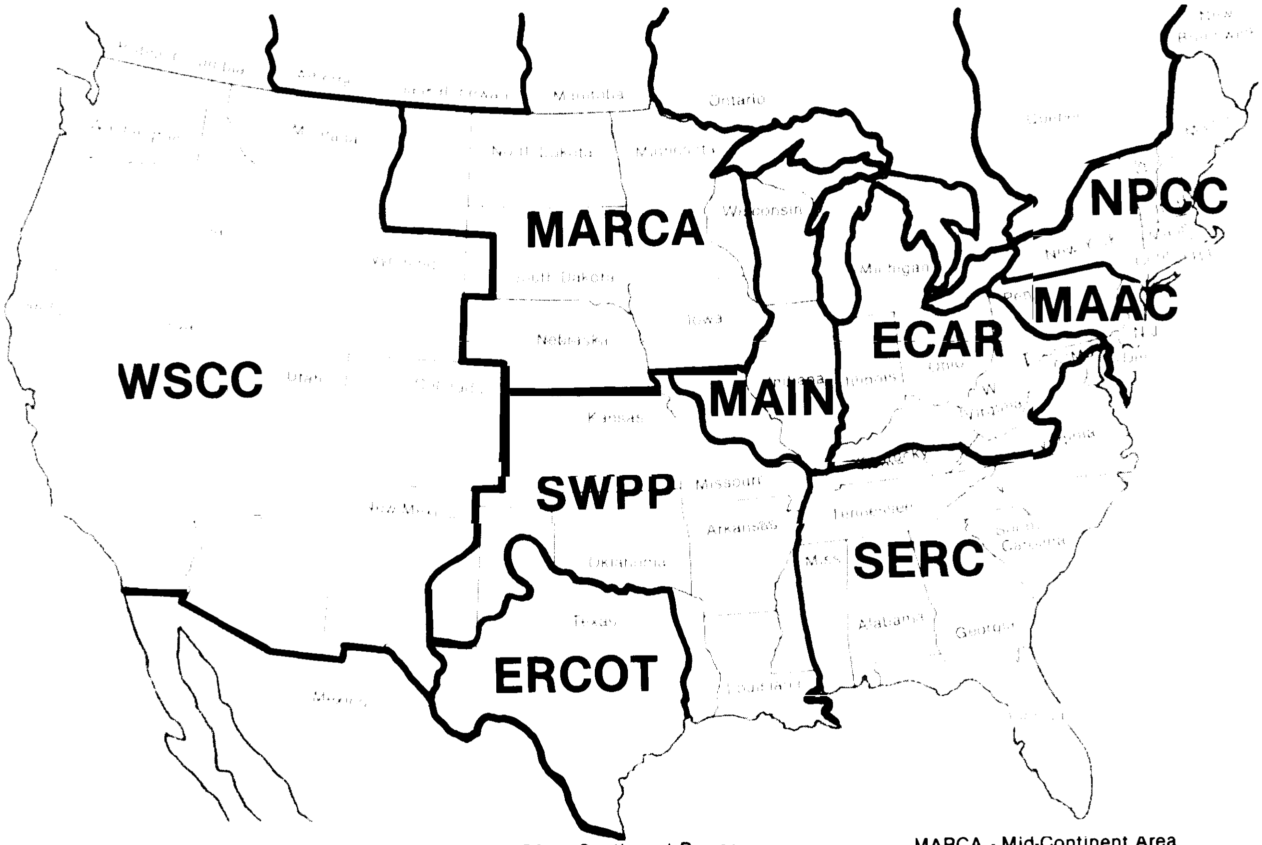
*Assumes that electric vehicle recharge energy is 0.4 kWh/mile.

Figure 5B-1.- ‘Relationship Between the Net Fuel Savings From the Use of EVs and the Fuel Used for Electric Generation



SOURCE: Office of Technology Assessment.

Figure 5B-2.— Regional Electric Reliability Council Areas



ECAR - East Central Area Reliability Coordination Agreement
MAIN - Mid-America Interpool Network
MAAC - Mid-Atlantic Area Council
SWPP - Southwest Power Pool
ERCOT - Electric Reliability Council of Texas
WSCC - Western Systems Coordinating Council
MARCA - Mid-Continent Area Reliability Coordination Agreement
NPCC - Northeast Power Coordinating Council
SERC - Southeastern Electric Reliability Council

SOURCE: Department of Energy, Energy Information Administration, April 1978

5B-4 can be used to determine the fuel efficiency that would be required of a small automobile if the overall oil consumption of the small automobile is to be equivalent to an EV in each region. For example, at one extreme, the Texas region uses not oil in its baseload, so an EV always consumes less oil, and at the other extreme, in the northeast a gasoline-fueled car would have to get about 50 mpg if it were to consume an equivalent amount of oil as an EV. In terms of premium fuel, * the extreme points are several hundred mpg in the midcontinent area and about 40 mpg in the Texas region to achieve a fuel-use equivalence between a small car and an EV.

