Technological Trends in Automobiles

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The introduction of technological advances into automobile design and manufacture is determined by competition, availability and cost of fuel, government legislation, the cost of the product, and the investment needed to produce it. The 1970's saw all these influences affecting the automobile simultaneously in the United States. Technological trends elsewhere in the world, although not affected by identical influences, closely paralleled U.S. developments.

Summary. Current technological trends in the automotive industry reflect many diverse disciplines. Electronics and microprocessors, new engine transmission concepts, composite and ceramic materials, and computer-aided design and manufacture will combine to make possible the creation of advanced automobiles offering outstanding quality, fuel economy, and performance. A projected "average" vehicle of the 1990's is described to illustrate the application of these new concepts.

A strong government influence was the Clean Air Act of 1970, which focused the development of engine technology on the control of exhaust emissions. The Safety Acts required new concepts in vehicle design to achieve greater safety. Although the Energy Policy and Conservation Act of 1975 increased the emphasis on fuel economy, the customer began to demand even more fuel-efficient vehicles than were required by law. At the same time, the consumer continued to expect many convenience features, such as automatic transmission and power steering, while being attracted to a host of new electronic features. Thus, the application of new technologies grew with unusual rapidity.

Trends in fuel economy illustrate the progress that has been made (*1*). The fuel economy of cars between 1974 and 1983, as measured by the prescribed federal test procedure, improved 83 percent. By 1985, when the industry achieves the federally mandated Corporate Average Fuel Economy (CAFE) level of 27.5 miles per gallon, the improvement will be better than 100 percent. Figure 1 shows the best fuel economy for the most fuel-efficient gasoline-powered cars of 1984, plotted as a function of their inertia test weight. Inertia test weight, used in fuel economy tests by the Environmental Protection Agency, includes provisions for options, passengers, and fuel and is taken to be 300 pounds (1 pound = 0.454 kilogram) more than the curb weight (weight of a motor vehicle with standard equipment, including maximum capacities of fuel, oil, and coolant). The dependence of fuel economy on vehicle weight is obvious. Less evident is the influence of technical improvements, such as improved combustion chamber design, fuel handling systems, electronic controls, transmissions, aerodynamics, and the matching of components.

An examination of the fuel economy at a specific inertia weight shows the effect of these improvements. Figure 2 shows the best fuel economy obtained from vehicles in the 2125-pound inertia weight class from 1980 through 1984. Not all weight classes would show identical improvements because of varying engine design, aerodynamic styling, and other features used by different manufacturers.

These improvements in fuel economy were obtained notwithstanding the requirement that vehicle performance—driveability, acceleration, cold- and hot-start capability, and durability—had to be maintained or improved. Despite vehicle downsizing, passenger and luggage space had to meet consumer and market demands. Emission standards imposed restrictions on engine and transmission operating parameters, and the cost to the consumer was, of course, always a manufacturer's consideration.

Trends Through 1985

Aerodynamics. During the early 1980's, aerodynamics, expressed as a drag factor or coefficient (C_d), has become as common a vehicle specification as wheelbase or horsepower. Drag coefficient is an engineering expression for the "shape efficiency" of a body moving through air. The most efficient shape known is that of an airfoil, which has a C_d of 0.05. For obvious reasons, a parachute has one of the highest C_d's, 1.35. The horsepower needed to propel a vehicle against aerodynamic drag is given as C_dAV^3, where A is the projected frontal area of the vehicle and V is the forward velocity.

Total road load of a vehicle is the sum of the horsepower to overcome aerodynamic drag and rolling losses, the latter including tire resistance, brake and bearing drag, and driveline losses (transmission, axle, and so forth). For example, at 50 miles per hour (1 mile = 1.6 km), the aerodynamic drag of a 1984 Ford Escort with a C_d of 0.40 is 6.5 horsepower (1 horsepower = 746 W) and the rolling losses are about 4.2 horsepower, for a total road load of 10.7 horsepower. If the C_d were reduced by 10 percent to 0.36, aerodynamic horsepower also would be reduced by 10 percent, or 0.65 horsepower. Total road load of the Ford Escort would be reduced about 6 percent, from 10.7 to 10.0 horsepower.

The 10 percent reduction in C_d would improve fuel economy approximately 2 percent. Because of the effect of velocity, the improvement would be somewhat lower in city driving, where rolling losses dominate. In highway driving the improvement would be somewhat higher than 2 percent.

A combination of factors, including low, sloping hoods, spoilers or air dams on the rear trunk and under the front and rear bumpers, elimination of drip moldings over doors, installation of glass flush with the body sheet metal, and new aerodynamic head lamps can reduce C_d to about 0.30.

