Chapter 3

Technologies for Advanced Vehicles Performance and Cost Expectations

This chapter discusses the technical potential and probable costs of a range of advanced vehicle technologies that may be available for commercialization by 2005 and 2015 (or earlier). As noted, projections of performance and cost can be highly uncertain, especially for technologies that are substantially different from current vehicle technologies and for those that are in a fairly early stage of development. In addition, although substantial testing of some technologies has occurred--for example, the Advanced Battery Consortium has undertaken extensive testing of new battery technologies through the Department of Energy's national laboratories--the results are often confidential, and were unavailable to the Office of Technology Assessment (OTA). Nevertheless, there is sufficient available data to draw some preliminary conclusions, to identify problem areas, and to obtain a rough idea of what might be in store for the future automobile purchaser, if improving fuel economy were to become a key national goal.

The chapter discusses two groupings of technologies:

1. **Technologies that reduce the tractive forces that a vehicle must overcome,** from inertial forces associated with the mass of the vehicle and its occupants, the resistance of the air flowing by the vehicle, and rolling losses from the tires (and related components); and

2. **Technologies that improve the efficiency with which the vehicle transforms fuel (or electricity) into motive power,** such as by improving engine efficiency, shifting to electric drivetrains, reducing losses in transmissions, and so forth.

Technologies that reduce energy needs for accessories, such as for heating and cooling, can also play a role in overall fuel economy--especially for electric vehicles--but are not examined in depth here. Some important technologies include improved window glass to reduce or control solar heat input and heat rejection; technologies for spot heating and cooling; and improved heat pump air conditioning and heating.

WEIGHT REDUCTION WITH ADVANCED MATERIALS AND BETTER DESIGN

Weight reduction has been a primary component of efforts to improve automobile fuel economy during the past two decades. Between 1976 and 1982, in response to federal Corporate Average Fuel Economy (CAFE) regulations, automakers managed to reduce the weight of the steel portions of the average auto from 2,279 to 1,753 pounds by downsizing the fleet and shifting from body-on-frame to unibody designs.[1] Future efforts to reduce vehicle weights will focus both

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[1] Peter T. Peterson, "Steel, Not Plastic, Reduces Auto Weight--A Myth Dispelled, "*Metal Forming,* November 1991. p. 2.

on material substitution--the use of aluminum, magnesium, plastics, and possibly composites in place of steel--and on optimization of vehicle structures using more efficient designs.

Although there is widespread agreement that improved designs will play a significant role in weight reduction, there are several views about the role of new materials. On the one hand, a recent Delphi study based on interviews with auto manufacturers and their suppliers projects that the vehicle of 2010 will be composed of materials remarkably similar to today's vehicles.[2] At the other extreme, some advocates claim that the use of strong, lightweight polymer composites such as those currently used in fighter aircraft, sporting goods, and race cars, coupled with other reductions in tractive loads and downsized powertrains, will soon allow total weight reductions of 65 percent to 75 percent.[3] The factors that influence the choices of vehicle materials and design are discussed below.

Vehicle Design Constraints

The most important element in engineering design of a vehicle is past experience. Vehicle designs almost always start with a consideration of past designs that have similar requirements. Designers rarely start from "blank paper," because it is inefficient for several reasons:

- *Time pressure.* Automakers have found that, as with so many other industries, time to market is central to market competitiveness. While tooling acquisition and facilities planning are major obstacles to shortening the development cycle, they tend to be outside the direct control of the automaker. Design time, however, is directly under the control of the automaker, and reduction of design time has, therefore, been a major goal of vehicle development.

- *Cost pressures. The* reuse of past designs also saves money. In addition to the obvious time savings above, the use of a proven design means that the automaker has already developed the necessary manufacturing capability (either in-house or through purchasing channels). Furthermore, because the established component has a known performance history, the product liability risk and the warranty service risk is also much reduced.

- *Knowledge limitations.* Automakers use a various analytical methods (e.g., finite element codes) to calculate the stresses in a structure under specified loading. They have only a rough idea, however, of what the loads are that the structure will experience in service. Thus, they cannot use their analytical tools to design the structure to handle a calculated limiting load. Given this limitation, it is far more efficient to start with a past design that has proven to be successful, and to modify it to meet the geometric limitations of the new vehicle. The modified design can then be supported with prototyping and road testing.

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2 University of Michigan Transportation Research Institute, Office for the Study of Automotive Transportation, "Delphi VII Forecast and Analysis of the North American Automotive Industry," February 1994.

3 Arnory B. Lovins and L. Hunter Lovins, "Reinventing the Wheels," ***The Atlantic Monthly,*** **January 1995,** p. **76.**

This normative design process has been central to automobile design for decades. Although it , has generally served the automakers well, it also has some limitations. In particular, this strategy is unfriendly to innovations such as the introduction of new materials in a vehicle design. The advantages of a new material stem directly from the fact that it offers a different combination of performance characteristics than does a conventional material. If the design characteristics are specified in terms of a past material, however, that material will naturally emerge as the "best" future material for that design. In other words, if a designer says, "Find me a material that is at least as strong as steel, at least as stiff as steel, with the formability of steel, and costing no more than steel for this design that I derived from a past steel design," the obvious materials choice is steel.

Materials Selection Criteria

Five key factors affect the auto designer's selection of materials: manufacturability and cost, performance, weight, safety, and recyclability.

Manufacturability and Cost

A typical mid-size family car costs about $5 per pound on the dealer's lot, and about $2.25 per pound to manufacture. Of the manufacturing cost, about $1.35 goes to labor and overhead, and $0.90 for materials, including scrap.[4] The reason cars are so affordable is that steel sheet and cast iron, the dominant materials, cost only $0.35 to 0.55 per pound. Advocates of alternative materials such as aluminum and composites are quick to point out, however, that the per-pound cost of materials is not the proper basis for comparison, but rather the per-part cost for finished parts. Although they may have a higher initial cost, alternative materials may offer opportunities to reduce manufacturing and finishing costs through reduced tooling, net shape forming, and parts consolidation. In addition, a pound of steel will be replaced by less than a pound of lightweight material. Nevertheless, the cost breakdown given above suggests that, if finished parts made with alternative materials cost much more than $1.00 per pound, overall vehicle manufacturing costs will rise significantly.[5] This severe constraint will be discussed later.

For comparison, the per-pound and per-part costs of alternative materials considered in this study are given in table 3-1, along with the expected weight savings achieved by making the substitution. On a per-pound basis, glass fiber-reinforced polymers (FRP), aluminum, and graphite FRP cost roughly 3 times, 4 times, and 20 times as much as carbon steel, respectively.[6] Because these materials are less dense than steel, however, fewer pounds are required to make an equivalent part, so that, on a part-for-part basis, the difference in raw materials cost relative to steel is 1.5 times, 2 times, and 5 times, respectively.[7] High-strength steel costs 10 percent more

[4] Frank Stodolsky et al., "Lightweight Materials in the Light-Duty Passenger Vehicle Market: Their Market Penetration Potential and Impacts," paper presented at the Second World Car Conference, University of California at Riverside, March 1995.

[5] 1bid

[6] National Materials Advisory Board, *Materials Research Agenda for the Automotive and Aircraft Industries,* NMAB-468 (Washington, DC: National Academy Press, 1993), p. 34.

[7] Assuming current composite manufacturing technology.

per pound than ordinary carbon steel, but 10 percent less is required to make a part, so, on a part basis, the two have roughly equivalent cost.

Manufacturing costs

As with any mass production industry, cost containment/reduction (while maintaining equivalent performance) is a dominant feature of the materials selection process for automotive components. Customarily, this objective has focused the automobile designer upon a search for one-to-one substitutes for a particular part, where a material alternative can provide the same performance for lower cost. More recently, the focus has broadened to include subassembly costs, rather than component costs, which has enabled consideration of materials that are initially more expensive, but may yield cost savings during joining and assembly. Manufacturers can also reduce costs by shilling production of complex subassemblies (such as dashboards, bumpers, or door mechanisms) to suppliers who can use less expensive labor (i.e., non-United Auto Worker labor) to fabricate components that are then shipped to assembly plants.

Thus, the manufacturer's calculation of the cost of making a materials change also depends on such factors as tooling costs, manufacturing rates, production volumes, potential for consolidation of parts, scrap rates, and so forth. For example, the competition between steel and plastics is discussed not only in terms of the number of units processed, but also the time period over which these parts will be made. Because the tooling and equipment costs for plastic parts are less than those for steel parts, low vehicle production volumes (50,000 per year or less) and short product lifetimes lead to part costs that favor plastics, while large production runs and long product lifetimes favor steel. As automakers seek to increase product diversity, rapid product development cycles and frequent styling changes have become associated with plastic materials, although the steel industry has fought this generalization. Nevertheless, styling elements like fascias and spoilers are predominantly plastic, and these elements are among the first ones redesigned during product facelifts and updates.

Life Cycle Costs

The total cost of a material over its entire life cycle (i.e., manufacturing costs, costs incurred by customers after the vehicle leaves the assembly plant, and recycling costs) may also be a factor in materials choices. For example, a material that has a higher first cost may be acceptable, if it results in savings over the life of the vehicle through increased fuel economy, lower repair expense, and so forth. However, this opportunity is rather limited. For instance, at gasoline prices of $1.20 per gallon, fuel cost savings owing to extensive substitution of a lightweight material such as aluminum might be $580 over 100,000 miles of driving--about $1 per pound of weight saved. These savings are insufficient to justify the added first cost of the aluminum-intensive vehicle (perhaps as much as $1,500, see below). Moreover, manufacturers are generally skeptical about the extent to which customers take life cycle costs into consideration in making purchasing decisions.

Materials choices also influence the cost of recycling or disposing of the vehicle, though these costs are not currently borne by either the manufacturer or consumer. This situation could change in the near future, however, with increasing policy emphasis on auto recycling around the world (see recycling section below).

Manufacturability

Steel vehicles are constructed by welding together body parts that have been stamped from inexpensive steel sheet materials. Over the years, this process has been extensively refined and optimized for high speed and low cost. Steel tooling is expensive: an individual die can cost over $100,000 dollars, and with scores of dies for each model, total tooling costs maybe several tens of millions of dollars per vehicle. A stamped part can be produced every 17 seconds, however, and with production volumes of 100,000 units or more, per-part costs are kept low.

Aluminum-intensive vehicles have been produced by two methods: by stamping and welding of aluminum sheet to forma unibody structure (a process parallel to existing steel processes); and by constructing a “space frame” in which extruded aluminum tubes are inserted like tinker toys into cast aluminum nodes, upon which a sheet aluminum outer skin can be placed.

An advantage of the stamped aluminum unibody approach is that existing steel presses can be used with modified tooling, which keeps new capital investment costs low for automakers and permits large production volumes. Ford used this method to produce a test fleet of 40 aluminum-bodied Sables; as did Chrysler in the production of a small test fleet of aluminum Neons.[8] The Honda NSX production vehicle was also fabricated by this method.

The aluminum space frame approach was pioneered by Audi in the A8, the result of a 10-year development program with Alcoa. Tooling costs are reportedly much less than sheet-stamping tools, but production volumes are inherently limited; for example, the A8 is produced in volumes of about 15,000 units per year. Thus, per-part tooling costs for space frames may not be much different from stamped unibodies.

Manufacturability is a critical issue for using composites in vehicle bodies, particularly in load-bearing structures.[9] Although composite manufacturing methods exist that are appropriate for aircraft or aerospace applications produced in volumes of hundreds or even thousands of units per year, no manufacturing method for load-bearing structures has been developed that is suitable to the automotive production environment of tens or hundreds of thousands of units per year.

The most promising techniques available thus far appear to be liquid molding processes, in which a fiber reinforcement “preform” is placed in a closed, part-shaped mold and liquid resin is injected.[10] The resin must remain fluid long enough to flow throughout the mold, thoroughly wetting the fibers and filling in voids between the fibers. It must then “cure” rapidly into a solid structure that can be removed from the mold so that the process can be repeated. A vehicle

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[8]Jack Keebler, "Light Waits," *Automotive News*, Mar. 14, 1994.

[9]Large volume production methods for inexpensive, low-performance composites such as sheet molding compound, are well established for low-load-bearing parts such as fenders, hoods, and tailgates. However, such composites do not have sufficient strength and stiffness to enable their use in the load-bearing parts of the vehicle structure.

[10]U.S. Congress, Office of Technology Assessment, *Advanced Materials by Design,* OTA-E-35 1 (Washington DC: U.S. Government Printing Office, June, 1988), p. 155.

constructed from polymer composites might be built with a continuous glass FRP or carbon FRP structure made by liquid molding techniques, with chopped fiber composite skin and closure panels made by stamping methods.

Liquid molding can be used to make entire body structures in large, integrated sections: as few as five moldings could be used to construct the body compared with the conventional steel construction involving several hundred pieces. However, a number of manufacturing issues must be resolved, especially demonstrating that liquid molding can be accomplished with fast cycle times (ideally 1 per minute) and showing that highly reliable integrated parts can be produced that meet performance specifications. Suitable processes have yet to be invented, which is the principal reason that the composite vehicle is used in the 2015 “optimistic” scenario.[11] At present, manufacturing rates for liquid molding processes are much slower than steel stamping rates (roughly 15 minutes per part for liquid molding, 17 seconds for steel), so that order of magnitude improvements in the speed of liquid molding will be necessary for it to be competitive.

While advocates of automotive composites point to the General Motors (GM) Ultralite as an example of what can be achieved with composites, in some ways this example is misleading. First, the Ultralite was manufactured using the painstaking composite lay-up methods borrowed from the aerospace industry, which are far too slow to be acceptable in the automotive industry. Second, the Ultralite body cost $30 per pound in direct materials alone (excluding manufacturing costs). This is at least an order of magnitude too high for an automotive structural material.

Performance

Sometimes a new material offers a degree of engineering performance that cannot be met using a conventional material. For instance, the high strength of advanced composite materials may be essential to fabricate flywheels for power storage that must spin at up to 100,000 rpm without rupturing. Gas turbines may only be economical for vehicles if they operate at temperatures of 1,300° Centigrade or above--temperatures that can only be achieved with advanced ceramic materials. Similarly, the unique formability of plastics and composites make some complex body designs feasible that simply cannot be executed in steel.

Among the most important performance criteria affecting the choice of materials are yield strength, elastic modulus, thermal expansion coefficient, fatigue resistance, vibration damping, corrosion resistance, and density. The most critical engineering characteristics of automobile design over the past 15 years have been specific stiffness (the elastic modulus of a material divided by its density) and specific strength (the strength of a material divided by its density). Strength and stiffness of the car’s structural members directly affect the driving performance, ride characteristics, and safety. The emphasis on “specific” properties reflects the automakers’ desire to achieve better performance with less weight.