The electricity requirements and oil/premium fuel savings for an EV fleet which constitutes 20 percent* of the total vehicle fleet are shown in table 5B-2. As can be seen, as long as the EV fleet can be recharged using baseload capacity, regions should be able to meet the additional load with existing available baseload capacity. In general, the Northeast, West, and Southeast regions would utilize the greatest absolute amounts of oil-fueled baseload capacity if EVs were

---

*Oil + natural gas = premium fuel.

*A 20-percent market penetration is considered to be the upper bound on EV use through 2010,

Table 5B-1.—Utility Capabilities by Region (contiguous United States) [a]

Region [b]	Installed capacity (x10^{3}MW)	Net capability (x10^{3}MW)[c]	Available baseload capacity (x10^{3}MW)[d]	Available peaking capacity (x10^{3}MW)[e]	Percent of baseload that is fueled by:	
					Oil	Gas
ECAR	84.9	79.1	19.6	1.3	6.7	0.2
MAAC	44.0	40.6	7.1	2.2	35.3	0.0
MAIN	43.1	39.9	7.6	0.6	12.7	1.1
MARCA	25.4	24.4	5.1	0.8	2.5	0.9
NPCC	50.9	49.8	11.4	2.3	60.4	0.0
SERC	113.7	103.1	17.5	2.6	17.9	0.2
SWPP	48.9	46.1	6.8	0.4	21.6	42.8
ERCOT	40.9	39.9	9.7	0,0	0.0	75.7
WSCC	94.6	93.3	22.0	1.4	26.9	2.3
Total	546.4	516.2	106.8	11.6	20,9	10.8

[a] **Unless otherwise** indicated, data are taken from the *1980* Summary, National Electric **Reliability** Council, Juiy **1980.**

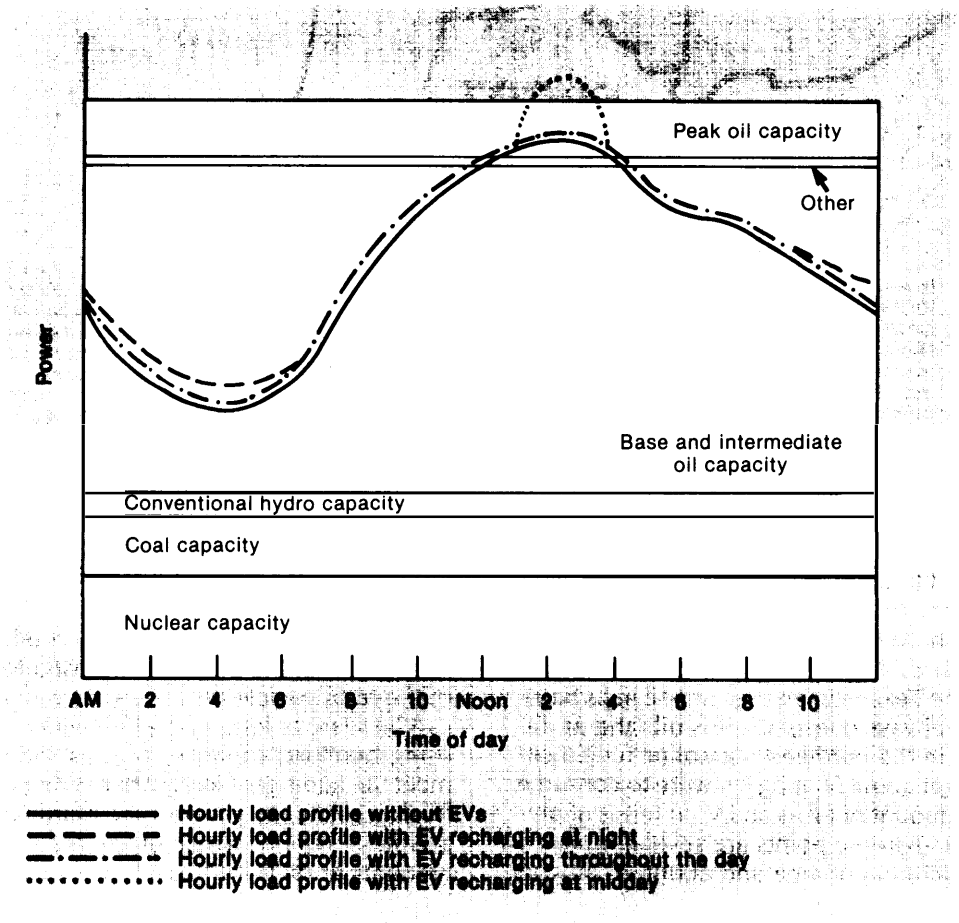
[b] **See attached** map in **fig. 5B-2**.

