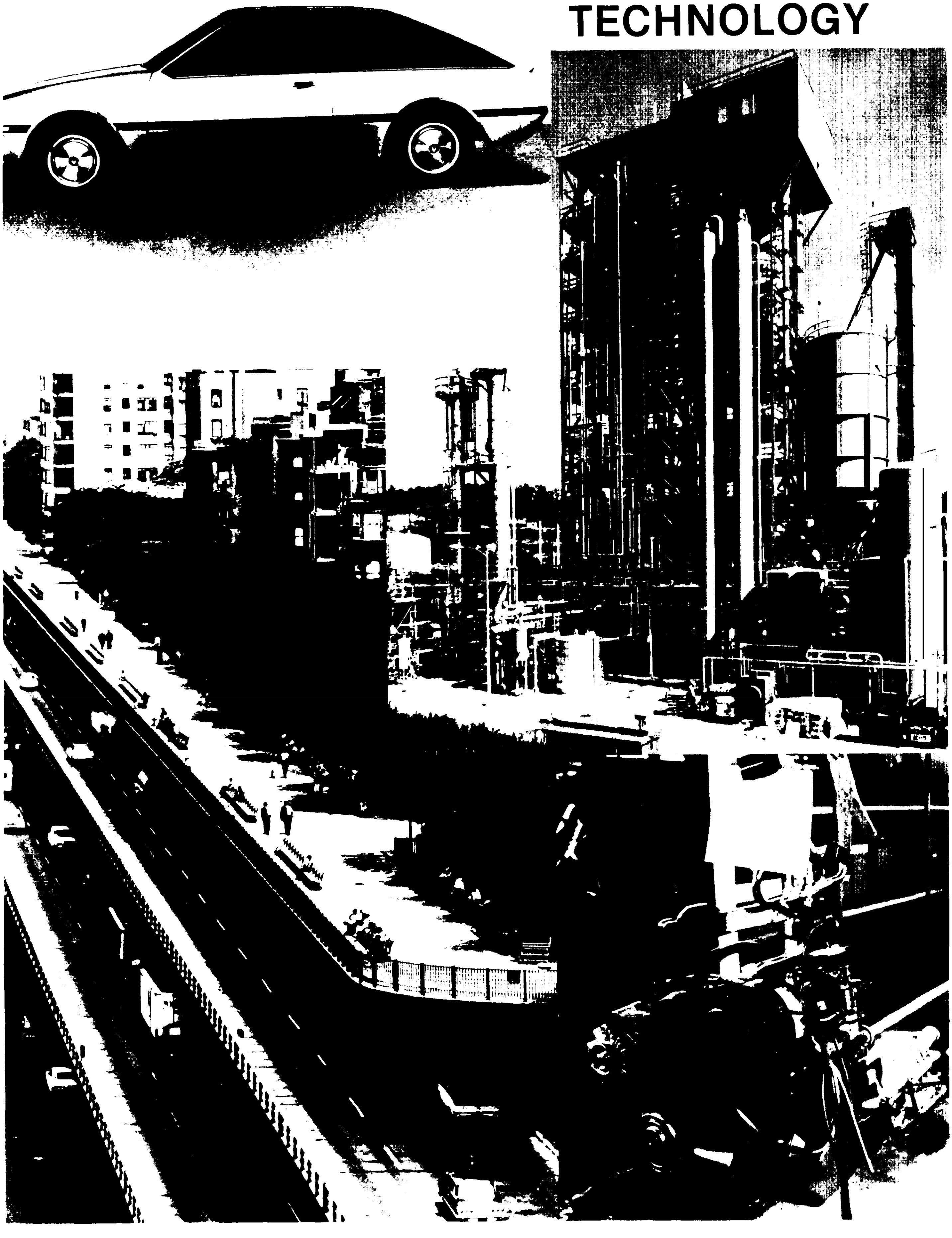
Chapter 10

TECHNOLOGY



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SUMMARY

During this century, automobile manufacturing has evolved from a small group of struggling entrepreneurs into a massive industry and Government complex. The evolution of the industry has been largely determined by the capability of automobile manufacturers to mass produce vehicles to satisfy public demand at an affordable price. While there has been intense competition among manufacturers, the technology that has developed is remarkably uniform in terms of vehicle size, performance: and component characteristics. Until recently, the factors that influenced general vehicle characteristics and the success of particular models were styling, performance, comfort, convenience, reliability, and cost. As this formula was mastered by automobile manufacturers, the climate of the industry became that of an established and mature technology.

Within the past decade, however, the established pattern may been upset. Through a combination of public concern, Government action, and the force of circumstances, automobile technology has had to take new directions. The industry has had to be more mindful of environmental impacts, fuel economy, and safety. This has introduced new design requirements, new production techniques, new manufacturer responsibilities, and new costs. The characteristics of the automobile have begun to undergo a transformation in terms of both the technology employed and the rate at which changes are introduced. Some of these changes will be seen in the near term, by 1985. Others will take much longer to emerge and may not be on the market until sometime around 2000.

The technological aspects of the automobile transportation system that are likely to change in the near term are:

- Downsizing programs now underway will reduce the average size and weight of the vehicle fleet. Wasted space resulting from styling and image features will be greatly reduced.
- Substitution of lightweight materials such as aluminum, plastics, and high-strength low-alloy steels will reduce vehicle weight further.
- Changes in vehicle layout, such as front-wheel drive, will allow further size and weight reduction.
- Additional increases in fuel economy will be achieved by improvements in transmissions and drive trains and by reduced power requirements for accessories.
- Several new engines or refinements of existing engines have been introduced recently or probably will be on the market in the near future:
  - —diesels (several offered now),
  - —stratified charge (offered now by Honda),
  - —Ford PROCO type (single-chamber) stratified charge,
  - —valve selectors (ready now, but not on the market), and
  - —turbocharging (offered now by GM and Ford).
- Electronic fuel control and ignition systems will come into widespread use and will help to maintain efficient engine performance and to reduce the need for tuneups.
- The introduction of these technological improvements should permit the 1985 automobile fuel-economy goals to be met, and possibly exceeded.

- Emission goals, as currently legislated, can be met using existing technology and anticipated refinements without serious penalty in fuel economy.
- Vehicle safety will be enhanced by the addition of passive restraints in the early 1980's.
- On the other hand, small cars increase the potential for serious injury, unless crashworthiness is improved. Small cars can be designed to match the crashworthiness of present full-size cars at a nominal weight and cost penalty.
- Basic design and manufacturing processes will not change substantially, except where the use of new materials requires new processes .
- Advanced vehicle and propulsion technologies such as Stirling and turbine engines, electric vehicles, and alternative fuels will not significantly penetrate the marketplace by 1985.
- Other characteristics, such as comfort, handling, and convenience options will be much like today. Durability, damageability, and maintenance and service requirements will be essentially the same. The variety of products now offered by manufacturers will remain, but the sales mix will shift toward smaller vehicles.

There are several research and development programs on automobiles and fuels now being conducted by Government and industry. The outcomes of these programs are expected to have an important influence on the direction that automotive technology will take in the period 1985-2000. These research and development activities include:

- the gas turbine development program;
- development of the Stirling engine, and its derivatives;
- R&D on electric and hybrid vehicles and identification of prospective markets and roles;
- long-range development of highly efficient engines, such as the adiabatic turbocompound diesel;
- R&D on materials—including ceramic components for engines, base metal catalysts, and energy-absorbing composites;
- development of a homogeneous, all-plastic tire;
- definition of the health effects of automobile emissions—both those now regulated and those expected from new engines and fuels; and
- exploration of the processes and facilities needed to provide new fuels—alcohol, broad-cut petroleum fuels, synfuels, and hydrogen.

INTRODUCTION

The future of the automobile transportation system will be determined in part by the new technologies introduced in the next 25 years. In order to assess new technologies and their effects and impacts on the future characteristics of the automobile transportation system, it is necessary to make estimates of a number of factors:

- Which new technologies are likely to be developed within the next 25 years?
- What potential benefits do they offer in terms of improved mobility, reduction of emissions, energy conservation, or improved safety?
- What are the technical or social drawbacks of these technologies?
- When will they be commercialized and at what rate will they penetrate various markets?
- How much will they cost the consumer?
- How much will the development process cost?
- How do they compare with alternative technologies?

In addressing these questions, this chapter first describes the present technology of automobiles and the automobile industry, and changes through 1985 that are already in prospect because of Government regulations, industry commitments, and firm economic and marketing considerations. The following topics are covered:

- vehicle characteristics,
- manufacturing and materials,
- fuel economy,
- emission control,
- safety technology,
- Otto cycle engines,
- diesels,
- drivetrains and accessories, and
- electronics.

The final part of the chapter discusses research on future systems or improvements beyond **1985,** including major technological problems and opportunities. Included are discussions of advanced-propulsion systems, advanced-vehicle designs, safety improvements, electric and hybrid vehicles, and alternate fuels.

HISTORICAL AND CURRENT TRENDS

The U.S. auto industry has accumulated a monumental store of technological expertise, experience, and research facilities in almost all aspects of its business. In addition to the multitude of products and developments brought to public attention, the auto industry engages in extensive research and development activities. Although some of these R&D activities are publicized, many are not, either for competitive reasons or because the results were negative (as is the case for much of the research in all industries), or because the research lacks direct or current applicability.

Some of the more important elements of the overall technological base and the factors which influence technology are discussed in this section, both to describe the probable vehicle and system characteristics through 1985 and to serve as a basis for forecasts to 2000 and beyond.

Several determining characteristics of the U.S. automobile industry and transportation system have been:

- a high degree of standardization of vehicles and components,
- high production rates and relatively low unit prices,
- uniformity of service and repair facilities, and fuel supply systems,
- aggressive industry advertising aimed at selling more cars and at influencing consumer tastes,
- R&D efforts focused on targets of high marketability or, in recent years, high public or governmental concern,
- a high degree of sales competition among domestic firms and with imports,
- a business system which is characterized by a conservative, predictable, low-risk approach in order to maintain competitive strength, and
- a market which has traditionally been resistant to abrupt or unusual product changes.

As a consequence of such influences, U.S. passenger car models have evolved into remarkably similar groups of vehicles in terms of size, performance, and component characteristics. Competition has centered on performance, comfort, and convenience—leading to gradual, incremental increases in size and weight. Different buyer needs and levels of affluence have been accommodated by each manufacturer by supplying a similar range of vehicles, with prices that were highly competitive within size and performance categories.

Many variations of the basic four- to six-passenger car have evolved — two-passenger sports cars, economy cars, limousines, and recreational vehicles—but the basic concept and mechanical components remain much the same. The primary industry goal continues to be to supply a range of products (at a profit) that will meet the mobility needs of most U.S. family units. In recent years, this range has broadened considerably.

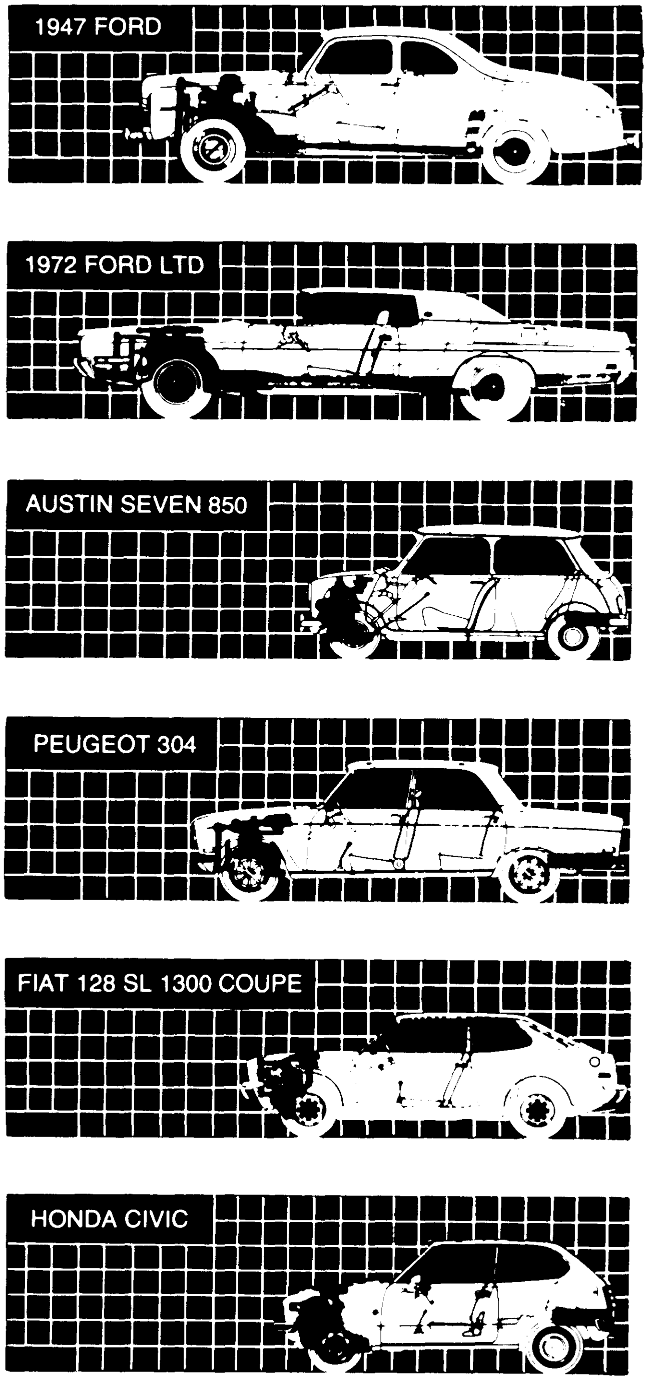
The size and performance characteristics of specific models or classes of vehicles have shown a trend of reasonably steady increases over the past 30 years. Recently, however, emission regulations required tuning engines to lower performance ratings, and in 1977, overall vehicle downsizing began to reduce weight for added fuel economy. The most popular U.S. sizes were in the range of 115- to 118-inch wheelbase and 3,000- to 4,500-pound curb weight. The sales-weighted average passenger car weight remained remarkably constant at about 3,350-pound curb weight from the late-1940's to 1974. The sales-weighted average price also remained essentially constant in constant dollars over these years.[1]

Figure 54 shows selected past and recent U.S. and foreign models to illustrate the wide variety of packaging efficiency, and the potential for length reduction without significant change to the length and height of the passenger compartment. Table 129 shows that over the past 25 years, the basic passenger compartment for standard-size vehicles of U.S. manufacture changed little in its critical dimensions, despite the wide range and steady increase in overall size and weight.

During this same period, an increasing number of comfort and convenience options were introduced and enthusiastically accepted. (See figure 55.) A leveling off of purchases of some of these options and sharp declines in some, particularly the V-8 engine, is forecast in the next few years. Most of these devices add appreciably to fuel consumption and to manufacturers' profits, as their percentage markup is typically on the order of half again that of the basic vehicle.

In the mid- and late-1950's, imports, typically with 80- to 110-inch wheelbase and 1,500- to

Figure 54.—Illustrative Automobile Sizes



SOURCE: *Road and Track Magazine*, various issues.

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[1] SRI International, *Potential Changes in the Future Use and Characteristics of the Automobile*, contractor report prepared for OTA, January 1978; and supplemental submissions (hereinafter cited as SRI Supplement).

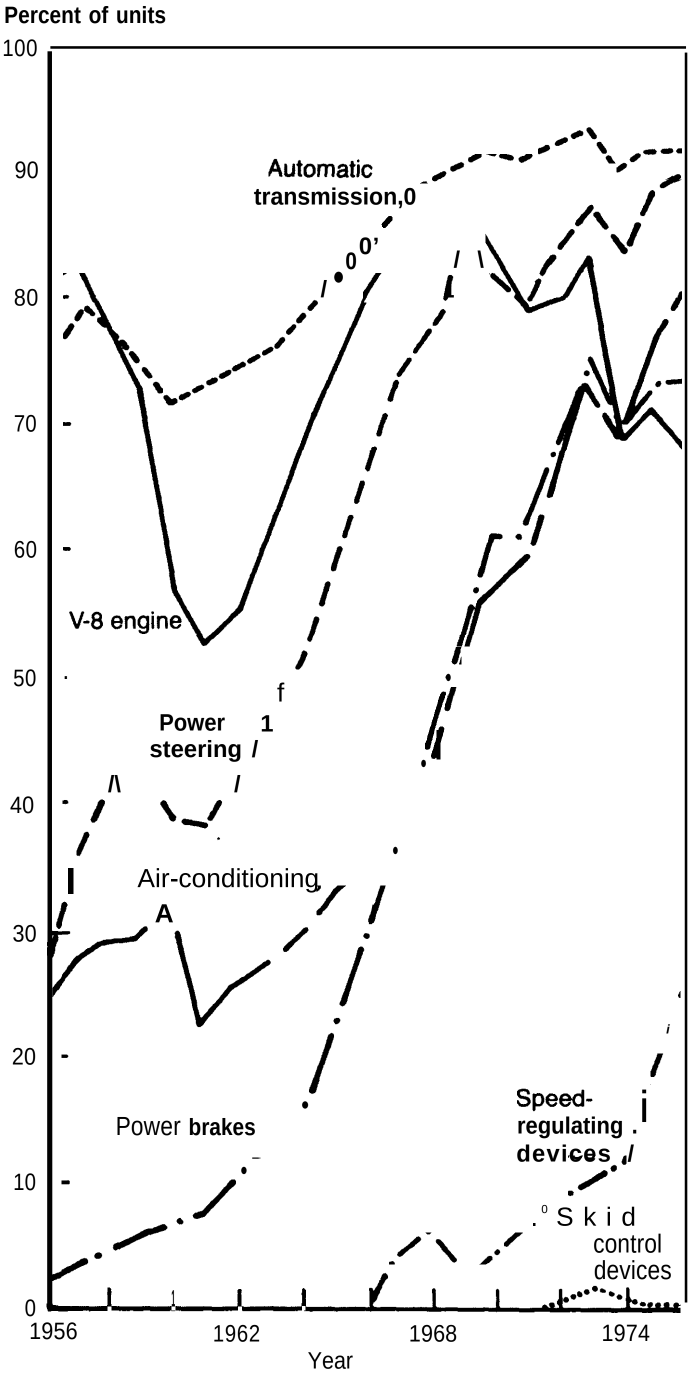
2,800-pound curb weight, began to capture an increasing share of the market. The U.S. manufacturers' response was to introduce a family of compact and intermediate-sized cars, which reduced the import penetration from 10 percent to 5 percent in 3 years. However, the smaller U.S. cars began to grow steadily in size and weight and by 1975, the import share of the market rose to over 18 percent—a share that they still hold.[2] Imports are attractive for the feature content, efficiency of space utilization and, in many cases, performance, handling, and subjective views of quality and image.

During the early *1970's,* the U.S. auto manufacturers moved more strongly into overseas manufacture and assembly for the U.S. market. Efforts to bring captive imports into the United States were marginally successful, and some died out after a few years of promising performance. (See table 130.) Under existing fuel-economy regulations, captive imports cannot be averaged into the U.S. manufacturers' fuel-economy figures after 1980. Thus, the extent of overseas manufacture and assembly of cars and parts for U.S. sale will be reduced significantly after that date.

The foreign-based import sales in the United States come mostly from a few large companies—typically the top five firms hold more than 65 percent of the U.S. market.[3] Most of these firms are large, broadly based, and technologically innovative. There are also several smaller firms that export to the United States. They and the larger firms often try new technologies or novel vehicle layouts at a relatively early stage of development as a market entry tool.[4]

All of these major trends in the United States auto industry occurred with little direct regulatory pressure. However, when the influences of fuel-economy, emissions, noise, safety, and

Figure 55.—Factory Installation of Selected Equipment from 1956 to 1976



SOURCE Motor Vehicle Manufacturers Association, *Motor Vehicle Facts and Figures, '78.*

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[2] Motor Vehicle Manufacturers Association, *Motor Vehicle Facts and Figures 78*

[3] In 1976, the top five import firms were Toyata, Datsun, Volkswagen, Honda, and Fiat. They accounted for 969,587 of a total of 1,491,910 import sales, R.A. Wright, "Imported Cars Draw U.S. Attention," *Automotive News 1977 Market Data Book issue,* Apr. 27, 1977, p. 70.

[4] Examples of this are the Honda stratified-charge engine (CVCC), the Mazda rotary engine, the VW diesel engine, and the many import firms offering the increasingly popular front-wheel-drive layout.

Table 129.—Vehicle Characteristics (full-size Chevrolet 4-door sedan)

	1950	1957	1967	1974	1975	1976	1977
Wheelbase (in.)	115	115	119	121.5	121.5	**121.5**	116
Length	197.5	200	213.2	222.7	222.7	**222.7**	212.1
Width (in.)	73.9	73.9	79.9	79.5	79.5	**79.5**	76
Height (in.)	65.75	61.5	55.4	53.9	54.5	**54.7**	56
Front headroom (in.)		36	39.1	39.6	38.9	**38.5**	39
Front legroom (in.)		44.7	42.2	42.5	42.5	**42.6**	42.2
Curb weight (lb)	3,145	3,304	3,570	4,389	4,318	**4,361**	3,771
Standard engine displacement (cu in.)	216.5	283	327	350	350	**350**	305
Optional engine displacement		348	427	454	454	**454**	350

SOURCE: *Automotive Industries Magazine,* Statistical Issues, 1950-1978

Table 130.—U.S. Sales of Captive Imports (thousands)[a]

	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Opel	40	82	91	83	89	69	68	59	40	10	29
Capri	—	—	—	16	56	92	113	75	55	30	22
Simca	6	5	7	6	5	3	—	—	—	—	—
Colt	—	—	—	—	28	21	36	43	60	49	71
Arrow	—	—	—	—	—	—	—	—	—	30	47
Cricket	—	—	—	—	28	13	4	—	—	—	—
English Ford	12	23	21	10	—	—	—	—	—	—	—
Challenger/ Sapparo	—	—	—	—	—	—	—	—	—	—	3
Fiesta	—	—	—	—	—	—	—	—	—	—	41

[a] Values are approximate because of rounding and use of several data sources.
SOURCE: *Automotive News, 1978 Market Data Book* and earlier Almanac Issues

damageability regulations are added, it is obvious that the industry and its products have entered a period of unprecedented change.

Materials, Design, and Manufacturing Processes

Capabilities in the field of automotive materials, design, and manufacturing processes have reached a very high level in the automobile industry. Requirements, schedules, and future goals are relatively clear. Production volumes are adequate to make exploration of relatively minor improvements worthwhile. The design goal is the optimum combination of performance, cost, risk, and flexibility of application.

A typical car includes about 50 percent carbon steel, 15 percent cast iron, 8 percent other iron and steel, 6 percent rubber, 2.5 percent plastics, 2.5 percent glass, and 2.6 percent aluminum. (See table 131.) The primary manufacturing processes of concern are sheet-metal stamping and welding, followed by ferrous casting. These are well-established processes with little chance for innovations other than responses to the changing economics of energy and process emission control.

Alloy steels are used in gears, bearings, forgings, and other highly stressed parts. Typically, these parts are forged and machined, and are continually the subject of improved manufacturing processes. “Chipless machining” concepts

Table 131 .—Automobile Material Used in a 1974 Plymouth Valiant

	lbs/car	% Wgt.
Plain carbon steel	1,630	52.4
Cast iron	436	14.2
Other iron & steel	254	8.2
Aluminum	70	2.6
Rubber	183	5.9
Plastics	77	2.5
Glass		2.5
Copper/zinc/lead	89	2.9
Soft trim	76	2.4
Sound deadeners	52	1.7
Misc. (fluids, paint, solder)	165	5.3
Total	3,111	100

SOURCE SRI, p V 37

such as spline rolling and powder metal fabrication are preferred and are being expanded as fast as their process economics become favorable.

Most aluminum parts are cast or made of stamped sheet. Aluminum usage has risen to about 100 pounds per car in **1977,** and is expected to go to 150 pounds by 1980. Extensive R&D on stamping and spot welding of aluminum may enable carmakers to replace more and more steel parts with aluminum. The need for weight reduction and the availability of cylinder wall-coating processes (e. g., the Nikasil or the Kawasaki exploding wire scheme) could conceivably reawaken interest in the Chevrolet Vega die-cast aluminum-engine concept. If such a cylinder block went into production, it would replace heavier cast iron with another **50** pounds or so of aluminum per car. Also, manufacture of aluminum wheels of competitive price and performance out of strip with a welded-in center section has recently been accomplished, These parts are expected to replace a fair percentage of steel wheels.

Years ago, plastic parts were generally injection molded or extruded, In recent years, the use of sheet-molding compounds has taken over the bulk of plastic applications by weight. The use of plastics rose to about **160** pounds per car in **1977,** and is expected to go up to 240 pounds per car by 1980, replacing heavier materials. Research into the use of plastics and integrated foam structures for structural and body parts may provide further possibilities in this area,

Because iron and steel are plentiful, and because many parts of cars can ‘be made of alternate materials, automotive materials are not viewed as a problem, either from a standpoint of availability or ability to meet performance needs well beyond **1985.**

The basic design and structure of the automobile has remained essentially unchanged for many years. Two basic configurations have evolved—the unit body and frame and the “conventional” separate body and frame. In the latter, the vehicle consists of a steel chassis or

Photo Credit. General Motors Corporation frame to which the suspension system, wheels, engine, and drivetrain are attached. The vehicle body (consisting of floor, firewall, roof, door, fender, hood and trunk panels, along with inner panels, support members, seats, etc., welded and bolted into place) is then fastened to the frame.

In the unit body and frame concept, the suspension, drivetrain, and engine are attached to reinforced areas of the body, rather than to a separate frame. A variation of this theme is the stub frame concept in which the engine and front suspension are mounted to a short or stub frame attached to the unit body in the vicinity of the firewall. A unit body and frame is generally lighter and more compact, but it is much more difficult to isolate the occupants from engine and road noise. U.S.-manufactured pickup trucks are all of the full-frame type. Two of the three U.S.-built vans have unibody construction.

All of these vehicle structures offer comparable qualities of durability, cost, ease of manufacture, marketability, etc. The level of efficiency achieved through these assembly processes allows the automobile industry to produce an average of 25,000 to 30,000 passenger cars per day.

Propulsion Systems

The first patented internal combustion engine (ICE) was a two-cycle, developed by a Belgian named Etienne Lenoir in Paris around 1860. The four-cycle engine was developed 20 years later by a German, Nicholas Otto. Ironically, coal gas, which was over half hydrogen, was the primary fuel for these early engines. Petroleum products came into play as the industry developed.[5]

In the early years, the ICE faced stiff competition from electric motors and steam engines. However, because of the ICE's higher thermal efficiency and the ability to run long periods of time at high speeds, it became the primary powerplant in motor vehicles.

The ICE began as a one- or two-cylinder machine. It was heavy, noisy, dirty, and only semidependable. As the industry expanded and progressed, so did the engines, into 4-, 6-, 8-, 12-, and even 16-cylinder engines. In the 1950's, the smooth, dependable overhead-valve V-8 engine was introduced on a wide scale and rose in popularity quickly. In recent years, it has been used in more than 70 percent of passenger cars manufactured in the United States. (See figure 55.) However, the need to reduce fuel consumption is expected to reverse this trend as more smaller and lighter cars are introduced.

In the post-World War II period, engine efficiency was increased through higher compression ratios and reduced friction. Increased efficiency was accompanied by an increase in the octane rating of motor fuel. As octane numbers approached 100, refining costs increased much more rapidly, and high-performance engines were approaching the point where only marginal gains in efficiency could be achieved from higher compression ratios. Also, anticipated increases in international shipments of refined petroleum products acted to keep U.S. octane levels more in line with the lower levels elsewhere in the world. As a result, octane numbers peaked around 1970. (See figure 56,)

In response to early emission control requirements (1968), engines were detuned (e. g., retarded spark, changed valve timing, and fuel mixture changes). In 1971, engines were modified to accept lead-free gasoline. The modifications included reducing compression ratios and making related changes to valves and seats. With the advent of catalytic converters in 1975, engines were retuned to attain optimum performance and minimum fuel consumption. Now most engines are designed to run on regular-grade (91 octane) unleaded fuel.