Specific strength and stiffness properties are an area where new materials excel by comparison to traditional steel alloys, however, this superior performance must be balanced against their

11 Another reason is the current inability to model the crash performance of composite vehicle strictures (see the safety discussion below).

generally higher costs. A comparison of some of these properties for various alternative automotive materials is provided in table 3-2.

Weight

Weight is a primary determinant of such critical vehicle characteristics as acceleration, handling, fuel economy, and safety performance. According to one estimate, 75 percent of a vehicle's fuel efficiency depends on factors related to weight, with the remaining 25 percent dependent on the vehicle's air resistance.[12] For a typical vehicle with an internal combustion engine, a 10 percent reduction in weight results in a composite (city/highway) fuel savings of 6.2 percent.[13]

In the future, the substitution of new, lightweight materials for steel holds the promise of making vehicles lighter without sacrificing size and comfort for passengers. Table 3-1 gives estimates of possible weight savings compared with steel using various alternative materials. On an equivalent part basis, relative to carbon steel, high-strength steel saves 10 percent, glass FRP 25 to 35 percent, aluminum 40 to 50 percent, and graphite FRP saves 55 percent. On an entire vehicle basis, maximum practical weight savings are about two-thirds of these values, because only a fraction of components are candidates for substitution.[14]

Weight reductions in primary vehicle components also enables secondary weight savings in the supporting subsystems. For example, the engine, suspension, and brake subsystems can be downsized for lighter vehicles, because their performance requirements decrease as the total weight of the vehicle drops. The ratio of secondary to primary weight savings can be estimated only roughly, but a general rule of thumb is that about 0.5 pounds of secondary weight reduction can be achieved for each pound of primary weight removed, provided the secondary subsystems are redesigned.

When coupled with a smaller, fuel-efficient powertrain, these weight savings can be used to make vehicles more fuel efficient and environmentally friendly. Alternatively, the weight savings could be used primarily to obtain increased performance (e.g., increased horsepower to weight ratio) or to offset weight increases in other parts of the car so as to maintain compliance with environmental regulations. The market continues to pull vehicles in the direction of larger sizes, shorter O to 60 times, and so forth, with the result that the average horsepower to weight ratio of new cars has been increasing every year. This suggests that the use of lighter weight materials to achieve higher fuel economy will only occur if the market values fuel economy more highly than acceleration performance, or if the market is pushed in this direction by policies such as higher gas taxes and Corporate Average Fuel Economy standards.

As long as lighter weight materials carry a cost premium that cannot be recouped by the customer through fuel savings, substitution will tend to occur in vehicles in the luxury or high-performance class (e.g., the Honda NSX and the Audi A8) where customers are willing to pay more for the better acceleration and handling characteristics of a lighter car.

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[12] Audi, "The New Mobility Enterprise: Revolutionary Automobile Technology by Audi," brochure, August 1993, p. 6.

[13] Energy and Environmental Analysis, "Documentation of Attributes of Technologies To Improve Automotive Fuel Economy," report prepared for Martin Marietta Energy Systems, Oak Ridge, TN, October 1991, p. 2-16.

[14] Assuming comparable size and interior room.

Safety

Materials (and the designs in which they are used) play a critical role in automobile crashworthiness. The general concept of vehicle design for crash energy management involves two aspects. The first is that the front and rear of the vehicle are intended to be collapse/crush zones. Their main function in a crash is to provide maximum absorption of the vehicle kinetic energy. In the crush zone, the ideal structure collapses progressively in a predetermined mode, while avoiding instability and buckling. In a frontal crash against a fixed barrier at 35 mph, the crush distance is typically 20 to 35 inches.[15] The resistance of the structure to crush forces (sometimes called vehicle "stiffness") should be such that during the crush, the forces transmitted to the passenger compartment remain constant, just below the tolerance level for passenger injury. This defines the most efficient use of crush space.

The second principle of sound crash design is that the passenger compartment should maintain its structural integrity, to minimize intrusion into the passenger space. As a rule, high-strength materials are required, especially in the side structure, where there is relatively little space between the passenger and the door.

Currently, sheet steel products constitute the principal material used in the automobile chassis and body structure. Considerable experience has been derived over the years in modeling the behavior of sheet steel structures in crash situations, and designers have confidence in their ability to predict this behavior. Alternative materials, such as aluminum or composites, offer some potential advantages in crash energy management over steel, but have far to go to match the comfort level designers have with steel.

One advantage of aluminum is its high specific energy absorption (energy absorbed divided by density). Pound for pound, aluminum structures have a 50 percent higher energy absorption than identical steel structures.[16] Recent crash tests suggest that weight savings of 40 percent or more can be achieved in aluminum structures with a comparable or even an increased crash performance compared with steel.[17] Automakers interviewed by the Office of Technology Assessment (OTA) expressed a surprisingly high comfort level with the crash performance of aluminum-intensive test vehicles. A concern, however, is that while an aluminum vehicle may perform well in a crash test against a fixed barrier, it will be at a disadvantage in a crash with a heavier steel vehicle, owing to the transfer of momentum from the heavier to the lighter vehicle. This may mean that lighter aluminum vehicles will have to be designed with additional crush zone space or other safety features to compensate.

Several studies have now shown that composite structures can have an energy absorption potential comparable to, and in some cases better than, that of metal structures.[18] The difference between metal and composite structures is that the metal structures collapse by plastic buckling,

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15 A. Paluszny, "State-of-the-Art Review of Automobile Structural Crashworthiness," report prepared for the American Iron and Steel Institute, June 1992.

16 V. K. Banthia et al., "lightweighting of Cars with Aluminum for Better Crashworthiness," paper presented at the SAE International Congress and Exposition, Detroit, MI, Mar. 1-5, 1993 (SAE Technical Paper Series number 930494).

17 Ibid

18 P. H. Thornton and R. A. Jeryan, "Crash Energy Management in Composite Automotive Structures," *International Journal of Impact Engineering, vol.* 7, No. 2, 1988, pp. 167-180.

while the composites collapse by a combination of fracture processes. Whereas metals are isotropic[19] and comparatively easy to model, composites are internally much more complex, involving a wide range of resins, fibers, fiber orientations, and manufacturing processes, and, consequently, are much harder to model.[20] Thus far, an understanding of the mechanisms responsible for energy absorption in composites and a methodology for its quantitative prediction have yet to be developed. Theoretical studies, laboratory, component, and fill vehicle crash testing will be required to complete the necessary development work. Finally, appropriate repair strategies and techniques for crash-damaged composite structures, while familiar in the context of advanced aircraft, have yet to be worked out in the automotive industry.

The lack of experience of automotive designers with the crash behavior of aluminum and composites remains a significant barrier to their use, particularly for composites. This, combined with unresolved manufacturing issues with these materials, is the principal reason that OTA projects that mass production of aluminum-intensive vehicles will not begin before approximately 2005, and composite vehicles before approximately 2015 (see the discussion of materials use scenarios below).

Recyclability

The ultimate disposition of vehicle materials is becoming an increasingly important consideration for vehicle designers. In Germany, for example, legislation is pending that would make auto manufacturers responsible for recovering and recycling vehicles, similar to legislation already passed for the recovery and recycling of product packaging. The prospect of this legislation has already stimulated German car companies to consider changes in design strategies such as reducing the number of different kinds of plastics used in the vehicle and "design for disassembly" to facilitate the cost-effective removal of parts from junked vehicles for recycling.[21] Anticipating that this type of regulation may be coming in the United States, the Big Three and their suppliers have formed a consortium under the auspices of the U.S. Council for Automotive Research (USCAR) called the Vehicle Recycling Partnership to address the recycling issue.

Currently, 25 percent of the weight of a vehicle (consisting of one-third plastics--typically about 220 pounds of 20 different types--one-third rubber and other elastomers, and one-third glass, fabric, and fluids) cannot be recycled and generally is landfilled. In the United States, this automotive residue amounts to about 1.5 percent of total municipal solid waste. Sometimes the residue is contaminated by heavy metals and oils or other hazardous materials.

Most of the concern about auto recycling focuses on the quantity of this residue, specifically the amount of plastics on vehicles. In the quest for increasing fuel efficiency in the 1970s and early 1980s, the plastic content of cars did increase slowly as lighter weight plastics were substituted for metals. In the future, the trend toward increasing use of plastics is expected to continue. With current recycling technology and economics, this will lead to increasing amounts of solid waste

[19] *Isotropic* means that the physical properties **are the same in all directions.**

[20] Additional variables that can affect their crush behavior include laminate design, impact rate, temperature and environmental effects, angular and bending loads, and void content.

[21] U.S. Congress, Office of Technology Assessment Green Products by Design: Choices for a Cleaner Environment, OTA-E-541 (Washington DC: U.S. Government Printing Office, October, 1992), p. 59.

from vehicle scrappage, though the increase is likely to be gradual unless use of composites in vehicle structure becomes widespread.

In the future, alternative propulsion systems could raise new concerns about recycling. For instance, if large numbers of electric vehicles powered by lead acid batteries are produced and sold, this would result in dramatic expansion of battery handling, transport, and recycling operations, with attendant increases in the release of lead to the environment. Other more exotic battery types, such as sodium sulfur, nickel metal hydride, or lithium-polymer, could raise new issues in materials handling, recycling, and disposal.

Future Scenarios of Materials Use in Light Duty Vehicles

With the above material selection criteria as background, in this section we discuss some possible future scenarios for materials use in automobiles. The scenarios attempt to characterize the automotive materials innovations that may become commercially available in the years 2005 and 2015, assuming two different levels of technological optimism: "advanced conventional" and "optimistic." Advanced conventional involves adoption of materials and manufacturing processes that appear to be straightforward extensions of those currently under R&D. Optimistic involves materials and manufacturing processes that may require significant breakthroughs by the years indicated, but nevertheless appear feasible with a concentrated R&D effort.

The scenarios discussed below are illustrative only, and are not intended to represent OTA's forecast of the probable evolution of vehicle materials technology. In fact, it is arguable that they are quite unrealistic: it seems unlikely that the automakers would rely as much on a single material as the scenarios would suggest. Rather, it seems more likely that vehicle components will continue to be constructed from whichever materials (iron, steel, aluminum, plastic, composites) give the best combination of cost and performance. Nevertheless, the scenario approach adopted here is analytically simple and gives a good indication of the largest weight reductions that might be achieved through the use of alternative materials.

The analysis focuses on a typical mid-size five-passenger car (e.g., a Ford Taurus) which currently weighs about 3,200 pounds. A breakdown of the estimated weights of the various subcomponents of the Taurus (circa 1990) is presented in table 3-3. The scenarios, along with the assumptions underlying them, are discussed below.

2005-Advanced Conventional

This vehicle contains an optimized steel body. A recent study by Porsche Engineering Services estimated weight and cost savings available if the current Taurus body-in-white structure[22] were optimized with steel. The constraints were maintenance of equivalent torsional stiffness of the vehicle, and the use of current materials and manufacturing methods. The results indicated that redesign could achieve a 140-pound reduction (17 percent of the body-in-white) at a cost savings of about $40.[23] These design changes are expected to be achievable by approximately 1998.

Encouraged by the results of this study, some 28 steel companies around the world are currently finding a follow-up study that relaxes some of the above constraints. In this case, Porsche has been directed to take a "clean sheet" design approach that incorporates new steel alloys and new manufacturing methods, such as hydroforming, and adhesive bonding. At this writing, results were not yet available, but weight savings of 30 percent or more in the body-in-white are anticipated. For a Taurus (table 3-3), this would mean a reduction of at least 11 percent of the curb weight. With a downsized aluminum engine, total curb weight reduction could be around 15 percent.

Steel company spokesmen contacted by OTA indicated that this optimized steel scenario might be achievable by 2005, since this would allow for a seven-year period for R&D, followed by a three-year vehicle production time. Costs for such a scenario are estimated at $200 to 400 per vehicle.[24]

2005-Optimistic

This vehicle is a "first generation" aluminum vehicle with extensive substitution of aluminum in the current Taurus body-in-white, but not in the suspension, brakes, and engine mounts. This vehicle would be similar to the aluminum Taurus prototypes that Ford has already built and is currently testing. In these vehicles, Ford has demonstrated weight savings approaching 50 percent for the body-in-white, and with secondary weight reductions, curb weight could be reduced by about 20 percent.

All of the major auto companies are building and testing aluminum-intensive prototypes, and, as mentioned above, there are two aluminum production vehicles on the road today (the Honda NSX and the Audi A8). However, these two vehicles are relatively expensive (a sports car and a luxury car, respectively,) and produced in limited numbers (one thousand and fifteen thousand per year, respectively). Several manufacturing issues must be resolved before a mass-market vehicle such as the Taurus can be converted to aluminum. These include improving welding and adhesive bonding technologies and preventing corrosion at joints. Although these problems are challenging, it seems feasible to overcome them by 2005.

The major barrier to the increased use of aluminum is the cost of the material (about $1.50 per pound for aluminum sheet, compared to about $0.33 for steel) No breakthroughs are foreseen

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22 The body-in-white is the basic auto body structure to which doors, windows, drivetrain, suspension, and so forth are attached.
23 American Iron and Steel Institute, "Holistic Design with Steel for Vehicle Weight Reduction," February 1994.
24 Peter Peterson, U.S. Steel, personal communication, 1995.

that would significantly reduce the raw materials cost. Reliable estimates of the increased cost of the vehicle above are difficult to obtain. According to one estimate, the incremental price would be around $800.[25] This estimate includes raw materials cost only, however, and assumes that handling and manufacturing costs for aluminum will be the same as for steel (they are currently higher). OTA does not make this assumption until 2015. OTA estimates the price increment in 2005 is in the range from $1,200 to $1,500 for a mid-size car.

2015-Advanced Conventional

This vehicle is an optimized, all-aluminum design.[26] In contrast to the 2005 optimistic vehicle, which still contains more than 1,000 pounds of steel in the drivetrain, chassis, suspension, and brakes, this vehicle would substitute aluminum and magnesium for steel in almost all metal components. In addition, a clean sheet design approach is assumed that allows designers to take maximum advantage of the physical and manufacturing characteristics of these light metals. Such a design might be a judicious combination of the stamped sheet metal approach featured in the Honda NSX with the "space frame" concept of aluminum extrusions and castings featured in the Audi A8.