Material substitution. Weight is a principal factor affecting fuel economy; the sensitivity of fuel economy to inertia weight was illustrated earlier. Vehicle downsizing and weight reduction began in 1975, when the average car weighed approximately 3800 pounds. In 1985 the average car will weigh approximately 2700 pounds.

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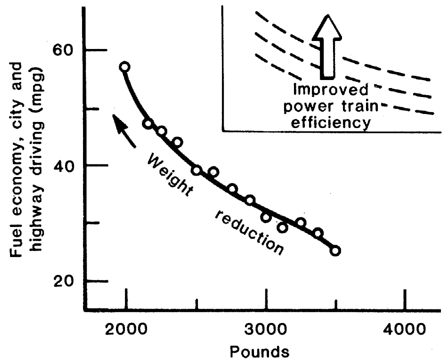


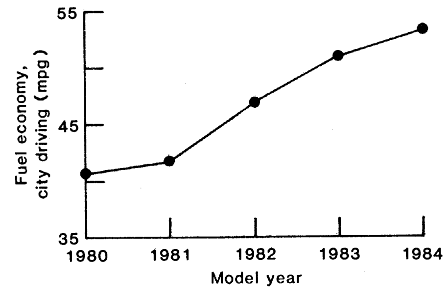


Fig. 1 (left). Fuel economy of the best vehicle in each inertia weight class; mpg, miles per gallon. Inset shows effect of improved power train efficiency on curve. Fig. 2 (right). Fuel economy of the best vehicle in the 2125-pound inertia weight class, 1980 through 1984. The improvements in fuel economy include the effects of improvements in engine technology, drive train, accessories, and rolling and aerodynamic resistance. Effects of weight reduction are not included.

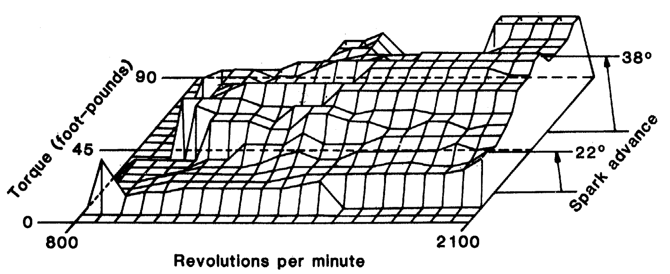


Fig. 3. Three-dimensional plot of a typical spark advance schedule with exhaust emission constraints that limit the allowable advance at various engine speeds and torques.

Downsizing a vehicle will involve reducing the size of the body and chassis. For an all-new vehicle, the engine, transmission, brakes, cooling systems, and even the spare tire can also be reduced in weight—all resulting in a lighter vehicle to accelerate and stop. The use of lightweight materials, especially aluminum, plastics, and high-strength steel (*2, 3*), has increased throughout the period of this trend (Table 1). Since 1975 the use of high-strength, low-alloy steel (HSLA) increased 151 percent, plastic 48 percent, and cast aluminum 65 percent. The HSLA steels have very high tensile strengths, ranging from 8×10^4 to 1.5×10^5 pounds per square inch, compared to 5×10^4 pounds per square inch for the cold-rolled, low-carbon steels currently used. The higher strength permits the use of thinner gauges, with resulting weight reductions of as much as 20 percent in a particular component. HSLA steels are used mainly in body panels and in structural members like cross members and safety guard beams in door assemblies. Plastics have replaced metal components in most decorative applications and, as new formulations and manufacturing techniques are developed, they find increasing use in all areas of vehicles, including body panels, bumpers, and fuel tanks. Cast aluminum is used mainly in the cylinder heads and blocks of smaller and lighter engines. Sheet aluminum is used only for selected body panels.

Power train. Power train technology (engine and transmission) has gone through distinct phases in the past 10 years (*4*). In the early 1970's, development of engine technology centered on controlling exhaust emissions. Scientists and engineers concentrated on understanding the formation of hydrocarbons, carbon monoxide, and nitrogen oxides and on devising techniques for controlling them.

In the mid-1970's federal fuel economy legislation made it necessary to improve mileage without causing a deterioration of exhaust emission controls. Computer modeling brought a new dimension to combustion design and development and helped attain lower exhaust emissions and improved fuel economy. Computer models combined engine parameters such as combustion chamber configuration and friction characteristics with vehicle parameters such as inertia test weight, transmission and axle ratios, and aerodynamic drag in order to predict emissions, fuel economy, and driveability.

Since 1975 the technology of gasoline engines has progressed dramatically, resulting in improved fuel economy (*5*). The continued search for still further improvements in fuel economy has focused research on fast- and lean-burn combustion, turbulence and swirl in the combustion chamber, airflow in the induction system, and friction reduction in the entire power train. New fast- and lean-burn combustion systems reflect high turbulence and swirl in the engine cylinder and chamber. Modeling of manifold dynamics has ensured intake and exhaust manifold configurations that maximize airflow.