Drivetrain

With few exceptions, U.S. passenger cars for the last 50 years have used a front engine with attached transmission and rear-wheel drive. Automatic transmissions first appeared in the late 1930's; they now comprise about 90 percent of the market.

Early mechanical schemes, including automatic clutches and preselected gear changes,

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[5] John B. Rae, *The American Automobile* (Chicago: University of Chicago Press, 1965).

flourished briefly, as did fluid couplings (no torque multiplication). However, these lost out to the hydrokinetics torque converter combined with two- or three-speed planetary gear sets which are engaged by disc or band clutches. These units are the only automatics available today in the U.S. passenger cars. Some four-speed automatics and some automatics with torque converter lockup were available in the 1940's and 1950's, but disappeared because of cost and lack of interest in fuel economy.

A manual transmission with a single-disc, dry-plate clutch is the only alternative to the automatic now available. These transmissions are usually associated with sports, performance, or economy cars. For U.S.-made cars, the majority of manual transmissions have been three-speed. Four-speed units are usually associated with the large high-performance engine or with fuel-efficient imports. In the last few years, four-speed and even five-speed units have become available for economy cars. Essentially, all manual and automatic transmissions are direct drive in the final gear, although a limited number of U.S. cars have been available with an overdrive attached to the manual transmission. Although overdrive had a gear ratio as low as 0.7 and provided some improvement in fuel economy, it was never particularly popular.

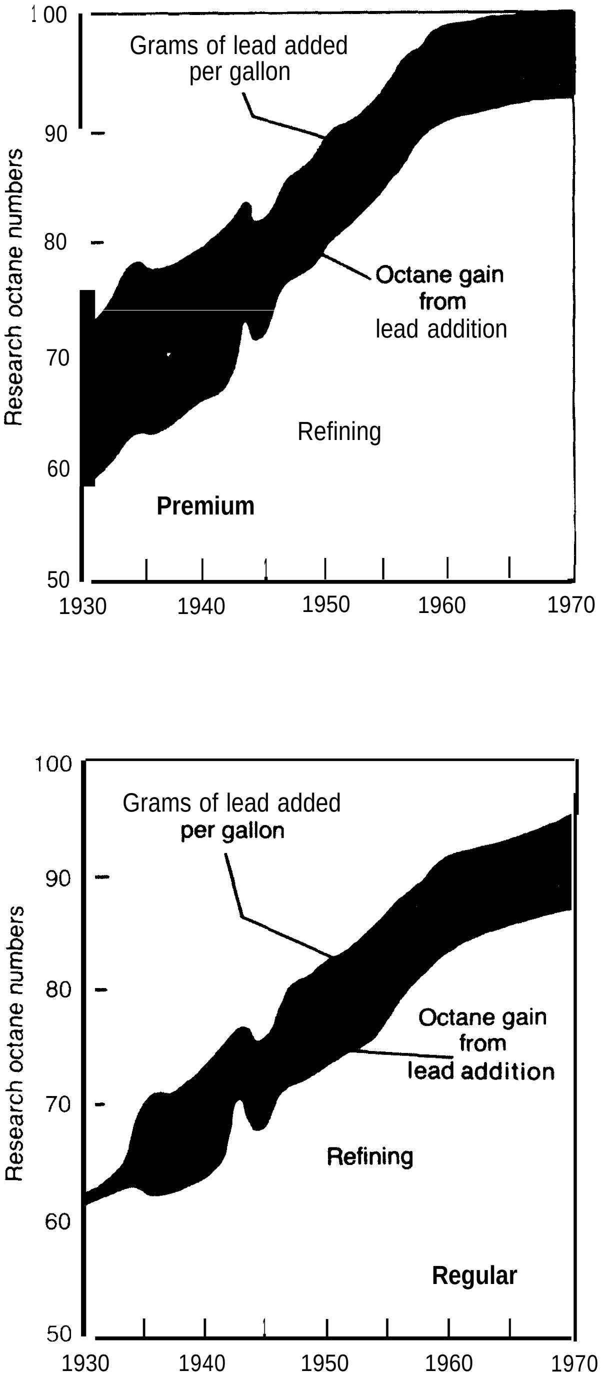
U.S. cars have almost universally used a unit rear-axle housing with a hypoid geared differential. In order to achieve improved fuel economy, this final drive gear ratio has dropped in recent years from the range of 3.5 to **4.o** to about 2.o for large cars.

Regulation

Traditionally, the passenger car industry has been regulated only in the tax, antitrust, and similar business-oriented areas. In the 1960's, it became apparent that automobiles and their use were responsible for a number of serious social problems, and a series of emission control and safety regulations were initiated. In 1973, the oil embargo prompted Government regulation of fuel economy.

Attempts to improve consumer protection by controlling automobile design features have been initiated, and appear to be at least some-

Figure 56.—Historical Source of Octane Quality in Commercial Gasolines



SOURCE S/3/, p v-10

what effective. Mandatory provision of product information may also influence vehicle designs.

The major remaining area in which regulation is likely is the limitation of places or conditions of auto use. (See chapter 6.) Auto use restrictions are of concern technologically because they could increase the demand for small, low-performance, nonpolluting commuter cars. However, specialty cars probably will not become a significant part of U.S. auto production through the year 2000 unless specific policies encouraging such vehicles are adopted.

Other potential regulatory topics such as recycling and materials use do not yet appear on the horizon, although at some point they may be of importance from the perspective of overall national goals.

Emissions

The history of U.S. auto emissions control is presented in table 132. The regulatory effort progressed from a relatively modest start in California to a major broadly based Federal effort characterized by frequent changes to the regulated emission levels. A strong regulatory agency evolved and industry responses soon became a major part of their R&D activities.

Early efforts in controlling vehicle emissions resulted in penalties in fuel economy. The oil embargo made clear the requirement for a balanced approach to reduced emissions and improved fuel economy. Fortunately, some of the technological responses, such as the stratified-charge engine or the catalytic converter, allow substantial reductions in emissions and operation at minimum fuel consumption. Health effects, atmospheric phenomena, and other aspects of air quality are not completely understood, but air pollution is widely perceived by the public as a health problem and a blight to cities. Thus, vehicular emission control will undoubtedly be continued and possibly even tightened.

Currently, three products contained in the exhaust of automobiles are controlled on the basis of grams per mile emitted. They are hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x). The manufacturers must certify that their engines will meet the grams per mile emission requirements for 50,000 miles of vehicle travel before their vehicles can be sold to the public.

The Federal requirements for 1979 model year passenger cars are 1.5 grams per mile HC, 15 grams per mile CO, and 2.o grams per mile NO,. In 1981 and beyond, the Federal requirements will be 0.4 HC, 3.4 CO, and 1.0 NO_x. California has a different, more stringent schedule and lower allowable levels for these emissions. (See table 132.)

Table 132.—Summary of California and Federal Passenger Vehicle Exhaust Emission Standards, 1970 to 1982 and Later

	Hydrocarbons (gm/mi)		Carbon monoxide (gm/mi)		Oxides of nitrogen (gm/mi)	
Model year	California	Federal	California	Federal	California	Federal
1 970a.	2.2	2.2	23	23	no std.	no std.
1971a.	2.2	2.2	23	23	4.0	no std.
1972[b].	3.2	3.4	39	39	3.2	no std.
1973[b].	3.2	3.4	39	39	3.0	3.0
1974[b].	3.2	3.4	39	39	2.0	3.0
1975	.9	1.5	9	15	2.0	3.1
1976	.9	1.5	9	15	2.0	3.1
1977	.41	1.5	9	15	1.5	2.0
1978	.41	1.5	9	15	1.5	2.0
1979	.41	1.5	9	15	1.5	2.0
1980	.41	.4	9	7	1 .0[c]	2.0
1981	.41	.4	3.4	3.4	1 .0[c]	1.0
1982 and later	.41	.4	7	3.4	.4	1.0

[a] Tests conducted using 7 mode" test cycle a 137 second driving cycle

[b] Tests conducted using crs-72 test cycle, a constant volume sample including cold start For 1975 and later the test cycle is a crs 75, which includes cold and hot starts

[c] For California orly, a 100.000 mile certification is optional with the NO_x standard at 1 5 g mi/mi

SOURCE *SRI* p V 23

Several components and systems for meeting these emission standards are currently being used or are in the development or planning stages. These include designs for improved combustion (e.g., electronic control of ignition timing and fuel metering, stratified-charge concepts), improved after-treatment systems (e. g., three-way catalyst), diesel engines, turbines, and Stirling engines.

The detailed list of technological options is long, and there is a high probability of meeting regulatory goals. The present exploratory phase of industry development will gradually shift toward full exploitation of the optimum combinations that evolve. The manufacturers will probably choose different combinations of options, although electronic control of the air-fuel ratio and ignition timing will probably be virtually universal by 1981.

The announcement of a 0.4-gram-per-mile NO_x standard for California passenger cars in 1982 and beyond introduces a more difficult technical problem than does the Federal standard of 1.0 gram per mile. To date, no concepts have been demonstrated that can meet this level with typical large U.S. spark-ignition engines (SIE). Volvo, Saab, and GM have demonstrated that they can meet this 0.4 NO_x requirement with a three-way catalyst system on four-cylinder engines. However, the ability to meet the requirement for 50,000 miles without maintenance and under high-production conditions has not been demonstrated.

Fuel Economy

Passenger car fuel consumption in the aggregate is measured on the basis of gasoline tax receipts and total vehicle miles traveled (VMT). These measures reflect a long-term decline in fuel economy per auto from about 15.3 mpg in 1940 to 13.1 mpg in 1973.[6] The national speed limit of 55 mph, the catalytic converter, and industry efforts to improve fuel economy resulted in improvement to 13.5 mpg by 1975. Total fuel consumption is a function of VMT, the way these miles are driven (speed, acceleration, etc.), and the inherent efficiency (expressed as miles per gallon) of the average vehicle. Only the latter parameter is considered in this section.

The Energy Policy and Conservation Act of 1975 mandated new car fuel economies of 20 mpg by 1980 and 27.5 mpg by 1985 on a manufacturer's fleet average basis.[7] It seems that these goals can be met, but the industry is concerned about consumer acceptance of the vehicle modifications that are necessary. Prospective methods for meeting the goals include weight reduction; improved engine efficiency; reduced losses in tires, drive line, transmission, and accessories; and improvements in aerodynamics and overall vehicle optimization. The challenge lies in finding the combinations that meet the public needs of adequate performance, capacity, emissions, safety, cost, durability, and general appeal.

Safety

Regulation of motor vehicle safety above and beyond evolutionary improvements in the design, construction, performance, and handling of motor vehicles, is achieved primarily through the application of the Federal Motor Vehicle Safety Standards, issued and enforced by the National Highway Traffic Safety Administration (NHTSA). Approximately 50 safety standards are in effect, most of which apply to passenger cars. (See table 133.) The technology required to meet many of the Federal Motor Vehicle Safety Standards is not particularly complex; once it is developed and incorporated into a vehicle, the unit cost in most cases is not great. The regulated vehicle safety features are considered to be partially responsible for the reduction in the rate[8] of highway deaths since 1966.

Another responsibility of NHTSA is the investigation of vehicle defects, often leading to recall campaigns by the auto manufacturers. In

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[6] *SRI*, p. V-12. (Originally from U.S. Statistical Abstracts and MVMA data.)

[7] These fuel consumption values are based on chemical analysis of the exhaust (done as part of emission testing) and are not necessarily comparable to the previously mentioned values. The Environmental Protection Agency values of fuel consumption are up to 20 percent higher than actual values. U.S. Environmental Protection Agency, Emission Control Technology Division, Office of Mobile Source Air Pollution Control, *Evaluation of the Representativeness of EPA Fuel Economy Estimates*, January 1978.

[8] The fatality rate, expressed in deaths per hundred million vehicle miles of travel, dropped from 5.7 in 1966 to 3.4 in 1975, (U.S. Department of Transportation, National Highway Traffic Safety Administration, *Traffic Safety '76:* A Report by the President on the Administration of the Highway Safety Act of 1966, as amended, Jan. 1, 1976 - Dec. 31, 1976) and to 3.2 in 1976 (U.S. Department of Transportation, National Highway Traffic Safety Administration, *Motor Vehicle Safety '77*).

Table 133.—Chronology of Federal Motor Vehicle Safety Standards and Regulations

Date Issued	Standard	
January 31, 1967	Standard No. 101	Control Location, Identification, and Illumination
	Standard No. 102	Transmission Shift Lever Sequence, Starter Interlock, Transmission Braking Effect
	Standard No. 103	Windshield Defrosting and Defogging
	Standard No. 104	Windshield Wiping and Washing Systems
	Standard No. 105	Hydraulic Brake Systems
	Standard No. 106	Brake Hoses
	Standard No. 107	Reflecting Surfaces (Chrome Trim)
	Standard No. 108	Lamps, Reflective Devices, and Associated Equipment
	Standard No. 111	Rearview Mirrors
	Standard No. 201	Occupant Protection in Interior Impact
	Standard No. 203	Impact Protection for the Driver From the Steering Control System
	Standard No. 204	Steering Control Rearward Displacement
	Standard No. 205	Glazing Materials (Automobile Windshield Glass)
	Standard No. 206	Door Locks and Door Retention Components
	Standard No. 207	Seating Systems
	Standard No. 208	Occupant Crash Protection
	Standard No. 209	Seat Belt Assemblies
	Standard No. 210	Seat Belt Assembly Anchorages
	Standard No. 211	Wheel Nuts, Wheel Discs, and Hub Caps
	Standard No. 301	Fuel System Integrity
November 8, 1967	Standard No. 109	New Pneumatic Tires
	Standard No. 110	Tire Selection and Rims
February 12, 1968	Standard No. 202	Head Restraints
April 24, 1968	Standard No. 112	Headlamp Concealment Devices
	Standard No. 113	Hood Latch Systems
	Standard No. 114	Theft Protection
July 3, 1968	Standard No. 115	Vehicle Identification Numbers
August 13, 1968	Standard No. 212	Windshield Mounting
December 24, 1968	Standard No. 116	Motor Vehicle Brake Fluids
January 17, 1969	Part No. 567	Certification Regulation
	Part No. 569	Regrooved Tires
March 23, 1970	Standard No. 213	Child Seating
July 17, 1970	Standard No. 118	Power-Operated Window Systems
October 22, 1970	Standard No. 214	Side Door Strength
November 5, 1970	Part No. 574	Tire Identification and Recordkeeping
December 31, 1970	Standard No. 302	Flammability of Interior Materials
February 10, 1971	Part 573	Defect Reports
February 19, 1971	Standard No. 121	Air Brake Systems
April 9, 1971	Standard No. 215	Exterior Protection (Bumpers)
April 14, 1971	Standard No. 117	Retreaded Pneumatic Tires
December 3, 1971	Standard No. 216	Roof Crush Resistance
March 1, 1972	Standard No. 122	Motorcycle Brake Systems
	Standard No. 125	Warning Devices
March 31, 1972	Standard No. 124	Accelerator Control Systems
April 4, 1972	Standard No. 123	Motorcycle Controls and Displays
May 3, 1972	Standard No. 217	Bus Window Retention and Release
August 3, 1972	Standard No. 126	Truck-Camper Loading
January 17, 1973	Part No. 577	Defect Notifications
January 22, 1973	Part No. 555	Temporary Exemptions From Federal Motor Vehicle Safety Standards
January 31, 1973	Part No. 580	Odometer Disclosure Requirements
July 26, 1973	Part No. 572	Anthropomorphic Test Dummy
August 9, 1973	Standard No. 218	Motorcycle Helmets
November 5, 1973	Standard No. 119	New Pneumatic Tires
May 20, 1975	Part No. 575	Consumer Information—Uniform Tire Quality Grading
June 9, 1975	Standard No. 219	Windshield Zone Intrusion
September 4, 1975	Part No. 552	Petitions for Rulemaking, Defect and Noncompliance Orders
	Part No. 570	Vehicles in Use Inspection Standards
January 19, 1976	Standard No. 120	Tire Selection and Rims for Vehicles Other Than Passenger Cars
January 22, 1976	Standard 220	School Bus Rollover Protection
	Standard No. 221	School Bus Body Joint Strength
	Standard No. 222	School Bus Seating and Crash Protection
February 27,1976	Part 581	Bumper Standard (Incorporates Standard 215)

SOURCE U S Department of Transportation, National Highway Traffic Safety Administration. *Traffic Safety '76*

the period 1966 to 1975, 52 million vehicles were recalled, or 43 percent of total production.

It is generally agreed that the majority of crashes are the result of driver error or misperception. Thus far, there are few suggestions for improving the capability and reliability of the typical driver. Regulatory efforts have focused on improved occupant protection and, to a lesser extent, accident avoidance.

Accident avoidance includes features such as better acceleration, improved brakes, improved lighting and visibility, and improved handling. Such features are marketable commodities, but some are costly. Also, there is not clear evidence that all of these features contribute significantly to reductions in the number of crashes.

In contrast, occupant protection is effective, and the results can be evaluated. Passive restraint systems are required for introduction in the 1982-84 model years. This technology is developed and no technical difficulties are foreseen. However, the data on the effectiveness of these systems are still being debated and additional field experience is desirable. Also, public acceptance of passive restraints is presently unknown.

Most safety goals conflict with fuel-economy goals since additional safety equipment or structure means more weight and lower fuel economy. Also, small fuel-efficient cars have the potential for relatively higher fatality rates because occupant protection is partly a function of crush distance and relative vehicle weights.

Although the "no-damage" bumper was introduced under Federal Motor Vehicle Safety Standard 215, there is a slim justification for considering this to be a safety feature. It is now part 581 of the 1972 Motor Vehicle Information and Cost Savings Act. It is expected that this requirement will stay in effect and, through design improvements, the cost and weight penalties will be minimal.

Potential Regulatory Areas

Passenger car noise will probably become the subject of Federal regulation in the future. However, at present, trucks are by far the loudest sources of highway noise and are more appropriate targets for regulation.

So far the only significant passenger car noise standards are those in California. The California limits are 76 dBA below 35 mph and 82 dBA above 35 mph. Current gasoline-powered automobiles already meet the California standards. Diesel engines are noisier than spark ignition engines at low speeds, but at medium and high speeds, tire and wind noise dominate for both types of vehicles. Reduction of tire noise is the object of much research.

In the case of radiation of electromagnetic energy by the automobile's ignition system, it is reported that the industry is establishing standards of its own.[9] However, some Federal agency may well add this to its regulatory spectrum.

Regulations designed to control corrosion damage may evolve in the near future, particularly in view of the obvious and unnecessary financial impacts of corrosion. Canada is working very hard on establishing a uniform code that would limit corrosion damage.

As one avenue of engine design turns more and more to very lean mixtures and high compression heterogeneous fuel/air charges (Ford PROCO, Texaco TCCS), ignition systems with even higher energy content per discharge are required. Some contemplated systems could produce a lethal shock for the unwary mechanic. Products such as these are unlikely to be offered in the general marketplace.

Recent information indicates that various fluorocarbon gases react with the ozone in the Earth's atmosphere, with the potential for increasing the amount of sunlight (at certain wavelengths) that reaches the Earth's surface. To minimize this effect, such compounds are being eliminated as propellants for spray cans. Similar compounds (e.g., Freon ® 12) are the preferred working fluid in most small refrigerative air-conditioners, including those used in motor vehicles. All such vehicle systems are of the nonhermetically sealed type, and thus have a potential for leakage, either when in use or when scrapped. As a result, such systems may be inappropriate. An alternative approach is to use a refrigerative cycle where the air to be cooled is the working fluid (e. g., ROVAC or turbo expander). These systems, at least in their present forms, are bulkier, more complex and more costly. As experience is gained, this situation may be greatly improved.

Under the 1972 Motor Vehicle Information and Cost Savings Act, NHTSA must determine crash susceptibility, crashworthiness, associated insurance costs, and ease of diagnosis and repair of mechanical and electrical problems. This information must then be made known to the public for each make and model of car. Although Sweden has had most elements of such a program in effect for years, this program has yet to be implemented in the United States. If it should, the effects on the competitive posture of at least some of the various domestic and import automobiles would likely be noteworthy. Small cars might suffer a setback in public acceptance for safety reasons, and favorable ratings would be crucial to the survival of smaller manufacturers.

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[9] SRI, p V-38

AUTOMOTIVE TECHNOLOGY TO 1985

As discussed in the previous section, many of the regulatory patterns and resulting technological responses that will appear between now and 1985 have already been established—at least in broad terms. The auto industry has publicized a number of alternative plans for meeting regulated economy goals, and it is generally conceded that the goals can be met from the standpoint of technology.

However, the changes involved are costly in terms of R&D, tooling, and facilities, and are required on a schedule that is much faster than normal industry response times. Also some of the changes could easily affect customer acceptance of major segments of the new car offerings. The industry feels that if sales were to drop significantly, cash flow would be affected and the ability to finance these massive changes would be a problem. Accordingly, this is viewed by the industry as a period of high risk in which only the technologies with a high probability of success can be relied upon.

Downsizing and Materials Substitution

The most important changes which are slated to occur between now and 1985 center around the requirement to meet a corporate average fuel-economy level of 27.5 mpg and, simultaneously, the statutory emission standards of 0.41 HC, 3.4 CO, and 1.0 NO_x. The industry response has been to embark on a major program of downsizing all cars in the product line, reducing weight by changes in materials, design, and vehicle layout, and instituting fuel-saving features in almost every component of the vehicle. Simultaneous developments in engine modifications and new engines and fuels are being pursued; Government incentives and assistance are being provided in this latter area. Individual major aspects of this overall program are discussed below.

Major gains in weight reduction are being achieved by both downsizing and materials substitution. Materials substitution includes the use of lightweight designs and materials, and is a somewhat slower process than simple size changes.

Weight reduction by downsizing generally takes the form of closer packaging of the main vehicle components reducing interior waste space and, in some cases, reducing width from three- to two-abreast seating. Some of the most important gains are achieved by shortening the trunk overhang and reducing styling-induced waste space from the firewall forward. Such major body changes are equivalent to, but more extensive than, the major styling changes that the industry previously undertook for competitive reasons. In the smallest car categories, it is generally agreed that the most practical way to achieve maximum efficiency of packaging power train components is to use a front engine, front-wheel-drive layout. Many small European cars and several U.S. cars have adopted this concept. Costs are slightly higher than for a conventional rear-wheel-drive layout, but this may now be offset by the importance of saving weight and optimizing interior volume. As more experience is gained, front-wheel drive will probably be tried on new, lightweight larger cars.

Weight reduction by materials substitution is inextricably intertwined with considerations of cost, performance, appearance, durability, materials compatibility, and similar parameters. Some substitution concepts allow the redesign of not only the principal part but also associated parts. This effect is referred to as "cascading," that is, the iterative effect of weight reduction.

Other forms of weight reduction include elimination of the spare tire as a result of improved tire durability and puncture resistance, use of a smaller tire for the spare, reduction of engine block casting-wall thickness, and lighter wheels and batteries. Most of these are "one-shot" opportunities, but not all have been exploited.

Associated with downsizing is the planned reduction in engine size, usually described **as** cubic inch displacement (CID), and reduction in the size of all related transmission and drivetrain components. The size of these components can be reduced to the minimum level that will produce acceptable performance (typically zero to 60 mph acceleration times of about 16 to 18 seconds).

Engine downsizing results in improved fuel economy because of reduced weight and because the engine is run with the throttle open farther more of the time. This reduces throttling loss, which is a factor affecting overall engine efficiency. However, too small an engine for a given car can actually result in reduced fuel economy because much of the time, the engine would operate in an overloaded, inefficient power range.

Department of Transportation (DOT) studies indicate that a 10-percent reduction in weight with a reduction of engine size for constant acceleration performance can produce a 6.8-percent improvement in fuel economy. This, in conjunction with other efficiency improvements in vehicle systems, constitutes the general strategy for meeting the fuel-economy goals set at 27.5 mpg for 1985.

Presently, it appears that there are no major technical problems with downsizing. However, there are technical limitations on materials substitution; progress in this area is being accomplished as the industry develops designs and processes that are compatible with other manufacturing processes. The weight reduction program requires considerably greater expenditures than the industry's customary annual investments for redesign and retooling. Cost considerations are particularly important in the area of materials substitution. Some substitution of lightweight materials (plastic, aluminum, and high-strength steels) has occurred, but only when the cost was lower and all other capabilities of the substitute material were equivalent to or higher than the original material. However, it is expected that greater emphasis will be placed on weight saving, despite a slight increase in cost.

One potential drawback to the downsizing plan is safety. It has been reported that the rate of fatality or serious injury in a multiple-car collision is twice as high in a small car as in a large car. In a crash, the rate and duration of deceleration of the vehicle is part of the mechanism that produces injury. This is a function of the distance through which the deceleration occurs, referred to as the stopping distance or crush distance. Smaller cars have much less crush distance available. Theoretically, 4 feet is sufficient to decelerate a properly restrained, forward-facing human from 60 mph, so that the person incurs little or no injury. Most small cars today have that distance in front of the windshield.[12] However, the occupant compartment typically extends beyond the windshield. Since the engine is incompressible, the available crush distance is reduced further. Even in the largest cars, the crush distance is only marginally adequate.

For small cars, additional mechanisms are required to help decelerate the occupants in high-speed barrier crashes. The only current contenders are energy-absorbing restraint systems, such as air bags, or special belt systems that allow the occupants to decelerate while moving closer to the dash and firewall (thus utilizing all of the available interior space as well as the vehicle crush distance). At this time, this is somewhat academic, since current barrier crash requirements, set at 30 mph, are easily met by large and small cars.

Another obvious drawback to downsizing is the reduction in capacity of vehicles, and the reduction in comfort associated with space. The current six-passenger full-size sedan will most likely be replaced by a car offering the same level of comfort for only four passengers.

The reduction in engine sizes to achieve higher fuel economy and the increased engine efficiency, achieved through operating with the throttle closer to wide open, may reduce engine life expectancy. In addition, increased emissions of nitrogen oxides can occur.

The major domestic manufacturers are deeply involved in extensive downsizing programs. These programs are projected to reduce average inertia weight by about 800 to 1,000 pounds during the 1978-81 model years. A second round of downsizing is also planned to permit achievement of the 1985 fuel-economy standards.

The corresponding improvements in new car

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[10] U.S. Department of Transportation, National Highway Traffic Safety Administration, *Fatal Accident Reporting System: 1976 Annual Report*, November 1977.

[11] W. Haddon, Jr., "Reducing the Damage of Motor-Vehicle Use, " *Technology Review*, July-August 1975, p. 59.

[12] Data from the Insurance Institute for Highway Safety.

fleet fuel economy expected from the initial downsizing programs are about 3 to 4 mpg. Table 134 summarizes the potential new car fleet average inertia weight achievable through body redesign by 1981.

The specific plans for downsizing and for alternatives for different conditions of timing and emission penalties were submitted by the U.S. manufacturers in response to a Federal inquiry. GM, for example, reduced the length—both wheel-base and bumper-to-bumper—of its 1977 model year full-size cars to obtain weight savings of 650 to 950 pounds.

The manufacturers' plans have been adjusted many times, and may well be changed again. However, it seems likely that the response will be along the lines illustrated by the General Motors Alternative III approach, which consists of:

- weight reduction by redesign and materials substitution;
- use of some diesels; and
- engine, transmission, and miscellaneous improvements.

The general categories of changes, the projected timing, model-by-model differences, and engine selections are given in figure 57 and tables 135 and 136, using the GM documentation as an example. Changes will differ among companies, and additional changes beyond those listed may be made as 1985 approaches. Some of these differences include:

- Timing and sequence of weight reduction redesigns by car model will differ.
- Schedules for improvements in engines, transmissions, and miscellaneous components will differ.
- Ford appears to be pursuing stratified-charge technology rather than diesel as a means of achieving a modest step-improvement in specific fuel consumption (SFC)[13] and emissions.
- Weight reductions resulting from materials substitution are already being introduced on a scheduled basis, and could be called upon to provide improvements beyond those presently planned.
- A surge of interest in safety considerations could require weight additions that are not included in the current planning.
- Further emissions control requirements could cancel some of the anticipated gains in engine efficiency.
- Scheduling of such extensive and costly product changes 8 years ahead of the final goal must be considered tentative and will be subject to many unforeseen economic, social, and regulatory pressures.