[c] Net **capability is** calculated **based** on the ratio of Net Capability to Installed Capacity as reportad in the ***Electric Power Monthly,*** U.S. Department of **Energy, Energy** Information Administration, August **1980.**

[d] **Calculations assume** that the total **available** capacity is **allocated** between baseload and peaking capacity according to the ratio of peaking to **baseload capacity within** the system. Total **available** capacity - (net capability) – **(peakload).**

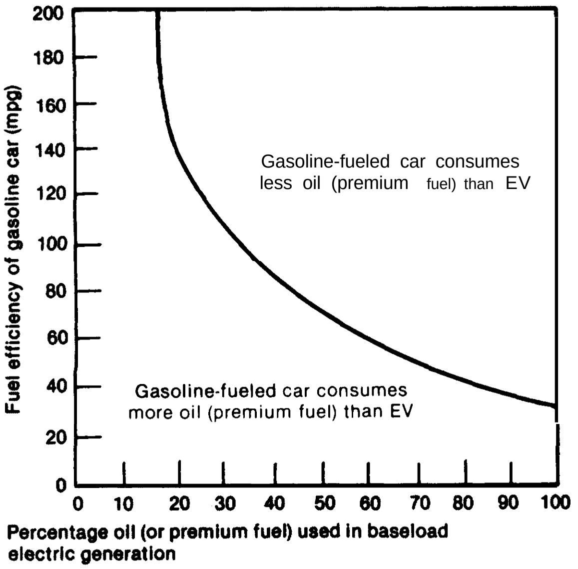
SOURCE: Office of Technology Assessment.

Figure 5B=3.— Illustrative Load Profile With and Without Electric Vehicles



SOURCE: Office of Technology Assessment

Figure 5B-4.— Dependence of Net Oil (premium fuel) Consumption on Efficiency of Gasoline Car Replaced and Fuel Used in Baseload Electric Generation



SOURCE: Office of Technology Assessment.

introduced, whereas the midcontinent, East-Central, and Texas regions would utilize the smallest amounts of oil-fueled baseload capacity.

Petroleum savings accruing from the substitution of EVs (as opposed to 60-mpg gasoline-fueled vehicles) for 20 percent of the total vehicle fleet would be approximately 0.1 MMB/D of oil and 0.07 MMB/D of premium fuel. The greatest oil savings would be in the East-Central, Southeast, and West regions. The smallest amount of oil savings would occur in the Texas, Southwest, and midcontinent regions; substituting EVs for small cars in the Northeast would actually increase oil usage. The greatest premium fuel savings accruing from the substitution of small cars would occur in the East-Central, Southeast, and West regions. Increased premium fuel use would occur in Texas, the Northeast, and the Southwest. In the future, however, both oil and premium fuel savings with EVs will increase as utilities switch away from the use of these fuels for electric generation.

Analyses conducted at the national and regional levels cannot be used to assess the attractiveness of EVs for individual cities or utilities. For example, individual utilities may experience significant increments to their loading, and hence, require a change in baseload capacity and/or mix of fuel use, depending on the time pattern of recharging assumed, the percentage of market penetration, and the technical characteristics of the battery and charging system (e. g., amperage, voltage, and efficiency profiles).

Table 5B.2.—Electricity Requirements and Oil Savings With an Electric Vehicle Fleet With 20= Percent Penetration

Region	Total vehicles 1979[a] (x 10^6)	Electricity capacity required if 20°/0 penetration by EVs[b] as percent of available baseload (percent)			Case A[f] baseload capacity that would be fueled by:		Fuel consumed by fleet of small cars[g] (MMB/DOE)	Fuel saved by replacing 20°A of small cars with EVs[h]	
		Case A[c]	Case B[d]	Case C[e]	Oil (MW)	Premium (MW)		Oil saved (MMB/DOE)	Premium fuel saved (MMB/DOE)
ECAR	19.9	0.15	0.07	0.87	194	200	0.191	0.027	0.027
MAIN	9.2	0.19	0.09	1.14	474	474	0.088	0.011	0.010
MAAC	10.9	0.21	0.11	1.26	203	220	0.105	0.005	0.005
MARCA	5.8	0.16	0.08	0.99	21	29	0.056	0.009	0.008
NPCC	14.7	0.19	0.09	1.13	1296	1296	0.141	–0.004	–0.004
SERC	21.2	0.18	0.09	1.06	554	560	0.203	0.021	0.021
SWPP	9.0	0.19	0.10	1.16	284	846	0.087	0.008	–0.003
ERCOT	6.5	0.10	0.05	0.59	0	716	0.063	0.010	–0.005
WSCC	22.6	0.15	0.07	0.90	887	962	0.217	0.017	0.015
Total	119.8	0.16	0.08	0.98	3913	5303	1.151	0.104	0.074

[a] *Ward's Automotive Yearbook 1980*. For each State served by more than one council, vehicles are distributed among the regions according to the percentage Of the State's residential consumers served by each council as estimated by the State's public utility commission.

[b] EVs require 0.4 kWh/mile and are driven 8,000 miles Per year.

[c] Recharging occurs over 12 hours during the night (1 Year ≈ 8,766 hours).

[d] Recharging occurs evenly throughout the day.

[e] Recharging occurs over 2 hours at midday

[f] Assumes that the fuel used t. generate electricity for EVs is in the same percentage as used for baseload generation (See table 5B-1).

[g] Small automobile gets 60 mpg and drives 10,000 miles per year

[h] EV replaces 80 percent of the miles driven by 20 percent of the cars, Negative sign indicates fuel use increases rather than decreases

SOURCE: Office of Technology Assessment.