The term lean-burn describes combustion with more air than the amount required stoichiometrically to consume the fuel. This excess of air reduces combustion temperatures and improves thermodynamic efficiency. Fast-burn is important because the stability of combustion from cycle to cycle is directly affected by the rate of combustion (*6*). Increasing this rate improves an engine's ability to run with lean air-fuel mixtures and high rates of exhaust gas recirculation into the induction system. Some new engines feature combustion chambers with lean air-fuel ratios, good gas-fuel ratio capability, fast burn rates without excessive heat loss, and high resistance to spark knock (*7*). Attaining these characteristics requires superior volume distribution relative to the spark plug and superior swirl and turbulence of the air and air-fuel mixtures (*8*). Electronic fuel injection systems were combined with electronic control systems to provide the precise fuel metering required to take advantage of the new combustion chambers. The growing use of computer modeling helps optimize these parameters within an engine's physical and mechanical limits.

In the control of emissions, research has demonstrated that the source of unburned hydrocarbons is not, as was previously believed, a layer at the walls of the combustion chamber where the combustion process is quenched. Experiments with a single-cylinder engine, on which a gas sampling valve was installed in the wall of the combusion chamber, indicate that a piston ring crevice quenching oil film and absorption-desorption from surface deposits play a much more prominent role (*9*). More thorough understanding of this discovery will permit development of improved computer simulations and modeling, resulting in better design of engine components for lower emission and increased fuel economy.

Engineers have always striven to minimize friction, but recent years have seen the beginning of a revolution in friction reduction. Computer modeling and simulations have provided a means of analyzing and designing new piston and ring combinations with unique piston ring profiles and piston skirt contours that reduce friction and improve sealing. Roller valve rocker arms and tappets are but a few of the valve train components under study. Bearing materials, coatings, seals, oils, and greases have been changing as a result of these developments (*10*).

To improve performance, almost every auto manufacturer has introduced turbochargers on at least one model. New developments may make the turbocharger standard equipment. To better match the engine's airflow requirements at all speeds and flows, variable geometry controlled by the electronic engine control system will be used. Ceramic impellers reduce the inertia of rotating components, improving acceleration time. (Eventually, it may be desirable to build the turbocharger into the engine as an integral component similar to a water pump rather than bolt it on like other accessories.)

Much of the interest in the diesel engine for passenger cars resulted from its inherent fuel economy advantage over the gasoline engine. Five years ago this advantage was about 30 percent. With the improvements in the gasoline engine noted earlier, this advantage has decreased to 10 to 15 percent. Through a change in the fuel injection process, the next-generation diesel engine will regain much of its earlier advantage. While most diesel engines have used an indirect injection process whereby the fuel and air mixture is ignited in a secondary chamber from which the flame travels to the main combustion chamber and there ignites the main portion of the mixture, the next-generation diesel engine will directly inject the fuel into the main chamber to achieve improved efficiencies.

New transmissions have also contributed to the improvements in fuel economy. Front-wheel drive transaxles have replaced some of the conventional rear-wheel drive transmissions and conventional rear axles. With their more efficient helical and spur gears replacing hypoid gears, front-wheel drive transaxles have improved fuel economy up to 7 percent.

Five-speed manual transmissions, with gear ratios selected to allow the engine to operate in more economical ranges, have been introduced in both front- and rear-wheel drive versions. Automatic transmissions have not been neglected; new developments include (i) locking features to bypass the less-efficient (but smooth) torque converter after start-up and (ii) fourth-gear overdrives. Both types permit more efficient engine operation.

Electronic controls. Since the late 1970's electronics and microprocessor technologies have further enhanced engine control and operation. Air-fuel ratio, spark timing, and exhaust gas recirculation can now be controlled to provide the best fuel economy for most operating conditions (*11*). A great advance in power train technology and application began when microprocessor-based engine controls were introduced in 1977. Today, virtually all automakers use some form of microcomputer-based engine controls.

Table 1. Use of materials in U.S. passenger cars, 1977 to 1985. Values are percentages.

Material	1977	1981	1985
Cast iron	17	13	10
Aluminum	3	4	8
Plastics	4	7	9
Glass	3	3	2
High-strength steel	2	9	12
Other steels	60	52	46
Other	11	12	13
Total	100	100	100

The complexity of controlling spark timing is shown in Fig. 3, which illustrates a typical three-dimensional spark advance schedule for an engine with emission constraints under various speed and torque outputs. Under transient driving conditions, the control strategy for spark may be even more complex. It would be extremely difficult to accomplish these three-dimensional schedules with a mechanical ignition system, and virtually impossible to provide the adaptive response of electronic controls. Ford's fourth-generation electronic engine control system, EEC-IV (Fig. 4), is a state-of-the-art control system that is currently used in most Ford vehicles. The system became a reality through the development of a 16-bit microprocessor and companion memory chip by using high-performance metal oxide semiconductor technology.