Although it is difficult to estimate potential weight savings for such a vaguely specified design, it is possible to get an idea of the upper limit of such savings based on current concept cars. In particular, Ford has built a "maximum substitution" aluminum Taurus called the Synthesis 2010 that uses aluminum in every feasible component, and is powered by a small aluminum two-stroke engine. The total curb weight reduction with respect to the production steel Taurus is more than 1,000 pounds. This result is exaggerated somewhat by the fact that the two-stroke engine in the concept car reportedly does not provide equivalent acceleration performance to the current production car, and an equivalently performing engine would add additional weight. However, the design of the Synthesis 2010 is essentially a steel design that does not take fill advantage of the aluminum substitution, suggesting that with a clean sheet approach, further weight reduction is possible. Thus, an upper-limit estimate of a 1,000-pound weight reduction, or about 30 percent of curb weight, may be reasonable for the all-aluminum mid-size vehicle.

Once again. the incremental cost of this vehicle is difficult to estimate. At current prices for steel and aluminum, the added cost for raw materials alone would be in excess of $1,000. Optimistically, we assume that in 2015 the manufacturing costs for aluminum will be reduced so as to be comparable with those for steel. Under this assumption, one estimate places the cost increment of such a vehicle from $1,200 to $1,500 above a comparable steel vehicle.[27]

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25 Stodolsky et al., see footnote 4.

26 This scenario, which assumes it will take more than 20 yearn (five model generations) to introduce an optimized, all-aluminum vehicle may be Seen as too conservative, in view of the fact that an aluminum-intensive production car such as the Audi A8 is on the road today. Undoubtedly, ears containing much greater amounts of aluminum than today's cars will be introduced before that time. However, solving the problems of massive aluminum substitution, a new desigm and new manufacturing methods will take time, particularly for a mass-market vehicle such as the Taurus. This process could be hastened by a concentrated R&D program, for example, if aluminum vehicles become the focus of the PNGV effort.

27 Stodolsky et al., see footnote 4.

2015-Optimistic

This scenario involves a vehicle constructed with polymer composites, as is the GM Ultralite concept car. Such a vehicle might consist of a continuous glass- or carbon-fiber reinforced plastic structure made by liquid molding techniques, with chopped fiber composite skin and closure panels made by stamping methods. The GM Ultralite example may be useful to examine the potential weight savings available in a future graphite composite automobile. The vehicle was designed from scratch to take advantage of the unique properties of carbon fiber--its high specific stiffness and strength, which can lead to a 55 percent weight reduction compared with steel on a component basis. Although the Ultralite's purpose-built design makes it impossible to compare directly with an existing steel vehicle, estimates are that its curb weight is from 35 to 40 percent less than a steel car of the same interior volume.

A more cost-effective composite option would be a continuous glass FRP, although this would involve a considerable compromise on weight savings. Glass fibers cost less than graphite--about $1 to $2 per pound; however, glass fibers are much denser than graphite and also have a lower stiffness (table 3-2), which means more material must be used to achieve an equivalent structural rigidity.[28] On a component basis, maximum weight savings with respect to steel are probably 25 percent, yielding perhaps a 15 percent reduction in curb weight (roughly half that available in the maximum aluminum case).

Estimating the costs of a future composite vehicle is difficult, but some guidelines are available. Assuming that a rapid, low-cost manufacturing method can be developed (it does not yet exist), a glass FRP vehicle could conceivably cost the same as a steel vehicle.[29] The basic materials cost more than steel, but comparatively low-cost tooling and part integration help to offset the higher cost of the resin and fiber.

The graphite FRP vehicle is more problematic from a cost point of view. Graphite FRP parts for racing cars typically sell today from $100 to $400 per pound. An optimistic estimate of future carbon fiber production costs, even at high volumes, is $3 to $4 per pound (they are currently around $15).[30] Even this optimistic result would mean that the vehicle structure would cost several thousands of dollars more than steel. One estimate is that a graphite composite vehicle would cost an additional $5,000, assuming fiber costs of $10 per pound.[31]

In practice, the cost of an all-aluminum vehicle probably puts a constraint on the cost of a graphite vehicle, since aluminum offers 75 percent of the incremental weight savings at perhaps 25 percent of the incremental cost. Thus, to be competitive with aluminum, the cost of graphite structures must be reduced substantially below the most optimistic current estimates, which will require breakthroughs in both graphite production technology and composite manufacturing technology.

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[28]A probable solution would be to use a hybrid composite in which small quantities of high stiffness fibers (e.g., steel or graphite) would be used in stiffness-critical areas of the design. This capacity to design the material to fit the fictional requirements is one of the advantages of composites.

[29]National Materials Advisory Board, see footnote *6, p. 34.*

[30]Carbon fiber production is expensive because it involves pulling thin polymer filaments through a high-temperature oven under carefully controlled atmospheric conditions.

[31]Stodolsky et al., See footnote 4.

Conclusions

The most striking feature of the history of materials use in the automobile is how slowly it has evolved, despite significant changes in fuel price and government fuel economy regulations. The reason is that auto design is highly normative, and the introduction of alternative materials requires new design procedures, new life cycle performance modeling capabilities, cost competitiveness with mature steel technologies, and, possibly, a new servicing and repair infrastructure.

Through optimization of steel designs, additional weight savings of at least 15 percent of curb weight are still available, at moderate incremental costs. Given the pressure from alternative materials, especially aluminum and plastics, it is very likely that this steel optimization will actually be implemented--probably within 10 years--which places an additional burden on would-be replacement materials to demonstrate cost-effective weight reduction.

For years, auto companies have been interested in using aluminum parts, and aluminum use has been on the rise, from 86 pounds per vehicle in 1976 to 159 pounds in 1990. Undoubtedly, the use of aluminum will continue to increase, particularly in castings such as engine blocks, where it is most cost competitive. The major barrier to the increased use of aluminum in body structures is that it costs twice as much as steel for a part that weighs half as much. Processing and repair costs for aluminum are currently somewhat higher than steel, but in the future could become comparable. Nevertheless, an all-aluminum mid-size car is projected to cost at least $1,000 more than a comparable steel car owing to differences in raw materials costs alone. This is likely to mean that market penetration of such vehicles will first occur in luxury or high performance niches, exemplified by the aluminum-intensive Audi A8 and the Honda NSX, respectively. In the absence of dramatic increases in fuel prices, fuel economy standards, or other government mandates, penetration of aluminum vehicles into mass market segments is doubtful.

Structural composite vehicles remain far in the future. Adequate mass production technologies have not yet been invented and, once invented, will probably require a decade of development before they are ready for vehicle production lines. Other problem areas of composites include the present lack of capability to understand and model their crash behavior, and the lack of a cost-effective recycling technology.

Glass FRP composites could become cost-competitive with steel in the long term, providing new manufacturing methods can be developed. Thus, glass FRP may be adopted for economic reasons even though its weight savings potential is relatively modest. Even with heroic assumptions about drops in fiber production costs, it is difficult to foresee how graphite composite vehicles could compete even with aluminum vehicles in the next 20 years. Aluminum appears to offer 70 to 80 percent of the weight reduction potential of graphite, at about one-quarter of the incremental cost. Breakthroughs in production costs of carbon fiber and in composite manufacturing technology will be required to change this conclusion.

Fuel economy is not very sensitive to weight reduction per se. As described in the scenarios above, drastic changes in vehicle design, as well as manufacturing plant and equipment are required to achieve relatively modest fuel economy improvements in the range of 15 to 25 percent. In the most optimistic case of a **40** percent mass reduction using carbon fiber, the fuel economy increase owing to mass reduction would be only about 33 percent. To achieve 300 percent improvements or more, as envisioned in PNGV, weight reduction must be combined with improvements in power plant efficiency, reduced rolling resistance, and more aerodynamic design.

AERODYNAMIC DRAG REDUCTION

The aerodynamic drag force is the resistive force of the air as the vehicle tries to push its way through it. The power required to overcome the aerodynamic drag force increases with the cube of vehicle speed,[32] and the energy/mile required varies with the square of speed. Thus, aerodynamic drag principally affects highway fuel economy. Aside from speed, aerodynamic drag depends primarily on the vehicle's frontal area, its shape, and the smoothness of its body surfaces. The effect of the vehicle's shape and smoothness on drag is characterized by the vehicle drag coefficient CD, which is the nondimensional ratio of the drag force to the dynamic pressure of the wind on an equivalent area. Typically, a 10 percent C_D reduction will result in a 2 to 2.5 percent improvement in fuel economy, if the top gear ratio is adjusted for constant highway performance.[33] The same ratio holds for a reduction in frontal area, although the potential for such reductions is limited by interior space requirements.

The C_D of most cars sold in the United States in 1994 and 1995 is between 0.30 and 0.35, and the best models are at 0.29. In contrast, C_D for most cars in 1979 to 1980 was between 0.45 and 0.50. The pace of drag reduction has slowed considerably during the mid-1990s, and automakers claim that the slowdown reflects the difficulty of reducing C_D values much below 0.30 for a typical mid-size sedan. Meanwhile, however, highly aerodynamic prototypes have been displayed at motor shows around the world. Interesting historical examples include the Chevrolet Citation IV with a C_D of 0.18, and the Ford Probe IV with a C_D of 0.15, which is the lowest obtained by a functional automobile.[34] (See figure 3-l).

In interviews, manufacturers pointed out that these prototypes are design exercises that have features that may make them unsuitable for mass production or unacceptable to consumers. Such features include very low, sloping hoods that restrict engine space and suspension strut heights. Windshields typically slope at 65 degrees or more from vertical, resulting in a large glass area that increases weight and cooling loads and causes potential vision distortion. Ground clearance typically is lower than would be required for vehicles to traverse sudden changes in slope (e.g., driveway entrances) without bottoming. The rear of these cars is always tapered, restricting rear seat space and cargo volume. Wheel skirts and underbody covers add weight and restrict access to parts needed for wheel change or maintenance, and make engine and catalyst heat rejection more difficult. Frontal wheel skirts may also restrict the vehicle's turning circle. In addition, radiator airflow and engine cooling airflow systems in highly aerodynamic vehicles must be sophisticated and probably complex. For example, the Ford Probe IV uses rear mounted radiators

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[32] Actually, with the relative speed of the air and the vehicle. If the vehicle is moving into a headwind, therefore, the relative speed-and thus the &c drag-will be greater.

[33] Without such an adjustment, vehicle performance will increase, and the net fuel economy benefit of the improvement in drag coefficient will be somewhat less.

[34] "Going With The Wind," *Car and Driver, August 1984.*

and air intake ducts in the rear quarter panels to keep the airflow “attached” to the body for minimum drag. Liquids are piped to and from the front of the car via special finned aluminum tubes that run the length of the car. An attitude control system raises and lowers the chassis to minimize ground clearance at high speeds when aerodynamic forces are high and avoid clearance problems at lower speeds. While such designs may have minimum drag, the weight and complexity penalty will overcome some of the fuel economy benefits associated with low drag.[35]

The tradeoffs made in these vehicles may not be permanent, of course. Engineering solutions to many of the perceived problems will be devised: advanced design of the suspension to overcome the reduced space; thermal barriers in the glass and lighter weight formulations to overcome the added cooling loads and weight gain associated with steeply raked windshields; and so forth. Presumably, the more conservative estimates of drag reduction potential do not account for such solutions. Of course, there is no guarantee that they will occur.

Drag Reduction Potential

Manufacturers were conservative in their forecast of future potential drag coefficient. The consensus was remarkably uniform that for average family sedans, a C_D of 0.25 was the best that would be possible without major sacrifices in ride, interior space, and cargo space. Some manufacturers, however, suggested that niche market models (sport cars, luxury coupes) could have C_D values of 0.22. Other manufacturers stated that even 0.25 was optimistic, as maximizing interior volume for a given vehicle length, to minimize weight, would require drag compromises.

In contrast to these moderate expectations of drag reduction potential, some prototype cars not as extreme as the Probe, with shapes that do not appear to have radical compromises, have demonstrated drag coefficients of 0.19 to 0.20. For example, the Toyota AXV5, with a C_D of 0.20, appears to offer reasonable backseat space< and cargo room. The car does, however, have wheel skirts and an underbody cover; it is also a relatively long car as shown in figure 3-2. Removing the wheel skirts typically increases C_D by 0.015 to 0.02, and the AXV5 could have a C_D of 0.22 and be relatively accessible for maintenance by the customer. This suggests that attaining a C_D of 0.22 could be a goal for 2015 for most cars except subcompacts (owing to their short body), and sports cars might aim for C_D levels of 0.19. For these cars, underbody and wheel covers could add about 40 to 45 lbs to vehicle weight, assuming they were manufactured from lightweight plastic or aluminum materials. This increased weight will decrease fuel economy by about 1 percent, although the reduced drag will offset this increase.

Light trucks have much different potential for C_D reduction. Pickup trucks, with their open rectangular bed and higher ride height, have relatively poor C_Ds; the best of today’s pickups are at 0.44. Four-wheel-drive pickups are even worse, with large tires, exposed axles and driveshafts, and higher ground clearance. Compact vans and utilities can be more aerodynamic, but their short nose and box-type design restrict drag co-efficients to high values. Manufacturers argue that tapering the body and lowering their ground clearance would make them more like passenger

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35 The effect of weight on fuel economy is obvious, but increased air intake complexity can lead to lower engine efficiency, while increased cooling loads increase accessory power requirements.

cars, hence unacceptable to consumers as trucks. GM's highly aerodynamic Lumina Van has not been popular with customers, partly because the sharp nose made it difficult to park; the Lumina Van was recently redesigned and its C_D was increased from the previous value of 0.32.

Manufacturer's projections of potential improvements in future truck C_D are given in table 3-4.

Effect of Advanced Aerodynamics on Vehicle Prices

The costs of aerodynamic improvements are associated primarily with the expense of developing a low drag body shape that is attractive and then developing the trim and aerodynamic detailing to lower CD. The essential inseparability of drag reduction and styling costs makes it difficult to allocate the fixed costs to aerodynamics alone. Manufacturers confirmed that current body assembly procedures and existing tolerances were adequate to manufacture vehicles with C_D levels of 0.25 or less.

Previously, aerodynamic styling to C_D levels of 0.30 required investments in the range of $15 million in development costs.[36] Requiring levels of C_D to be less than 0.25 would likely double development costs owing to the need to stabilize underbody airflow and control engine and internal air flow. Unit variable costs to an automobile manufacturer (from supplier data) are:

- Flush glass windows: $8 to $10 (for four),
- Underbody cover (plastic): $25 to $30,
- Wheel skirts: $5 to $6 each.