Materials substitution is a continuing process in the auto industry; however, special emphasis on materials substitution is expected in the 1982-85 period. On a part by part basis, aluminum can, in some instances, save up to 50 percent of the weight of the original part. Plastics can sometimes offer even greater savings. The attractiveness of materials substitution lies in the cascading effect which it produces. Reducing the weight of a car's body by 50 pounds through the use of substitute plastics or aluminum can lead to as much as 75 pounds of other savings. This is because the chassis can then be made lighter and a smaller engine can be chosen (which in turn reduces the structural needs). Table 137 illustrates some of the recent trends in the use of materials in automobiles. Table 138 shows a hypothetical case of materials substitution illustrating the cascading effect.

Downsizing and materials substitution have important cost implications for the auto industry. In the past, many components of the suspension and running gear systems, accessories, and even some of the body panels remained the same during a major model change. However, with downsizing almost all of these components will change completely. Also, the complete product line will have to change in less than 8 years. This represents a difficult task from the standpoint of required capital, design and production, and engineering effort. The historical expenditures for new plants and equipment are shown in figure 58.

Capital requirements for vehicle downsizing depend partly on the capacity and flexibility of

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[13] U.S. Department of Transportation, National Highway Traffic Safety Administration, Office of Automotive Fuel Economy, *Data and Analysis for 1981-1984 Passenger Automobile Fuel Economy Standards* Document 2, Vol. 1, Feb. 28, 1977,

Table 134.—Vehicle Weight, 1976 and 1981

Manufacturer	Current (1976) average inertia weight	Downsized (1981) average inertia weight
Chrysler	4,150	3,400
Ford	4,100	3,300
General Motors	4,450	3,480
American Motors	3,550	3,400

SOURCE: U.S. Department of Transportation, National Highway Traffic Safety Administration, *Data and Analysis for 1981-1984 Passenger Automobile Fuel Economy Standards*, February 1977.

Table 135.—General Motors Weight-Reduction Technology (weight[a] in pounds)

		Baseline		Body redesign		Material substitution	
Car concept	Performance	Curb	Inertia	Curb	Inertia	Curb	Inertia
Full-size regular sedan	Lo	3,700	4,000	—	—	3,410	3,500
	Med	3,800	4,000	—	—	3,430	3,500
	High	4,000	4,500	—	—	3,570	4,000
Wagon	Med	4,260	4,500	—	—	3,940	4,000
	High	4,400	4,500	—	—	3,940	4,000
Full-size luxury sedan	Med	4,170	4,500	—	—	3,870	4,000
	High	5,190	5,000	—	—	—	—
Mid-size regular sedan	Lo	3,830	4,000	3,200	3,500	3,000	3,500
	Med	3,830	4,000	3,220	3,500	3,020	3,500
	High	4,260	4,500	3,500	3,500	3,155	3,500
Wagon	Med	4,300	4,500	3,470	4,000	3,270	3,600
	High	4,420	4,500	3,590	4,000	3,390	3,500
Mid-size luxury sedan	Med	—	—	3,590	4,000	3,390	3,500
	High	4,340	4,500	3,610	4,000	3,410	3,500
Mid-size special sedan	Med	4,060	4,500	3,245	3,500	3,045	3,500
	High	4,180	4,500	3,370	3,500	3,170	3,500
Compact regular sedan	Med	3,330	3,500	2,680	3,000	2,480	2,750
	High	3,500	4,000	—	—	—	—
Wagon	Med	—	—	3,050	3,500	2,850	3,000
	High	—	—	3,170	3,500	2,870	3,000
Compact special sedan	Med	3,460	4,000	2,900	3,000	2,700	3,000
	High	3,600	4,000	—	—	—	—
Subcompact regular sedan	Lo	—	—	2,270	2,500	2,120	2,500
	Med	2,690	3,000	2,290	2,500	2,140	2,500
Wagon	Med	2,740	3,000	2,360	2,740	2,210	2,500
Subcompact mini sedan	Med	2,060	2,500	1,820	2,000	1,820	2,000
Subcompact special sedan	Med	—	—	3,250	3,500	3,100	3,500
	High	3,670	4,000	—	—	—	—

[a] "Inertia" weight refers to the equivalent weights needed for the simulated urban and highway driving cycle dynamometer tests used in emissions measurements.
SOURCE: U.S. Department of Transportation, National Highway Traffic Safety Administration, *Data and Analysis for 1981-1984 Passenger Automobile Fuel Economy Standards*, February 1977.

Table 136.—General Motors Corporation Alternative Ill, Model Year 1985 Engine Production Summary

Engine (CID)	Number of cylinders	Transmission	Percent sales
85.0	4	A	1.83
85.0	4	M	2.08
Subtotal			3.91
98.0	**4**	**A**	**2.40**
98.0	**4**	**M**	**2.00**
Subtotal			**4.40**
151.0	6	A	24.35
151.0	6	M	2.27
Subtotal			26.62
231.0	6	A	29.55
231.0	6	M	0.21
Subtotal			29.76
301.0	8	A	9.30
305.0	8	A	3.34
350.0 (diesel)	8	A	22.67
Subtotal			35.31
Total			100.00

[a] A = automatic, M = manual.

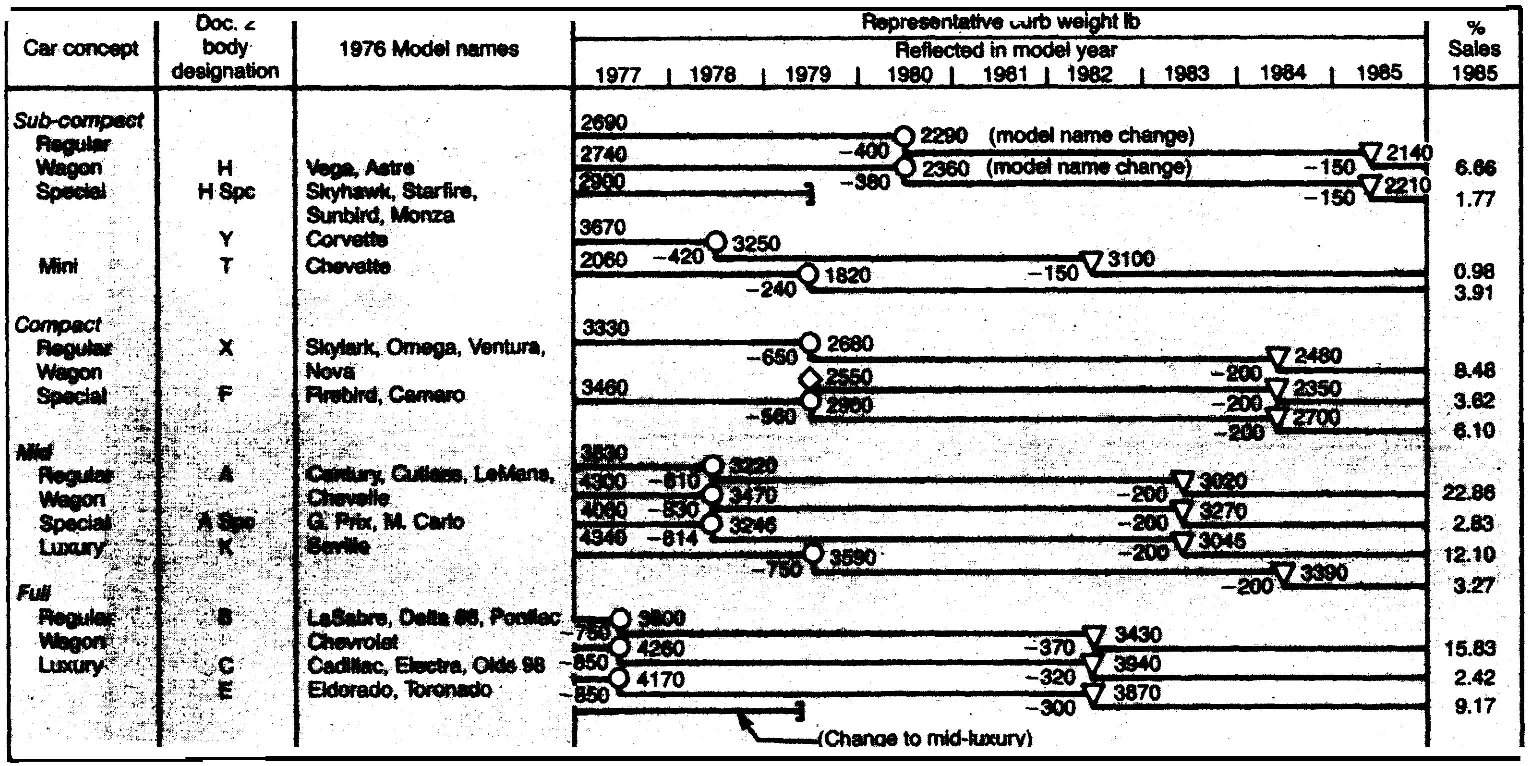
SOURCE: U.S. Department of Transportation, National Highway Traffic Safety Administration, *Data and Analysis for 1981-1984 Passenger Automobile Fuel Economy Standards*, February 1977.

Table 137.—Materials Used in a Chevrolet Impala (pounds)

Material	1974	1977	Percent change
Steel	2,708	2,221	– 18
Iron castings	690	620	– 10
Plastics	138	200	+ 43
Glass	107	115	+ 7
Aluminum	59	69	+ 17
Nontire rubber	37	35	– 5
Copper	27	25	– 7
Zinc	24	20	–17
Other	548	405	–26
Total	4,338	3,710	–14

SOURCE: *Business Week*, Aug. 2, 1976, and May 23, 1977.

Figure 57.—Time-Phased Introduction of GMC Weight-Reduction Technology



KEY
○ Body redesign
▽ Material Substitution (Alternatives II & III Only)
◇ New car concept

SOURCE: U.S. Department of Transportation, National Highway Traffic Safety Administration, *Data and Analysis for 1981-1984 Passenger Automobile Fuel Economy Standards*, February 1977.

Table 138.—Hypothetical Vehicle Upper and Lower Body Weight Reductions (pounds)

Area and component	Original weight	Materials substituted	Total weight savings
Upper body			
Windshield, cowl, dash	90	High-strength steel (reduced thickness)	14
Center pillar	25		5
Qtr. panel, wheel hsg.	124		19
Deck panel shelf	54		7
Roof, rear window	66		9
Front-end sheet metal	237		43
Hood assembly	105	Aluminum (increased thickness)	46
Deck-lid assembly	55		33
Door assembly	170	Aluminum on panels Ultra-high strength steel on door guard Beams	27
Glass & tracking	110	Thinner glass	17
Interior & exterior trim & seats	279	Aluminum & high-strength steel in selected components	42
Lower body			
Underbody (rails, floor pan)	272	High-strength steel	62
Sills	49	Iterative reductions	12
Total bodyweight savings			333

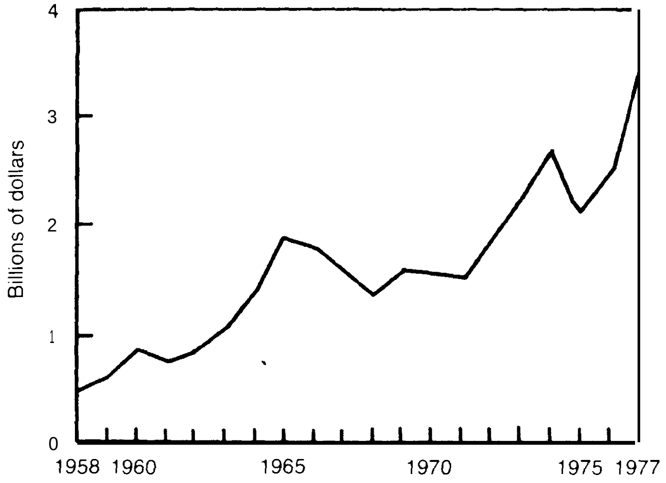
			Savings from chassis materials substitution	Iterative savings from: Body	Iterative savings from: Chassis	Total weight savings
Chassisgroup						
Power plant	793	High-strength steel		109	13	122
Final drive	188			39	5	44
Forestructure	181		7	47	5	59
Suspension	248		9	60	7	76
Steering system	76			21	2	23
Brakes	199			56	6	62
Wheels&tires	244		10	52	6	68
Exhaust system	46			14	2	16
Fuel system	33			5	1	6
Bumpers	177	Aluminum&high-strength steel	22	44	5	71
Total chasis weight savings			48	447	52	547
Other	459					
Total	4,280					880 (21%)

SOURCE *SRL p* V-18

the existing plants. Capital requirements for conversion of all the necessary production facilities for a 400,000-unit-per-year capacity assembly plant have been estimated to be in the area of $150 million to $250 million. This includes provision for unassociated 10-to20-percent increase in small-engine production capacity. Capital requirements for downsizing a major part of a manufacturer's annual production (e.g., 1 million cars) have been estimated to be in the range of $400 million to $700 million. This is a one-time expense, and compares with total industry projected capital expenditures of $21.3 billion in the 1976-80 time frame (roughly $5 billion per year).” This adds up to about $50 billion by 1985.

“Ibid,

Figure 58.—U.S. Auto Industry New Plant and Equipment Expenditures



SOURCE: *SRI*, p. V-16.

Otto Cycle Engines

This category of engines includes the conventional spark ignition engine, which uses a homogeneous mixture of gasoline and air that is premixed upstream of the intake valve. It also includes prechamber and single-chamber stratified-charge concepts, and various forms of rotary engines.

The vast majority of automotive experience and R&D effort is associated with Otto cycle engines. There appears to be opportunity for improving such engines in terms of emissions, size, weight, and specific fuel consumption. In addition to direct engine improvements, there is considerable potential for cleanup of exhaust emissions downstream of the basic engine. Also, various methods for reducing effective engine size, such as turbocharging or the Eaton valve selector, can help improve vehicle fuel economy.

Most of the changes that have been made to meet emissions and fuel-economy regulations affect internal or external aspects of conventional engines. Examples of "internal" changes include:

- control of ignition timing and duration,
- higher energy spark,
- quick warmup features,
- modifications to manifold flow passages,
- valve timing and overlap,
- increased swirl in the combustion chamber for better combustion,
- improved mixture preparation, and
- optimum mixture ratios through more accurate control systems (e. g., electronic).

The "external" approaches have included:

- exhaust gas recirculation (EGR),
- air injection into exhaust ports (air pump system),
- catalytic converters, and
- feedback control of mixture ratio (control system with external sensors).

Continuations, refinements, and extensions of these concepts are proceeding in a variety of development programs. These developments will probably contribute significantly to meeting the emission requirements and mandated fuel-economy goals.

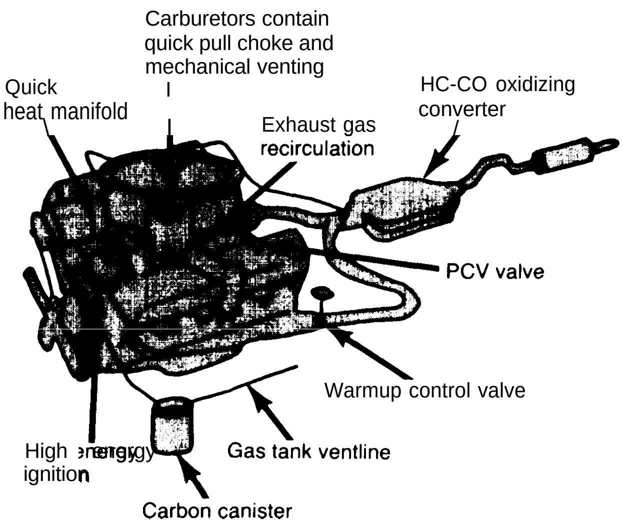
Catalytic Control of Exhaust Emissions

The typical emissions control system on most domestic new cars is shown in figure 59. Its main components are the oxidation catalyst and supportive engine controls. The oxidation catalyst was first installed on most domestic new cars in model year 1975. Through exhaust gas recirculation (EGR), NO_x emissions are generally controlled by diluting the incoming charge with relatively inert exhaust gases. This added exhaust gas reduced peak combustion temperature (a controlling factor in the reaction of nitrogen and oxygen to form NO_x).

The two-way oxidation catalyst commonly uses platinum and palladium to oxidize hydrocarbons and carbon monoxide. It can meet the emission standards of 0.41 gram per mile for HC and 3.4 grams per mile for CO in almost all cases. Oxidation catalysts generally operate at lower temperatures and allow engine tuning for better fuel economy than is achieved by thermal reactors (used by at least one foreign manufacturer) that require excess oxygen.

The three-way catalyst is expected by most industry sources to be the system chosen for achieving 1981 Federal emission standards while obtaining close to maximum fuel economy. This system is now used in some California cars.

Figure 59.—Typical Emission Control System



SOURCE: Harbridge House, Inc., *Automobile Technology Assessment: Case Studies of Foreign Government Policies and Experience,* Draft, March 1977,

The three-way catalyst employs platinum, rhodium, and palladium as the active noble metal ingredients for conversion of CO, HC, and NO_x. Very precise air/fuel ratio control is required, and this can be provided by carburetors or fuel injection in conjunction with an oxygen sensor feedback control system. Optimim emission control and close to optimum fuel economy are achieved simultaneously by running at stoichiometric (chemically correct) air/fuel ratio.

There are no significant technical restraints accompanying the use of the oxidation catalyst in meeting current emissions requirements other than degradation of this system over time. There is some concern that the system will not perform well near the end of the 50,00&mile lifecycle and that consumers may not replace the catalysts when necessary.

Early indications that the oxidation catalyst was a fire hazard have subsided. Also, a suspected increase of emissions of sulfur oxides through the use of the catalytic converter has proven unfounded.

Primary obstacles to marketing the three-way catalyst are:

- Rapid depletion of the available supply of rhodium may result from using a high platinum/rhodium ratio in the construction of the three-way catalyst and from high platinum loading per cubic inch of engine displacement. The naturally occurring platinum/rhodium mine mix of 19:1 is being experimented with, although a platinum/rhodium ratio of 5:1 gives better control. The development of base metal catalysts would be desirable in order to relieve the demand for noble metals.
- The oxygen sensor, critical for operation of the system, currently lasts about’ 15,000 miles, and replacement is necessary.
- The cost of the complete three-way emission control system is somewhat higher than that of the two-way catalyst. EPA’s summary of retail sticker price increases, derived from manufacturers’ estimates, shows a range of $113 to $176 over 1977

model year base prices for the three-way system.

Catalyst reactor systems have been applied in new cars since **1975.** Use of even more effective catalyst-based emission control systems may become universal in 1981.

Volvo has installed the Engelhard three-way catalyst and electronic feedback control on some of its 1977 cars. Ford and General Motors have introduced this system on a limited number of their 1978 new cars in California in order to comply with the tighter California emission standards and to gain operating experience prior to full-scale use. Further research by U.S. automakers involves refinement of the equipment for greater durability and improved efficiency.

The prospects for development of an effective and durable base-metal catalyst are uncertain and no realistic time frame can be suggested. However, this advance is important from a standpoint of protecting against disruption or diminution of foreign sources of noble metals.

Some small additional investment in R&D on advanced catalyst systems will probably continue, and work on base-metal catalysts will continue. Much of this will be funded by the suppliers to the auto industry as well as the auto manufacturers.

Stratified-Charge Engines

In a general sense, the term stratified charge is applied to any engine in which combustion occurs with large variations in mixture ratio in the overall combustion chamber. Charge stratification is a fundamental aspect of any engine where fuel is injected directly into the combustion chamber and ignition occurs before the fuel air mixture becomes homogeneous (as a result of diffusion, turbulence, swirl, etc.). All diesels, direct-injection gasoline engines (such as PROCO, TCCS and the like), and most external combustion engines can be included in this category.

Another general form of charge stratification has received much attention in recent years. It uses two separate chambers with a rich fuel/air ratio in one (usually a small prechamber containing the spark plug) and a very lean mixture in the other (or main) combustion chamber. In most such engines, a relatively homogeneous gasoline-air mixture is fed into both chambers; the flame from the fuel-rich prechamber ensures ignition and relatively complete combustion of all of the lean mixture in the main chamber. This concept originated early in the century and was the subject of research by British, French, Russian, American, and other developers. The Honda CVCC (Compound Vortex Controlled Combustion) and current U.S. efforts are relative latecomers on the scene.

The two-chamber stratified-charge engines attempt to reduce emissions by two mechanisms. First, the two chambers operate at mixture ratios such that NO_x formation is reduced. Second, the flame ignition of the main charge is supposed to be vigorous enough so that the amount of unburned hydrocarbons is reduced at all load conditions. These effects do occur, but the Honda CVCC currently requires an exhaust manifold reactor to meet HC regulations and will require EGR to meet future NO_x standards. Fuel economy should be little different from any other engine running at the best overall economy mixture ratio (slightly below stoichiometric). Disadvantages of this system include the higher cost of the more complex cylinder head, prechamber, and third-valve system, and the extra maintenance associated with these components.

The single-chamber, direct-injection stratified-charge engines include the Ford PROCO (Programmed Combustion), Texaco TCCS (Texaco Controlled Combustion System), GM DISC (Direct Injection Stratified Charge), MAN-FM (Maschienenfabrik Augsburg—Nurnberg A. G.-Frau Meurer), and others. Several of these can use a variety of fuels ranging from diesel to high-octane gasoline. The MAN-FM is generally viewed as being a spark-ignited diesel, while the others are viewed as direct-injection gasoline engines.

The direct-injection gasoline engines have either very low or no octane requirement, and generally operate at moderate compression ratios. At 11:1 compression ratio, the PROCO can operate on 80-octane gasoline, while the TCCS has no octane or cetane limit.

The PROCO engine proponents feel that its performance will equal or excel that of **a** typical passenger car diesel in all important parameters, including emissions, fuel economy, noise, cost, starting, weight, size, and durability.

In the PROCO engine, intake manifold and ports handle only air and, if EGR is used for NO_x control, exhaust gas. Therefore, the intake manifold system need not contend with the fuel atomization, vaporization, and distribution problems common in other Otto engines. Fuel is injected into the swirling air in the main combustion chamber under moderate pressure during the compression process, and injection terminates before ignition occurs. The proper timing of fuel injection and ignition events is important to satisfactory operation of the engine. The PROCO engine utilizes either one or two spark plugs per cylinder. An oxidation catalyst is required if HC emissions are to be less than 1 to 2 grams per mile, especially in larger cars.

The current PROCO engines operate at 11. O- to 11.5 -to-l compression ratio, and EGR of up to **25** percent will be required to meet future NO_x limits. The engine was originally developed to run unthrottled with output controlled by the amount of fuel injected, as in a diesel. However, to meet the HC requirements, a modest amount of throttling is required at part load and idle.

Physically, the TCCS and DISC engines are very similar to the PROCO, differing mainly in details of fuel injection timing and pattern, and in combustion chamber geometry and air flow patterns. The various types of direct-injection stratified-charge engines offer considerable potential for simultaneously achieving low emissions, good fuel economy, and tolerance for a wide range of fuels. Particulate and odor problems, however, may be similar to those of current diesels.

Honda has been successful in marketing their stratified-charge engine (the CVCC). No other manufacturers have chosen to produce the dual-chamber stratified-charge engine, although Honda has sold the rights to at least one U.S. manufacturer.

Domestic car companies are investing primarily in the single-chamber direct-injection version. However, investment levels are unknown and production and marketing of these engines is not expected until the mid-1980's,

Valve Selector

Eaton Corporation recently developed a system for keeping selected valves closed in an internal combustion engine, while the rest of the engine continues to operate normally. The result is a reduction from six-cylinder operation to five, four, or three cylinders, depending on the power requirements. A solenoid-controlled device is added to the rocker arms of the selected valves and, upon activation, these valves stay closed. Keeping the intake and exhaust valves closed on one cylinder means that the air in the cylinder is repeatedly compressed and expanded with much less loss in energy. An improvement in fuel economy of about 10 percent is typical, although this varies for different engine/vehicle combinations.

The second part of the system is an electronic control that selects the number of cylinders to be deactivated depending on speed and load. Transition from operation of all cylinders to half the number can be quite smooth, and engine roughness or wear is not a problem.

This system has been tested on a variety of four-, six-, and eight-cylinder engines. It is currently scheduled to be introduced in 1980 on a Ford V-8 engine.

Turbocharging

Turbocharging is a concept in which the energy in the exhaust of an internal combustion engine is used to compress the incoming air or fuel/air mixture. Turbochargers for passenger car use are typically small high-speed devices (up to 140,000 RPM) with a centrifugal compressor and radial inflow turbine mounted on a common shaft. With the engine throttle wide open, most turbos will supply a continually increasing amount of air until the engine fails. To avoid this, an automatic waste gate control is usually provided to bypass some of the exhaust around the turbine.

In theory, turbochargers should provide an improvement in fuel economy (and sometimes in emission control) through a variety of mechanisms. The fundamental engine cycle efficiency is improved, and mixing and vaporization of the incoming fuel/air charge is usually improved. Hydrocarbons and carbon monoxide in the exhaust are usually more fully consumed. Finally, a smaller engine may be used, so that fuel economy is better (more time is spent closer to wide-open throttle, thus reducing throttling losses); maximum performance is retained because the turbo becomes more effective at the higher RPM. In practice to date, however, only the last factor has proved significant.

A number of problems accompany the use of turbocharging and the several previous attempts by U.S. manufacturers usually lasted for only a few years. Cost is considerably higher than for conventional engines (about $550 for the 1978 Buick). Mechanical complexity and related maintenance, service, and repair problems are much greater. Also, because the indicated mean effected pressure is increased and the incoming charge is heated by being compressed, it was necessary to add a safety system to the 1978 turbocharged Buick. This system detects detonation and automatically retards the ignition timing. (One result is that trailer towing is specifically not recommended.)

There are several alternative solutions to the detonation problem, some of which have been developed for trucks and racing cars. These solutions include aftercooling and antidetonant injection, as well as a more responsive waste gate control. There are over 20 factory-type passenger car turbo projects in progress worldwide, although most are aimed at the performance image rather than at fuel economy.

Turbocharging and the Eaton valve selector are almost parallel concepts for achieving "small" engine fuel ecomomy while retaining full power for the occasional times when it is needed. In terms of simplicity and cost the valve selector should be superior, but consumer preference for the turbo/racing image may prove to be important. If consumer acceptance is favorable, turbocharging can be added to almost any Otto cycle or diesel engine, although increased structural strength of the engine may be required in some cases.

Rotary Engines

Over the last 40 to 50 years, a wide variety of rotary engines have been conceived or developed to various stages. The Wankel is the most prominent of these, although it is not generally realized that the engine that was finally produced is only 1 of over 130 significantly different configurations explored by the inventor. The currently produced Wankel consists of an approximately triangular rotor, turning inside an epitrochoidal housing. The housing is cooled by water (or air) and the rotor is cooled by the engine oil. The fuel/air mixture enters and exits through ports (in the periphery of the housing and/or the end plates) as they are uncovered by the rotor.

The practical geometry of the system prevents high compression ratios (a two-stage version was required to reach diesel compression ratios), and the combustion chamber is characterized by high surface-to-volume ratios. The tips and sides of the rotor must seal against the housing and end plates, and these strip-seals proved to be a difficult design and development problem. The seals must slip over the port openings as in a two-cycle engine, and the intake and exhaust port areas are at considerably different temperatures, thus leading to thermal distortions. All of these features led to serious reliability and life problems with the early Mazda Wankels; however, the engine has gradually evolved into a reasonably acceptable form.

The basic Wankel configuration provides high specific output (in terms of both weight and volume) and can be "stacked" in any number of modules on the crankshaft. It is extremely smooth but somewhat lower in torque than a comparable reciprocating engine at low RPM. Wear of the seals is a serious problem unless exotic and costly combinations of materials are used. Early engines required the use of oil mixed in the fuel (or injected separately) to minimize the seal wear.