Electronic modules, however, are only part of Ford's engine control system. Ten sensors are used, including sensors of temperature, pressure, airflow, throttle position, crankshaft location, and knock. Actuator controls for air, fuel, and exhaust gas recirculation complete the system. A recent advance in sensors is the silicon capacitance absolute pressure (SCAP) sensor developed for use with EEC-IV. A silicon diaphragm forms the pressure-sensing member. The design is inherently rugged to withstand the environment of a vehicle engine compartment and is accurate, with typical repeatability within 0.05 percent.

While the electronic engine control microprocessor system signaled the beginning of a new era of electronics in the mid-1970's, other electronics are found in all parts of vehicles (*12*). Alternator and rectifier diodes were introduced in the 1960's. For example, the 1964 Ford was the last vehicle that Ford built without any electronic technology. Alternators with semiconductor devices were introduced in 1965 to replace generators. The 1970's saw the use of digital speed control systems, breakerless ignition systems, solid-state voltage regulators, and various new electronic entertainment systems. Electronic air suspension, trip computers, electronic temperature control, keyless door locks, voice synthesis, and new instrument panel displays are among the features introduced in the 1980's.

The use of new technologies during the past 10 years has also resulted in vehicles with improved safety. Computer-aided engineering was used in the design of side intrusion structures in vehicle doors and of energy management systems in front and rear body and chassis structures. New materials and electronics have been used in occupant restraint and protection systems, including seat belts and air bags.

The above technological accomplishments described above have also been accompanied by a dramatic improvement in the quality of the vehicle.

Beyond 1985

Vehicles will, of course, continue to change in the future. Aerodynamic design will be expanded in scope and be referred to as airflow management. Vehicle styling will lead to still lower C_d factors, with 0.20 not impractical. Airflow beneath and through the vehicle will receive special attention. Under development are new side-entry cooling systems that will eliminate the need for front-end grilles. Vehicles will have a variety of electronically controlled ride and suspension systems. New antiskid braking systems and navigational aids will probably become available.

Three technologies, however, are likely to provide the most dramatic changes: power train electronic controls, new materials, basic engines and power trains.

Electronics. Future power train electronics will see the engine control system expanded to include the transmission. New transmissions will be electronically controlled to provide smooth, indiscernible shifts from one gear ratio to another. The electronic control module will continuously monitor the requirements for maximum fuel economy, performance, and exhaust emission control and will select the optimum combination of engine and transmission parameters.

Control of engine accessories can produce improvements in fuel economy. Electronic control of the alternator, engine cooling fan, power steering pump, air conditioning compressor, and other accessories will optimize their performance with minimum power demands.