Hence the retail price effect (RPE) is calculated as follows:

- Unit investment cost: ~$30,
- Variable costs: ~$48 to $64,
- RPE: ~$125 to $150.

These RPE's would be associated with C_D levels of 0.20 to 0.22, while RPE for achieving a C_D levels of 0.24 to 0.25 would not require wheel skirts, reducing theRPEto$90to$115.

Price effects for trucks are expected to be similar to autos, for a similar percentage reduction in drag. Of course, the absolute values of C_D will be higher.

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[36]Energy and Environmental Analysis, Inc., ***Documentation of the*** *Fuel Economy Performance and Price impact of Automotive Technology,* prepared for Oak Ridge National Laboratory, Martin Marietta Energy Systems, July 1994.

ROLLING RESISTANCE REDUCTION

Background

The rolling resistance of a tire is the force required to move the tire forward, and represents nearly a third of the tractive forces on a vehicle. The force is directly proportional to the weight load supported by the tire, and the ratio of the force to the weight load supported by the tire is called the rolling resistance coefficient (RRC). The higher the RRC, the more fuel needed to move the vehicle.

Tires are of two construction types: bias-ply and radial-ply. Bias-ply tires have been largely phased out of the light-duty truck and car markets except in certain rough-duty applications, but still retain some market share in the medium-duty and heavy-duty commercial truck and bus markets. In general, bias-ply tires have significantly, higher RRCs than radial tires. The RRC of radial tires has also decreased over time owing to improvements in materials and design.

The primary source of tire rolling resistance is internal fiction in the rubber compounds as the tire deflects on contact with the road. Reducing this "hysteresis loss" has typically involved a tradeoff with other desirable tire attributes such as traction and tread wear, but advances in tire design and rubber technology have brought significant reduction in rolling resistance without compromising other attributes.

This evolution of passenger car and light truck tires maybe divided into three phases:

- The first radials (generation one), which used a type of synthetic rubber,[37] had 20 percent to 25 percent lower rolling resistance than bias-ply tires, and became available during the late 1970s.
- The second phase (generation two), using new formulations of synthetic rubber,[38] achieved an additional 20 percent to 25 percent reduction in rolling resistance over generation one radials, and became available during the mid-1980s.
- The third phase (generation three), which adds silica to the tread compounds, achieve an additional 20 percent reduction,[39] and has recently become available in limited quantities.

In addition to changing the tread materials, RRC reductions can be realized by changing the shape of the tread and the design of the shoulder and sidewall, as well as the bead. The type of material used in the belts and cords also affects the RRC. For example, DuPont has suggested the use of aramid fibers to replace steel cords and monofilament replacement of current polyester multifilament to modify stiffness. Aramid yams have been available for over a decade, and their

37 Emulsion-polymerized styrene-butadiene rubber, or SBR, in particular.
38 Solution-polymerized SBR-based formulations.
39 Goodyear, "The Environmental Tire" September 1991.

use can cut rolling resistance by 5 percent.[40] Polyamide monofilament have been recently introduced that improve the tire sidewall stiffness and reduce rolling resistance by about 5 percent. These new materials also contribute to reducing tire weight (by as much as 4 kg/tire), which provides secondary fuel economy benefits and improved ride.

The rolling resistance values of current OEM tires are not well documented. Anecdotal evidence from experts states that most normal (i.e. not performance-oriented) tires have RRCs of 0.008 to 0.010 as measured by the Society of Automotive Engineers (WE) method.[41] Performance tires used in luxury and sports cars, and increasingly in high performance versions of family sedans, use H- or V-rated tires that have RRC values of (SAE) 0.012 to 0.013. Tires for compact vans have RRC values of 0.008 to 0.009 while four-wheel-drive trucks and sport utilities feature tires with RRC values (SAE) of 0.012 to 0.014.

Potential for Rolling Resistance Improvement

Most manufacturers OTA interviewed had similar expectations for tire rolling resistance reduction over the next decade. The expectation was that an overall reduction of 30 percent was feasible by 2005, resulting in normal tires with an RRC of 0.0065 (if the current average is 0.009). Most also believed the H-rated or V-rated tires would have similar percentage reductions in rolling resistance so that they would have RRCs of 0.009 to 0.01 by 2005. Very similar percentage reductions in RRC for light truck tires were also expected. **A** 30 **percent reduction in rolling resistance can translate to a 5 percent improvement in fuel economy,** if the design is optimized for the tire. Manufacturers were unwilling (or unable) to estimate additional RRC reductions in the post-2005 time frame, possibly owing to their unfamiliarity with tire technologies in the research stage at this time.

These 30 percent reductions are expected to be achieved with virtually no loss in handling properties or in traction and braking. Manufacturers suggested that some loss in ride quality may occur because of the higher tire pressure, but this could be offset by suspension improvements or the use of semiactive suspension systems. However, manufacturers expected noise and tire life to be somewhat worse than those for current tires. Both of these factors are highly important--noise may represent a special problem because the improved aerodynamics and, possibly, electric drivetrains of advanced vehicles will reduce other sources of noise.

An optimistic view for the 2015 time frame suggests that RRC values as low as 0.005 may be achievable. Such low rolling resistance tires have already been built for electric cars. Auto manufacturers believe that such tires are not yet commercially acceptable because prototypes have suffered from losses in handling, traction, and durability. Tire manufacturers have expressed the view that technological improvements during the next 20 years could minimize these losses, and an RRC of 0.005 could be a realistic goal for a "normal" tire in 2015, as an average, which implies that some tires would have even lower RRC values.

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[40] "AramidReinforced Tires," *Automotive Engineering,* vol. 99, No. 8, August 1990.

[41] SAE has defined a test procedure for measuring the RRC of a tire alone against a steel drum. When measured on the car wheel, brake drag and friction associated with bearings and oil seals increase the total RRC from the SAE-measured 0.008-0.010 to 0.0105-0.0115.

Only two auto manufacturers discussed other components of rolling resistance, including brake drag and wheel/drivetrain oil seals and bearing loss. Brake drag accounts for **6** percent of total rolling resistance, while bearing and seal drag account for about 12 percent of rolling resistance, with the tires accounting for the remaining 82 percent. The use of highly rigid calipers, pads, and shoes to avoid brake pad contact with the rotor when the wheels are spinning can reduce brake drag by as much as **60** percent. Bearing and oil seal relative friction can be reduced by:

- Downsizing bearings and reducing preload
- Using low-tension oil seals
- Using low-viscosity lubricants

Manufacturers anticipate that these frictional losses can be reduced by 20 to 25 percent by 2005. **A composite analysis of total rolling resistance suggests that a 25 percent reduction** is **possible by 2005, and up to 40 percent by 2015, if new tire technologies are successful** There is some disagreement among engineers about the effect such reductions will have on vehicle fuel economy, with some asserting that the **25** percent reduction in resistance would translate into no more than a 3 percent fuel economy increase, and the 40 percent reduction into a **5** percent fuel economy increase. OTA is more optimistic than this; we conclude that **the projected reductions in rolling resistance may yield as much as a 5 percent improvement in fuel economy by 2005 and an 8 percent improvement by 2015 for an optimized vehicle design.**

Price Effects of Reduced Rolling Resistance

Costs of low rolling resistance tires were computed from the recently available third generation radials from Michelin. Aftermarket tire price to OEM tire cost ratios were derived from data provided by tire manufacturers in earlier Department of Energy (DOE) studies. Incremental prices were based on P180-70/14 and P215-75/15 all-season tires with a treadwear rating of 40,000 to 50,000 miles. Based on available data, retail price increments in the aftermarket were approximately $15 per tire over a second generation radial. This leads to new car RPE effect of $6.75 per tire, or a total RPE of $27, for a tire with an RRC of 0.0065 to 0.007.

Costs of tires that have RRC levels of 0.005 were not provided, but tire manufacturers suggested that the incremental price effect between a third generation and second generation radial would be an indication of the price differential between fourth and third generation radials. Accordingly, an RPE of $30 per vehicle is assumed for the incremental price effect for fourth generation radials, relative to third generation radials.

IMPROVEMENTS TO SPARK IGNITION ENGINES

Overview

The spark ignition (SI) engine is the dominant passenger car and light truck powerplant in the United States. The theoretical efficiency of the SI engine is:

$$\text{Efficiency} = 1 - l/m\text{-}l$$

where r is the compression ratio and “n” the polytropic expansion coefficient, which is a measure of the way the mixture of air and fuel in the engine expands when heated. For a compression ratio of 10:1, and an n value of 1.26 (which is correct for today’s engines, which require the air-fuel ratio to be stoichiometnri, that is, with precisely enough air to allow complete burning of the fuel), the theoretical efficiency of the engine is 45 percent. This value is not attained in practice, but represents a ceiling against which developments can be compared.

Four major factors limit the efficiency of SI engines. First, the ideal cycle cannot be replicated because combustion is not instantaneous, allowing some fuel to be burned at less than the highest possible pressure, and allowing heat to be lost through the cylinder walls before it can do work. Second, mechanical friction associated with the motion of the piston, crankshaft, and valves consumes a significant fraction of total power. Friction is a stronger function of engine speed than of torque; therefore, efficiency is degraded considerably at light load and high rpm conditions. Third, aerodynamic fictional and pressure losses associated with air flow through the air cleaner, intake manifold and valves, exhaust manifold, silencer, and catalyst are significant, especially at high air flow rates through the engine. Fourth, SI engines reduce their power output by throttling the air flow, which causes additional aerodynamic losses called “pumping losses” that are very high at light loads.

Because of these losses, production spark ignition engines do not attain the theoretical values of efficiency, even at their most efficient operating point. In general, the maximum efficiency point occurs at an engine speed intermediate to idle and maximum rpm, and at a torque level that is 60 to 75 percent of maximum. “On-road” average efficiencies of engines used in cars and light trucks are much lower than peak efficiency, since the engines generally operate at very light loads--when pumping losses are highest--during city driving and steady state cruise on the highway. The high power that these engines are capable of is utilized only during strong accelerations, at very high speeds or when climbing steep grades. And during stop-and-go driving conditions typical of city driving, a substantial amount of time is spent at idle, where efficiency is zero. **Typical modem spark ignition engines have an efficiency of about 18 to 20 percent on the city part of the Environmental Protection Agency driving cycle, and about 26 to 28 percent on the highway part of the cycle.**

During the 1980s, most automotive engine manufacturers improved engine technology to increase thermodynamic efficiency, reduce pumping loss and decrease mechanical fiction and accessory drive losses. These improvements have resulted in fuel economy benefits of as much as 10 percent in most vehicles.

Increasing Thermodynamic Efficiency

Increasing the thermodynamic efficiency of SI engines can be attained by optimum control of spark timing, by reducing the time it takes for the fuel-air mixture to be fully combusted (burn time), and by increasing the compression ratio.

Spark timing

For a particular combustion chamber, compression ratio and air fuel mixture, there is an optimum level of spark advance for maximizing combustion chamber pressure and, hence, fuel efficiency. This level of spark advance is called MBT for "maximum brake torque. " Owing to production variability and inherent timing errors in a mechanical ignition timing system, the average value of timing in mechanically controlled engines had to be retarded significantly from the MBT timing so that the fraction of engines with higher than average advance owing to production variability would be protected from knock. The use of electronic controls coupled with magnetic or optical sensors of crankshaft position has reduced the variability of timing between production engines, and also allowed better control during transient engine operation. More recently, engines have been equipped with knock sensors, which are essentially vibration sensors tuned to the frequency of knock. These sensors allow for advancing ignition timing to the point where trace knock occurs, so that timing is optimal for each engine produced regardless of production variability. Manufacturers expect that advanced controls of this sort can provide small benefits to future peak efficiency.

Faster combustion

High-swirl, fast-bum combustion chambers were developed during the 1980s to reduce the time taken for the air fuel mixture to be fully combusted. The shorter the burn time, the more closely the cycle approximates the theoretical Otto cycle with constant volume combustion, and the greater the thermodynamic efficiency. Recent improvements in flow visualization and computational fluid dynamics have allowed the optimization of intake valve, inlet port, and combustion chamber geometry to achieve desired flow characteristics. Typically, these designs have resulted in a 2 to 3 percent improvement in thermodynamic efficiency and fuel economy.[42] The high swirl chambers also allow higher compression ratios and reduced "spark advance" at the same fuel octane number. More important, manufacturers stated that advances in this area are particularly useful in perfecting lean-bum engines.

Increased compression ratios

Compression ratio is limited by fuel octane, and increases in compression ratio depend on how the characteristics of the combustion chamber and the timing of the spark can be tailored to prevent knock, or early detonation of the fuel-air mixture, while maximizing efficiency. Improved electronic control of spark timing and improvements in combustion chamber design are likely to increase compression ratios in the future. In newer engines of the 4-valve dual overhead cam

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42 J. W. Walker et al., "The GM 4.3 Valve V-6 Gasoline Engine," SAE paper 841225,1984

(DOHC) type, the spark plug is placed at the center of the combustion chamber, and the chamber can be made very compact by having a nearly hemispherical shape. Engines incorporating these designs have compression ratios up to 10:1, while still allowing the use of regular 87 octane gasoline. High compression ratios also can increase hydrocarbon emissions ***from*** the engines, although this is becoming less of a concern with newer combustion chamber designs. Manufacturers indicated that increases beyond 10:1 are expected to have diminishing benefits in ***efficiency*** and fuel economy and compression ratios beyond 12:1 are probably not beneficial, unless fuel octane is raised simultaneously. The use of oxygenates in reformulated gasoline could, however, allow the octane number of regular gasoline to increase in the future.

Reducing Mechanical Friction

Mechanical friction losses can be reduced by converting sliding metal contacts to rolling contacts, reducing the weight of moving parts, reducing production tolerances to improve the fit between pistons and bore, and improving the lubrication between sliding or rolling parts. Friction reduction has focused on the valvetrain, pistons, rings, crankshaft, crankpin bearings, and the oil pump. This is an area where OTA found considerable disagreement among manufacturers interviewed.

Rolling contacts and lighter valvetrain

Roller cam followers to reduce valvetrain friction are already widely used in most U.S. engines. In OTA interviews, some manufacturers claimed that once roller cams are adopted, there is very little fiction left in the valvetrain. Other manufacturers are pursuing the use of lightweight valves made of ceramics or titanium. The lightweight valves reduce valvetrain inertia and also permit the use of lighter springs with lower tension. Titanium alloys are also being considered for valve springs. A secondary benefit associated with lighter valves and springs is that the erratic valve motion at high rpm is reduced, allowing increased engine rpm range and power output.