Because of the low compression ratio and built-in EGR (blowby), NO. emissions from a Wankel are usually low. However, the large surface-to-volume ratios and corners in the combustion chamber shape result in higher hydrocarbon emissions than from a reciprocating engine.

Wankels have been produced commercially by NSU and Mazda for passenger cars, and by other companies as motorcycle, snowmobile, outboard, diesel, and various other engines. GM purchased the rights to produce Wankels for $5o million but, shortly before reaching production, returned the project to R&D status. GM later terminated work on the Wankel engine. The combination of cost, durability, emissions, and fuel consumption of the Wankel does not appear to be sufficiently competitive with that of a comparably performing reciprocating engine. However, a variety of companies are continuing experimentation on Wankels.

Diesel Engines

The diesel is a form of stratified-charge internal combustion engine that uses the heat of compression for the ignition of distillate fuel. Fuel and air are not premixed outside the cylinder as in carbureted gasoline engines; instead, air is drawn into the cylinder through an unthrottled intake manifold and compressed. Fuel is separately injected near the top of the piston's compression stroke and burns with the air already in the cylinder. Ignition from spark plugs is not required but is being considered for advanced engines as a means of obtaining more accurate timing of the ignition point.

Diesel engine combustion systems are normally divided into two categories—direct injection, and precombustion or indirect injection. The direct-injection engine has a single combustion chamber, usually formed in the piston crown. Fuel is injected directly into the space above the piston. The injection process is considered a critical component of the direct-injection system since it must optimize fuel atomization and penetration into the air in the combustion chamber. Air utilization and engine performance are improved by creating air swirl in the combustion chamber. This is accomplished by using directional intake ports and by proper shaping of the piston crown. Combustion begins before the piston reaches the top of the compression stroke (top dead center) and causes relatively high gas temperature and pressure rises.

The design of the indirect-injection diesel includes a prechamber, which connects to the main chamber by means of an orifice. All of the fuel is injected into the prechamber. Two types of prechamber designs—quiescent and swirl—are in automotive use. The quiescent indirect-injection engines are designed for prechamber-to-total-combustion-chamber volume ratios of 1 to 4. (Combustion chamber volume is measured with the piston at the top dead center.)

The swirl chamber employs a larger volume ratio (up to one-half) and the prechamber is characterized by a spherical or near-spherical design. The throat is arranged to permit a fast air swirl or vortex to be formed in the prechamber, thus promoting rapid burning of the entire charge. Heat release rates are lower with this design and rates of pressure rise are reduced, lowering noise and structural requirements.

Traditionally, passenger car diesel engines have demonstrated advantages in fuel economy. However, these same vehicles have suffered from excessive weight, poor cold-starting ability, high cost, odor, smoke, need for frequent oil changes, poor acceleration, high noise, and high emissions of particulate and nitrogen oxides. Research during the past few years has concentrated on trying to find ways of eliminating these disadvantages.

Fuel Economy

Direct-injection diesels generally give about 5 to 10 percent better fuel economy than the indirect-injection types. However, at the present state of combustion technology, indirect-injection diesels are required for passenger car engines in order to reduce loads on the rods and crank, allow high RPM, and improve starting.

The fuel-economy advantage of a diesel over a comparable gasoline engine varies according to the operating mode. In steady, high-speed operation on the open road, the diesel has only a small advantage. In city traffic the efficiency of the diesel may be as much as **40** percent greater than the gasoline engine. NHTSA estimates that for average driving conditions, the diesel offers a 25-percent fuel-economy advantage on a miles-per-gallon basis.[15] A part of this advantage stems from the fact that diesel fuel contains about 10 percent more energy per gallon than gasoline. Thus, on a "per-barrel-of-crude-oil" basis, the diesel engine is about 15 percent more efficient than a gasoline engine. Features—such as valve selectors, electronic fuel metering, and turbocharging—could be added to improve the specific fuel consumption of gasoline engines, but some of these features (e.g. turbocharging) could also be added to diesels and allow them to

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[15] Specific fuel consumption is a measure of the efficiency of an engine, expressed in pounds of fuel consumed per horsepower-hour (lb/hp-hr).

retain their relative advantage. On the whole, the diesel—due to its higher compression ratie—would remain more fuel efficient than a comparable gasoline engine.

Durability

Heavy truck engines achieve excellent durability (e.g., 500,000 miles before overhaul) by a combination of conservative design, best possible materials and components, heavy construction, careful maintenance, and very consistent and favorable operating conditions. Also, they operate at relatively low compression ratios compared to the lightweight, high-speed passenger car diesel engines (i. e., 13.5 to 18 versus 21 to 23.5). Average U.S. large gasoline engines last well over 100,000 miles, but small engines and imports tend to require overhaul appreciably earlier and to be much more variable in this regard.

Popular opinion, encouraged in part by optimistic manufacturers, tends to ascribe to a passenger car diesel all of the virtues that are found in truck and industrial engines, However, this is not necessarily true.

The recently introduced passenger car diesels (GM and VW) are conversions to diesel from a production gasoline engine. "Simple conversion" of the GM **350** CID gasoline engine to diesel required replacement of the cast iron crankshaft with a forged version employing larger bearings, but durability is still a serious concern. The only inherent durability factor favoring a "converted" diesel is that the incoming charge of air that is compressed prior to ignition has no fuel in it and, therefore, does not wash the thin film of lubricant from the cylinder walls. Also, corrosiveness of the exhaust and crankcase gases may well be different, but not necessarily better.

As a result, the durability of the "converted" diesels (GM and VW) could be less than their basic gasoline engine counterparts initially. However, their durability will probably be raised to the level required for public acceptance. Also, from the public's point of view, engine durability is frequently judged on accessories rather than fundamental factors affecting the combustion process. Improvements in these accessory features depend upon the manufacturer's cost estimates and assessment of market potential, rather than technological feasibility.

Weight

"Converted" diesel engines weigh more than the engine from which they are derived (111 pounds more in the case of the Oldsmobile 350 CID design). Future plans for weight saving in conventional engines by using thinner walled castings will not be possible for the diesel version. Thus, future savings of 5 to 15 percent in the total engine weight must be given up for diesels. In addition, there are vehicle weight increases associated with the diesel; these include dual batteries, and increased cooling capability.

Emissions

Passenger cars powered by modern diesel engines meet all HC and CO emissions standards without after-treatment. NO_x emissions, however, can present problems, depending on the stringency of the standards. Two nonregulated pollutants—particulates and aldehydes—also are found in diesel exhaust in much greater concentrations than in spark-ignition engine exhaust.

Formation of nitric oxide is dependent on the duration and temperature of the combustion process. Reducing peak cycle temperatures during the diesel's combustion phase will reduce the NO_x levels. Current design concepts that reduce NO_x formation include reduced compression ratio, fuel injection modifications, water injection, and exhaust gas recirculation. The use of EGR has some disadvantages. The recirculation of exhaust gases through the cylinders also recirculates particulate matter and thereby increases engine wear. The EGR also tends to cause an increase in hydrocarbons.

It appears that diesel engines perform better than gasoline-powered engines in terms of degradation of emissions of the presently regulated pollutants. In tests of up *to* **80,000** miles, the rate of increase of emissions from diesel engines has been shown to be 2 to 3 times lower than those of a comparable gasoline-powered engine.]' However, diesels may encounter problems with pollutants that are now unregulated.

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[16] Private communication by contractor with Dr. Hergenrath, Transportation Systems Center, Cambridge, Mass.

EPA is conducting research on the potential carcinogenic properties of the particulate and aldehydes in diesel exhaust. Preliminary tests indicate that the particulate are mutagenic. Further tests to determine if, and to what degree, diesel exhaust is carcinogenic are in progress. ”

In summary, it may be difficult for diesel engines, especially large-displacement engines, to meet the 1981 Federal NO_x standard of 1.0 gram per mile or the California standard of 0.4 gram per mile. A further difficulty is meeting the particulate emissions standard recently proposed by EPA. However, small diesels have demonstrated the ability to meet both these requirements. The interest in diesels by foreign and domestic manufacturers indicates some confidence that future diesels will have satisfactory emission characteristics and offer fuel savings over the gasoline engine.

Cold Starting

Most high-speed diesels currently used in automobiles require starting aids to preheat the air in the precombustion chamber. Current diesel designs combat cold weather starting difficulties by several means: designing passenger car diesels for a higher compression ratio than large truck engines; using glow plugs to preheat the air; using block heaters; and adjusting properties of the diesel fuel.

The minimum compression ratio of diesel engines depends in part on the cetane number of the fuel used. Swirl prechamber design is usually used for high-compression, high-speed, automobile engines.

From a fuel-economy standpoint, the optimum compression ratio for diesel engines is around 12 to 14 to 1; piston ring friction becomes more important than increased cycle efficiency above this range. Passenger car engines suffer from this loss in efficiency, plus decreased durability and greater noise, in order to meet cold-starting and high RPM requirements.

Noise

Diesel-powered vehicles produce noticeably higher noise levels during idle than carbureted vehicles. At road speed, tire noise is predominant. In general, the noise transmitted by the diesel engine to the passenger compartment can be attenuated through the use of proper acoustical materials.

Time Frame

Presently announced plans for diesel engine penetration of the U.S. market include the following:

- GM introduced a 350-CID diesel for the Oldsmobile, for the Cadillac Seville, and for some light trucks in **1978;** GM may supply diesels for a greater portion of its fleet later.
- VW diesel Rabbits and Dashers have been available in the United States since model year 1977. The Mercedes 240D, Mercedes 300D, and Peugeot 504 diesel are also available.
- In addition to the above companies, various other European and Japanese firms now produce or are planning production of diesel passenger cars; any or all of these could be brought to the U.S. market. These companies include Opel (GM), Ford of England, British-Leyland Motor Company, Chrysler-France, Nissan, Fiat, Citroen, and Volvo (using a VW engine).
- **1978** production rates for both GM and VW were planned to be 100,000-plus. GM’s actual production was approximately 65,000; the planned level of production for 1979 is 190,000 units.

VW will probably allocate its diesel cars worldwide. Both VW and GM will use considerable caution in testing consumer acceptance and checking for unforeseen field problems. However, both companies can expand production quite rapidly, since the engines in question are basically gasoline engines currently being made on existing, high-capacity production lines. Peugeot and other small producers are largely locked into existing specialized diesel production lines of low or modest capacity. The need to build new plants will seriously constrain entry into the field and/or expansion by many of the potential diesel-engine passenger car suppliers.

The technology of passenger car diesels will have a significant effect on their acceptance, as

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[17] Telephone conversation with Richard Briceland, U.S. Environmental Protection Agency, Apr. 11, 1978.

well as on their achieved fuel economy. Other problems with diesels so far have included parts availability, repair infrastructure, and unfamiliarity on the part of do-it-yourself mechanics.

Investment and Costs

Depending on the extent of retooling necessary, the capital cost necessary to convert a spark-ignition engine assembly plant to the production of diesels could range from $30 million to $150 million for a 400,000-unit capacity line. Assuming annual new car sales to be 11.8 million in 1985 with 10-percent diesel penetration, total capital expenditures could range from $90 million to $440 million.

The added cost (price premium) of diesel cars and multipurpose vehicles in 1977 ranged from about $195 to $2,200. The GM premium was $740 or $850, depending on the engine it replaced. A major portion of the additional cost of the diesel is for the fuel injection system. The low VW price differential of $195 is somewhat misleading, since their gasoline engine has fuel injection, whereas the GM gasoline counterpart does not.

In addition to the direct-injection and indirect-injection engines whose differences have been discussed, several other types of diesels are in use or under development. The most common of these is the two-stroke diesel engine. This version is lighter than a comparable four-stroke engine, but is generally slightly lower in fuel economy and emits more pollutants. It is quite competitive in heavy trucks and bus operations, but probably would not be competitive in a passenger car application.

A form of diesel that was recently developed for a British tank engine employs what are essentially two Wankel engines in series. The first partially compresses the incoming charge of air, and the second completes the compression and handles the combustion. Other promising variations in diesel technology, particularly the adiabatic diesel (and additions to it such as turbocompounding and bottoming cycle) are discussed later in this chapter.

Drivetrain

A major factor in achieving better fuel economy is the ability to operate an engine at the combinations of throttle position and RPM where the lowest possible values of specific fuel consumption can be achieved. This is approximated by changing transmission gear ratios under varying conditions of vehicle acceleration and speed. In the case of an automatic transmission, the torque converter smooths the transition between gear ratios and supplies increased torque to the wheels at low engine speeds, but with some loss of power.

Typical power losses in the automatic transmission, drive line, differential, and rear axle for a full-size car vary with speed, approximately as shown in table 139. Only 3 to 4 percent of these losses are in the axle, differential, and drive line. Improvements in this area are generally limited to greater precision in manufacturing processes and improvements in lubrication.

Table 139.—Drivetrain Losses

		Drivetrain loss	
Speed (mph)	Total wheel horsepower	Hp	%
20.	5.0	1.24	25
40.	14.4	3.17	22
60.	31.7	5.09	16
80.	60.0	7.99	13

SOURCE Environmental Protect Ion Agency *Factors A ffecf[ng Fue/ Economy,* May 1976

Transmissions, like engines, have a variety of basic types. These may be categorized as hydrokinetics (torque converter), standard gear change (“stick shift”), hydrostatic (e.g., Orshansky or Sunstrand Responder), traction (e.g., GM Toric, Tracer, or Forster), variable sheave (e. g., “Vee” belt), clutched gear sets, and oscillatory. Each of these transmission types has a variety of possible configurations—for example, the hydrokinetics transmission is currently available with three, four, or five elements, torque multiplications from 2:1 to 6:1, all fixed or some movable vanes, and lockup features. Many of these transmissions are used in combination with each other and with associated clutches, dual path schemes, and retarders. For example, the conventional passenger car “automatic” uses a torque converter plus clutched gear sets. Control systems include mechanical, hydraulic, and electronic types. Improved automatics with a lockup clutch, tighter tolerance torque converter, and a wide ratio, four-speed gear set are considered by the auto industry to be the most likely candidates for providing the desired near-term improvements in efficiency. Because of their better internal efficiency, the lockup feature and gear ratios that optimize the engine/vehicle match, fuel-economy improvements up to 18-plus percent over a present day 3-speed automatic have been obtained in experimental vehicles. (table 140).

Table 140.—Hydrokinetic Transmission Improvements

Transmission type	Percent improvement
3-speed automatic with low slip torque converter	2-3
3-speed wide ratio automatic	3-6
3-speed automatic with TCLU’	3-6
3-speed wide ratio automatic with TCLU	8-13
4-speed automatic with TCLU	8-13
4-speed wide ratio automatic with TCLU	8-18

[a] Torque converter lockup.
SOURCE: U.S. Department of Transportation, National Highway Traffic Safety Administration, *Data and Analysis for 1981-1984 Passenger Automobile Fuel Economy Standards*, February 1977.

A typical, present-day passenger car automatic contains a three-element, fixed-vane torque converter of about 2 to 1 multiplication and a three-speed planetary gearbox with hydraulic control. Efficiency of the torque converter ranges from zero at stall to 91 percent; most driving occurs in the 80 to 90 percent region. Typical efficiencies of the various transmission types (table 141) show there is interest in the efficiency of the newer traction, sheave, and oscillatory types—as well as in their continuously variable feature.

Other less obvious (but still worthwhile) improvements which will be made in conventional automatic transmissions include reduced clearance in the torque converter, lower viscosity oil, reduced band and clutch drag, and reduced oil pump power.

Ford is planning to introduce a four-speed automatic transmission in the early 1980’s. The capital costs involved in converting to a four-speed transmission will be an added financial burden to the auto manufacturers, but will not be as serious as engine changes.

Capital requirements for producing three- and four-speed automatic transmissions with torque converter lockup (TCLU) features in a 500,000-unit facility are estimated by industry to be:

- three-speed automatic with TCLU—$5 million to $10 million, and
- four-speed automatic with TCLU—$150 million to $200 million.[18]

Both of these values are believed to be based on making the changes with minimal disturbance of existing production (which typically operates on a three-shift basis). The conversion to the three-speed TCLU would consist of minor changes to the existing plant; however, the change to four-speed TCLU would probably require installation of an almost parallel facility beside the existing plant. (A totally new plant would cost on the order of **$35o** million.) Total capacity (and/or productivity) of such a facility would probably be increased significantly.

Table 141 .—Current and Potential Transmission Efficiencies

Transmission element	Efficiency’
Torque converter (automotive types, including 3, 4, and 5 element)	75-91% for majority of use 0% at stall
Change gear	97% + per gear set
Hydrostatic	88% maximum at no multiplication
Traction (rolling balls or discs)	80-90%
Variable sheave (metallic)	90-93%
Mechanical oscillatory	91-96%
Clutched gear (planetary)	95% per gear set

[a] Values include efficiency of the basic mechanism and a typical value for parasitic losses (e.g., windage, control hydraulics, bearings, etc.). Values are approximate because of wide variations in mechanism and system configurations.
SOURCE: *SRI*, p. V-46.

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[18] U.S. Department of Transportation, *Data and Analysis for 1981-1984 Passenger Automobile Fuel Economy Standards*.

Accessories and Accessory Drives

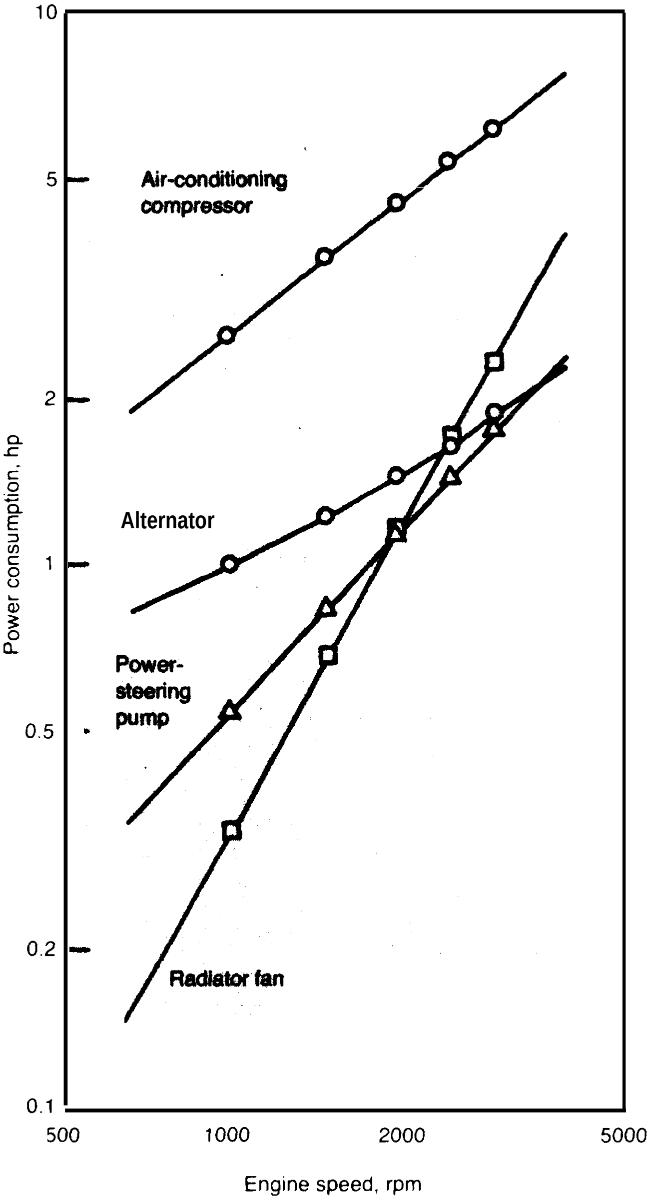
Power-driven systems (fan, water pump, alternator, oil pump) and options such as air-conditioning have traditionally consumed a significant amount of engine power, as shown in figure 60. Large percentage reductions in the power required can be achieved for the fan and air-conditioner through the use of effective demand drive units. Most power-steering systems have recently been converted to a type that requires very little power, except when turning.

Demand drive systems are already on the market, but have received only limited acceptance because of the prior unimportance of fuel economy. Systems likely to see widespread future use include:

- electric motor drive for cooling fans;
- air-conditioner drive and control system that fully disconnects except when cooling is required (already widely used); and
- speed-limiting drive for water pump, alternator, and oil pump.

Full utilization of these systems should provide an overall fuel-economy improvement of about 4 percent.

Figure 60.—Accessory Horsepower



SOURCE: Jet Propulsion Labs, *Should We Have A New Engine?, An Automobile Power Systems Evaluation,* August 1975.

Electronics

Electronic controls for fuel metering and ignition, as well as for a number of other vehicle systems, have become a subject of importance to the automotive and electronics industries. Emission control, fuel economy, safety, comfort, convenience, and maintainability will all benefit from the rapidly evolving technology. The list of present and potentially different types of electronics systems for passenger cars numbers over **50.** The electronics industry estimates that at least 6 million units of electronic engine control systems will be used on 1981 model cars. These include the ignition, fuel metering, EGR, and valve selector functions handled by a central microprocessor, Additional capabilities will be built into the microprocessors and, by 1985, as many as a dozen different systems may be controlled by the central unit. As confidence and interaction between the two industries grows, the number of electronics applications will probably increase.

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[19] Demand drive units are components that allow their respective accessories to "free-wheel" or to draw essentially no power when they are not needed. For example, a thermostatically controlled fan could probably be cut out of the system except during long periods of idling or pulling heavy loads in hot weather. This feature is already in use by some foreign manufacturers. All U, S.-manufactured cars with air-conditioning have used a viscous drive fan which limits the maximum power absorbed as engine speed increases.

However, there is continued competition between electronic and the more conventional mechanical/hydraulic controls. Considerable improvement in these latter systems could result from the stimulus of such competition, possibly reducing the magnitude of the trend to electronics,

Multiplexing or other sophisticated wiring concepts may be considered as a subset of automotive electronics. Such schemes promise some reduction in vehicle assembly cost and in the use of copper, with the benefit of improved recyclability. It is probable that such systems will not be introduced on a production basis until well after a central microprocessor comes into general use,

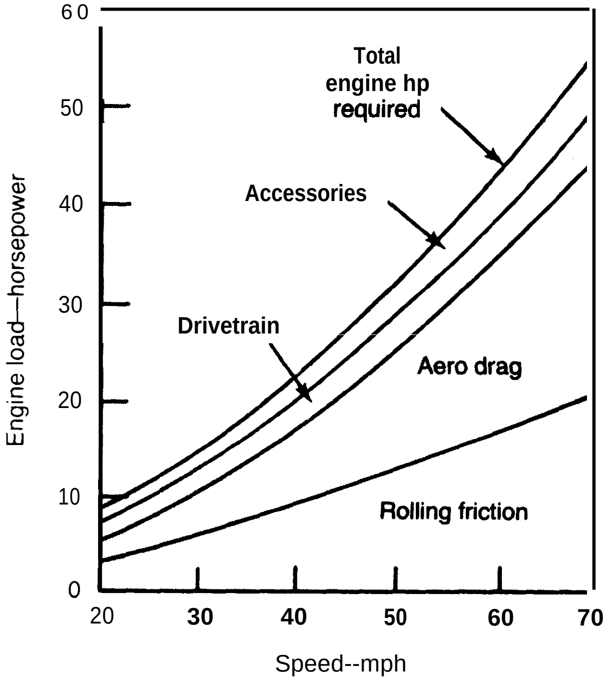
Aerodynamic Drag and Friction

The importance of the effects of rolling friction and aerodynamic drag on required engine power are shown in figure **61.** Rolling friction is almost entirely a result of energy loss due to deformation of the tires as they contact the roadway. Rolling friction increases almost linearly with speed. Radial tires can have up to 20 percent less rolling resistance than bias-belted tires and 40 percent less resistance than plain bias tires, producing a fuel-economy improvement of up to 3 percent. Higher inflation pressures also reduce rolling resistance, but require suspension changes and affect tire-roadway adhesion.

Aerodynamic drag increases with speed much more rapidly than does rolling resistance (i. e., as the square of velocity). At 55 mph, it absorbs about 40 percent of engine power. Drag is also a direct function of vehicle size and shape (more specifically of frontal area and the drag coefficient). Minimum frontal area is essentially fixed by the requirements of passenger compartment size plus the safety-related lateral crush distance. Automobile height is remarkably standard; heights are within 2 inches for a Ford LTD and an Austin Mini or Honda Civic. Typical frontal areas for current U.S. passenger cars are shown in table 142.

Drag coefficients for present day production cars range from about 0.50 to 0.325, averaging about 0.45. An experimental low-drag model has reached about 0.16.[20] A 25-percent reduction in drag may be expected to improve fuel economy over the composite driving cycle by about 5 percent .[21] Theoretically, fuel savings associated with drag reduction are on the order of 10 to 15 percent over the driving cycle, with greater savings at steady high speeds. Some reduction in drag can be achieved through changes in body styling, but perhaps at the expense of reduced volume-efficiency compared to present "boxy" body designs. Further reduction of drag could be accomplished by elimination or redesign of features such as outside mirrors, rain gutters, roll-down windows, and wheel covers.

Figure 61 .—Effect of Speed on Power Requirements (Standard-size car)



SOURCE Jet Propulsion Laboratories, *Shou/d We Have A New Engtne~, An Automobile Power Systems Evaluation,* August 1975

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[20] The Pininfarina test model shown in the photograph, and the Mercedes C lll/3 have demonstrated a drag coefficient of .16.

[21] Jet Propulsion Laboratory, California Institute of Technology, *A Study of Automotive Aerodynamic Drag,* prepared for U.S. Department of Transportation, Office of the Secretary, Report No, DOT-TSC-OST-75-28 (Pasadena, Calif.: Jet Propulsion Lab), September 1%'5.

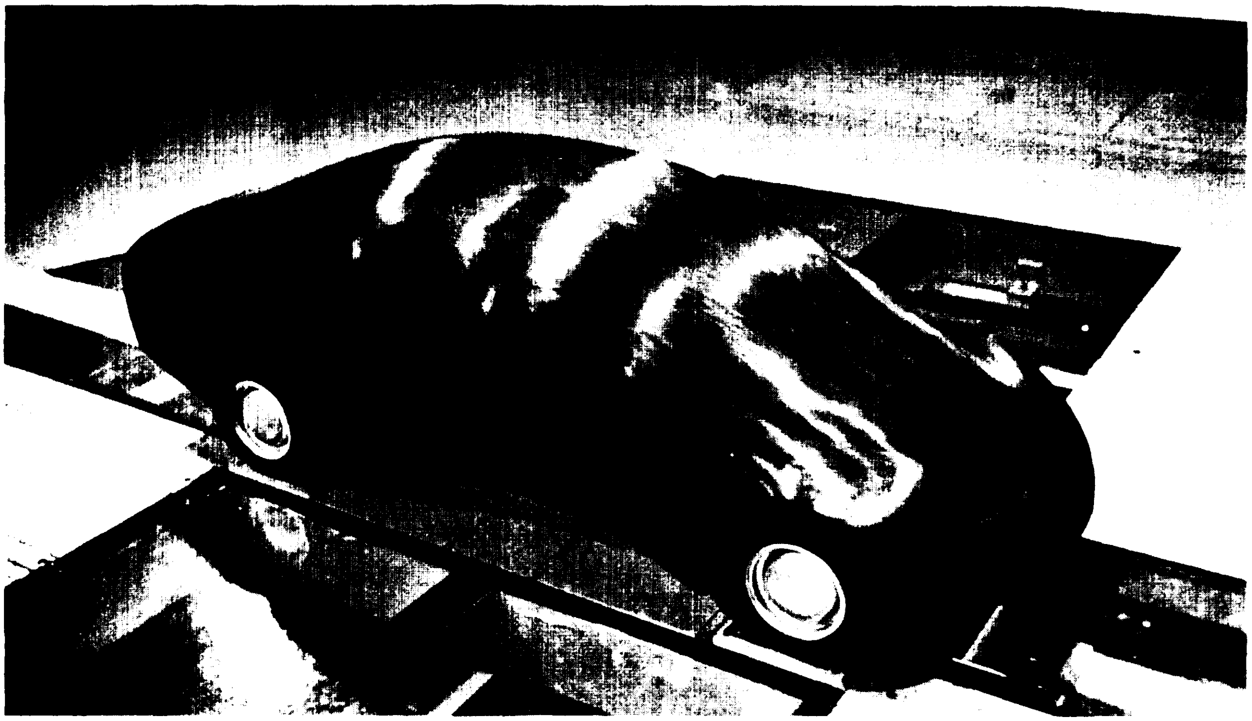

Photo Credit Automotive News

Aerodynamic body model by Pinninfarina

Table 142. —Frontal Area for Typical Passenger Cars

	Curb weight (pounds)	Frontal area (square feet)
Subcompact	2,500	17.5
Compact	3,200	19.0
Standard	4,400	21.5
Luxury	5,300	22.5

SOURCE: Jet Propulsion Laboratory, *Should We Have a New Engine? An Automobile Power Systems Evaluation*, August 1975

Safety Technology

There are many technological approaches to vehicles and roadways that can be applied to both crash severity reduction and crash avoidance. The technologies discussed in this section (near-term) are those which are likely to be implemented by **1985.**

Vehicles

The U.S. Department of Transportation recently issued a safety plan in which proposed revisions of existing standards and new areas of rulemaking were identified. Table 143 shows those standards applicable to the **1985** time period.