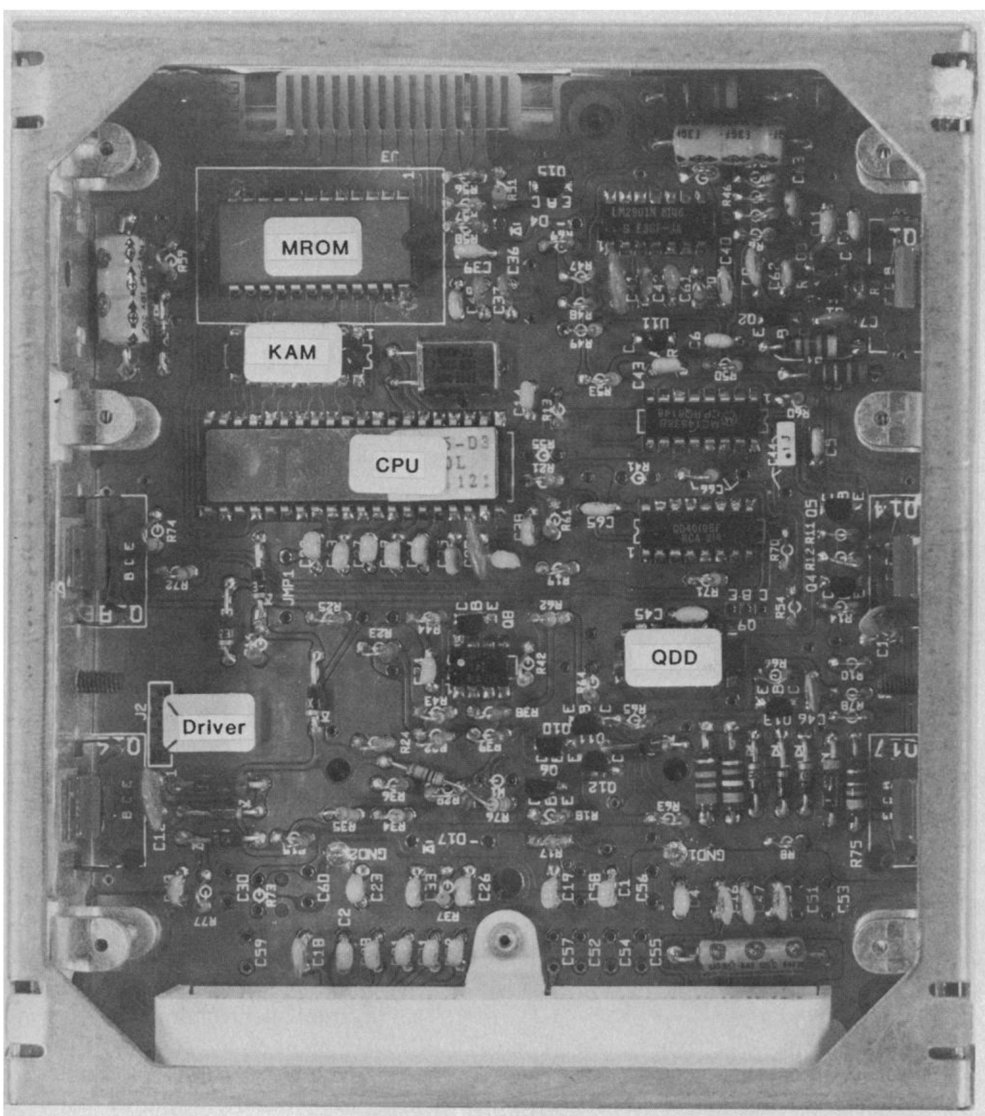
Many evolving semiconductor and electronic technologies will be required to fully implement the systems and features just described. The new nonvolatile random access memories (NVRAM's) and erasable programmable read only memories (EPROM's) can be electrically reprogrammed without removal from the circuit.

Adaptive control strategies, vehicle diagnostics, and instrumentation memory requirements, such as electronic odometers, are but a few of the possibilities. As conventional vehicle wiring systems become more complex with the addition of electronics, fiber optic technology will transform signal transmission and power distribution in the automobile. Sensors that measure pressure, temperature, rotation, current, voltage, and acceleration are being developed for use with fiber optics. Reduced weight, improved reliability, and immunity to electromagnetic interference are three significant advantages of fiber optics. Several manufacturers are already investigating a time-division multiplex system that uses two-fiber optical cables for full bidirectional communication.

Other electronic and semiconductor technologies of importance to future automotive systems include low-cost "smart" power devices, electronic component packaging, voice-recognition technology, low-cost sensors based on semiconductor technology, and thick-film circuits.

Materials. Two materials, composites and ceramics, are emerging as materials of the future. Plastic composites—that is, plastics reinforced with glass or graphite fibers—exhibit outstanding strength and low weight. Weight reductions of up to 60 percent over comparable steel components are possible. Full utilization will make possible the combination of many individual stamped and welded steel components into one unitized part. As the trend to lightweight vehicles continues, manufacturing process required to increase the use of composites will be developed. Complete prototype vehicles that replicate their steel counterparts have been built (*13*). Vehicle suspension leaf springs and driveshafts are already in limited production.

Adhesive bonding will replace welding as composite materials replace steels. Various aircraft structures are bonded with adhesives today, and new adhesives are under development that will have reduced curing times without loss of strength or reliability. Adhesive bonding will also permit new concepts in vehicle design and assembly: we will be able to join completely painted and finished components, whereas the steel vehicle of today is assembled first and then primed, painted, and finished.



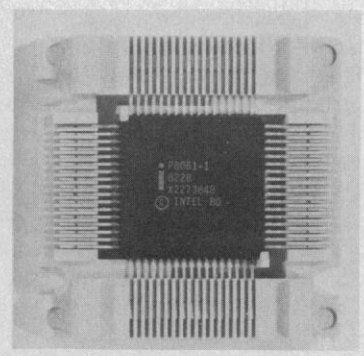


Fig. 4. Ford's EEC-IV module, showing major components. Labeled are the MROM (masked read-only memory), which contains the program and data for engine control; KAM (keep-alive memory), a low-power read-write memory that remembers what has been written into it when vehicle power is off; Driver, which provides multiple-power transitions to drive fuel injection; QDD, a special-power transition to drive the stepper motor on small solenoids; and CPU (central processing unit). The item at right is a 68-pin CPU that can replace the 40-pin CPU shown in the module.