Fewer rings

Pistons and rings contribute to approximately half of total fiction. The primary function of the rings is to minimize leakage of the air-fuel mixture from the combustion chamber to the crankcase, and oil leakage from the crankcase to the combustion chamber. The ring pack for most current engines is composed of two compression rings and an oil ***ring.*** The rings have been shown to operate hydrodynamically over the cycle, but metal-to-metal contact occurs often at the top and bottom of the stroke. The outward radial force of the rings is a result of installed ring tension, and contributes to effective sealing as well as fiction. Various low-tension ring designs were introduced during the 1980s, especially since the need to conform to axial diameter variations or bore distortions has been reduced by improved cylinder manufacturing techniques. Elimination of one of the two compression rings has also been tried on some engines, and two-ring pistons may be the low friction concept for the future. Here again, we found considerable disagreement, with some manufacturers stating that two-ring pistons provided no friction benefits, while others suggested fiction reduction of 5 to 10 percent.

Lighter pistons

Reducing piston mass is the key to reducing piston fiction, and engine designers have continuously reduced mass since the 1980s. Analytical results indicate that a 25 percent mass reduction reduces fiction mean effective pressure by 0.7 kilopascals at 1500 rpm.[43] Secondary benefits include reduced engine weight and reduced vibration. Use of advanced materials also results in piston weight reduction. Current lightweight pistons use hypereutectic aluminum alloys, while future pistons could use composite materials such as fiber-reinforced plastics. Advanced materials can also reduce the weight of the connecting rod, which also contributes to the side force on a piston. Manufacturers agreed that a 25 to **30** percent reduction in piston and connecting rod weight could occur by 2015.

Coatings

Coating the piston and ring surfaces with materials to reduce wear also contributes to fiction reduction. The top ring, for example, is normally coated with molybdenum, and new proprietary coating materials with lower fiction are being introduced. Piston coatings of advanced high-temperature plastics or resin have recently entered the market, and are claimed to reduce fiction by 5 percent and fuel consumption by 1 percent.[44] Some manufacturers claimed that coatings wear off quickly, but others suggested that advanced coatings were durable for the life of the engine. These differences may be owing to proprietary advantages in coating technology with some manufacturers.

Improved oil pump

Friction in the oil pump can be reduced by optimizing oil flow rates and reducing tolerances for rotor clearance. Some manufacturers suggested fiction can be reduced by 2 to 3 percent with improved oil pump designs, for a 0.3 to 0.4 percent fuel economy benefit.

Lubricants

Improvements to lubricants used in the engine also contribute to reduced fiction and improved fuel economy. Friction modifiers containing molybdenum compounds have reduced friction without affecting wear or oil consumption. Some manufacturers stated that future synthetic oils combining reduced viscosity and fiction modifiers could offer good wear protection, low oil consumption, and extended drain capability, as well as small improvements to fuel economy in the range of 1 percent over current 5W-30 oils.

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43 J. T. Kovach et al. "Engine Friction Reduction for Improved Fuel Economy," SAE paper 820085, 1982. Friction mean effective pressure is a measure of the amount of engine power that is used to overcome friction rather than to provide usable torque at the engine's output shaft.

44 A. Tanaka et al., "Development of Toyota JZ Type Engine," SAE paper 930881, 1990.

Reducing Pumping Loss

Reductions in flow pressure loss can be achieved by reducing the pressure drop that occurs in the flow of air (air fuel mixture) into the cylinder, and the combusted mixture through the exhaust system. The largest part of pumping loss during normal driving results from throttling, however, and strategies to reduce throttling loss have included variable valve timing, "lean-bum" systems, and "variable displacement" systems that shut off some engine cylinders at low load.

Intake manifold design

There are various strategies to reduce the pressure losses associated with the intake system and exhaust system. Efficiency can be improved by making the intake air flow path as free as possible of flow restrictions through the air filters, intake manifolds, and valve ports.[45] Intake and exhaust manifolds can be designed to exploit resonance effects associated with pressure waves similar to those in organ pipes. By properly tuning the manifolds, high pressure waves can be generated at the intake valve as it is about to close, which increases intake pressure, and at the exhaust valve as it is about to open, which purges exhaust gases from the cylinder. Formerly, "tuned" intake and exhaust manifolds could help performance only in certain narrow rpm ranges. Recently, the introduction of new designs, including variable resonance systems (where the intake tube lengths and resonance volumes are changed at different rpm by opening and closing switching valves) have allowed smooth and high torque to be realized across virtually the entire engine speed range. Manufacturers expect variable intake systems to be in widespread use over the next 10 years.

Multiple valves

Another method to increase efficiency is by increasing valve area, especially by increasing the number of valves. A four-valve system that increases flow area by 25 to 30 percent over two-valve layouts has gained broad acceptance. The valves can be arranged around the cylinder bore and the spark plug placed in the center of the bore to improve combustion. While the peak efficiency or brake-specific fuel consumption (bsfc) of a four-valve engine may not be significantly different from a two-valve engine, there is a broader range of operating conditions where low bsfc values are realized. Analysis of additional valve layout designs suggests that five valve designs (three intake, two exhaust) can provide an additional 20 percent increase in flow area, at the expense of increased valvetrain complexity.[46] Current expectations are that most engines will be of the four-valve types by 2005.

Under most normal driving conditions, throttling loss is the single largest contributor to engine efficiency losses. In SI engines, the air is throttled ahead of the intake manifold by means of a butterfly valve that is connected to the accelerator pedal. The vehicle's driver demands a power level by depressing or releasing the accelerator pedal, which, in turn, opens or closes the butterfly valve. The presence of the butterfly valve in the intake air stream creates a vacuum in the intake manifold at part throttle conditions, and the intake stroke draws in air at reduced pressure, which

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[45] The shaping of valve ports to increase swirl in the combustion chamber can lead to reduced volumetric efficiecy, leading to a tradeoff between combustion and volumetric efficiency.

[46] K. Aoi et al., "Optimization of Multi-Valve Engine Design: The Benefit of Five-Valve Technology," SAE paper 860032, 1986.

results in pumping losses. These losses are proportional to the intake vacuum, and disappear at wide open throttle.

Lean-burn

Lean-bum is one method to reduce pumping loss. Instead of throttling the air, engine power can be reduced by reducing the fuel flow so that the air-fuel ratio increases, or becomes leaner. (In this context, the diesel engine is a lean-bum engine). Most SI engines, however, do not run well at air: fuel ratios leaner than 18:1, as the combustion quality deteriorates under lean conditions. Manufacturers provided data on engines constructed to create high swirl and turbulence when the intake air and fuel are injected into the cylinder that can run well at air: fuel ratios up to 22:1. Lean-bum engines actually run at high air-fuel ratios only at light loads; they run at stoichiometric or rich air: fuel ratios at high loads to maximize power. The excess air combustion at light loads has the added advantage of having a favorable effect on the polytropic coefficient, n, in the efficiency equation. Modem lean burn engines commercialized recently ***in*** Japan do not completely eliminate throttling loss, but the reduction is sufficient to improve vehicle fuel economy by 8 to 10 percent. A disadvantage of lean-bum engines, however, is that they cannot use conventional three-way catalysts to reduce emissions of nitrogen oxides (NO_x, and the in-cylinder NO_x emission control from running lean is sometimes insufficient to meet stringent No_x emissions standards. There are developments in "lean NO_x catalysts," however, that could allow lean-bum engines to meet the most stringent NO_x standards proposed in the future, which will be discussed later.

Variable valve timing

Variable valve timing (VVT) is another method to reduce pumping loss. Instead of using the butterfly valve to throttle the intake air, the intake valves can be closed early, reducing the time (and volume) of air intake. The system has some problems at very light load (the short duration of the intake valve opening leads to weaker in-cylinder gas motion and reduced combustion stability). Moreover, at high rpm, some throttling losses occur at the valve itself.[47] Hence, throttling losses can be decreased by 80 percent at light load, low rpm conditions, but by only 40 to 50 percent at high rpm, even with fully VVT.[48]

Aside from improved fuel economy, VVT also increases power output over the entire range of engine rpm. Fully variable valve timing can result in engine output levels of up to 100 brake horsepower (BHP)/liter at high rpm without the decline in low-speed torque that is characteristic of four-valve engines with fixed valve timing. In comparison to an engine with fixed valve timing that offers equal performance, fuel efficiency improvements of 7 to 10 percent are possible. The principal drawback has historically been the lack of a durable and low cost mechanism to implement valve timing changes. Honda has commercialized a two stage system in its four-valve/cylinder engines where, depending on engine speed and load, one of two valve timing and

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[47] At high rpm, the duration of the intake stroke is so short that the valve is partially open--with the intake air throttled by the partially-opened valve itself--for a significant portion of the stroke.

[48] Y. Urata et al., "A Study of Vehicle Equipped with Non-Throttling S.I. Engine with Early Intake Valve Closing Mechanism," SAE paper 930820, 1993.

lift schedules are realized for the intake valves. (This type of engine has been combined with lean burn to achieve remarkable efficiency in a small car.)[49]

Another version of VVT also shuts off individual cylinders by deactivating the valves. For example, an eight-cylinder engine can operate at light load as a four-cylinder engine (by deactivating the valves for four of the cylinders) and as a six-cylinder engine at moderate load. Such systems have also been tried on four-cylinder engines in Japan with as many as two cylinders deactivated at light load. At idle, such systems have shown a 40 to 45 percent decrease in fuel consumption, while composite fuel economy has improved by 16 percent on the Japanese 10-15 mode test since both pumping and fictional losses are reduced by cylinder deactivation.[50] Earlier systems had problems associated with noise, vibration, and emissions that resulted in reduced acceptance in the market place, but more recent systems introduced in Japan have solved most of the problems. OTA had the opportunity to drive Mitsubishi's MIVEC V-6 which features VVT and cylinder shutoff, and noise and vibration effects on this vehicle from cylinder shutoff were barely noticeable.

Total effect

All of the aforementioned technologies can reduce pumping loss, increase volumetric efficiency, increase specific output, and reduce fuel consumption at part load, but the benefits are not additive. Most manufacturers provided estimates of benefits for several combinations; for example, a recent paper by engineers from Porsche forecast a 13 percent reduction in fuel consumption with no loss in performance for a system featuring variable valve timing and lift, variable resonance intake, and cylinder cutoff (from a baseline vehicle featuring a four-valve engine with a two-stage resonance intake and cam phase adjustment) .51 This estimate is more optimistic than what many manufacturers believed to be possible.

DISC and Two-Stroke Engines

Direct Injection Stratified Charge (DISC) Engines are considered as the highest level of technology refinement for SI engines. These engines are almost completely unthrottled, and will require variable valve timing to reach their maximum potential fuel efficiency. Their high efficiency is associated with high compression ratio (up to 13), absence of throttling loss, and favorable characteristics of the products of combustion. Although DISC engines have been researched for decades (with some versions such as Ford's PROCO almost entering production) there is renewed excitement about DISC owing to:

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[49] U.S. En vironmental Protection Agency Test Car List, Honda Civic VX Test Result," 1993.

[50] K. Matano et al., "Development of a New Multi Mode Variable Valve Timing Engine," SAE paper 930878, 1993. BMW has tested a similar system on an eight-cylinder engine, with slightly more modest results--35 percent reduction in fuel consumption at idle, 7 percent overall reduction in DIN 1/3 test. Karl-Heinz Ziwica, BMW, personal communication May 15, 1995.

[51] C. Brustle, "Lightweight Engines with High Specific Power," FISITA Congress, Peking, October 1994.

- Advancements in fuel injection technology (e.g., the air atomized injection system developed by Orbital, and new fast-response piezo-electric injectors developed by Toyota).

- Improved understanding and control of vortex flow in the combustion chamber (e.g., Mitsubishi's vertical vortex system maintains charge stratification through the compression stroke over a wide speed/load range. Increased turbulence in the chamber can also be used to support combustion to very lean A/F ratios-as lean as 40: 1).

- Developments in lean NO_x catalysts.

DISC engines still have problems associated with meeting future hydrocarbon (HC) and NO_x standards. Manufacturers indicated that the HC problem was easier to solve than the NO_x problem, and meeting a standard of 0.4 g/mi NO_x or lower would require a "lean-NO_x" catalyst capable of conversion efficiency over 60 percent. The development of the lean-NO_x catalyst is discussed below, but several manufacturers appeared to be optimistic about the future prospects for the DISC.

Two-stroke engines

The two-stroke engine is a variant of the four-stroke DISC engine, with the potential to produce substantially higher specific power. The reduced engine weight provides fuel economy benefits in addition to those provided by the DISC design. The two-stroke design is thermodynamically less efficient than the four-stroke, however, because part of the gas expansion stroke cannot be used to generate power.

Two-stroke engine designs have been developed by various research groups and manufacturers, with Orbital, Toyota, and Chrysler publicly displaying alternative designs. The Orbital engine uses crankcase scavenging (like a traditional motorcycle two-stroke engine), with a specially developed direct injection system with air assisted atomizers. An Orbital engine installed in a European Ford Fiesta has achieved 44 mpg city, 61.3 mpg highway, for a composite fuel economy of 50.4 mpg on the EPA test cycle.[52] Orbital claims a 22 percent benefit in fuel economy for this engine,[53] although it is difficult to verify this claim with available tests because the baseline vehicles have different peformance.

The Orbital engine uses a very low-fiction design, with roller bearings for its crankshaft, but manufacturers doubt the durability of this system. Chrysler uses an externally scavenged design with an air compressor, so that crankcase induction and lubrication problems are avoided. Toyota uses an external induction system with exhaust valves in the cylinder head. These designs are likely to be more durable, but lose the fiction advantage, so that their fuel economy benefits are lower than the Orbital design. However, a four-stroke DISC will be more thermodynamically efficient than a two-stroke DISC, and the current opinion is that the four-stroke's effect on fuel economy will be greater than the two stroke's despite the latter's weight advantage.

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52 U.S. Environmental Protection Agency, "Evaluation of Research Prototype Vehicles Equipped with DI Two-Stroke Engines" EPA Report No. EPA/AA/CTAB/92-01, January 1992.