All of these proposed requirements have been under consideration for years and should not require any major new technological achievements. The most significant feature is the extension of passenger car standards to light trucks and multipurpose vehicles. Other important revisions are in upgrading the quality of seat belts (FMVSS 208), upgrading side door strength (FMVSS 214), improving rear vision (FMVSS 111), and improving direct fields of view (new standard). However, the major piece of safety equipment to be added in the near-term is the passive restraint system (FMVSS 208), required in the 1982 model year for large cars and for all cars by the 1984 model year.

The ongoing evaluation of the safety standards should provide important information on the regulatory process and on technologies for the future .22 This evaluation focuses on whether vehicles are performing in accordance with the standards and whether the standards, as written, are actually addressing the problem for which they were intended.

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[22] Discussion with U.S. Department of Transportation, Office of Program Evaluation, April 1978.

Table 143.—Federal Motor Vehicle Safety Standards, Near-Term Improvements Under Consideration for Passenger Vehicles

Current standards	Inclusion of light trucks[a]	Upgrading of standard
FMVSS No. 201 —Occupant Protection in Interior impact.	XX	
FMVSS No. 2034—impact Protection for the Driver from the Steering Control Systems	XX	X
FMVSS No. 204—Steering Control Rearward Displacement.	XX	X
FMVSS No. 208—Occupant Crash Protection.	XX	X[b]
FMVSS No. 213—Child Restraint Systems		X
FMVSS No. 214—Side Door Strength.	XX	X
FMVSS No. 101 —Control Location, Identification, and Illumination.	XX	X
FMVSS No. 105—Hydraulic Service Brake, Emergency Brake, and Parking Brake Systems.	XX[c]	
FMVSS No. 108—Lamps, Reflective Devices, and Associated Equipment	XX[c]	X
FMVSS No. 109—New Pneumatic Tires.	(d)	X
FMVSS No. 11 1—Rearview Mirrors.	X	X
FMVSS No. 114—Theft Protection	XX	X
FMVSS No. 115—Vehicle Identification.		X
New proposed standards[e]		
Exterior protrusions, (minimize)		
Truck Rear Underride Guard (heavy trucks)		
Low Tire Pressure Warning		
Direct Fields of View		
Handling and Stability performance requirements		
Brake System Inspectability		
Speedometers/Odometers (limit speed indication)		

[a] Items marked X already apply; marked XX are intended to apply.
[b] Upgrading quality of active seat belts prior to passive restraint requirement.
[c] Will be extended to all motor vehicles (except motorcycles).
[d] For passenger car tires, many of which are used on light trucks.
[e] Vehicle applicability not always specified.
SOURCE: U.S. Departmnet of Transportation, National Highway Traffic Safety Administration, "Five Year Plan for Motor Vehicle Safety and Fuel Economy Rulemaking and Invitation for Applications for Financial Assistance," *Federal* Register 43. pp 11 100-11107

Restraint Systems

The air cushion restraint system (ACRS), or air bag, was first conceived of in the 1950's and the basic principles are unchanged today. A sensor mechanism, activated by a crash (usually a barrier-equivalent crash of 12 mph or greater) activates an inflator (either compressed gas or a chemical gas generator). This fills a nylon bag in the area in front of the driver and front-seat passengers. The driver bag is housed in the steering wheel hub. The passenger bag is in the area typically used for a glove compartment (figure 62).

Technically, the system is extremely reliable. Operationally, it provides good protection in front-end collisions, which account for more than 50 percent of vehicle occupant fatalities. The probability of inadvertent inflation of the ACRS is virtually nil; experiments have demonstrated that if it does occur, no real problems, such as loss of control of the vehicle, are likely to occur.[23] It is possible to utilize air bag technology for protection of other than front-seat vehicle occupants, although that is clearly the most effective use of the system.

Safety belts come in a variety of configurations—lap belts, three-point lap/torso belts, torso belt with knee bolster, and the four-point

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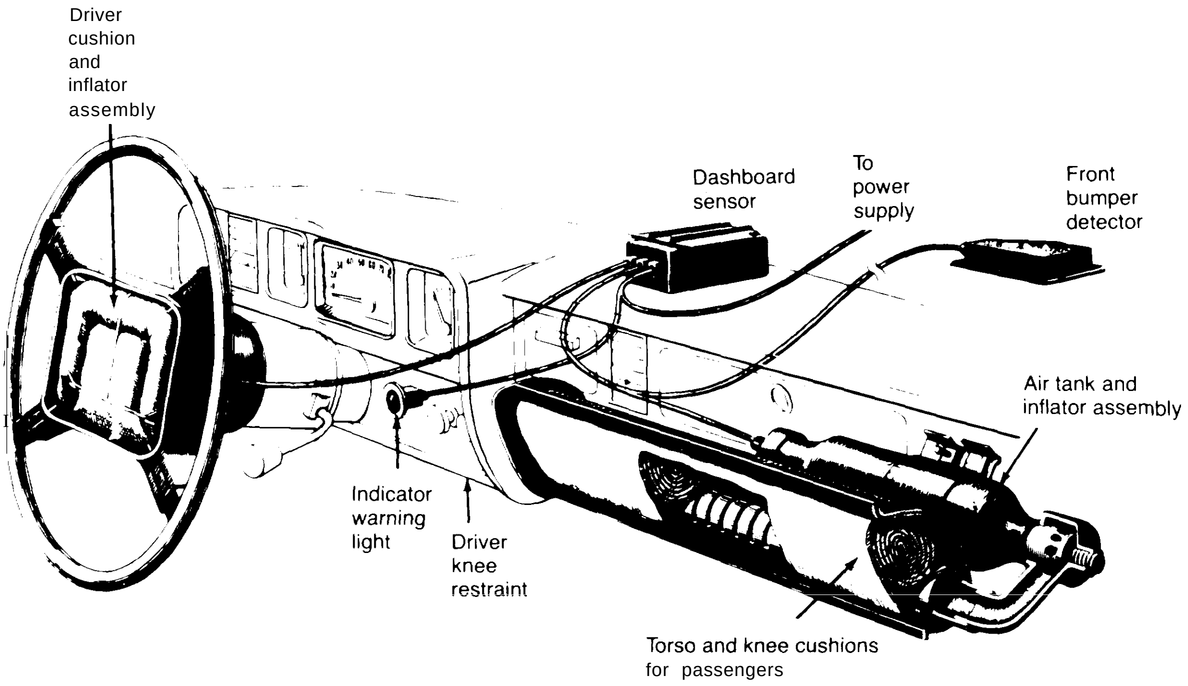
[23] Committee on Commerce, Science, and Transportation, *Automobile Crash* Protection, Report No. 95-481, Oct. 7, 1977.

Figure 62.—Schematic of Air-Cushioned Restraint System



SOURCE Allstate Insurance Company, *Autornotwe Air Bags C?uesf/ons and Answers,* June 1977

lap/shoulder harness. Several effectiveness enhancement features are also possible. These include pretensioning devices, energy-absorbing systems, inflatable belts, and force-limiting belts. Also there has been a recent surge of interest in passive belts, which automatically go into place after the occupant is seated.

Three-point safety belts provide a level of protection almost equivalent to that of the ACRS. In general, they are better than the current air bag alone in multiple impact, rollover, or side collisions. The ACRS with the lap belt offers better high-speed protection. (See table 144.) However, there is still. a possibility that many individuals will disconnect the passive belts unless they are made to be very comfortable.

The air bag system is considerably more expensive than the simple seat belt system. Estimates of the cost difference range from $112 to $235. The passive belt system is estimated to cost **$25** more than the conventional three-point system.[24]

Highways

Improvements in highway features that could reduce the incidence or severity of traffic crashes are shown in table 145, Most of the devices or design techniques have been developed, but have not been universally applied. Skid resistance requires more research since it involves trade-offs with tire noise, tire wear, pavement cost, and durability.

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[24] Ibid.

Table 144.—Occupant Crash Protection System Effectiveness Estimates[a]

	Lapbelt	Lap and shoulder belt	Air cushion	Air cushion and lapbelt	Passive belt and knee bolster	Knee bolster
A IS injury level:						
1	0.15	0.30	0	0.15	0.20	0.05
2	.22	.57	.22	.33	.40	.10
3	.30	.59	.30	.45	.45	.15
4-6	.40	.60	.40	.65	.50	.15

[a] Effectiveness shown is the fraction of the vehicle occupants not injured at the specified Injury level who would be injured without the use of the restraint system

SOURCE Committee on Commerce, Science, and Transportation, *Automobile Crash Protection*, Report No 95.481. Oct 7, 1977

Table 145.—Technical Features for Highway Safety

1. Impact absorbing roadside safety devices.
2. Skid resistance.
3. Breakaway sign and lighting supports.
4. Guardrail.
5. Bridge rails and parapets.
6. Bridge widening.
7. Shoulders.
8. Wrong-way entry avoidance techniques.
9. Roadway lighting.
10. Traffic channelizaiton.
11. Roadway alinement and gradient.
12. Clear roadside recovery area.
13, Median barriers.
14. intersection sight distance.
15. Railroad highway grade-crossing protection.
16. Pavement marking and delineators.

SOURCE Abbreviated from the countermeasures examined in the *National Highway Safety Needs Report*, U.S Department of Transportation, April 1976

Recycling

The recovery of motor vehicle scrap metal is a relatively well-established industry. Wrecking yards and scrap processors recycle about 80 percent of junked motor vehicles. The wrecker removes salvageable parts for resale and the scrap processor extracts the ferrous material in as pure a form as possible—usually well below that of industrial ferrous scrap. Shredding is the favored process and produces the highest purity product. It is also a high-volume, capital-intensive process with only about 100 shredder units in operation in this country.

As the content of plastics and nonferrous metals in cars increases, separation problems will become more difficult and the scrap will become slightly less valuable. Materials selection and design features could help to alleviate this problem but presently, there is little incentive to do so.

Tires are a major recycling problem, particularly the steel-belted variety. The following approaches are in various stages of development, but none appears yet to be a clearly economical solution:

- burning to produce thermal energy;
- cryogenic, shredding, or other processes to recover the rubber for subsequent use (e. g., as an asphalt extender);
- conversion to carbon black, and
- processing to produce a form of synthetic liquid fuel.

AUTOMOBILE TECHNOLOGY BEYOND 1985

In the period from **1985** to **2000,** it is expected that technological development will proceed along three lines. First will be efforts to develop and commercialize advanced engines capable of operating at much higher efficiency than the 25 percent typical of the best engines of today.[25] A four-passenger vehicle equipped with such a propulsion system could have a operational fuel economy of 60 mpg or more.[26] A second line of development will be improvement of other automobile components to provide even greater fuel economy. It is anticipated that efforts will concentrate on continuously variable transmissions, low-friction tires, and improved aerodynamics. The need for, and emphasis on, more efficient vehicles will be partly determined by success in a third area of development—alternate energy sources. It is expected that the technology to produce fuels from sources other than petroleum and to use electrical energy could reach a high state of refinement. If so, the pressure for greater automotive fuel economy would be correspondingly less. This section of the report examines some of these potential advances in auto and fuel technology and assesses the outlook and the problems associated with their development and use.

Propulsion Systems

New engines or power sources that are under development for automotive applications include: Brayton (or gas turbine); Stirling; diesel: Otto- diesel hybrid; adiabatic diesel; stratified charge; various rotaries (including Wankel); Rankine; battery; fuel cell; and other energy storage devices, such as flywheel and thermal sink.

It is also possible to add "upstream" systems such as superchargers, turbochargers, Comprex "superchargers, " and regenerators (heat exchangers). Also a great variety of fuels from different sources could be used. They include gasoline, diesel, liquefied petroleum gas, liquefied natural gas, petroleum natural gas, hydrogen, alcohol, ammonia, ether, and hydrazine. Finally, compounding, or combining two or more different engine types, adds new possibilities.

The list of concepts which have been Formulated is extremely ions, but it is unlikely that more than a few will make their way into passenger-car use by **2000.** A qualitative evaluation of the relative merits of the basic types of engines in terms of their key characteristics *is* given in figure 63.

Research and development programs for advanced heat engines are being conducted by both Government and industry. The Department of Energy, acting under the Energy Reorganization Act of 1974 and the Federal Non-Nuclear Energy Research and Development Act of 1974, has been pursuing the development of the gas turbine and Stirling engines for passenger-car application. More recent legislation, the Automotive Propulsion Research and Development Act of 1978, directs DOE to support research and development t that would lead to introduction of alternate automobile propulsion systems with in the next decade. The Act also calls for dissemination of technical information on advanced engines. The intent of the Act is to supplement the research and development efforts of private industry and to encourage and facilitate competition in developing alternate engines. Although little has yet been accomplished under the Act, it does provide the basis for unifying and focusing the Government efforts in assisting R&D on alternate automotive propulsion systems.

Stirling Engines

The Stirling engine converts heat energy from the burning air/fuel mixture to mechanical energy through the alternative compression and expansion of a confined working fluid. The working fluid (normally a small quantity of high-pressure hydrogen or helium) is cooled during the compression stage and heated during the expansion stage. Residual heat energy is recycled through a heat exchanger that stores a

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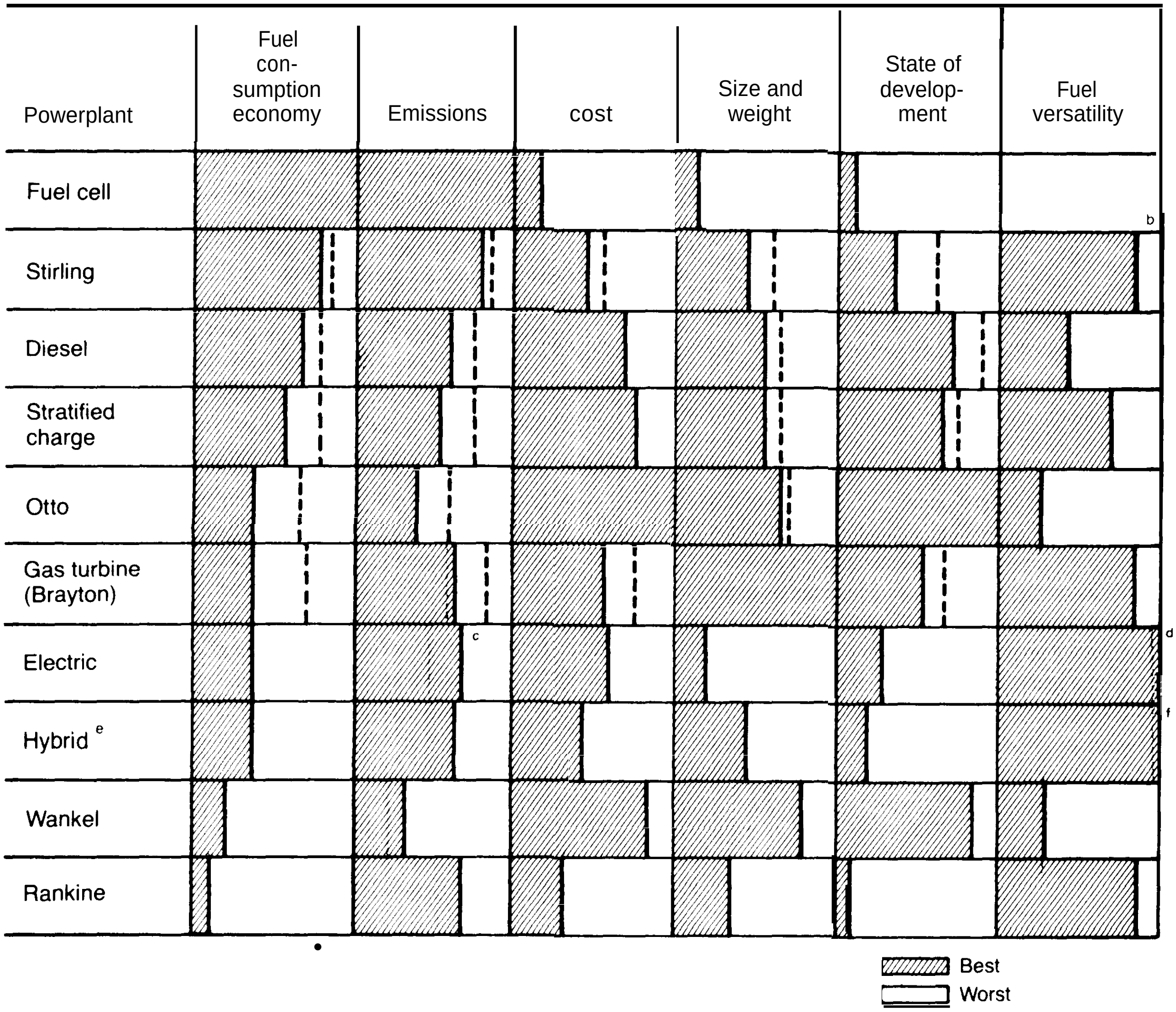
[25] Engine efficiency is simply the energy output of an engine divided by the input energy (that contained in the fuel). The adiabatic turbocompound diesel has been tested at 48 percent efficiency. Adding a bottoming cycle was calculated to raise the efficiency to 63 percent. Improvements are expected in other engine cycles, particularly the Stirling and Brayton whose efficiencies are now about 40 percent. SRI Supplement.

[26] The turbocharged VW diesel Rabbit has registered 60 mpg in the combined EPA mileage rating. U.S. Department of Transportation, Office of Public Affairs, *Fact Sheet: Volkswagen Integrated Research Vehicle,* June 28, 1977.

Figure 63.—Characteristics of Automotive Propulsion Systems[a]



[a] Passenger car application.

[b] D!fferent fuel cells use different fuels, but a fuel cell will only use the fuel for which it was designed.

[c] Depends on extent of emissions from electric-generating plant and the Importance of point versus dispersed emıssıons

[d] Can use any fuel used to generate electricity.

[e] Typically, an internal combustion engine plus battery or flywheel.

[f] Can use any fuel used to generate electricity, and those usable in the secondary power plant.

SOURCE" SRI, p. V-44, and OTA.

large portion of the heat of the working fluid after expansion and returns it to the working fluid after compression.

A sequence of four events occurs during a full work cycle of the engine:

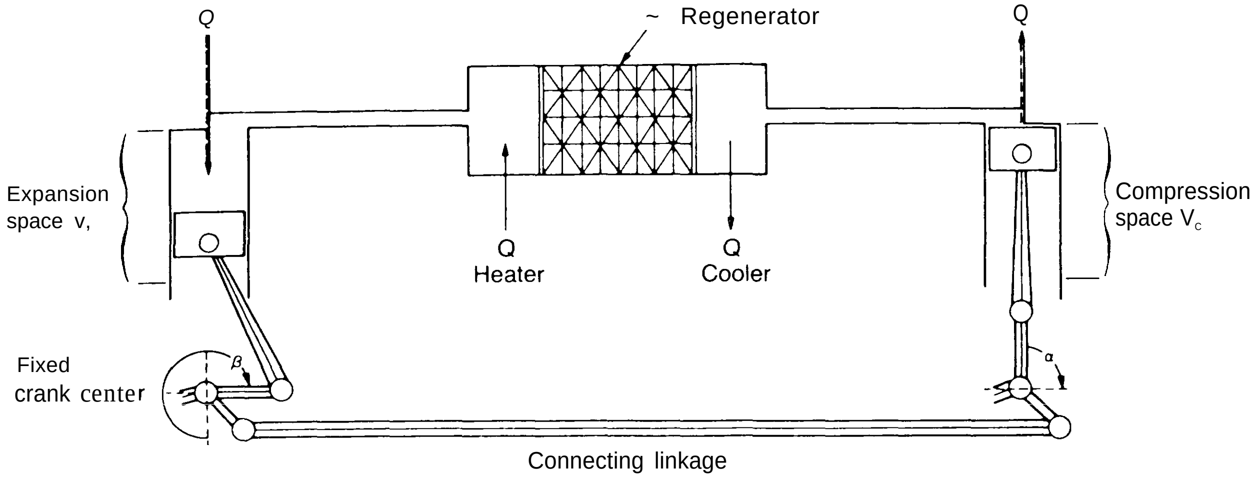
- The working fluid is transferred from the hot space through the heater, regenerator, and cooler to the cold space. This occurs with a relatively small change in total working space volume.
- A compression process occurs when the working fluid is located primarily within the cold space and the adjacent cooler.
- The working fluid is transferred from the cold space through the cooler, regenerator, and heater to the hot space, with a relatively small change in total working space volume.
- The working fluid expands when it is

located primarily within the hot space and the adjacent heater.

The expansion and compression spaces are phased so that the working fluid is located in the hot space of the engine as total working space volume increases. As total working volume decreases, the working fluid is found mainly in the cold space of the engine. The four processes are repeated for each revolution of the crankshaft.

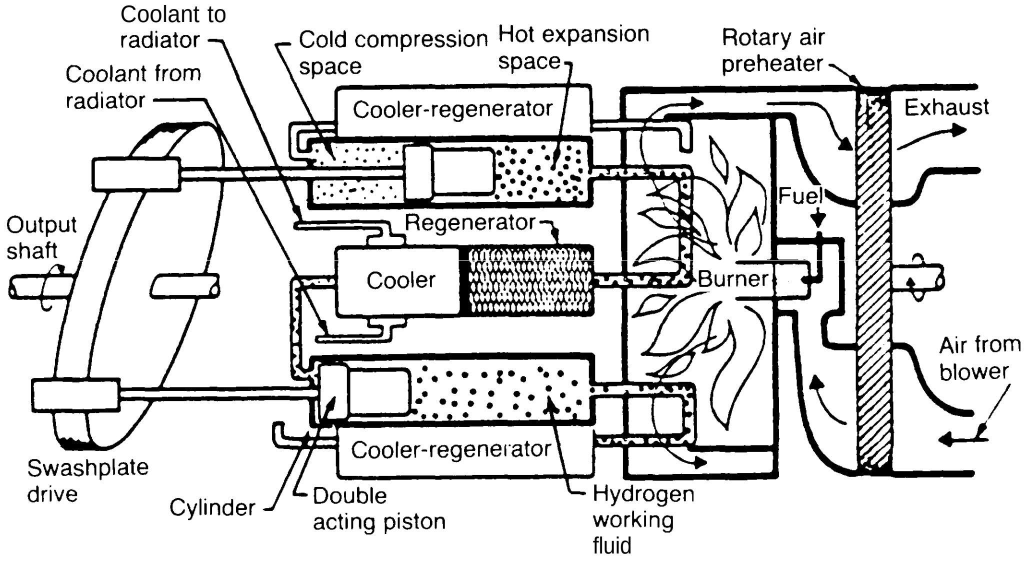
The motions of the mechanism and the gas flow can best be understood by examining the two-piston analogous mechanism and its volume crank angle diagram shown in figure 64. This configuration is not currently used as a Stirling engine, but is useful in illustrating the principle. A schematic drawing of the double-acting, swash plate, piston-type Stirling (which is an operating engine) is shown in figure 65.

Figure 64.—Principle of the Stirling Engine



SOURCE SRI

Figure 65.—Stirling Engine With Swash Plate



SOURCE” *SydecEEA,* p II-21

The other common type of Stirling has a rhombic-drive, inline piston displacer configuration. However, Wankel expanders, valved versions, and similar variants are under study.

The Stirling engine shows significant potential when compared to the conventional internal combustion engine. It has lower noise levels because of the continuous burning process and reduced emissions. The Stirling can burn a variety of fuels. Its operation is smooth and without vibration. Finally, the engine has cycle efficiencies approaching 40 percent.

The problems in the development of the Stirling are all technical or cost-related, They may never be overcome on a cost-competitive basis. These problems include:

- high temperatures with attendant problems of materials, sealing, thermal cycling, etc.;
- high-pressure areas and the basic technological difficulties concerning the sealing so that gas does not leak out of the engine or into other parts of the system (efficiency improves with system pressure and units have been run at well over 3,000 psi);
- cost, complexity, and availability constraints centering on the use of sophisticated electronic controls, ceramic components for the heat exchanger, and extensive stainless steel tubing required to withstand the very high pressures and temperatures inside the engine;
- uncertainty regarding the feasibility of producing many of the engine components which are new and have never before been mass-produced (the production processes of engine manufacturers and component vendors would have to be refined before cost-effective mass production could take place);
- need for large, high-capacity radiators and the severe loss in efficiency when the heat is rejected to high ambient temperatures (e. g., 100°F or greater);
- complexity and low efficiency of the gas volume control system and slow response to changes in speed and load demand;
- uncertainty regarding engine durability and the feasibility of producing engines in different sizes; and
- fuel economy actually attained to date for the complete powerplant (with accessories) is about that of a conventional Otto-cycle engine.

Until recently, most experience with the Stirling engine has been in the research laboratory. The only commercial application of the Stirling cycle to date has been in a cryogenic machine for producing liquid air. However, some development work has been done on potential application of the Stirling in heavy-duty trucks, and there has been minor production for military hardware. Work on the feasibility of a four-cylinder 170 horsepower (hp) Stirling for automobiles was conducted by Ford and the Department of Energy (DOE) under a licensing agreement with N.V. Phillips Gloeilampenfabriken of the Netherlands. Laboratory testing of the engine was completed in 1976. The second phase sought to improve engine durability and performance in road tests, to determine potential feasibility, to assess the potential for engine size modification, and to initiate R&D work with other firms. Table 146 shows some features of the Stirling engine compared with the baseline standard engine.

Ford recently completed a feasibility study, funded by DOE, involving the conceptual design and evaluation of an 80 to 100 hp Stirling engine for use in a passenger car of the 2,500- to 3,000-pound weight class. Subsequently, Ford announced its withdrawal from the DOE Stirling engine program.

DOE is also funding Mechanical Technology, Inc., United Stirling of Sweden, and AM General Corporation in a joint effort to develop three generations of engines in the 55 to 130 hp range. The first portion of this work was to demonstrate a Stirling engine in an Opel Rekord. Installation was completed, and road testing was begun in the summer of 1978. Preliminary test results are encouraging. The Stirling Opel equaled a diesel-powered Opel in fuel economy and easily met the future statutory emissions standards.