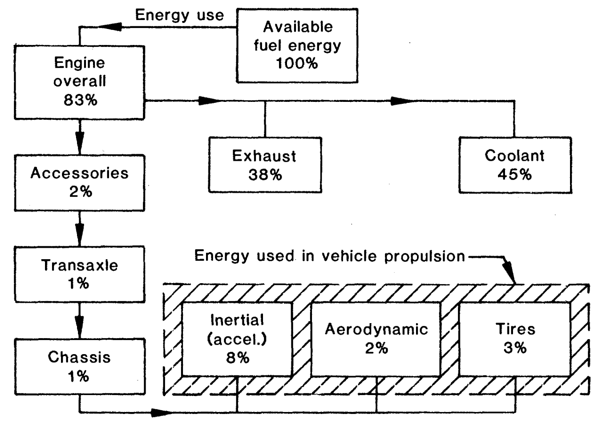


Fig. 5. Breakdown of energy use in a Ford Escort during the U.S. federal metro driving cycle.

Ceramic materials will be used for their ability to withstand high temperatures and to insulate (*14*). These characteristics make ceramics an attractive material for future power plants.

Engines and power train. Long-range forecasts are establishing the direct-injection diesel as the the prime alternative power plant to the gasoline engine. The rotary engine, Stirling engine, and gas turbine were most frequently discussed as prime candidates in the past. The demand for excellent fuel economy has eliminated the rotary engine from recent forecasts, while the high-temperature gas turbine, with its ceramic materials used in the flow path of the hot gas, remains a contender (*15*).

Engine cooling requires about 45 percent of the fuel energy (Fig. 5). A 38 percent loss occurs through the exhaust system. Turbocharging is becoming an important contributor to improved fuel economy by utilizing the energy in the hot exhaust gases to provide increased power. Optimization of the power train, in turn, has permitted the use of smaller displacement engines and new transmission and axle gear ratios to further improve economy.

The use of ceramics in the diesel engine is an approach to reduce or eliminate the proportion of heat used for cooling. The so-called adiabatic diesel is an engine with specially designed combustion chambers and related components that incorporate materials and design techniques to minimize heat loss from the combustion gas. This concept is applied to a diesel because diesel combustion, with compression ignition, is aided by hot chambers. Gasoline combustion is vulnerable to preignition and octane requirements when the combustion chamber is hot. Application of ceramics in the diesel engine could extend to cylinder liners, pistons, rings, prechambers, valves, cams and cam followers, piston pins, and bearings.

Using ceramic components in the direct-injection, adiabatic diesel engine (Fig 6) may lead to reductions in waste heat, internal friction, noise, and emissions; elimination of the liquid cooling system; possible elimination of the lubrication system; and increased tolerance for low-quality fuels. An 8 to 15 percent improvement in fuel economy has been projected for such a diesel relative to a conventional water-cooled direct-injection diesel (*16*). Long-range developments in diesel technology, such as turbocharging, intercooling, higher combustion pressure, low-friction features such as ringless pistons, and two-stroke rather than four-stroke design, have the potential to provide still further improvements in fuel economy.

Whether one forecasts a new fast-burn, low-friction gasoline engine or an advanced ceramic diesel engine, new transmission and power train matching is required to complete the scenario. Future automatic transmissions will provide wider gear ratio ranges than are available in conventional three-speed automatic transmissions by using more forward gears or variable ratio components. Locked-up torque convertors or wet clutches will be used instead of torque convertors to minimize transmission losses. The new transmissions will permit lower engine speeds and higher engine loading for more efficient engine operation.

Continuously variable transmissions (CVT's) are among the devices under development. A CVT currently being tooled for production in Europe has a wet clutch for start-up and a steel belt with variable diameter pulleys to provide a wide range of ratios. A gear set provides reverse gear operation. A CVT transmission is estimated to provide fuel economy equal to that of a five-speed manual transmission.

Implementing the New Technologies

New computer technologies designed to improve engineering and manufacturing productivity will provide the methodology needed to translate these ideas into reality. The application of interactive graphics, finite element analysis, kinematic analysis, and dynamic simulation to the design and development of products is termed computer-aided engineering (CAE). Computer-aided design (CAD) is the application of an interactive computer graphics system to the design and drafting process. Computer-aided manufacturing (CAM) is the use of computer technologies in all aspects of the manufacturing process, from simple tool and die design to the complex simulation and control of a manufacturing facility.

The product design, development, and manufacturing process of the future will rely on the integration of a wide range of computer-based application programs operating from a common body of data. The boundaries between CAE, CAD, and CAM will disappear; the term computer-integrated manufacturing (CIM) can properly be used to refer to this level of development. The growing integration of CAE, CAD, and CAM is already allowing the engineer to do more of his own analyses and to move directly from initial modeling studies to component or system design. These computer technologies are leading to (i) increased productivity, (ii) improved quality by reducing the need for engineering changes, (iii) more sophisticated products due to the ability to optimize designs, and (iv) reduced product lead time (*17*).