53 Orbital Engine Co., "OCP Technical Presentation," December 1990.

Summary of Engine Technology Benefits

Estimates of engine technology benefits are given in table 3-5, assuming that a lean-NO_x catalyst is available for lean-bum and DISC engines. The mean for all manufacturers over the long term suggests that use of a DISC engine coupled with available friction reduction technologies can yield a 17 to 18 percent fuel consumption reduction, while an optimistic view suggests that as much as 25 percent may be available. These reductions can be achieved with no tradeoff in performance although cost and complexity will increase.

Lean-NO_x Catalysts

The potential for conventional lean-bum and DISC engines to meet future emissions standards is critically dependent on lean-NO_x catalysts. Traditional three-way catalysts do not reduce No_x in the lean air-fuel ratio region, since the reduction reaction does not take place in the presence of oxygen.

The new zeolite catalysts being developed have shown the ability to reduce NO_x in lean exhaust, providing some hydrocarbon is present. First generation zeolite catalysts, however, had very poor durability. New zeolite catalysts have shown NO_x conversion rates of over 60 percent at 500° C in laboratoy tests, but this rate falls to 40 percent or less at higher temperatures of 700° C--temperatures characteristic of high load conditions. Relatively new zeolite catalysts have been tested in cars and provided NO_x conversion efficiency of close to 60 percent, while maintaining HC conversion efficiencies over 90 percent. If such conversion efficiencies are maintained over the useful life of a vehicle, it makes lean-bum engines viable even at California low emission vehicle (LEV) and ultralow emission vehicle (ULEV) standards. However, the catalysts available thus far are very bulk.[54]

The pace of development in lean NO_x catalysts has been remarkable. Several manufacturers are working with nonzeolite catalysts that have been more resistant to thermal degradation and have displayed high NO_x conversion efficiencies. At least two manufacturers stated that they were optimistic that lean-NO_x catalysts could be ready for production by 2005. Considerable research into catalysts is continuing at all major manufacturers; Japan is finding these developments at national laboratories, and materials such as Ag/Al_2O_3 have shown NO_x conversion efficiencies as high 90 percent in the laboratory. Hence, both the conversion efficiency and the thermal durability of such catalysts could be equivalent to current three-way catalysts by 2005 (current three-way catalysts maintain NO_x conversion efficiencies of more than 70 percent throughout a useful life of 100,000 miles).

It should also be mentioned that Toyota and Mazda have introduced catalysts with lean-bum engines in Japan in their 1995 models.[55] The Toyota catalysts are apparently not true lean-NO_x catalysts, but are "NO_x storage" catalysts. NO_x is stored when the engine is operating lean, but released to the catalytic material during periods of rich operation (for example, during

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[54] Ford Motor Co., presentation to OTA, September 1994.

[55] "Technical Briefs: Mazda Lean Burn Catalyst," *Automotive Engineering*, vol. 102, No. 12, December 1994.

accelerations). These catalysts apparently have about 60 percent NO_x conversion efficiency on the Japanese test cycle, and represent practical solutions that are already commercially available. Toyota did not believe that this type of catalyst is suitable for U.S. conditions, as it is easily poisoned by fuel sulfur, which is very low in Japan but high in the United States. Nevertheless, such a solution is available if EPA requires reformulated gasoline to meet new sulfur specifications of 10 ppm, equivalent to the sulfur content of Japanese gasoline.

The Mazda catalyst is a "lean-NO_x" zeolite catalyst with platinum, rhodium and iridium as the noble catalytic materials. The catalyst is used on the Protege model and has a volume of 1.7 liters, as compared with 0.5 liters for the conventional catalyst on the nonlean bum Japanese model. Mazda claims a NO_x reduction efficiency of over 50 percent in the lean regime.[56]

Price Effects of Engine Improvements and Advanced Engines

Many of the potential improvements to piston engines, both gasoline and diesel, have been introduced commercially in a few models in Europe and Japan. In cases where these technologies are available in mass-market cars, and available from more than one manufacturer, the option price should reflect the true RPE effect on average.

Four-valve engines are already widely available, with an average price differential of$110 to $120 relative to an overhead cam (OHC) four-cylinder two-valve engine of <u>equal performance</u>, not equal displacement.[57] A two-stage variable resonance manifold was estimated at $30 to 35 relative to a one-stage manifold.

The RPE for the two-position Variable Valve Lift and Timing (VVLT) system by Honda is estimated from several available models at $250 to $300 for a four-cylinder engine. These comparisons are based on the "adjusted" RPE for <u>an equal power</u> engine. The actual price increment is higher for many models because the VVLT system improves horsepower by 15 percent and torque by 7 to 8 percent (at low rpm). The Mitsubishi MIVEC V-6 with both VVLT and valve shutoff has an adjusted RPE in Japan of about $700 to $750, but Japanese prices are higher owing to higher taxes than in the United States, and an equivalent U.S. RPE maybe in the $530 to $600 range, for a V-6. Prices for a four-cylinder should scale approximately as the ratio of number of cylinders, although an in-line six-cylinder engine could have lower costs for VVLT and valve deactivation.

Lean-bum engines have also been recently commercialized in Japan by Mitsubishi, Honda, and Mazda. For each of these cases, there are comparable "three-way catalyst" equipped models, and the RPE for lean-bum varies from $300 to $360 (calculated at 110 yen to the dollar). It appears that about half the price increase is associated with the lean-bum catalyst. These costs could decline with the "learning curve" effect and the RPE decrease to about $250 in the future.

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[56] Ibid.
[57] Martin Marietta Energy Systems, see footnote 36.

The cost of a DISC engine is best estimated from the cost of a diesel engine, since the fuel injection system complexity rivals that of an indirect injection (IDI) diesels' fuel injection system and the higher compression ratio imposes higher pressure loads on the cylinder block and reciprocating parts. In the Martin Marietta analysis,[58] RPEs for IDI diesels are estimated to be $400 to $450 for a four-cylinder, $550 to $600 for a six, and $750 to $800 for a V-8 engine. These incremental RPE effects are likely to be applicable to the DISC engine, but the incremental effect of a lean-NO_x catalyst must be included. If the DISC uses variable valve lift and timing, the price increments should be approximately additive so that the prices shown in table 3-6 may be reasonable.

Low-fiction components are relatively low-cost items and were examined in some detail in the Martin Marietta report. Estimates of supplier costs of low-fiction components were obtained directly from engine valvetrain and piston component suppliers who provided the following range of incremental costs:

- Roller earn followers: -$0.50 each
- Lightweight valves/springs: -$1.00 each (titanium/ceramic)
- Lightweight pistons: ~1.00 each
- Piston coatings: -$0.50 each

The total investment for each of the four items was provided by auto manufacturers at $4 million for each component type for tooling, engineering and launch costs. The RPE for each item (for four-valve engines) is shown in table 3-7. Given the values shown in the table, friction reduction should result in an RPE of $65 to $120 depending on number of cylinders. ***Note*** that many engines already have roller cam followers.

DIESEL ENGINES

Background

Diesel engines differ from SI engines in their method of fuel ignition; instead of igniting the mixture of fuel and air with a spark, diesels rely *on* compression alone to ignite a mixture of fuel and heated air. Diesel engines enjoyed a brief burst of popularity during the early 1980s, following the second oil price shock of 1980. Since the oil price collapse of 1986, diesels have practically disappeared from the U.S. market. In Europe, however, diesels have recently enjoyed a rebirth, and their market penetration is over 30 percent in some countries such as France.

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[58] Ibid.

The major advantage of the diesel engine over the gasoline engine is its high fuel efficiency. Diesels are more fuel efficient than gasoline engines for two reasons. First, the diesel cycle uses high compression ratios (16:1 to 24:1) to ignite the fuel spontaneously upon contact with hot compressed air, which leads to high engine efficiency. Gasoline engines cannot employ such high-compression ratios because the gasoline/air mixture would ignite prematurely under such conditions; the octane number of the fuel limits the compression ratio to about 10:1 for an engine using regular gasoline. Second, diesels do not experience the pumping losses characteristic of SI engines because they do not throttle their intake air; instead, the power output of the diesel engine is controlled by regulating the amount of fuel for each combustion event while the air inducted is unthrottled. The SI engine's throttling of intake air leads to power losses (refereed to as pumping loss) that increase at light loads (typical in city driving) which are absent in the diesel, and its fuel efficiency benefit under light load conditions over a gasoline engine is impressive.

On the negative side, diesel engines have much higher internal mechanical fiction because of their high cylinder pressures, and they must expend additional energy to drive their high-pressure fuel injection pumps. The high compression ratio and combustion process also lead to higher engine weight relative to a similar displacement gasoline engine, as well as reduced specific output and increased noise and vibration. These last three factors of reduced power, increased noise, and higher vibration are often blamed for the lack of widespread acceptance of the diesel in the U.S. marketplace, where the value of the diesels' enhanced fuel efficiency is low.

A potentially more serious factor affecting diesel engines in the United States is potential difficulty in meeting current and future emission standards. Diesel engines have very low gaseous HC and carbon monoxide (CO) emissions but relatively high nitrogen oxides (No_x) and particulate emissions. The very lean air-fuel ratios employed by the diesel under most driving conditions and the resulting low exhaust temperature has made catalytic treatment of NO_x and particulates difficult, but recent developments with higher pressure, electronically controlled fuel injection systems, and improved oxidation catalysts have reduced the particulate emission problem. Diesels have a waiver from current NO_x standards for cars, but, if the waiver were revoked, their ability to meet Tier I, Tier II, and California LEV standards is still uncertain.

The status of diesel technology relative to its fuel efficiency, power output, acceptability, and ability to meet emissions standards will be discussed.

Performance of New Diesel Engines

The latest designs of diesel engines recently unveiled in Europe provide significant improvements in virtually all of the characteristics of interest. Most of the development in diesel technology is centered in Europe. Diesel penetration in the Japanese market is low, and Japanese automakers are focusing primarily on lean-bum gasoline engine concepts. Diesel penetration ***is*** occurring, however, in the Japanese sports utility vehicle market.

Until 1991, diesel powered passenger cars and light trucks sold in the United States were all of the IDI type, where fuel is sprayed into a prechamber, partially mixed and combusted with air before further mixing and combustion occurs in the main combustion chamber. The prechamber design results in smoother combustion with less noise and lower NO_x emissions. However, heat transfer from the prechamber and pressure losses from the partially combusted gases as they flow through the small passages connecting the prechamber to the main combustion chamber result in reduced efficiency. In fact, the peak efficiency of an IDI diesel is comparable to, or only slightly better than, that of a spark ignition engine; most of its efficiency advantage occurs at light loads.

Direct injection (DI) systems avoid the heat and flow losses from the prechamber by injecting the fuel directly into the combustion chamber. The fuel injection system must be quite sophisticated, as it must be capable of injecting very little fuel during the ignition delay period, while providing highly atomized fuel and providing intensive mixing during primary combustion. Advancements in fuel injection technology and diesel combustion chamber design has led to the recent introduction of passenger car DI diesels by Volkswagen in their Audi and VW model lines.

Turbocharging has also been found to be particularly effective in combination with diesel engines. Many new diesel engines, including the Volkswagen DI diesel engines, are turbocharged and some feature intercoolers, which provide a cooler, denser charge to the engine. As a result, the specific power of diesel engines with turbocharging now exceeds the specific power output of naturally aspirated, two-valve per cylinder gasoline engines and approaches that of four-valve per cylinder gasoline engines. Turbocharging and intercooling are quite costly, however, and turbocharged engines still have some low-speed drivability deficiencies.

Four valve per cylinder technology has also been introduced by Mercedes Benz in 1994 for several of their diesel engines. These engines have attained a specific output of 45 BHP/liter without the use of turbocharging, levels only slightly lower than typical two-valve spark ignition engines.[59] The four-valve engines are of the IDI type, but the central placement of the prechamber possible in a four-valve cylinder head has resulted in improved emissions and fuel consumption relative to a two-valve IDI engine. At full load, Mercedes claims an 8 percent reduction in specific fuel consumption relative to a two-valve engine, but the benefit is much smaller at light loads.[60]

Emissions of the new engines are also low enough to meet all U.S. standards given the current NO_x waiver. The Mercedes four-valve engine, in conjunction with California's low sulfur, low aromatic content diesel fuel can actually meet the LEV standards for HC, CO, and particulate. However, NO_x emissions are four times greater than applicable LEV standards. VW expects that its turbocharged DI diesels will have emission levels similar to those of the Mercedes four-valve IDI diesel, although the W diesel is not (yet) offered for sale in the United States but is expected for 1996.

Data are lacking on fuel economy benefits based on the U.S. test cycles, but considerable data exists for the European Test Cycle. The European City Cycle is significantly slower than the U.S. city cycle, with longer idle time, and, hence, reported ECE (European Economic Commission) city fuel economy values are 12 percent lower (on average) than U.S. FTP-based values. The ECE 90 km/h steady-state test results in fuel economy values similar to those recorded in the U.S. highway test, but there is no U.S. equivalent to the ECE 120 km/hr steady-state test. Official ECE

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59 F. Thoma and H. Fausten "The New 4-valve, 6 cylinder, 3.0 Liter, Mercedes-Benz Diesel Engine" SAE paper 932875, June 1993.
60 Ibid.

test results for 1994 cars were utilized to develop estimates of diesel fuel efficiency benefit over a gasoline engine.[61]

Table 3-8 shows the fuel economy benefits for a diesel engine relative to an equal performance gasoline engine on the EPA city/highway composite test, based on engine brake specific fuel consumption data, and consultation with auto manufacturers. In practice, it is difficult to obtain a good equal performance comparison between a diesel-and gasoline-powered vehicle, as the diesel will typically have more torque at low speed, but is rpm limited with lower peak power relative to the gasoline engine.

Table 3-9 is a representative sample of gasoline- and diesel-powered models of the same cars matched for approximately equal performance. In virtually every case, the percentage improvements in fuel economy are higher than the averages suggested by manufacturers, noted above; in particular, the DI turbocharged diesels from VW appears extremely fuel efficient. Table 3-9 also shows that a diesel's fuel efficiency benefit decreases with increasing speed, as a result of its high internal fiction. Moreover, modem four-valve spark ignition engines are closing the fuel economy difference, especially as technologies such as variable valve controls (which reduce pumping loss) are adopted.

Prospects for the Diesel in the United States

The potential for the diesel in the United States revolves around three issues--consumer acceptance, fuel prices, and ability to meet future emission standards.

Consumer acceptance of the diesel should improve significantly with the new generation of engines. OTA had the opportunity to evaluate the VW DI diesel and the Mercedes four-valve diesel, and these new engines minimize performance differences relative to their gasoline engine counterparts in terms of power, acceleration, noise, and vibration. In fact, diesel sales in Europe have increased significantly with the new engines despite unchanged fuel prices from 1993.