Even if all performances projections are realized and durability is demonstrated, the market

Table 146.—Stirling and Baseline Engine Data[a]

	“4-21 5“ Stirling[b]	351-2V V-8 Baseline	Clean Air Act’
Emissions (g/mi)			
Hydrocarbons	0.04	0.49	0.41
Carbon monoxide	1.98	6.05	3.40
Oxides of nitrogen	0.39	1.35	0.4
Fuel economy (mpg)			
City	13.5	11.0	
Highway	18.7	16.0	
Metro-highway	15.5	13.0	
Performance (sec.)			
0-60 mph	12.6	15.8	
25-60 mph	10.2	11.2	
50-80 mph	12.8	18.5	

[a] Stirling engine used was 4-215 170 hp engine. Baseline computed using 351-2V V-8 1975 Torino with California calibration.
[b] Projected from dynamometer and test rig data.
[c] Statutory emission standard before the 1977 Amendment.
SOURCE: Ford Powertrain Research Office, "Stirling Engine Program," *Fourth International Symposium on Automotive Propulsion Systems*, Apr. 20, 1977.

for the Stirling engine will probably be limited by cost, availability of materials, and technical considerations. The long leadtimes required to modify existing engine plants and to introduce new processes for the production of new engine parts make the commercialization of the Stirling engine unlikely until 1990 to 2000. The lag is likely to persist despite the fact the Government support doubled in **1978.**

Brayton Cycle Engines

A gas turbine (or Brayton cycle engine) is usually a continuous combustion powerplant in which the burning takes place in the working fluid. The main elements of the most common and simplest configuration are a compressor, a burner, and an expander (or turbine), with the entire gas stream proceeding through each. The compressor and turbine are usually on a common main shaft.

The combustion energy drives the turbine which, in turn, drives the compressor. This permits the extraction of power in the form of jet thrust, or shaft power, taken from the main shaft or from a separate power turbine in the exhaust gas stream. Many other types of compressors and expanders (rotary, reciprocating, lobe, screw, and vane) have been developed. However, only the axial, centrifugal, mixed-flow, or radial-inflow elements have found wide acceptance.

Present design practice for ground vehicle gas turbines favors the single-stage compressor and turbine on a common shaft, with a power turbine in the exhaust stream on a second shaft, and a regenerator (moving element heat exchanger) or recuperator (fixed element heat exchanger) to bring some of the exhaust waste heat back with the inlet air. Movable turbine nozzle vanes or a power transfer system are also included to improve part-load fuel economy. Recently, there has also been increased interest in small single-shaft designs operating at high speeds, high-pressure ratios, and without regeneration.

Turbine efficiency is a function of inlet air temperature, compression ratio, and turbine inlet temperature. Efficiency is also limited by the strength of the turbine blades at the high-operating temperatures typical of Brayton cycle engines. Blade cooling can allow slightly higher gas temperatures, but it is complex and costly, especially in the relatively small engines suitable for passenger cars. A very high overall air/fuel ratio (up to **40** to 1) is used to reduce the temperature of the burner and turbine wheel.

Maximum efficiency of the best recuperative versions of large-size turbines (400 hp) is nearly **40** percent. It is presently believed that all-ceramic engines with high-performance regenerators (or recuperators) may be able to achieve 38-

percent efficiency in the 100 hp size range.[27] It is more difficult to achieve high efficiency in a small gas turbine than in a large one; surface friction in a narrower flow path affects a greater portion of the total air flow and clearances between the moving parts and the housing account for a higher percentage of losses.

The power output of a single-shaft turbine decreases to nearly zero as engine speed drops by 50 percent. Thus, this turbine must operate over a much narrower speed range than most other engine types to maintain high efficiency. This requires the use of a wide-range continuously variable transmission (CVT) in order to match the narrow speed range of the engine to the variable speeds needed for operation of an automobile. Such transmissions are under development. The two-shaft configuration, or "free turbine" allows use of the standard automatic transmission employed in existing automobile designs, since the second turbine is able to operate at speeds considerably different from those of the main shaft.

The technical and performance potential of the gas turbine is attractive for the following reasons:

- There is the potential for high thermal efficiency, and thus good fuel economy (although this has not been realized to date).
- Gas turbines can be designed for a very wide range of gaseous or liquid fuels (multifuel capability).
- The turbine exhaust has substantially lower HC and CO emissions due to the more complete combustion associated with longer burning duration at higher temperatures. Also there is considerable research activity directed at achieving a "low NO_x" burner which should meet 0.4 gram per mile NO_x—the original statutory standard and the 1982 California requirement.
- The turbine has low weight and smooth operation, as well as a long life and reduced maintenance costs.

In order to realize the potential for high thermal efficiency, the turbine inlet temperatures need to approach 2,5000 F. Thus, the hot parts of the burner, ducting, nozzle ring, and turbine wheels require highly temperature-resistant materials. These can be sheet, forged, or cast "super alloy s," or ceramics. Ceramics would offer the best temperature resistance, long life, and lower production costs if the technology could be perfected.

One of the main limitations to ceramic materials is random undetectable defects in the crystal structure. As a result, conservative design practice requires use of stress levels of about one-quarter of those possible with a "perfect" material. A breakthrough in understanding the fundamental properties of ceramics with regard to their uniformity and freedom from random defects would enhance the gas turbine's competitive position.

Another problem with the ground vehicle turbine is the inability to achieve good fuel economy under partial load conditions and in acceleration and deceleration modes. Efforts to increase the fuel economy of the turbine are being made through redesign of the combustion chamber, compressor, and turbine. Most of the turbine engines presently being road tested use two shafts (the "free turbine"), fixed geometry combustors, and continuous fuel injection systems. In order to reduce fuel consumption when operating at less than full torque requirements, experiments are being conducted with intermittent fuel injection that varies with vehicle speed and with variable air-orifice geometry in the combustion chamber.

Gas turbines are not yet on the market, although both GM and Ford were close to offering large turbines in trucks and buses several years ago. The present GM turbine development program for both cars and trucks is quite active. However, Ford has essentially halted its truck turbine program. A consortium of AiResearch/Mack/KHD has also begun development of a large-truck turbine and could be the first with commercial sales.

The use of turbines in passenger cars is uncertain in the near future, but breakthroughs in ceramics could enhance their potential. The DOE/Chrysler target date for a competitive automobile turbine is 1983. GM has an ongoing development program, but its time frame is unknown. It is possible that GM is further along in

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[7] Discussion with Garret Research Corporation.

development than Chrysler/DOE; GM is not relying on ceramic materials at this time.

United Turbine A. B., a subdivision of Volvo, has developed a three-shaft turbine (the KIT) which it claims is competitive in fuel economy with its current ICE-powered automobile.[28] Volkswagen, Nissan, and Toyota are also active in turbine development.

Once turbine engines are fully developed, their costs could be attractive for the consumer, largely due to long life and reduced maintenance. Initial costs and fuel economy need to be brought to a competitive level, however, and high-temperature materials at low cost are required.

Diesels

The use of diesels through 1985 was discussed at length earlier in this chapter. As interest in passenger car diesels grows, many other concepts for improving the engine will be explored in greater depth. Most improvements will probably occur after 1985. Some of these developments are:

- variable compression ratio to improve starting and optimize operation over a wide range of conditions;
- positive timing of ignition (e.g., via spark plug);
- throttling to reduce smoke;
- modulated or pilot fuel injection to minimize need for indirect injection and/or massive construction;
- use of valve selector to cut out unneeded cylinders;
- various forms of capturing the waste energy in the exhaust of a conventional diesel (e.g., Rankine bottoming cycle—a small closed-cycle steam turbine coupled to the crankshaft—or Comprex "supercharging");
- innovative, very low-fuel-consumption concepts, such as the Cummins/TARADCOM adiabatic turbocompound diesel; and
- friction-reducing features such as an "air bearing" between piston and cylinder wall.

In view of the abundance of technological options, the relative emphasis on diesel versus gasoline engines may well hinge on the manufacturers' broad strategy considerations about the merits of developing two kinds of engines when either one would do the job. At the same time, diesel and gasoline engine technologies are tending to grow closer together (the Texaco TCCS concept and a "spark-timed" diesel concept are almost identical) and could conceivably merge. This potential merging has major competitive implications for the diesel engine industry and for the automobile manufacturers.

The adiabatic turbocompound diesel may provide thermal efficiency comparable to or higher than the Stirling in about the same time frame. The Cummins/TARADCOM program is exploring various changes to the diesel; by 1979, a test engine incorporating these changes should produce a thermal efficiency of 56 percent.[29] Thermal efficiency of up to 48 percent has already been achieved but the developmental engines, and even production versions, may be quite difficult to adapt to passenger car applications.

The major gain in efficiency is obtained by completely removing any form of cooling of the pistons and combustion chamber and by insulating the engine against radiant heat loss. Thus, the interior cylinder wall temperature of the engine is extremely hot in operation (above 2,000°F, compared to about 5000 F for a conventional diesel), and essentially all the waste heat goes out the exhaust. This high-energy exhaust stream is first used to drive a turbocharger and then to drive a power recovery turbine that is coupled to the crankshaft. The Wright Cyclone R3350 aircraft engine of the 1950's (using aviation gasoline) used this same turbocompound principle and achieved thermal efficiencies of over 40 percent in commercial service. It is conceivable that further compounding (e. g., addition of a Rankine unit) could raise the overall efficiency to greater than 60 percent.

The extreme temperatures of the power section require the use of ceramic pistons and unusual combinations of piston rings, cylinder wall, and lubricants. However, these problems are being worked out. The basic engine, plus compounding, could have 25 percent less vol-

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[28] S. O. Kronogard, "Advances in Automotive Gas Turbines," Mechanical *Engineering*, October 1977, pp. 38-43.

[29] SRI, p. V-52

ume than a naturally aspirated engine but the amount of hot ducts and thermal insulation would add appreciably to the effective engine volume. The cost of early engines would be several times that of existing engines and even in high production, costs would probably never drop below double. Also, it would take many years to arrive at a passenger car production version.

Fuel Cells

Fuel cells generate electricity from chemical energy through an electrochemical process. They have four primary ingredients: an electrolyte (conducive to ions such as hydrogen or oxygen); two electrodes per cell; a case for the cell or combinations of cells; and tanks for containment of fuel and oxident (if needed). Many fuel cells, especially those operating at or near room temperature require a catalytic agent, often platinum, in very small amounts on the electrode.

Many combinations of different types of the ingredients can be made into fuel cells. Some of the fuels used are hydrogen, methanol, hydrazine, ammonia, metallic fuels (e.g., zinc/air), and biological fuel. Some operate at a range of temperatures from room temperature up to 1,0000 Centigrade and higher.

Fuel cells have received most recent and widespread visibility by virtue of their use in satellites to produce electrical power. The process is inherently much quieter, cleaner, and more efficient than conventional power-generating equipment. The higher efficiency capability is a result of the fact that the fuel cell does not involve conversion of heat to mechanical energy, thus avoiding thermodynamic lower limits on efficiency.

Practical, cost-effective fuel cells are not yet available, and it is difficult to predict when such systems might be developed. Current costs of fuel cells are much higher than other practical energy conversion systems. Yet, the potential of fuel cells, both for stationary electric generation and to power vehicles, should not be underestimated or overlooked.[30]

Drivetrain and Tires

Ongoing improvements in transmission and drivetrain-related equipment are expected to be in production by the mid-1980's. A practical CVT will require a much longer time frame and, in light of other improved transmissions, may be limited in application.

In addition to the reduced rolling resistance associated with belted radial tires and the weight savings possible from using a "compact" spare (or eliminating the spare through a run-flat system), another tire innovation holds considerable promise. This is a cast, all-plastic tire with no cord or bead of any sort. One concept uses a fully closed torroidal form (likertube) mounted on a two-piece wheel. Another uses an integral plastic tire and wheel. Still another uses a conventional tire cross-section with a steel bead. Compared with current tires, these concepts have the promise of achieving simultaneously:

- equal durability with equal wet and dry traction,
- 50-percent weight reduction,
- reduced hysteresis (rolling friction),
- complete recyclability, and
- lower first cost[31]

However, the technical problems of noise, durability, heat buildup, etc., for these concepts are much the same as those of conventional tires.

The captive nature of the tire industry, the major shift that would be required in facilities and materials sources, the great reduction in required labor, and related institutional problems may slow the development of the all-plastic tire.

Vehicle Design and Manufacture

Post-1985 vehicle design and manufacturing changes could be motivated by several factors. These include the need to reduce the weight of vehicles further for improved fuel economy, the need to enhance the safety characteristics of vehicles, particularly in light of the reduction in

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[30] G Sandstede, ed., from *Electrocatalysis to Fuel Cells* (Seattle: University of Washington Press for Battelle Seattle Research Center, 1972).

[31] SRI Supplement.

size and weight of cars, and the need for more durable, longer lasting vehicle structures that are more corrosion-resistant. The limiting factors may be the engineering and design techniques and the availability of high-strength, lightweight durable materials to accomplish all of these objectives simultaneously.

Research in this area thus far has shown some promising results. For instance, smaller, lighter vehicles need not have a safety disadvantage. The creative use of lightweight materials (such as high-strength low-alloy steels, aluminum, composite structural plastics, and plastics, foams, and integrated foam-filled structures) has been demonstrated in the design of lightweight, sturdy vehicles.

The primary difficulty in new materials applications is in developing manufacturing processes that are competitive with steel forging, iron casting, and stamping in terms of manpower and time. Significant progress is being made with aluminum stamping, bonding plastics to metals, and molding large shapes of plastic. Such advances will encourage the use of these materials.

Durability, Corrosion, and Recycling

Durability and corrosion resistance depend on the materials used, the quality of vehicular components, and the ease of repairing or replacing those parts that are expected to wear. The plastic and aluminum parts will not rust, although the plastic may deteriorate over time, and aluminum will oxidize somewhat. Corrosion of steel parts can be controlled to a greater degree than at present by modifying design to limit the areas where salt and mud collect, by improving metal coatings (paints), by use of galvanized (zinc-coated) metals, and by improving sealing materials (undercoating). Progress is being made in these areas.

It is relatively easy to design stronger, and hence more durable, automobile parts. However, this generally entails added cost and increased weight. An overall saving in materials and in production energy might result. However, the cost-effectiveness of this approach requires careful study. Increased durability could lead to a fleet of older vehicles, made to earlier design standards, and possibly in poorer repair.

Recycling is now a well-established industry; its continuation and expansion depend more on will and economics than on technology. The increased use of plastics will require more attention to the recycling of these parts. Separation of plastics from metals will become increasingly difficult. Sorting of plastics for recycling is an almost insurmountable problem; a cost-effective solution will be difficult to find. Plastics that cannot be reclaimed pose a solid waste problem, since they do not decompose naturally.

Safety

There are a number of safety technology concepts in the automobile transportation system relating to vehicles, highways, and driver performance. Many of these concepts can be applied to crash avoidance or crash severity reduction, or to both in some cases. The following is a listing of some of these concepts:

- improved vehicle structural engineering / design / materials;
- advanced restraint systems;
- interior design concepts for safety;
- antilock and radar brakes;
- fuel systems and fuel tanks with reduced flammability;
- vehicle control augmentation;
- vehicle exteriors that minimize injury to pedestrian and pedacycle riders; and
- modal mix considerations (truck underride guard, for example).

Vehicle crashworthiness has two underlying objectives —maintaining occupant compartment integrity in the crash, and controlling the accelerations of the vehicle and the occupants throughout the event. By controlling the acceleration and spreading it out over time, the peak accelerations and overall level of accelerations on the vehicle occupants are reduced, Designs that can achieve higher levels of crashworthiness require application of known basic design principles. Computer-aided finite element analysis in vehicle design offers the capability for detailed examination of vehicle structural response characteristics. Also, routine application of engineering principles applied to crashworthiness criteria could produce vehicles of extremely high structural integrity.

Advanced restraint systems and interior design considerations for safety are an integral part of the occupant protection concept.[32] Considerable progress has been made in these areas and more improvements are expected.

Exterior designs that can lessen injuries in collisions with pedestrians, cyclists, and motorcyclists have not been fully explored yet. One approach to this concept has been a soft front-end design which tends to soften the initial blow and guide a struck pedestrian onto the hood of the vehicle. The efficacy and applicability of these ideas need further study. Certain features, such as breakaway or hinged outside mirrors and hinged hood ornaments, are already commonplace on vehicles.

Brakes

Several concepts regarding improved brakes are under consideration for 1985 and beyond. These include antiskid brakes and radar brakes.

Antiskid brakes have been developed for passenger cars. However, marketing of the early systems (which were developed without regulatory pressure or other incentives) was not very successful. Operating experience with such units has been quite satisfactory, despite early problems with the more complex units used on trucks. Technologically, such systems are quite feasible, but users have not viewed the benefits as being worth the added cost. A number of new antiskid braking concepts are under development. They could result in up to 10 percent less stopping distance in many cases, and several times that in a few severe conditions. More importantly, they essentially eliminate loss of directional control in emergency stops.

Since diesel engines have no engine vacuum, the Oldsmobile diesel uses a hydraulic booster to power the brakes. The hydraulic boost consists of using the power-steering pump for this second function. When antiskid systems are used, it probably will be preferable to use this form of power assist (rather than vacuum) for spark-ignition engines as well as diesel because of the much smaller actuators required.

Radar-assisted brakes are also under development. Their purpose is to perceive an inevitable collision event and respond faster than the human operator in applying the brakes. The system is not necessarily designed to avoid collisions, but to reduce the impact speed and thus the severity of a crash. Minicars, Inc., has developed such a system in conjunction with its work on the Research Safety Vehicle Program. They calculated a 60- to 90-percent reduction in collision energy at 50 mph compared with operator-actuated brakes, using a perceived hazard distance of 80 feet.[33] However, there is some concern that the widespread use of radar equipment may present a microwave radiation hazard.

Fuel Systems

Over 17,000 fires occur annually in the United States as a result of motor vehicle crashes.[34] In 1975, there were *55,000* vehicles involved in fatal crashes; more than 1,200 fires occurred.[35] The current FMVSS 301 standard on fuel system integrity considerably reduces the allowable fuel loss in 30 mph front, rear, and side collisions. The RSV program specifications, however, call for no fuel loss under much more severe test conditions. The technology for secure fuel systems is available. Bladder tanks, compartmentalized tanks, resealing tanks, foam filler blocks, and the like have been used extensively in aircraft and racing cars to reduce fire hazards. All of this technology is easily transferable to passenger cars at some modest increase in cost.

Another approach to minimizing problems with fires is to identify and eliminate the ignition source(s). An inertial switch is available which shuts off the electrical system in a crash. The electrical system has long been suspected to be a primary source of ignition in collision, fires.

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[32] John D. States, “Static Passive Occupant Restraint Systems, Without Airbags and Without Belts, Is It Possible?, ” *Fifth International Congress on Automotive Safety-Proceedings,* Cambridge, Mass., July 11-13, 1977, pp. 419-426.

[33] Rudolf Limpert, “Minicars RSV Brake System, ” *Fifth International Congress on Automotive Safety-Proceedings,* Cambridge, Mass., July 11-13, 1977, pp. 773-802.

[34] John Hubbard, Virginia Kelley, Russell Shew, “Fuel-Fed Vehicle Fires, ” *Trial,* January 1978.

[35] U.S. Department of Transportation, *Fatal Accident Reporting System, 1975 Report,*

Program and Concept Cars

Concept cars have been used as a means of corporate advertising, exploring public interests and tastes, and checking feasibility of new engineering and production concepts. More recently, concept cars have been used to investigate and stimulate innovative technical approaches that address national needs. The major auto companies routinely build such vehicles; the prototypes from small auto companies and inventors attempting to break into the automotive world can be viewed in this same category.

This class of vehicles includes the Chrysler gas turbine cars, the GM XP898 "all plastic" car, the Bricklin and DeLorean cars, the wide variety of cars used to explain new engines and/or fuels, electrics and hybrids and, finally, the series of safety cars. The safety car program started with the Liberty Mutual/New York State car of the *1960's*. It progressed through the NHTSA Experimental Safety Vehicle (ESV) Program of the early *1970's* to the present RSV (Research Safety Vehicle) Program, which attempts to integrate emission control and fuel-economy goals with the primary safety concepts.

As a parallel aspect of the ESV program, the major auto companies built their own versions of ESVs. These cars provided major improvements in meeting safety criteria, but retained much of the conventional full-size passenger car design, materials, styling, and production features. The ESVs, designed and built by nonautomotive developers, were not based on existing vehicles and had little in common with the conventional auto designs.

The current RSV program includes a very unconventional car from Minicars, Inc., as well as the Calspan/Chrysler vehicle, which is based on a modified Lightweight production sedan. At the same time, VW has developed a safety car version of their Rabbit model that achieves excellent fuel economy, emissions levels, and performance. The major U.S. auto manufacturers have not publicized any in-house integrated safety car efforts comparable to their earlier ESVs.

The information gained from the present RSV and parallel activities will probably provide both a basis for some of the future safety regulation and a fund of data and experience that will be extremely useful to the major auto producers. As an example, the VW safety car, which is a modified version of the Rabbit, weighs about **200** pounds more and is powered by a four-cylinder, turbocharged diesel. It obtains **60** mpg (composite), accelerates from O to **60** mph in less than 14 seconds, meets 1983 emissions standards, and provides 40 mph barrier (and 30 mph pole) crash survivability without serious injury. It is claimed that this car could be in production in 3 years.

Electric and Hybrid Vehicles

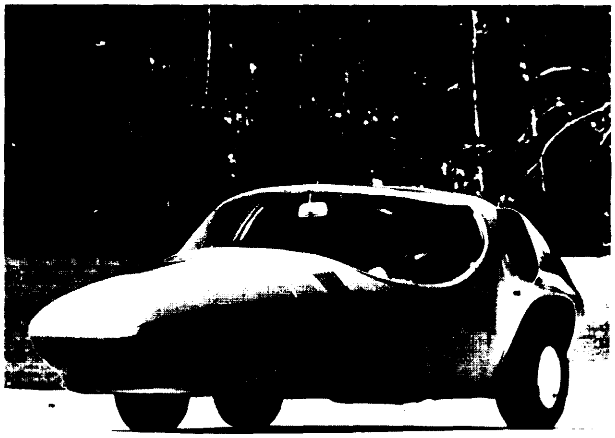
In the present environment of low-cost and plentiful gasoline, electric vehicles must be viewed as an alternative that is competitive in only very limited applications or under conditions of Government subsidy. In view of the inevitable depletion of petroleum resources and the continued problem of air pollution with petroleum fuels, Federal encouragement and subsidy of EVS is proceeding. The program has the dual objectives of conserving petroleum and assuring that the necessary technology and experience are in place before the need becomes urgent, since EVS can derive their energy from coal-fired or nuclear-generating systems.

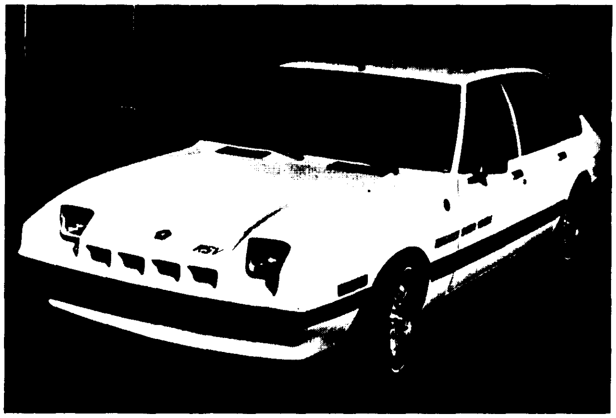
Many individual inventors, large corporations, and major auto manufacturers have been pursuing EV development programs, partly in the hope of providing a viable, currently competitive vehicle, and partly to be ready earlier than their competitors where EVs eventually become economically competitive. Present EV technology generally provides vehicles of such limited performance that public acceptance has been extremely low. For example, the only EVs commercially available are limited to about 35 mph, speed drops drastically on minor grades, and performance is much poorer near the end of the battery charge. Also, there is insufficient energy storage to include provisions for heater, defroster, air-conditioner, and similar features.

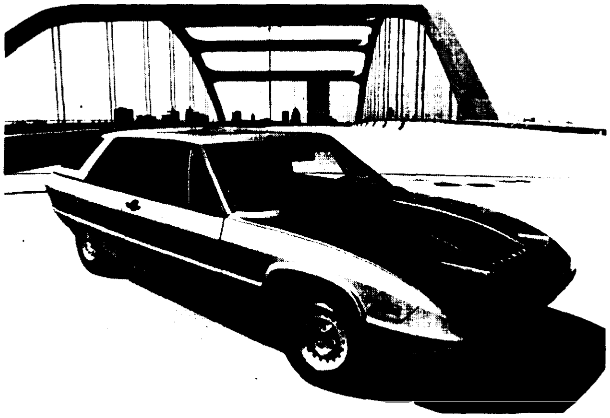
A typical electric-vehicle power train consists of storage batteries, provision for recharging from household or similar 110/220 volt sources, a controller to adjust speed and acceleration, and an electric motor that drives the road

Experimental Vehicle Designs

Pholo Credit U S Department of Transportation







wheels. The EV *may* also include regenerative braking, as well as a load-leveling device such as a flywheel to increase vehicle range.

The EV concept extends to a number of vehicles including delivery vans, urban passenger cars, buses, agricultural equipment, industrial lift trucks, and golf carts. Current research is focused on batteries, controls, and vehicles for personal transportation and light-duty commercial use.

The extremely limited energy storage capability of present day battery systems has led to the concept of combining a battery or similar energy storage system with a combustion engine system. This combination is known as a hybrid powerplant. Two hybrid concepts have been predominant—an internal combustion engine with a battery system, and an internal combustion engine with a flywheel energy-storage system.

Since the hybrid vehicle currently offers certain performance characteristics superior to EVs, it may provide a more acceptable alternative and may encourage the development and introduction of more advanced electric-vehicle systems. Flywheel and other energy storage systems currently under development may provide both electric and hybrid vehicles the performance and economy needed to improve their public acceptance.

Benefits

The successful development of an electric- or hybrid-vehicle power system (i.e., battery and power train technology) can provide a variety of benefits in the future. To the extent that electricity is generated from nonpetroleum sources and to the extent that electric- and/or hybrid-vehicle use replaces petroleum-vehicle use, the electric vehicle offers a means for substantial savings of petroleum.

Another benefit could be the virtual elimination of air emissions in urban areas. This benefit needs further examination because the emissions would be shifted to the utility. The ultimate impact would depend on the plants' locations as well as emission characteristics. However, unless emphasis is placed on vehicle safety, the increased use of small, lightweight vehicles may have an adverse effect on traffic safety.

Constraints

Consumer preferences may represent strong barriers to early sales of urban EVs and hybrids. The average range of a current EV is only about **50** miles, a major disadvantage for consumers. Although the hybrid vehicle does not suffer from the range limitations of the electric vehicle, it requires a more complex and expensive engine power train design and needs two energy sources.

Few EVs are currently equipped with the powerful motors and associated controls needed to match the acceleration of ICE-powered vehicles. Electric-vehicle users must adjust to lower speeds and reduced performance. Hybrids are not expected to perform much differently than EVs in this regard.

Many or most of the amenities that are commonplace in current ICE-powered vehicles are not expected on EVs or hybrids. Such equipment includes power steering, power brakes, extra interior space, and air-conditioning. However, in a serious energy shortage, this equipment would probably be discarded on ICE-powered automobiles as well.

Systems for servicing EVs or hybrids do not exist yet. Parts availability, maintenance know-how, and repair availability and costs are unknown.

State of the Art

In **1970,** the Edison Electric Institute defined the minimum desirable characteristics of electric vehicles for use by utility companies. (See table 147.) The purpose of the program was to encourage the manufacture and test operation of a significant number of special purpose electric vehicles.

The U.S. Postal Service is currently conducting a comprehensive electric-vehicle program. During the project, a set of technical goals for electric vehicles was developed. Except for the 4-year battery life, the technical goals of the postal electric vehicles (table 148) have been met by approximately **380** vehicles. A number of battery and control system failures were experienced by these vehicles. Preliminary results indicate that improved vehicle acceleration is desirable.