The present technique for designing and manufacturing body panels is an excellent example of CIM. A full-size model of the vehicle is made from clay, and the shape of the various surfaces is digitized by automatic scanners. The data are stored as three-dimensional point information in a computer data base. Designers, working with the computer, define the desired outer surface shape of a body panel by fitting curves through these points. Next, load-carrying inner panels are designed to fit the contours of these outer panels. Finite element techniques are used to analyze the inner panels to determine stress distributions. When the design is considered satisfactory the surface data are transferred to the manufacturing engineer, who uses computer programs to determine the paths of cutting tools, and numerical control machine tapes are created. Numerically controlled milling machines then use these tapes to machine the stamping dies. Sheet metal parts are stamped and the computer monitors production and product quality. Checking fixtures and gauges made manually from master models were once used to do this. Today, data taken by electronic scanning of stampings during the production process can be verified against master specifications established during the design process, ensuring that the stampings meet the original design requirements.

There are many other examples of product design and analysis with CAE and CAD. Although not as obviously a part of the CIM process, but of no less importance in the development of an efficient vehicle, other CAE analyses in use today include crash analysis, ride and handling studies, prediction of peak loading conditions on components under various operating conditions, finite element structural analysis, subsystem structural analysis, fuel economy and performance analysis, and vehicle systems integration programs for analysis of noise and vibration.

Similar techniques are being developed for the design and stress analysis of engine, transmission and chassis components, vehicle structural systems, and electronic systems (*18*). Systems are under development to link CAE, CAD, and CAM for moving directly from the design of the component to the design of the casting mold or forging die.

Solid modeling (complete surface definition of a given object) is becoming an important CAD and CAM system for handling power train and chassis parts. It permits better visualization of a component or its assembly. Solid modeling can be used for tolerance studies and checking for interferences, although it is not yet sufficiently accurate to directly determine clearances. Perhaps its most important attribute is that it permits generation of a data base for establishing numerically controlled cutting tool paths.

Computer simulations will permit the aerodynamicist to study the effects of all types of vehicle configurations without having to build vehicles or components. The aerodynamics computer designer signer will provide improved heating and cooling airflow patterns within the vehicle. This will permit the design of smaller, more efficient engine cooling systems.

Computer modeling is used extensively in the power train area of the vehicle. We have already pointed out how combustion chamber modeling has contributed to improvements in fuel economy. Transmissions, drivelines, and cooling systems are but a few of the power train systems benefiting from this technique.

Simulation models are also used to analyze vehicle systems for problems

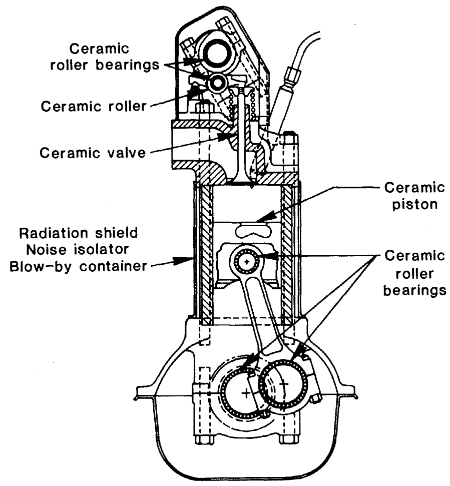


Fig. 6. Proposed direct-injection adiabatic diesel engine incorporating ceramic materials.

encountered during development programs. Simulations are used to analyze and define the problem, allowing potential solutions to be studied and the most effective solution proposed.

Manufacturing

The need to improve quality and reduce costs dictates that manufacturing technology be given high priority by researchers. Robots and computer-controlled machines are already fact. Flexible manufacturing systems that permit the machining of many different parts on the same line, neat forming processes that forge or cast components to near-final dimensions, and adhesive bonding to replace welding are but a few of the new technologies.

Among the most intriguing developments in manufacturing is the use of computer simulations of the total production process. While some models have been used for specific purposes, such as machining a specific engine or transmission casting, future models will include the detailed physical processes, allowing optimization of the operation. Models have been and are being developed for body, vehicle assembly, engine, and transmission plants. With these models it will be possible to simulate an entire facility for the optimized manufacture of a component or a complete engine, body, or vehicle.

Conclusions

It is evident that the design, development, and manufacture of today's automobile involves not just one high-technology discipline but a universe of many. The following technological trends have been identified:

1) The use of electronics in automobiles will continue to increase, providing improved vehicle fuel economy and performance without a deterioration in exhaust emissions and increased safety and comfort.

2) Composite materials will provide lighter vehicles without a deterioration in durability.