The major factors behind the lack of consumer interest in the United States are supposedly the low fuel prices and the higher price of diesel relative to gasoline. Undoubtedly, these factors do not help diesel market penetration, but they are not the sole factors controlling diesel market penetration. Figure 3-3 provides the diesel market penetration in Germany during a 15-year period, and also provides VW's explanations for the observed changes over the years.[62] As can be seen, W believes that vehicle tax policies, perceived emission benefits, and fuel prices have all contributed to the large oscillations in diesel sales. If W is correct, it may be possible to implement vehicle tax policies to favor the diesel, if the United States decides that fuel conservation is a high priority. Further, to the extent that consumer perceptions of poor performance and unreliability have influenced U.S. diesel sales, experience with the new generation of diesels conceivably might bolster a diesel comeback.

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[61] U.K. Department of Transportation "New Car Fuel Consumption - The Official Figures" January 1994.
62 VW research and Development, material provided to OTA, May, 1994.

The key to diesel's future in the United States is its ability to further reduce emissions. The manufacturers interviewed by OTA have a number of technological innovations for the DI diesel under development, which will reduce emissions and, in some cases, improve performance.

Variable geometry turbocharging of several types is being investigated by the industry. Current turbochargers are well matched to piston engine requirements only over a narrow range of rpm. New types of turbochargers includes those with pivoting inlet guide vanes, simpler variable inlet types, so called "jet" types, and new types with "wing' '-shaped impellers. According to two manufacturers interviewed, these turbochargers can extend the range of useful boost, and reduce the low-speed drivability deficiencies of normal turbos. The increased boost can also be translated into decreased particulate and HC emissions.

The four-valve head/central injector was already discussed with reference to the Mercedes production IDI engine. All German manufacturers interviewed stated that this concept is even more beneficial to a DI diesel engine and could reduce emissions by 10 percent to 15 percent. Swirl optimization is an inherent part of the design of the new four-valve head.

Improved fuel injection is associated with higher injection pressure, electronic control of injection rate, and the use of pilot injection. In particular, injection rate shaping and the use of pilot injection has resulted in very significant reductions in the NO_x/particulate tradeoff curve. Pilot injection was also found to lead to very large reductions in combustion noise (up to 12 decibels at high load) in DI diesels.[63]

Optimized exhaust gas recirculation (EGR) can be used principally to reduce NO_x. Owing to the very lean air-fuel ratio employed, high EGR rates (over 40 percent) are required at light loads, and such rates have been found to reduce NO_x and HC emissions simultaneously. In addition, EGR has also been found to eliminate noisy cold start combustion, although it may increase smoke slightly.[64]

Based on manufacturers' estimates, the total reduction in NO_x emissions (at near constant particulate emissions) possible are as follows:

- Variable geometry turbo: -3 to -5%,
- Four-valve head: -10 to -15%,
- Electronic fuel injection (FI) with pilot injection: -15 to -20%,
- Optimized EGR: -25 to -30%.

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[63]FEV Motoren Technik, "Study of Pilot Injection," SAE paper 940674, 1994.

[64]I. Fukutani and E. Watanabe, "Reduction of Idle Knock by EGR in a Passenger Car Diesel Engine," SAE paper 840421, 1986.

These benefits are not necessarily additive but hold the promise of a total NO_x reduction of over 50 percent from the current baseline of a two-valve DI diesel with no EGR and mechanically controlled fuel injection system that typically has a NO_x emission level of 0.8 g/mile.

The technologies also appear to have very favorable effects on consumer related variables. The variable geometry turbocharger and four-valve head will lead to improved power and better drivability, while pilot injection and EGR will result in reduced noise and vibration. Hence, the tradeoffs of emission control are quite favorable for a diesel engine.

Some current DI diesels such as the Audi 2.5L engine already feature "pre-injection" and electronic injection timing but still have NO_x emissions of 0.8 g/mi.[65] Nevertheless, manufacturers believed that DI diesels could achieve 0.4 g/mi NO_x with all of the above technologies, though they agreed it would be difficult to attain this goal. Hence, there is some potential for DI diesels to meet all current "Tier I" standards without a NO_x waiver and without a NO_x catalyst.

Manufacturers also believed that it was unlikely that LEV/ULEV standards of 0.2 g/mi NO_x could be met without a NO_x reduction catalyst. Most automanufacturers also commented On the fact that, although lean-NO_x reduction catalysts have undergone major development in the last few years, their application to diesel engines was far more difficult than their application to lean-bum gasoline engines. Little data on lean-NO_x catalysts with diesel engines was presented by the manufacturers, but there is guarded optimism that such catalysts may emerge from the research stage within the next five years. Commercialization may occur after 2005, making the diesel a contender in cars even under LEV standards by the 2010 timeframe.[ti]

Light trucks are potentially a more attractive market for the diesel. Even now, diesels sell very well in the 8,500 to 14,000 lb light-heavy truck market (classified as heavy-duty by EPA). The higher torque of the turbocharged DI diesel is more attractive to pickup truck owners, and light-truck emission standards are somewhat less stringent than passenger car standards. Moreover, the fuel consumption advantage makes diesels more cost-effective in trucks because they consume more fuel each year.

Direct Injection Diesel Price Effect

Costs of the DI diesel in both naturally aspirated form and in turbocharged form were estimated as a $100 increment over a IDI 4-cylinder engine. As the base IDI itself is a $400 to $450 increment over a gasoline engine, and turbocharging adds $450 to $500, the net RPE effect should be about $950 to $1,050. The VW DI turbodiesel is priced at 1,600 DM ($1,085) above the 1.6L gasoline engine, almost exactly at the upper limit of the above price estimate. Four-valve DI diesels with lean-NO_x catalysts will require another $110 (for the four-valves over two-valve) and about $100 for the catalyst so the total price impact for four-cylinder turbocharged four-valve

65 D. Stock and R. Bauder, "The New Audi 5-cylinder Turbo Diesel Engine," SAE paper 900648,1990-

66 There are a range of views concerning NO_x catalysts for diesels. The Japanese, who are well advanced on lean-bum catalysts for gasoline engines, are somewhat pessimistic about the potential for rapid progress on diesel catalysts; U.S. companies are more optimistic, and some believe commercialization of such catalyst could come before the year 2000. One interesting reference point: diesel oxidation catalysts have recently been introduced, 18 years after introduction of gasoline oxidation catalysts.

DI diesel over a two-valve gasoline engine is $1,160 to $1,260. Costs for a V-6 are estimated $1,570 to $1,680, and for a V-8 at $1,950 to $2,050. The turbocharged V-8 DI diesel is also currently available in Ford and GM light-heavy duty trucks and is priced at $2,200 to $2,300. These are two-valve engines with no catalyst, but they have very large displacement, so that an equal performance gasoline engine would reduce the RPE increment to about $1,700--approximately consistent with the estimate for a two-valve DI diesel.

ELECTRIC DRIVETRAIN TECHNOLOGIES

Introduction

The appeal of using electricity to power automobiles is that it would eliminate vehicular air pollution (although there would still be pollution at the power source), and that electricity can be reversibly translated to shaft power with precise control and high efficiency. The main problem with this use is that electricity cannot be easily stored on a vehicle. California's mandate for the introduction of zero emission vehicles in 1998 has resulted in a major research effort to overcome this storage problem. The only commercially available systems for storage today, however, are the lead acid and nickel-cadmium battery, and both have limited capabilities. The lead acid battery's limited storage capacity and substantial weight are ill-suited to a vehicle's needs, although advanced versions of this battery reduce some of these limitations; the nickel-cadmium battery is very expensive and requires careful maintenance.

Electricity can also be produced onboard a vehicle by using an engine and generator. Simply feeding the generated electricity directly into a drive motor to power the wheels, however, would probably be less efficient than a mechanical transmission, because the combined generator and motor losses may outweigh transmission losses. The total system can be made more efficient, however, if the engine is operated at near constant output close to its most efficient point, and any excess electricity is stored in a buffer, which is used to satisfy the variable electrical demands of the motor and other vehicle power demands. Vehicles with powertrains combining a device to store electrical energy and another to produce it are called hybrids. The storage or buffer device can be an ultracapacitor, flywheel, or battery, depending on system design; the electricity producer can be an internal combustion engine or, perhaps, a fuel cell, which would be both highly efficient and almost non-polluting.

The sections that follow discuss new technology under development for batteries for electrical energy storage, fuel cells for energy production, capacitors/flywheels for peak power storage, and motors for conversion of electrical power to shaft power. The discussions focus on a selected set of technologies likely to be competitive in the future marketplace (at least according to current wisdom), and their efficiency and cost characteristics. *The data and descriptions presented in this section can become out-of-date very quickly, especially if there are breakthroughs in the design or manufacturability of the technologies. Hence, the projections in this section represent an extrapolation of technology performance into the future based on information mailable as of*

mid-1994. New technology competitors may emerge very quickly and new findings may render existing "competitive" technologies poor prospects for the future.

Battery Technology

Requirements

A battery is a device that stores electricity in a chemical form that is released when an external circuit is completed between the battery's opposing terminals. The battery, which provides both energy and power storage, is the critical technology for electric vehicles. Unfortunately, the weak link of batteries has been their low energy storage capacity--on a weight basis, lower than gasoline by a factor of 100 to 400. Power capacity may also be a problem, especially for some of the higher temperature and higher energy batteries. In fact, power capacity is the more crucial factor for hybrid vehicles, where the battery's major function is to be a load leveler for the engine, ***not*** to store energy. Aside from increasing energy and power storage, other key goals of battery R&D are increasing longevity and efficiency and reducing costs.

Traditionally, the storage characteristics of conventional lead-acid batteries have been so poor that electric vehicles (EVs) have been extremely heavy, with poor acceleration performance and limited range. Battery technology research sponsored by the U.S. Advanced Battery Consortium (ABC) has sought to develop new batteries with improved storage and other characteristics. The performance characteristics of a battery relevant to use in vehicles can be defined by the following parameters, for which ABC has set goals.[67]

The **specific energy** is a measure of the total quantity of energy stored per unit of battery weight. ABC has set a goal of 80 watt-hours/kilogram (with 100 Wh/kg desired) as a mid-term goal and 200 Wh/kg as a long term goal for this parameter. In contrast, conventional lead acid batteries have specific energy levels of 25 to 28 Wh/kg.

Specific power is a measure of how much power per unit weight the battery can deliver per second to handle peak requirements for acceleration and grade climbing. ABC's mid- and long-term goals are 150 W/kg (200 W/kg desired) and 400 W/kg respectively for a 30-second pulse of power. Conventional lead acid batteries can provide as much as 100 W/kg when fully charged, but their peak power capability declines rapidly as they are discharged, and is about 60 W/kg at 80 percent depth-of-discharge (DoD). To some degree, specific power is a function of battery design, and especially trades off with specific energy. Hence, batteries designed for high power may differ from those designed for high energy.

The sustainability of peak power levels is an important issue for hybrid vehicles. The peak power values quoted in this section are based on a 30-second pulse. Batteries may not be able to sustain even half this peak level, if the duration is in the order of two to four minutes. However, the capability of the battery to deliver high power is a function of its design as well as the battery

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67 U.S. Advanced Consortium, "Update," October 1994.

cooling system installed to prevent thermal degradation. At this point, it is unclear whether all of the battery types described below can provide half the rated peak power for several minutes, as is required for a hill climb.

Life can be based on both calendar years and charge/discharge cycles. USABC has set mid- and long-term goals of 5 and 10 years and 600 and 1,000 cycles respectively. Conventional lead acid batteries in electric car use have a life of only about two to three years and 300 to 400 cycles. For some batteries, calendar life and cycle life may present different limiting constraints, and the life itself is affected by how deeply a battery is discharged.

There are several other parameters that are of major concern, such as the power density and energy density, which are measures of battery power and energy storage capabilities on a volumetric basis (to avoid very large batteries), power and energy degradation over the useful life, fast recharge time, range of ambient operating conditions, maintenance requirements, and durability. USABC goals for some of these parameters are shown in table 3-10. In addition, there are special concerns with each battery type that include behavior at low charge, special charging characteristics, and recyclability. This review of batteries is not meant to be comprehensive nor intended to cover all of the above factors. Rather, the intention of the review is to describe automanufacturer concerns and battery manufacturer inputs on the current status of battery development, while the conclusions reflect only OTA's opinion on battery prospects.

Credible specification of battery parameters is critical to judging EV capabilities, but in fact such specification is difficult to come by. Measuring battery parameters raises many issues, as the results are sensitive to the test procedure and ambient conditions employed. For example, most batteries display reduced energy densities at higher power levels, as well as during cyclically varying power draws (as will be the case in an electric vehicle). Yet, specific energy values generally are quoted at a constant discharge rate that would drain the battery in three hours (c/3). As noted, many batteries also display significant reductions in power density at low state-of-charge, and at reduced ambient temperatures, while available data may be for filly charged batteries at 20°C. Finally, battery characteristics are often different among single cells, modules, and collections of modules required for a high-voltage battery. In many battery types, the failure of a single cell, or variations (owing to production tolerances) between cells often has significant impact on battery performance.

Auto manufacturers interviewed by OTA universally agreed that many battery manufacturer claims about battery performance and longevity are unlikely to be reproduced in a vehicle environment. European manufacturers have devised new testing procedures through their joint consortium, EUCAR, that appear to be more stringent and comprehensive than those performed previously by USABC or by DOE affiliated laboratories;[68] similarly, USABC in 1994 also revised its testing procedures, which are now reported to be very stringent. Auto manufacturers stressed the need to test an entire high-voltage battery system with the thermal and electrical management systems included as part of the overall system to obtain a good picture of real-world performance.

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[68] EUCAR Working Group, "Battery Bench Tests," 2nd progress report, July 1994.

Battery Characteristics

For this discussion, batteries have been divided into four thematic groups: lead acid, alkaline, high temperature, and solid electrolyte. Various battery designs have been examined that would fall under the latter three types, and obtaining comprehensive data on their current development status and characteristics is challenging; a listing of the various types under development and their developers is given in table 3-11. The discussion focuses on batteries that are potential winners according to the current consensus, but it should be noted that the list of "winners" has changed considerably during the last five years. For example, in 1991, the nickel-iron and sodium-sulfur batteries were considered the most promising, but are no longer the leading contenders.