Table 147.—Desirable Minimum Characteristics— Electric Work Vehicle

Range	64 km (40 mi.)
Cruising speed	48 km/hr (30 mph)
Maximum speed	80-97 km/hr (50-60 mph) for emergency requirements
Acceleration to	48 km/hr (30 mph) in 10 seconds or less
Seats	Driver and passenger
Plus payload	227 kg (500 lbs.)
Stops per day	150-200 (not required to reach 48 km/hr (30 mph) after each stop)

SOURCE E A Campbell, *Analysis of On-Road Electric Vehicle Experience of 62 U S. Utilities,* SAE Paper 760074, 1976

Table 148.—Technical Goals of U.S. Postal Service Electric Delivery Vehicle

Range	32 km (20 mi.)
Maximum speed	53 km/hr (33 mph)
Acceleration to	48 km/hr (30 mph) in 20 seconds
Grade	10% at 16 km/hr (10 mph)—122 m (400 ft.)
Battery life	4 years

SOURCE. D P Crane and J.R Broman, "United States Postal Service Electric Vehicle Program," *Fourth International Electric Vehicle Symposium,* Dusseldorf, Germany, 1976

The Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976 (Public Law 94-413) included a provision to "demonstrate the economic and technological practicability of electric and hybrid vehicles for personal and commercial use in urban areas and for agricultural and personal use in rural areas . . ."[36] The Administrator of ERDA (now DOE) was required to "promulgate rules establishing performance standards for electric and hybrid vehicles to be purchased or leased. . ."[37] within 15 months of enactment. The 1976 Act originally called for the procurement of 2,500 EVs by December 17, 1979. Through an amendment in the law, the number has been reduced to 200 for the first year and 600 and 1,700 in the following 2 years. In all, an EV fleet of 7,500 vehicles will be on the road for test and demonstration in the 1981-84 period. It is important that this test fleet be viewed as a success or the future acceptance of EVs will be seriously jeopardized.

The DOE electric vehicle program has concentrated on the development of six components. They include the battery, charger, motor, controller, transmission, and body/chassis. Table 149 lists the components and characterizes a few typical design alternatives. Figure 66 shows two EV unit configurations with different charger systems. The onboard charger option would most likely be used for personal two- and four-passenger vehicles; the batteries of these vehicles would be charged at individual residences. Small commercial delivery vans might find it more convenient to utilize high-voltage offboard charging systems.

The key to a successful electric vehicle is the development of an improved battery with greater storage capacity, higher power density, and greater recycling capability at minimal cost increases. A number of electric-vehicle prototypes are currently being produced in the United States, Europe, and Japan. These generally incorporate state-of-the-art lead-acid battery technology. Such vehicles are typically limited to an operating range of about 25 to 30 miles between recharges; they generally have speed limitations of less than 50 mph because of low specific power. Also, the already-poor specific energy characteristics (28 to 32 watt-hour per kilogram) of lead-acid batteries degrade further when power demand is increased to maintain high acceleration and operating speeds.

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[36] *Electric arid Hybrid Vehicle Research, Development, and Demonstration Act of 1976,* P.L. 94-413, 94th Congress.

[37] Ibid.

Table 149.—Typical Electric Vehicle Component Design Alternatives

Component	Type
Battery	Lead-acid (current)
	Lead-acid (Advanced)
	Nickel-iron
	Iron-air
	Zinc-air
	Zinc-chlorine
	Sodium-sulfur
	Lithium-metal sulfide
Charger	Onboard
	Offboard
	Offboard, battery exchange
Motor	DC traction (series wound)
	DC separately excited (shunt)
	AC induction
	Others
Controller	Silicon controlled rectifier (SCR) chopper
	Inverter
	Variable resistance (Rheostat)
Transmission	Typical: 3-speed automatic with torque converter
	Continuously variable transmission
	Manual
	None
Body/chassis	Fiber reinforced plastics (fiberglass)
	Lightweight metals
Axles	Typical
Springs	Typical leaf layer coil
Brakes	Typical Self-adjusting hydraulic
	Regenerative
Tires	Typical
Auxiliary power	Battery and charger
	AC/DC converter
Accessories	Gasoline heater
	Thermal storage heater
	Air-conditioner

SOURCE US Energy Research and Development Administration Transportation Energy Conservation Division, *Environmental Development Plan*, September 1977

Europe and Japan are moving ahead in EV development. Japan has demonstrated an EV with a range of nearly 300 miles[38] and England has had a successful delivery fleet in operation for several years.

There are several types of lead-acid battery cars on the market. They suffer from the problems of short range, low speed, low performance, and flimsy vehicle structure and they have not sold well. General Motors has announced the possibility of marketing a delivery-type vehicle or small urban passenger car in the 1980's. GM will also provide a number of the electric vans in the DOE demonstration program.

Electric Vehicle Components

The propulsion system of the EV is made up of the electric drive motor, the controller, and the drivetrain. The drive motor may be either a DC or AC induction motor. Both systems may incorporate regenerative electric braking. The potential advantages ascribed to the AC induction motor relative to the DC drive include lower maintenance requirements, lower cost, better control of speed and torque, greater reliability, and better performance in rugged terrain. For either system, required battery voltages are in the range of 80 to 150 volts.

Attempts are being made to reduce overall vehicle weight and aerodynamic drag to improve performance. These goals can be attained

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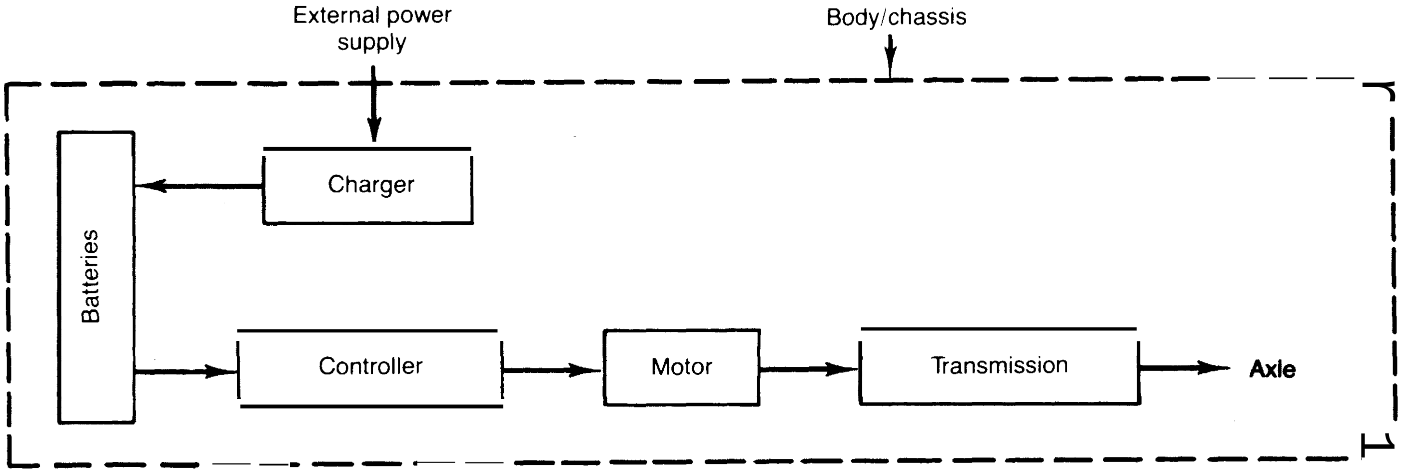
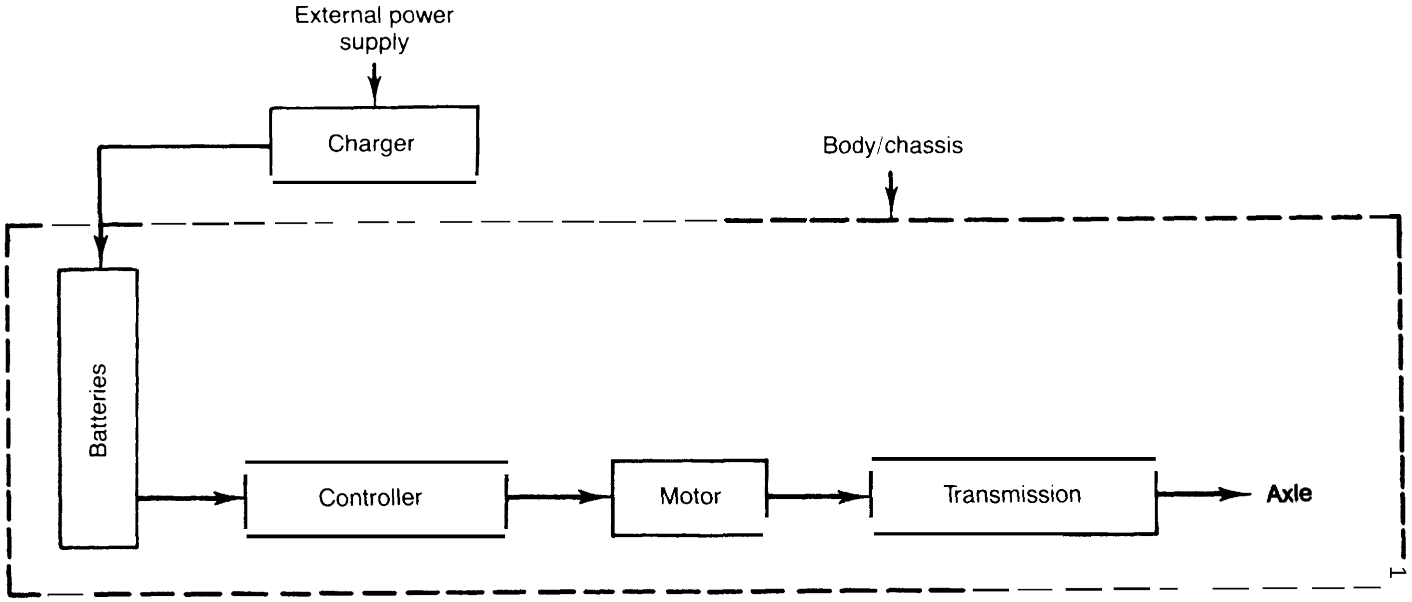
[38] Briefing by the U.S. Department of Energy, September 1977.

Figure 66.—Electric Vehicle Configurations



Electric vehicle with onboard charger



Electric vehicle with offboard charger

SOUI ICE U.S. Energy, Research, and Development Administration, Transportation Energy Conservation Division, *Environmental Development Plan*, September 1977.

by constructing the body and suspension of special lightweight but high-strength materials (aluminum, plastics, composites) and by suitably streamlining the configuration.

Hybrid Systems

Hybrids using internal combustion engines can be of the series or parallel type as well as other arrangements. (See figure **67.**) In the series configuration, the ICE is used to maintain the energy storage system at optimum operating conditions. The storage system is geared directly to the drive wheels to provide propulsion. In the parallel configuration, either the ICE or the energy storage system can supply power to the wheels, with each system operating as close to optimum as possible. In both configurations, the energy storage device is generally reversible and capable of accepting energy from regenerative braking systems.

The major subsystems of hybrid vehicles are shown in table 150. The number of possible permutations is quite large; however, preliminary investigations have indicated greater potential for certain configurations.

Reliable data on hybrid vehicles are unavailable because few vehicles have been built. However, extrapolation of certain characteristics suggests that a relatively small ICE (for highway cruising) combined with an electric drive (for urban driving) may prove to be a successful alternative to the severely limited range of purely electric vehicles.

Table 150.—Hybrid Vehicle Subsystem Typical Design Alternatives

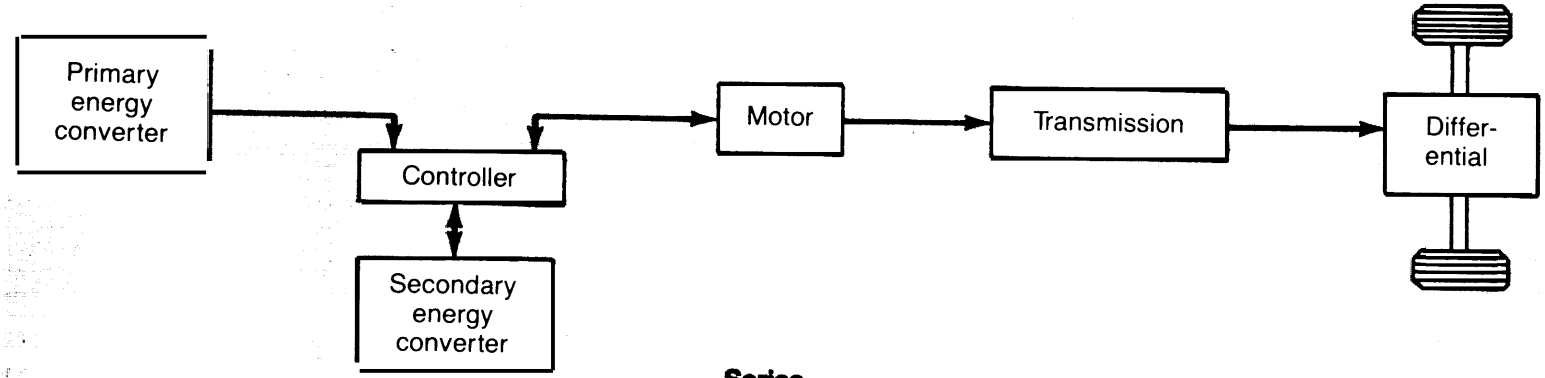
Vehicle subsystem	Alternative hardware
Primary energy converter	Heat engine Conventional (Otto cycle) Diesel Gas turbine Rankine Stirling Battery[a] Fuel cells
Secondary energy converter	Heat engine Flywheel Battery Fuel cell Hydraulic accumulator Pneumatic pressure vessel[b] Elastic storage (e.g., spring)
Motor/generator	AC DC
Controller	Inverter Cycloconverter Relays, switches Chopper
Transmission	Typical: a) 3-speed automatic with torque converter; b) manual Continuously variable transmission
Chasis	
Body	Fiber-reinforced plastics (fiberglass) Lightweight metals
Axles	Typical
Springs	
Brakes	Typical: Self-adjusting hydraulic Regenerative
Tires	Typical

[a] Battery flywheel and other such configurations that use a single energy source (e g electricity) are considered electric vehicles

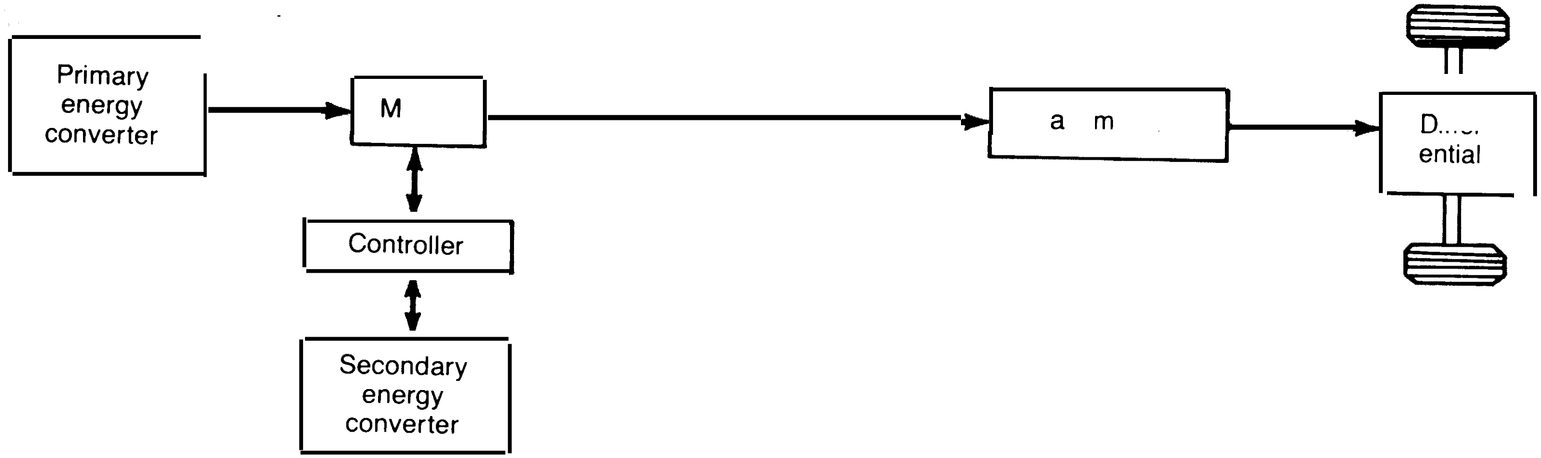
bean also be used as auxiliary storage for regenerative braking m a 3 part energy storage system

SOURCE U S Energy Research and Development Administration Transportation Energy Conservation Division *Environmental Development Plan* September 1977

Figure 67.—Hybrid Vehicle Power Systems



Series



Parallel

SOURCE: U.S. Energy Research, and Development Administration, Transportation Energy Conservation Division *Environmental Development Plan*, September 1977.

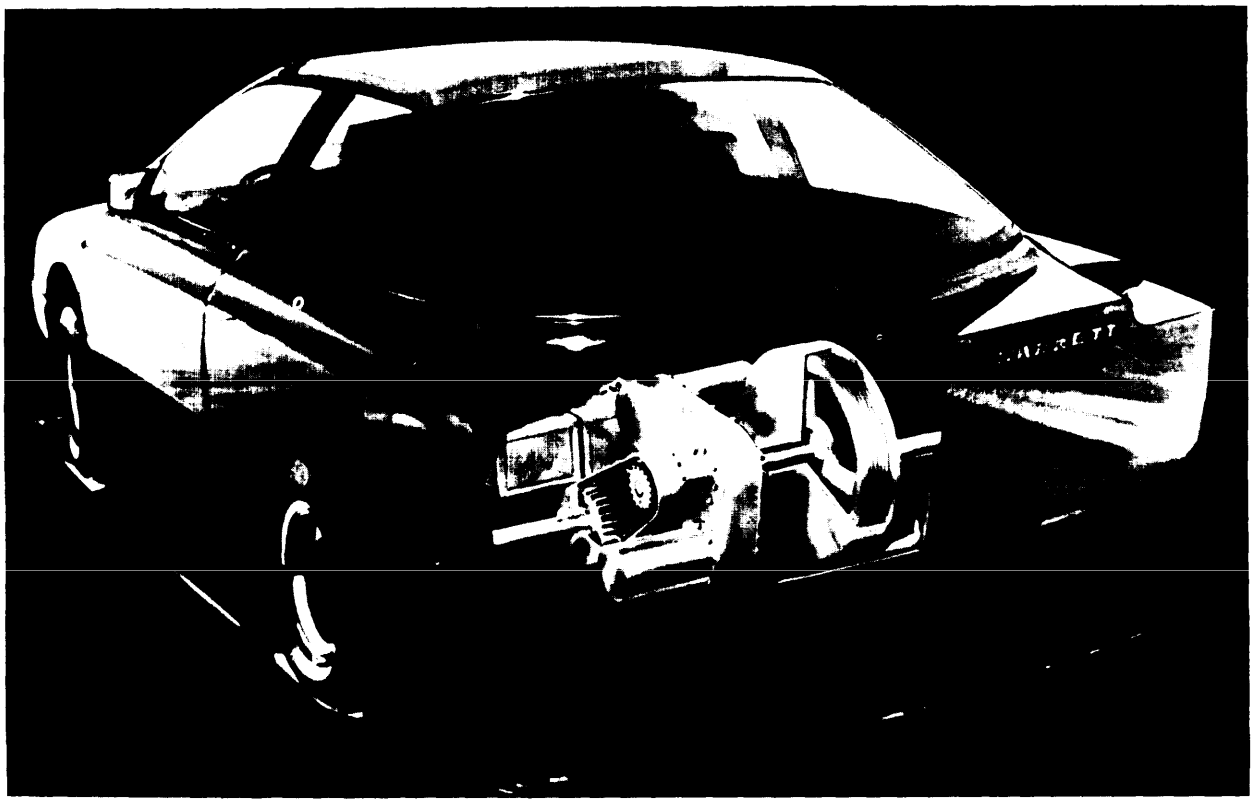


Photo Credit AiResearch Manufacturing Company

Both the electric-vehicle and hybrid-vehicle designs are in their infancy. Therefore, a wide range of developments are being considered and many of these are being pursued. Research efforts are continuing in the development of batteries with greater energy densities, longer life, and shorter recharging requirements. Flywheel development work has established objectives for energy density for 1980 and 1985. Supporting research is also being conducted on electrical components and materials. The NASA Lewis Laboratory (under contract to DOE) is trying to evaluate the more promising vehicle propulsion system configurations.

Investment and Costs

Current investment by the DOE for the EV and Hybrid Program is about $30 million for fiscal year 1978 and $37.5 million is requested for fiscal year 1979. The extent of private funding for research in the area is unknown at this time, although it is thought to be fairly sizable.

Electric-vehicle costs are hard to project because of the scarcity of data. A number of factors, including improvement of vehicle design, advancement in battery technology, and development of production economies of scale, will influence future costs of electric vehicles. In a study for DOE, General Research Corporation developed costs for near-term (1980) two- and four-passenger electric vehicles powered by lead-acid batteries. (See table 151,) A comparison of initial price shows a wide disparity between two- and four-passenger EVs, and conventional (1976) ICES. Four-passenger EVs cost about 20 percent more than conventional ICE compacts. The primary reason for the disparity lies in the cost of the lead-acid battery, which accounts for up to 22 percent of the total price of the EV. Four-passenger EVs are almost twice as expensive as two-passenger EVs. Because of greater size and weight characteristics, the four-passenger EV requires a larger (and, therefore, more expensive) battery power pack than that needed by the two-passenger EV. Two-passenger EVs cost about 25 percent less than conventional 1976 subcompacts. Again, the difference is primarily due to the smaller weight of the two-passenger EV.

Operating costs for electric vehicles will depend largely on improvements in the energy ef-

Table 151 .—Comparison of Costs for Electric and Conventional Cars (initial price, 1976 dollars)

Vehicle type	Base price	Battery cost	Total
2-passenger EV.	$1,901	$ 374	$2,275
4-passenger EV.	3,518	1,020	4,538
Conventional compact.	3,780	—	3,780
Conventional subcompact	3,060	—	3,060

SOURCE General Research Corporation. *Potential Applicability of a Lead-Acid Battery-Powered TwoPassenger Electric Car*, June 1976.

ficiency of the battery, battery life, and the battery-charging system. The rate of growth in the price of electricity will also be a factor. Maintenance costs for electric vehicles are expected to be less than those for conventional ICES simply because EVs have fewer mechanical working parts. The overall operating cost spread between ICES and EVs will also be influenced by the rate of improvement in ICE fuel economy and the rate of growth in the price of gas, An important addition to routine operating costs of a lead-acid battery system will occur about every 2 years. This is the replacement of the entire battery pack at a cost of about $500 to $1,000.

The costs of owning and operating hybrid vehicles are even less certain than for EVs. The initial cost is anticipated to be higher than that of an EV, since two propulsion systems are included. Operating costs are dependent on many of the same factors as the EV and also on the cost of the secondary fuel source.

ALTERNATE FUELS

The liquid and gaseous fuels that could be used in conventional and potential future automobile powerplants can come from a variety of sources and in numerous forms. Fuels which have been tried include: gasoline, diesel fuel, broadcut fuels, lower alcohols (ethanol and methanol), higher alcohols, ether, ammonia, liquid natural gas, propane, methane, hydrogen, and hydrazine. Any of these fuels can be used in pure form, and some can be blended or mixed with other fuels.

The sources of fuels are nearly as varied as the type of products. Coal, oil shale, tar sands, biomass (including municipal and agricultural waste as well as agricultural products), and water (for hydrogen), are considered likely alternate sources for fuel in the intermediate and long term. This section deals with the technical aspects of some of these sources, the end products, and their use in propulsion systems for automobiles.

Oil Shale

The oil in oil shale is contained in kerogen, a complex, high molecular weight organic substance composed of carbon, hydrogen, oxygen, sulfur, and nitrogen, intimately mixed with inorganic silt particles. Separation of the oil requires that heat be applied to the shale. This causes the kerogen molecules to break up, releasing liquid hydrocarbons, some combustible gases, and water from the inorganic spent shale residue. The liquid hydrocarbon mixture (crude shale oil) is then upgraded to syncrude to make it acceptable as a conventional petroleum refinery feedstock.

The use of substitute automotive fuels derived from oil shale does not require new engine technology. Oil shale products could supplement supplies of petroleum available to the auto sector. They could also be used as feedstocks for the petrochemicals industry, thereby allowing greater use of available petroleum supplies by the automotive sector.

Two basic processes for recovering the oil from oil shale are being developed: the above-ground process, and in situ processing. Above-ground shale processing consists of four basic steps: mining the shale; crushing it to the size necessary for the retorting vessel; retorting the shale through the application of heat; and upgrading the raw shale oil through the removal of contaminants (excess nitrogen and oxygen) to make it acceptable as a refinery feedstock. There are several above-ground shale oil processing methods, characterized primarily by different procedures used in heating and retorting the oil shale.

In situ recovery of oil shale differs from aboveground recovery in that the oil is recovered from directly within the bed of shale. The shale is fractured by explosives and then ignited by a flame from compressed air and a combustible gas pumped into the shale bed. The gases heat and retort the shale, producing an oily vapor. The vapor condenses to a liquid at the base of the in situ retort and is pumped to the surface for upgrading to the level of refinery feedstock quality. A “modified” in situ process is being developed in which a portion of the shale bed is first mined by conventional methods and retorted on the surface. The remaining shale is retorted underground. This process has been developed and is being tested by Occidental Petroleum Corporation with marginal success.

Oil shale production is constrained primarily by technology, production *cost,* and environmental impacts. The existing processes have yet to be implemented on a commercial scale in the United States. It is unclear whether full-scale production will entail changes or modifications in existing technology.

The existence of high Ievels of nitrogen, arsenic, and oxygen and high carbon-to-hydrocarbon ratios in oil shale necessitates fairly substantial upgrading to improve the quality of oil shale syncrude. This processing is one of the cost factors that makes oil shale noncompetitive with crude petroleum at current prices.

A major environmental constraint involving above-ground oil shale production is the problem of spent shale. Only about 12 percent (by weight) of oil shale can be converted to oil. (This figure varies depending on the quality of the deposit.) The remaining 88 percent is relatively useless. It has been estimated that a 1-million-barrel-a-day (bbls / day) shale industry using high-grade (3o gallons per ton) shale will generate 1.5 million tons of spent shale a day. This is after mining, crushing, and retorting. Crushing the rock and retorting causes the total volume to increase. Thus, all of the spent shale cannot be put back where it came from. The problem of disposing of this shale in an environmentally and economically acceptable fashion is a major constraint to the success of the oil shale industry. Dust can also be a problem, particularly if the processing reduces the shale to a fine powder.

In situ processing has some different environmental impacts from those of surface retorting of sha!e. Aboveground processing is characterized by problems such as significant land disturbance due to mining, large volumes of spent shale, relatively high water use, and air and water emissions from retort operations. In situ processing reduces some of these impacts but increases the potential for ground water contamination, aquifer disruption, and subsidence or uplifting at the surface. Modified in situ processing has a combination of the surface and underground impacts.

Primary air pollutants associated with oil shale processing include sulfur dioxide, hydrocarbons, nitrogen oxides, and particulate. Other pollutants that can occur include ammonia, carbon monoxide, hydrogen sulfide trace elements, and toxic substances. Conventional control systems are available for some of these pollutants, but their removal efficiency and dependability in these specific applications have not been demonstrated. These air pollutants are off-gas emissions and are associated with both the surface and in situ retorting processes, The effectiveness of in situ methods in reducing gaseous pollutant formation, and containing and treating them, will not be known until the technology has undergone additional field testing. The upgrading, refinement, and storage of the product are common steps to both processes, and similar impacts will occur.

The water use requirements of shale process-

Photo Credit: U.S. Department of Energy

In situ oil shale retorting

ing may constrain the development and use of major oil shale deposits in arid regions. The principal deposits of oil shale are found in Colorado, Utah, and Wyoming, where water supplies are limited. Extensive development of these deposits, using existing mining and surface retorting methods, could cause unacceptable burdens on water use in the area and cause economic hardships for farmers and industries using the available water in these areas. In situ processing requires less water for shale processing than current surface retorting and refining.

A major environmental impact which may occur with in situ processing is geological disturbance. Mining, hydraulic and explosive fracturing, and in situ retorting cause physical disruption and cracking of strata. They may also result in the severe disruption of adjacent ground-water-bearing aquifers and cause subsidence or uplifting at the surface. Depending on the proximity and structure of aquifers, ground water supplies may be contaminated and aquifer flow and storage characteristics may be changed. Subsidence at the surface, which may not occur immediately, can damage buildings and roadways or affect options for subsequent land use. Finally, since oil shale is concentrated principally in Colorado, Utah, and Wyoming, the effect of “boomtown” development and accompanying social problems could be considerable.