3) Ceramic materials will be used in the engine, providing improved fuel economy.

4) Continuously variable transmissions will provide the fuel efficiency of the manual transmission and the performance of the automatic transmission.

5) The microprocessor will be used to control the entire power train electronically to provide optimum operation under all conditions.

6) CAD and CAM will coalesce with CAE into an integrated manufacturing system.

So what might be an "average" vehicle of the late 1990's be like? It could be a four- or five-passenger vehicle in the 2000-pound inertia weight class with an aerodynamic drag coefficient of 0.20 or less. Its fiber and plastic composite body panels (assembled by adhesive bonding) would ride on an electronically controlled suspension system, with the driver selecting either a boulevard ride or a stiffer ride more appropriate for freeway cruising. Electronics would control a turbocharged, ceramic, adiabatic diesel engine and continuously variable transmission to provide smooth, effortless performance and fuel economy in excess of 100 miles per gallon on the highway. The increased costs of such a combination must be weighed against the savings in fuel cost. The appearance of such a vehicle will depend strongly upon the price of fuel.

The vehicle's fully electronic instrument panel would provide the driver with constant monitoring of all vehicle and power train operating conditions, and the on-board diagnostic system would warn of impending or actual malfunctioning. A push of a button would pinpoint the vehicle's position on the highway and provide guidance instructions and suggested operating conditions to enable the driver to arrive safely, quickly, and economically at his destination.

This sounds like the product not of a declining smokestack industry, but rather of an industry that spent almost $4.5 billion on research and development in 1982—more than any other industry in the United States.

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RESEARCH ARTICLE

Structure of the Gene Encoding the Immunodominant Surface Antigen on the Sporozoite of the Human Malaria Parasite *Plasmodium falciparum*

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The need for vaccines to relieve the current global resurgence of malaria is clear. Vaccines are being developed against each stage in the life-cycle of the malaria parasite because immunity to malaria is specific for each stage. The stages include sporozoites, which develop in mosquitoes and are injected by them into humans; asexual erythrocytic parasites, which cause the disease; and sexual stages, which develop in humans and transmit the infection to mosquitoes (*1*). A vaccine against sporozoites would, if effective, prime the human immune system to kill sporozoites injected by the mosquito and thus prevent the subsequent stages responsible for the disease and transmission of the infection to others.

Humans and other animals have been protected from malaria by immunization with irradiated sporozoites, but this method is impractical because of the limited supply and instability of sporozoites. The circumsporozoite (CS) protein that covers the surface of the sporozoite was first identified in *Plasmodium berghei*, a parasite of rodents (*2*). Monoclonal antibodies to this protein completely protected mice from challenge by infected mosquitoes (*3*). Analogous CS proteins have been identified for species of *Plasmodium* infecting monkeys and humans (*4*), including *P. falciparum*, the major cause of malaria in humans. The gene for the CS protein of *P. knowlesi*, which infects the Old World monkey *Macaca irus*, was cloned first because large numbers of sporozoites were available in infected mosquitoes for preparation of a complementary DNA (cDNA) library (*5*). This gene encoded a protein with a repeating amino acid sequence (12 amino acids repeated 12 times) which contained the epitope that bound the protective monoclonal antibodies. This repeating epitope was the major immunogen on the protein, because monoclonal antibodies blocked access of polyclonal antiserum to Triton X-100–solubilized sporozoite protein in the immunoradiometric assay (*6*). The presence of a repeating amino acid sequence is not a unique feature of the CS proteins. Such sequences are also found in other malarial proteins such as the S antigen (*7*).

We describe in this article the cloning of the gene for the CS protein of *P. falciparum*, its nucleotide sequence, and the amino acid sequence of the protein as deduced from the nucleotide sequence. Previously, the gene for the CS protein of *P. knowlesi* was cloned by using cDNA (*5*). The development of the technique of McCutchan *et al.* (*8*) made it possible to clone the intact gene for the CS protein of *P. falciparum* from genomic DNA of asexual erythrocytic parasites grown in continuous culture. We compare its structure with that of the previously described analogous protein of *P. knowlesi*.

Clones from the genomic DNA expression library. The *P. falciparum* genomic DNA library in the expression vector λgt11 (*9*) was produced with the use of mung bean nuclease as described (*8*). The library was made from the DNA of the 7G8 clone of the IMTM22 isolate of *P. falciparum* from Brazil (*10*). The library was plated at a density of 25,000 plaques per 150-mm plate on 27 plates and immunologically screened (*11*). A pool of five monoclonal antibodies (*12*) against the *P. falciparum* 7G8 CS protein (Table 1) was used at a dilution of 1:10,000 for screening. Thirty-five positive clones were obtained in the initial screening after 48 hours of autoradiography. Seventeen were rescreened at a

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