At the present time, no oil shale plants have been constructed or operated in the United States on a large-scale commercial basis. The technology is at the bench-scale to pilot-plant stage of evolution. Both Government and privately sponsored projects involving R&D of oil shale recovery processes have been underway since the 1920's. Both above-ground (conventional) shale processing and in situ shale processing are under development.

Several types of surface shale oil retorting methods are reportedly near the state of commercial application. Union Oil Company has announced plans to construct a 10,000-bbl-per-day oil shale plant in Colorado, providing they receive a proposed $3 per barrel tax credit. The Paraho Development Corporation is scheduled to produce a total of 100,000 barrels of shale oil for test purposes at its plant at Anvil Points, Colo., under joint Navy/DOE financing. Paraho has also proposed to build an 11,500-ton-a-day commercial-scale module. The TOSCO Corporation, in conjunction with Colony Development Corporation has recently designed a commerical-sized plant to produce 47,000 bbls per day of shale oil and 4,300 bbls per day of liquefied petroleum gas.

Additional research in aboveground oil shale conversion has been carried out by Union Oil Company, the Institute of Gas Technology, and the Superior Oil Company.

Several in situ processes have also been tested. Occidental Petroleum Corporation has been conducting a series of field tests since 1972. It has constructed three commercial-sized, modified in situ retorts. One of these produced 27,500 barrels of oil in 6 months from shale containing 17 gallons per ton. In addition, work is also being done at the Lawrence Livermore Laboratory and DOE's Laramie Energy Technology Center on variants of in situ oil shale recovery.

Estimates of commercialization of fuels from oil shale are subject to considerable speculation; a small amount of production could begin in the late 1980's or 1990's. However, it will be many years before the maximum economic recovery rate (commensurate with competing petroleum prices) will be attained. Current indications are that oil shale derived fuels will not be widely used by the auto sector before the year 2000, primarily because of cost considerations. Over the next 20 to 25 years, the likelihood of commercially available fuel from shale oil will increase as the price of petroleum increases.

Due to the continued uncertainty on such factors as oil shale technology, environmental requirements, disposal of spent shale, and problems of operating on a large scale, investment costs of oil shale plants are difficult to estimate with accuracy. The interplay of institutional, environmental, economic, and technological factors will have significant impact on capital and operating costs. Current estimates call for a $1 billion to $1.2 billion investment for a 50,000-barrel-a-day surface retort facility and at least $750 million for a similar size modified in situ operation.

For the same reasons, the projected retail price of shale oil is uncertain. Occidental Petroleum claims that it can produce oil from oil shale at a total cost of $12 a barrel.[39] However, another source (Continental Oil Company) claims that the addition of environmental costs and syncrude upgrading costs raises the per-barrel cost of oil shale to $16 to $26, a figure well above the current world crude price of about $13.50 a barrel.

Tar Sands

Tar sands (or bituminous sands) occur throughout the world in various types of deposits of varying viscosity. The bitumen in the sand ranges from 5 to 13 percent by weight. The best deposits are in Canada and South America, totaling 98 percent of the estimated 1,680 billion barrels of world reserves. The United States has less than 2 percent of world reserves and considerably less in tar sands than oil shale reserves. Consequently, tar sands are not considered a major domestic energy resource. Utah contains 93 percent of the estimated 27 billion barrels of oil in tar sand deposits in the United States.

The recovery process of tar sands is of two types: mining followed by surface extraction, and in situ extraction. Surface extraction processes are many:

- hot water (the only one used commercially),
- cold water,
- solvent extraction,
- mechanical extraction, and
- spherical agglomeration.

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[39] *Business Week*, Jan. 30, 1978

The types of in situ extraction that can be used are thermal stimulation and solvent extraction. The thermal stimulation technique has several approaches involving steam injection or flame propagation.

In situ and underground mining processes are critical to tar sand development since only 10 percent of the U.S. and Canadian tar sand can actually be surface-mined for extraction. The product is a heavy synthetic feedstock, high in sulfur (up to 5 percent) and relatively low in nitrogen (less than 1 percent), which can be cracked to synthetic crude oil and then refined. The mining, extraction, and in situ processes of tar sand have all of the problems of oil shale mining and extraction. There are various R&D projects ongoing in the United States. In Canada, there is a successful commercial tar sands plant producing **50,000** barrels per day of high-quality synthetic crude oil. Several others are scheduled for operation in the 1980's.[40]

Coal Liquids

Liquid hydrocarbons can be produced from coal by four categories of processes—solvent hydrogenation, pyrolysis, hydrocarbonization, and indirect liquefaction. During these processes, the coal is broken into smaller molecules, contaminants such as ash and sulfur are removed, and the proportion of hydrogen in the molecular structure is increased. Synthetic crude oil, premium fuels, feedstocks, or low-ash, low-sulfur boiler fuels are produced.

Indirect liquefaction (e.g., Fischer Tropsch synthesis) involves the gasification of coal in the presence of oxygen and hydrogen. The gas is then purified and passed over a catalyst, yielding liquid products ranging from methanol to heavy hydrocarbons. The process can be directed towards the production of motor fuel and substitute natural gas. This process is currently employed in a State-owned plant (SASOL) in South Africa.

In solvent hydrogenation processes, the coal is dissolved in process-derived solvent, and molecular hydrogen is added directly or indirectly via a hydrogen donor solvent. Solvent hydrogenation processes can be either catalytic or noncatalytic. Catalytic processes are further classified as fixed or ebullating bed reactors to describe how the coal, solvent, and hydrogen mixtures contact the catalysts. Pressure in the solvent hydrogenation reactor ranges from 1,000 to 4,000 psi and temperature ranges from 7500 to 9000 F.

Photo Credit U S Department of Energy

Mining for coal

Pyrolysis is similar to coal coking in that the coal is heated to remove tars, gas, and other volatiles, leaving a coal char that is largely carbon. Coal pyrolysis processes usually operate at low pressure (**20** to **50** psi) and moderately high temperature (1,600 °F), and are noncatalytic.

Hydrocarbonization is a refinement of the coal pyrolysis process and entails noncatalytic carbonization of the coal and thermal cracking of the heavy coal liquids in a hydrogen atmosphere to produce fuel oil, distillates, and gaseous fuels. Hydrocarbonization operates at

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[40] U.S. Department of the Navy, Energy and Natural Resources, Research and Development Office, *Energy Fact Book 1977* TT-A-64277-306, April 1977, pp. VII-1 to VII-20.

moderate pressure (500 psi) and temperature (1,000° F). Most of the research in the United States is on the direct liquefaction process (the latter three described).

The conversion of coal to a liquid product requires increasing the proportion of hydrogen, either by adding hydrogen or removing carbon. (The hydrogen-to-carbon ratio in coal is 0.9 to 1; in oil it is 1.75 to 1.) The hydrogen for the process can be derived from a catalytic reaction of steam and a light hydrocarbon (usually methane or naptha), a partial oxidation of heavier oil or coal, or an endothermic reaction involving carbon and steam. For the economics of the conversion to be favorable, the energy for hydrogen production must come from the coal itself. A major influence on the cost is the limited ability to produce a sufficient supply of hydrogen from the coal-generated energy to maximize the conversion of coal to hydrocarbons.

The use of substitute automotive fuels derived from coal would not require new engine technology. However, new engine technology could reduce fuel quality requirements, and thus fuel cost. Coal liquids could supplement supplies of petroleum available to the automotive sector. In addition, the use of coal liquids as feedstocks for the petrochemicals industry could allow greater use of available petroleum supplies by the automotive sector.

Major constraints to the development and use of coal liquids center on technology, economics, and environmental impacts. Since none of the coal liquefaction processes have been demonstrated in the United States on a commercial scale, it is not clear which process will prove to be the most energy-efficient and cost-effective. As a result, there is uncertainty about investment, operating costs, and production levels.

Coal liquefaction processes generally require high pressures, carefully controlled temperatures, and large reactors for coal conversion. This, in turn, requires specialized equipment that can withstand the corrosive and fouling effects of coal and can adequately control the flow of materials and heat in the reactors. Research is continuing into the development of equipment for commercial-scale application. However, as a result of these specialized equipment needs, the processes are highly capital-intensive.

Before coal liquids can be refined, ash particulate and unreacted solids must be separated and removed. Several processes for ash and solids removal have been developed and are being tested. A major goal is to eliminate excessive char buildup and clogging of feed lines and reactor equipment.

Unless heavily upgraded, crude oil derived from coal is generally inferior to natural crude oil because greater quantities of bound nitrogen are present in the synthetic crude. In addition, liquids from coal may be less stable than petroleum liquids. Although processes have been developed to upgrade the quality of coal-derived syncrude, they involve additional costs that hinder the competitiveness of coal liquids.

The price of available conventional fuel supplies (gas and oil) is also an important factor. Given current technology, coal liquids cannot be produced or sold (except at a loss) at current levels of petroleum import prices. Thus, the import price of crude oil must rise before investments in coal liquefaction become attractive, Crude oil prices will rise as existing world supplies of conventional fuels are depleted and/or as a result of a price hike by the OPEC cartel. Both of these mechanisms are largely beyond the control of the United States. Therefore, uncertainty with respect to the price and rate of depletion of existing fuels contributes to uncertainty with respect to the economics of investment in a coal liquefaction industry. Even if the cost of coal liquefaction becomes competitive with petroleum production, factors relating to risk acceptability and capital cost may delay the commercialization of coal liquids. Not only are production processes untested at the commercial level (with the notable exception of SASOL in South Africa), but also the substitution of coal liquids for conventional fuels is relatively untested. However, it is believed that any such changeover will be simple and straightforward.

In addition, few companies have immediate access to the large amounts of capital required for plant construction. Therefore, the rate at which capital can be mobilized (i. e., through the formation of joint ventures or consortia) will have an impact on the level and timing of coal liquids' commercialization.

Other drawbacks involve environmental considerations. Large-scale deployment of coal liquefaction processes could have significant impacts on the air and water quality of the regions in which they are developed. Sources of process emissions are known and conventional techniques are available for emissions control. However, the exact quantities of air and waste-water pollution are not well-known, nor have the overall cost effectiveness and dependability of conventional control techniques been demonstrated for large-scale coal liquefaction plants.

Two other environmental characteristics of liquefaction are of particular concern—the inherently hazardous nature of some organic compounds generated in this process, and the environmental impacts specific to the use of the product coal liquids. Great care must be taken to avoid hazardous exposures to process streams, products, and waste streams. The dangerous organic compounds that exist in air emissions, water effluents, and solid waste can be eliminated through oxidation and decomposition.

Many of the organic liquids derived from coal are both carcinogenic and toxic (as is natural crude oil) and it is not expected that the products of liquefaction will be rendered inert. One example relates to the benzene content of coal-derived liquids. Benzene has been recently recognized as a carcinogen, and both the Environmental Protection Administration and the Occupational Safety and Health Administration are stepping up their regulatory program accordingly. Regulations applicable to petroleum refining and gasoline handling are expected. Gasoline has about 2 percent benzene. Coal-derived gasoline will require greater control than conventional gasoline, since coal liquids have 5- to lo-percent benzene content.

Liquefaction produces a low-ash, low-sulfur fuel, but does little to reduce the nitrogen content of the fuel. To avoid damaging the catalysts in the refinery, most of this nitrogen must be removed before the fuel is refined to gasoline. Use of coal-derived gasoline can result in higher emissions of nitrogen oxide than use of petroleum-refined gasoline, unless the denitrification of the coal-based fuel reduces fuel-bound nitrogen below the level found in petroleum. In addition, coal-derived fuels contain proportionately larger amounts of aromatics and ring-structure compounds. Research is underway to test the effects of these differences in fuel chemical composition on engine exhaust emissions and combustion characteristics.

Still, the greatest technological barriers to coal liquids utilization lie in the production area. The major thrust of present Government and private research is on the development and improvement of coal liquefaction production technology. DOE is currently sponsoring the development of several conversion processes that are in the pilot-plant stage. In fiscal year 1977, $73 million had been spent on R&D for coal liquefaction. Among the chief efforts are the Solvent Refined Coal Process pilot plant at Fort Lewis, Wash.; the H-Coal Process pilot plant at Catlettsburg, Ky.; and Hydrocarbon Research, Inc.

Other projects include the Donor Solvent Liquefaction Process, being developed by EXXON Research and Engineering Company. The production of clean industrial and transportation fuels from coal is being investigated by the Lummus Company through the use of a bench-scale pilot plant.

While significant experimentation has been conducted to determine the optimum operating conditions for coal conversion processes, there has also been extensive research and testing of the ability of coal handling and feeding systems to withstand the corrosive and fouling effects of coal and coal products in the conversion process. Separation of ash and unreacted coal from the viscous coal liquids is a difficult problem common to all liquefaction processes and has also been the focus of considerable development effort. Many techniques are being investigated, including filtration, centrifugation, fractionation, and magnetic and solvent separation.

The time frame for commercialization of coal liquids is long term. As mentioned previously, the rate and extent of market penetration will depend on the price and availability of conventional fuels and the cost (relative to existing fuels) of producing and using coal liquids. In a study for DOE, Energy and Environmental Analysis, Inc., estimated that coal liquefaction plants will first become commercially profitable between 1988 and 2005.[41] Some industry

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[41] Energy and Environmental Analysis, Inc., *Integration of Uncertainty in to Industrial Evaluations of Fossil Energy Technologies*, February 1977.

sources predict that synthetic fuels could be available at approximately double the cost of producing liquid fuels from crude oil at current rates. On this basis and assuming assuming a 3-percent-per-year real increase in the current price of imported crude, (about $13 a barrel) coal liquids might become profitable around **2000.**

Estimates of capital costs for coal liquefaction plants with 50,000 -bbl-per-day capacity range from $650 million to $850 million.” These figures should be regarded with caution. Changes in institutional, environmental, economic, and technological factors could have significant effects on investment and funding levels. Moreover, few firms may be willing to invest in large-scale liquefaction plants until pilot plants have been successfully built and operated. This itself is a lengthy and expensive process, requiring at least 4 years and (depending on pilot plant size), **$50** million to **$200** million.[43]

Alcohol Fuel and Alcohol= Gasoline Blends

Alcohol fuels generally involve the use of either ethanol or methanol, although higher alcohols and ether are potential, but less likely, candidates. Ethanol (grain alcohol) can be manufactured by fermentation from biomass (i. e., municipal and agricultural wastes, plants, grain, etc.).

Methanol is currently produced from natural gas, heavy residuals, or naphtha. Recent research on synthetic fuels has also illustrated the potential for producing methanol from coal. Methanol can also be produced from biomass, but not as readily as ethanol.

Alcohol can be used as an automotive fuel in two ways. It can be blended with regular gasoline in concentrations of up to 20 to 30 percent by volume with only minor changes in automobile engines and fuel systems. Pure (neat) methanol or ethanol can be used only if the engine and fuel system are modified.

The high octane rating of alcohol allows for an increased compression ratio, which in turn provides better thermal efficiency. Thus, although the Btu content per unit volume of alcohol is only about half that of gasoline, it offers potential energy efficiency improvements of 3 to 10 percent relative to gasoline on a weight basis. ”

Problems associated with the use of neat methanol include corrosion, cold starting, and vaporlock. However, such problems are routinely solved during the development phase of various gasoline engine changes, and demonstration vehicles burning neat methanol have been successful.

The costs of modifying engine carburetion and fuel feed systems for the use of alcohol-gasoline blends are minor. In many cases, all that is required is carburetor adjustment. In these terms, the potential for the use of alcohol blends is greater than that for neat alcohol. Alcohol fuels can also be used in gas turbines, in external combustion engines such as the Stirling, and in boiler heating applications.

The emission characteristics of engines burning alcohol fuels compare favorably with gasoline-powered engines. In general, pure alcohol fuel shows a reduction in hydrocarbons, carbon monoxide, and nitrogen oxides, although the data are not perfectly uniform or consistent. Emissions tests using pure methanol have shown reductions in NO_x by a factor of two to three over similar tests with gasoline. Ethanol does not appear to offer **as** much of a reduction in regulated pollutants as methanol. Alcohol-gasoline blends seem to alter the emissions in proportion to the amount of alcohol in the blend.

Potential problems could exist with respect to the level of the presently unregulated unburned fuel (UBF) emissions of methanol engines. UBF emissions with methanol are as much as 5 times those of gasoline. Less than 2 percent of the UBF emissions are hydrocarbons; the remainder consist mainly of methanol and aldehydes. These emissions are currently unregulated; their air pollution significance in terms of reactivity and toxicity is not well-understood. If further study

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[42] S. Katell and L.G. White, "Clean Fuels from Coal are Expensive," *Hydrocarbon Processing*, July 1976.

[43] Energy and Environmental Analysis, Inc., *Integration of Uncertainty into Industrial Evaluations of Fossil Energy Technologies*.

[44] R.R. Adt et al., "The Effects of Blending Methanol with Gasoline on Geometric Distribution," *Fourth International Symposium on Automotive Propulsion Systems*, April 1977.

demonstrates undesirable impacts caused by aldehyde emissions (such as formaldehyde, which is an irritant) the potential for use of methanol in automotive engines could be limited. This potential problem does not appear to be as serious with ethanol fuel.

Storage and distribution is somewhat more difficult with alcohol. Part of the problem is that alcohol has only about half as much energy per gallon as gasoline; thus storage facilities must be larger to hold gasoline-equivalent amounts of energy. Alcohol and water are miscible, To keep the fuel pure, water contamination in shipping and storing must be prevented. Current gasoline shipping and storage facilities permit water contamination, since the two liquids do not mix and the water can be drained off easily. In the use of alcohol blends, water contamination will cause the two fuels to separate into their respective phases. Ethanol is slightly less subject to water absorption and phase separation than methanol, and may be more attractive in that respect.[45]

The potential availability of alcohol depends upon the costs of producing it relative to the cost of gasoline production from petroleum or other sources. Although methanol can be produced now from natural gas or petroleum, its value as an alternative automotive fuel will presumably rise only if it is produced from nonpetroleum sources.

The use of ethanol produced from organic wastes could become significant in a local or regional area where agricultural wastes are readily available. The use of methanol could be effective on a national scale if it is found to be an energy-efficient, cost-efficient coal conversion product,

Manufacturers can currently produce vehicles that will operate satisfactorily with either methanol or ethanol blends. Autos in Brazil have been operating routinely on 20 percent (and even up to 30 percent) ethanol blends for several years. Volkswagenwerk AG and General Motors have been engaged in prototype testing of methanol-fueled vehicles.[46] Volkswagen's test fleet of 45 methanol-blend test vehicles accumulated nearly 1.8 million kilometers. The only major, practical problem encountered was some corrosion of materials used for some components that came in contact with the methanol blend. Minor adjustments in carburetion are necessary to improve vehicle driveability.

Thus, the experience of test programs and the real experience in Brazil indicate that methanol or ethanol blends could be widely used with little or no problem. However, the production of alcohol fuels in large quantities will probably not be commercially feasible until beyond **1985.**

Research on the use of neat methanol indicates that driveability is presently unsatisfactory in the cold-start and warmup phase of engine operation. Volkswagen is studying the potential for improving driveability by mixing additives with the alcohol fuel or by using an auxiliary fuel during the cold-start phase. General Motors has found the driveability of neat methanol-fueled vehicles to be enhanced through the use of electronic fuel injection systems rather than carburetors. In addition, GM's research has shown that achievement of acceptable driveability requires redesign of the fuel intake system to provide the approximately nine-times-greater mixture heating needed for satisfactory fuel vaporization. Research is continuing in the study of various combinations of air-fuel ratios, ignition timing, and engine compression ratios to obtain the most acceptable compromise among driveability, fuel economy, and exhaust emissions with methanol. Preliminary development of corrosion-resistant automotive and fuel tank storage parts necessary for long-term methanol handling has been completed. In addition, much experience has been gained from the use of methanol in racing cars.

The production of methanol from coal essentially requires the gasification of coal in the presence of hydrogen under high pressure and very high heat. Estimates of costs for coal

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[45] U S. Department of Transportation, Office of the Secretary, *Fuels and Materials Resources for Automobiles in the 1980-1990 Decade*, Report of a Panel of the Interagency Task Force on Motor Vehicle Goals Beyond 1980, March 1976.

[46] N.D. Brinkman, "Vehicle Evaluation of Methanol-Compromises Among Exhaust Emissions, Fuel Economy and Driveability," *Fourth International Symposium on Automotive Propulsion Systems*, April 1977; General Motors Corporation, *1975 General Motors Report on Programs of Public Interest*, J. Van de Weide et al., "Alternative Fuels with Regard to LPG and Methanol, " *Fourth International Symposium on Automotive Propulsion Systems*, April 1977.

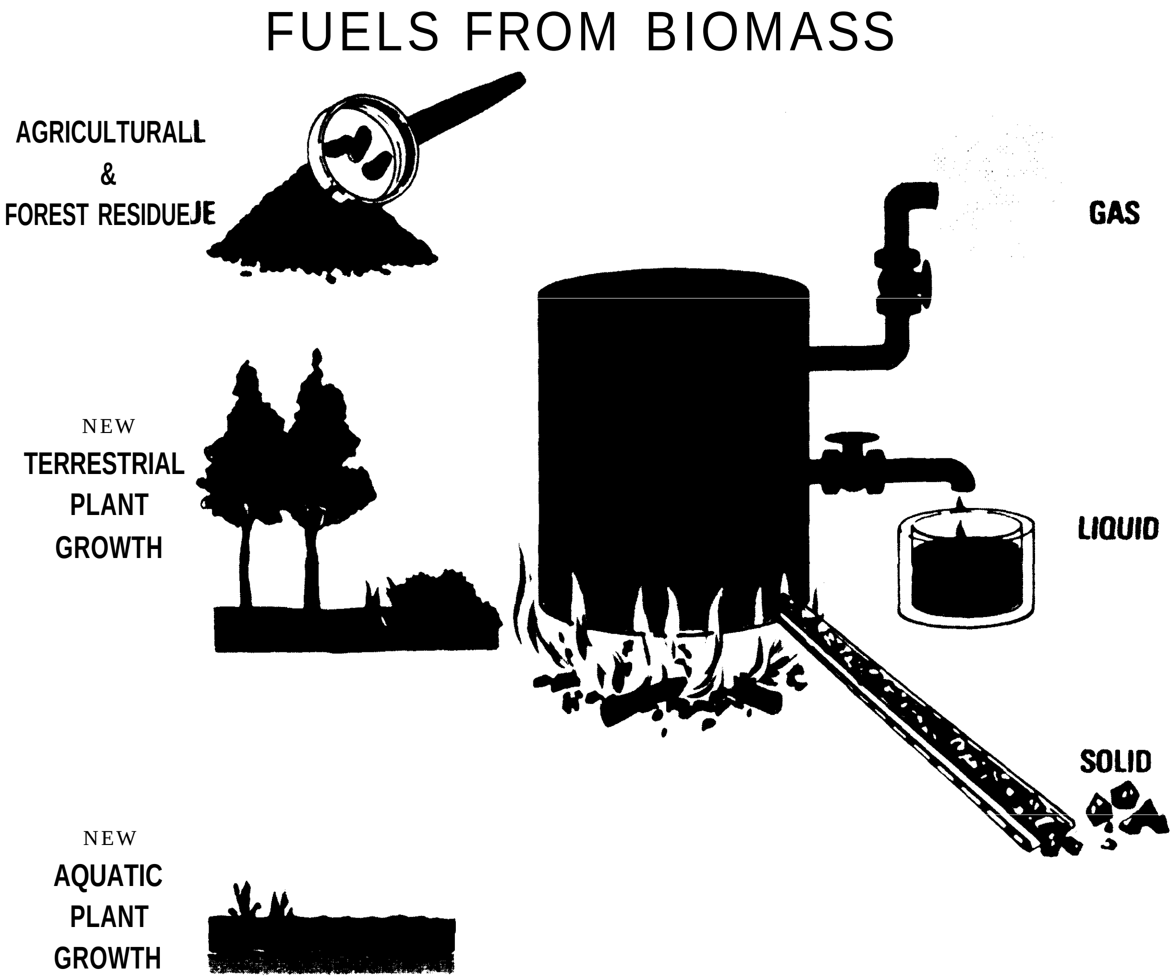

Photo Credit U S Department of Energy

gasification vary with assumptions regarding environmental regulations, coal prices, capital costs, and the commercial application of alternative conversion processes. The fact that there are no coal gasification plants in commercial-scale operation in the United States heightens the risk and cost for potential investors. One estimate of capital costs for the Synthane coal gasification process showed capital investment figures ranging from $420 million to $737.5 million for a 250 million standard-cubic-feet-per-day gas plant [47].

The production of ethanol requires construction of fermentation and distillation facilities that are much different than those currently used. The ability to produce ethanol on a smaller scale, with a local or regional resource and market base, may offer a production advantage over methanol from the standpoint of facility size requirements, startup time, and capital.

In 1974 through 1977, the Nebraska Agricultural Products Industrial Utilization Committee conducted a fleet test with 45 vehicles using a 10-percent ethanol blend. The vehicles traveled over 2 million miles, and no problems were reported with the use of gasohol. The Committee is now involved in facility site selection for ethyl alcohol plants in Nebraska.

In an effort to stimulate the development of alcohol production facilities, the California legislature recently approved a $1.00 per gallon investment tax credit on ethanol sold as a blend with gasoline. Gasohol is also available in Iowa and Illinois in limited quantities. The Colorado legislature recently approved a gasohol program for that State, reportedly because they believe that the use of gasohol in motor vehicles will

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[47] Katell and White.

significantly relieve the air pollution problem in the Denver area.

Current Federal policy consists of subsidizing R&D for coal gasification and liquefaction. A more active Federal policy might consist of price supports and subsidies for the capital and operating costs of producing methanol from coal, Biomass conversion to ethanol or methanol has the inherent advantage of recycling waste products of many types; support in developing these processes would accelerate development in this area.

The Mobil Process: Methanol to Gasoline

Mobil Oil Corporation recently reported the development of a process to convert methanol to gasoline. The process, using a zeolite catalyst, basically dehydrates the methanol. The end products from pure methanol are gasoline (about 38 percent), water (56 percent), and a small amount of liquid petroleum gas and fuel oil. The gasoline has no sulfur or nitrogen, and has a fairly high octane rating.

It is reported that, to obtain 1 gallon of gasoline, 2.4 gallons of methanol are required, plus $0.10 per gallon refinery costs. Thus the feasibility of commercializing this process depends heavily on the relative costs of methanol versus conventional gasoline. The advantages of this product are that no alterations are required in engines, shipping, or storage facilities. The purity of the product and high octane rating would also be beneficial.[48]

Hydrogen

In recent years, there has been considerable interest in hydrogen as a replacement for petroleum-based fuels. Hydrogen has a high energy content and, if burned with oxygen, is basically emission free. If burned with air in an internal combustion engine, H_2 has potential of greatly reduced emissions, although some NO_x is formed and there are problems with pre-ignition and explosions back through the intake system. Hydrogen is very compatible with alternative heat engines such as the gas turbine and the Stirling engine.

Other problems with hydrogen as a fuel for ground vehicles are centered around storage and the fueling infrastructure. Hydrogen is of very low density as a gas (the lowest of all elements) and would have to be stored and transported under extreme pressure. As a liquid, hydrogen is cryogenic, and the thermal insulation and special handling required would mean that the general use of hydrogen would be costly. Several developments are in progress for storing hydrogen as a metal hydride; they show some promise, but are a long way from practical application. Since hydrogen molecules are small, leakage would always be a problem. Because hydrogen is colorless and odorless, leaks cannot be easily detected or traced.

The potential for hydrogen use exists, but general use is not expected until many problems are solved. In addition, an adequate supply would probably not be available until a cheap, effective method of extracting hydrogen from water is developed.

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[48] Presentation by William T. Koehl, Mobile Oil Corporation at the Symposium on Alternative Fuels Utilization, University of Santa Clara, Santa Clara, Cant., June 18-23, 1978.