Lead acid

Lead acid batteries have been in existence for decades, and more advanced traction batteries with improved specific power and energy, as well as durability, are under development. Delco Remy's VRLA battery is perhaps is the most advanced battery commercially available (though in limited quantity), and it has claimed the following characteristics per battery module: a specific energy of 35 Wh/kg, specific power of 210 W/kg (filly charged) and 150 W/kg at 20 percent charge, and over 800 cycles of life at 50 percent DoD. Delco also offers a "battery package" including fill thermal and electrical management. An entire 312V system with 26 modules and battery management has a net specific energy of 30.5 Wh/kg.[69]

Other recent developments include the woven grid pseudo-bipolar lead acid battery from Horizon, which has a demonstrated specific energy of 42 Wh/kg and peak power of 500 W/kg at fill charge and 300 W/kg at 80 percent DoD at the cell level. Horizon claims life in excess of 900 cycles at C/2 and has begun delivery of complete batteries from a pilot production plant.[70] Horizon anticipates additional improvements to specific energy levels over 48 Wh/kg at the module level, and expects other benefits, such as fast charging, owing to the batteries' low internal resistance.

Bipolar lead acid batteries under development offer even higher power densities and energy densities than the Horizon battery, with specific power of 900 W/kg and specific energy of 47 Wh/kg demonstrated by ARIAS Research at the module level.[71] The traditional problem with bipolar batteries has been with corrosion at the electrode interfaces, and it is not yet clear whether this problem has been solved over the life of the batteries. Nevertheless, the new designs show promise in providing significant improvements in power and energy density, but providing reasonable life may still be a serious problem.

Alkaline Systems

The three most successful candidates in this category are nickel-cadmium, nickel-iron and nickel-metal hydride. Nickel-cadmium (Ni-Cd) batteries are available commercially, but the major

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69 Ibid
70 Ibid
71 David Harbaugh, "The Role of the SBLA Battery in Meeting California's Clean Air Act Goals," paper presented at the 12th International EV Symposium, December 1994.

problem has been their relatively modest improvement in specific energy over advanced lead acid batteries in comparison to their high cost. Modern Ni-Cd batteries have specific energy ratings up to 55 Wh/kg, which is about 25 percent better than the Horizon lead acid battery. They cost at least four times as much,[72] but these higher costs will be offset to an extent by Ni-Cd batteries' longer cycle lives. High-energy versions of these batteries require maintenance and their capacity changes with charge/discharge cycles. Sealed Ni-Cd batteries that are maintenance free have significantly lower specific energy (35 to 40 Wh/kg), although there is ongoing research to avoid this penalty. In addition, concerns about the toxicity of battery materials and the recyclability of the battery has resulted in reduced expectations for this battery.

<u>Nickel-iron</u> batteries received considerable attention a few years ago, but interest has faded recently. Their specific energy is about 50 Wh/kg, and their costs are similar to, or slightly lower than, those for Ni-Cd batteries.[73] Although they have demonstrated good durability, they require a sophisticated maintenance system that adds water to the batteries and prevents overheating during charge. In addition, they cannot be sealed, as they produce hydrogen and oxygen during charging, which must be vented and pose some safety problems. The formation of hydrogen and oxygen also results in reduced battery charging efficiency, and these features account for the lack of current interest in this battery.

<u>Nickel-metal hydride</u> batteries have received much recent attention lately, and Ovonic and SAFT are the leading developers of such batteries. The maintenance-free Ovonic batteries have demonstrated specific energy values in excess of 80 Wh/kg at the module level and specific power densities of over 200 W/kg.[74] However, automanufacturers have stated that these batteries have high internal self discharge rates, especially at high ambient temperatures, with losses of 32 percent over 5 days at 40°C.[75] Automanufacturers have also noted that Ovonic batteries have capacity limitations at low temperatures when discharged quickly, and they are worried about hydrogen buildup during charging. Nevertheless, the Ovonic batteries' demonstrated capabilities and the potential to overcome these problems has led to optimism about their prospects for commercialization. GM and Ovonics have entered into a joint venture to produce the battery, and pilot production may occur in late-1996. It should be noted that a complete battery to power an EV has only recently become available, and prototype testing will demonstrate the battery's durability in an EV environment.

Auto manufacturers do not believe that the Ovonic battery can be manufactured at low cost, especially as other battery manufacturers developing nickel metal hydride batteries do not support Ovonic's cost claims. Ovonic has suggested that the batteries can be manufactured at $235/kWh and perhaps below, whereas others expect costs to be twice as high (~$500/kWh) in volume production.[76] It should also be noted that the batteries are not yet easily recyclable, as the complex metal hydride used by Ovonic can only be regenerated today by an expensive process.

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[72] Nissan, presentation to OTA, June 1994.

[73] Eagle Pitcher Industries, Specification Sheets for EPI Nickel-Iron battery NIF-2005 used in Chrysler T-van, n.d.

[74] D.A. Corrigan et al., "Ovonic Ni-MH Electric Vehicle Batteries," paper presented at the 12th International EV Symposium, December 1994.

[75] EUCAR, see footnote 68.

[76] F.J. Kruger and R. Gereth, "Advanced Battery Systems for Electric Vehicles," paper presented at the 12th International EV Symposium December 1994.

High-temperature batteries

This category includes sodium sulfur, sodium-nickel chloride and lithium-metal disulfide batteries. All high-temperature batteries suffer from the fact that temperature must be maintained at about 300°C, which requires a sophisticated thermal management system and battery insulation and imposes a lack of packaging flexibility. Moreover, thermal losses must be compensated by electrical heating when the vehicle is not in use, so that these electrical losses are similar to self discharge. Hence, these losses may significantly increase total electrical consumption for lightly used vehicles. Meanwhile, these batteries offer much higher levels of energy storage performance than lead acid or alkaline systems and are insensitive to ambient temperature effects.

<u>Sodium sulfur</u> batteries have been in operation for more than a decade in Europe and offer high specific energy (100 Wh/kg) with relatively low-cost battery materials. They have the favorable characteristic of their specific power's not declining significantly with the state-of-charge, although the specific power value is a relatively low 130 W/kg.[77] More recently, Silent Power has unveiled a new design, the MK6, with a specific energy of 120 Wh/kg and specific power of about 230 W/kg.[78] However, the corrosivity of the battery materials at high temperature has led to limited calendar life (to date), and reliability is affected if the battery "freezes." Even now, a leading manufacturer, ABB, claims a battery life of less than three years for its sodium sulfur-battery. Silent Power has estimated a selling price of $250/kWh in volume production of 1050 units/month for its MK6 battery.

<u>Sodium-nickel chlori</u>de batteries have many of the sodium sulfur batteries' favorable characteristics along with reduced material corrosivity, so that they may have longer calendar life. These batteries are being extensively tested in Europe, and the latest versions (dubbed ZEBRA in Europe) have shown energy densities over 80 Wh/kg and specific power of over 110 W/kg at full charge.[79] Other advancements are expected to increase both specific energy and specific power. However, specific power drops to nearly half the fully charged value at 80 percent DoD, and possibly is also reduced with age or cycles used. Despite this problem, this battery type has emerged as a leading contender in Europe owing to its potential to meet a life goal of five years.

<u>Lithium-metal sulfide bipolar</u> batteries hold the promise of improvements in specific energy and power relative to the other "hot" batteries, but they are in a very early stage of their development. Work by Argonne National Laboratories has shown very good prospects for this type of battery. It is lithium's low equivalent weight that gives lithium batteries their high-energy content of three to five times that of a lead acid battery. Research efforts on lithium-metal sulfide batteries of the bipolar type are being funded by the USABC, and battery developers hope to achieve specific energy levels of over 125 Wh/kg and power levels of 190 W/kg.[80] Initial tests on cells have indicated approximately constant power output with battery DoD, and the system also holds the potential for long life and maintenance free operation, but substantial research is still required to

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[77] K. Scheurer and A. Goubeau, "The BMW-E1, A Purpose Designed Electric Vehicle," paper presented at the 11th EV Symposium, September 1992.

[78] W. Auxer, "Sodium-Sulfur High Energy Battery: Status of Development," paper presented at the 12th International EV Symposium, December 1994.

[79] D. Sahm and J. L. Sudworth, "Lifetime and Reliability Testing of Zebra-Batteries," paper presented at the 12th International EV Symposium, December 1994.

[80] Westinghouse, "Westinghouse Electric Propulsion Systems," brochure, 1994.

meet these goals. Problem areas include corrosion and thermal management, as well as durability. At this point, an EV-type battery or module has not yet been fabricated.

Lithium-Ion

This battery type has many supporters who consider it a leading long term candidate for EV power. The battery has been studied at the cell level and has demonstrated the following advantages[81]:

- high specific energy of about 100 to 110 Wh/kg,
- good cycle performance with a life of over 1,000 cycles at 100 percent DoD,
- maintenance free system,
- potential for low cost.

The battery developer, SAFT, has used a lithium-nickel oxide alloy ($LiNiO_2$) as the anode and a carbon cathode, with an electrolyte of confidential components to demonstrate a prototype cell with the above properties. SAFT has publicly stated that it can attain a specific power of about 200 W/kg, and costs near the $150/KWh goal, similar to the statements of other battery developers. Nevertheless, there is much development work to be done, as the current system is seriously degraded by overcharge or overdischarge, and a mass production process for the anode material is not well developed.[82] The battery holds promise for commercialization in the post-2005 time frame.

Solid electrolyte batteries

These batteries are potentially extremely “EV friendly” batteries in that they are spillage proof and maintenance free. A schematic of the lithium polymer battery is shown in figure 3-4, and the battery can be manufactured as “sheets” using manufacturing technology developed for magnetic tape production. Many problems still remain to be resolved for lithium-polymer rechargeable batteries including the need for reversible positive electrode materials and stable high conductivity polymers as well as scale-up problems associated with high voltages and current. Researchers at Oak Ridge National Laboratory (ORNL) have projected specific energy and power of 350 Wh/kg and 190 W/kg, respectively, but these figures are based on laboratory cell performance data.[83] Actual data from Westinghouse and 3M suggest that the specific energy and power from an entire battery may be at half the levels projected by ORNL for a single cell.[84] Other researchers have

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[81] R. Staniewicz, "Lithium-Ion Battery System- for EVs," paper presented at the 12th International EV Symposium, December 1994.

[82] Ibid.

[83] J.B. Bates et al., "Thin-Film Rechargeable Lithium Batteries," paper presented at the Automotive Technology Development Contractors Coordination Meeting, U.S. Department of Energy, October 1994.

[84] Westinghouse and 3M staff, persona1 communications, October 1994.

suggested that sodium-polymer batteries may be superior to lithium-polymer versions, and could have lower costs. However, even a prototype EV size battery is possibly several years away.[85]

As noted, the previous discussion covers only those battery types that are highly regarded today, but there are numerous other electrochemical couples in various stages of development with the potential to meet USABC goals. These include nickel-zinc, zinc-bromine, and sodium-polydisulfide systems; these are being actively researched but need considerable development before they can become serious contenders. Nickel-zinc and zinc-bromine batteries have energy densities comparable to Ni-MH batteries but significantly lower power densities of about 100 W/kg, so that they can compete only if costs are low and they have long life.[86] Sodium-polydisulfide batteries are in a very early stage of development and little is publicly known about their performance parameters.

Table 3-12 provides a summary of the state-of-the-art for batteries of different types. It is important to note that the actual <u>usable</u> specific energy and power can differ significantly from the values listed for some batteries. Lead acid batteries should not be discharged to below 80 percent DoD, for example, so that usable specific energy is only (40x 0.8) or 32 Wh/kg for the advanced lead acid battery.

Bringing an Advanced Battery to Market

Table 3-12 also shows the development status of the batteries, which differs considerably between battery types. Initial testing of a simple cell at the laboratory is basically a proof-of-concept, and is utilized to test the stability and output under carefully controlled conditions. A group of cells aggregated into a module is the first step toward a functional battery, and scaleup, cell packaging, interconnections between cells, and multiple cell charge and discharge control are demonstrated in this phase. The development of a prototype EV battery with an overall energy storage capability of 20 to 40 kwh at a voltage of 200 to 300 V involves collections of modules in an enclosure with appropriate electrical and thermal management. These batteries typically must be tested extensively in the real world EV environment to understand the effect of severe ambients, vibration, cell failures, and cyclically varying discharge rates--all which can have significant effects on the usable power, energy, and life of a battery that is not properly designed. A preproduction battery is one that has been redesigned to account for the real world experience, and is also suitable for mass production. Typically, preproduction batteries are built at modest volumes of a few hundred per year to ascertain whether the production process is suitable for high-volume output with low-production variability.

Many new entrants in the advanced battery arena have made bold claims about the availability of their particular battery designs for commercial use in time to meet the California “ZEV” requirements for 1998. More established battery manufacturers contest their claims, and have stated that several years of in-vehicle durability testing is required before a preproduction design can be completed, as batteries often fail in the severe EV environment. The case of ABB’s

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85 *There are rumors* of a breakthrough by Valence, Inc., which has a joint venture with Delco Remy in the development of a commercially viable lithium-polymer prototype battery, but no information is publicly available on actual battery performance.

86 G.L. Henriksen et al., "Advanced Batteries for Electric Vehicles,” ***CHEMTECH, November,*** 1994.

sodium-sulfur battery is illustrative. Early prototype batteries were available during the late- 1980s and tested by Mercedes and BMW. These prototypes had a calendar life of about six months and were plagued by excessive failures. Second generation prototypes were supplied to BMW and Ford, and these doubled calendar life to about one year. More recently, two of the Ford Ecostar vehicles have reported fires during charging. ABB is currently providing third generation prototypes to Ford, but even these are not considered production ready. ABB is willing to guarantee a calendar life of only one year in EV services for its latest sodium-sulfur prototypes, although actual life may be two to three years.[87]

Although the sodium-sulfur battery may pose especially difficult development problems, such *experiences are reported even for advanced lead acid batteries whose basic principles have been utilized introduction batteries for many decades.* INEL reports that the Sonnenschein advanced lead acid battery has demonstrated very good cycle life in the laboratory, but that its in-use reliability is very poor.[88] Once a battery has moved beyond the single-cell stage, manufacturers estimate that a minimum of three years per stage is required to move to the module, prototype battery, and preproduction battery stages, and a total testing time of nearly a decade will be necessary for a proven production model.

This estimate of time assumes that problems are successfully tackled in each stage and that manufacturing processes can replicate cells with very little variability in mass production--an assumption that remains unproven for almost all advanced battery types demonstrated to date. Based on this, it is reasonable to conclude that batteries whose status is listed “3” in Table 3-12 will not be mass produced until 2000 at the earliest.[89]

Vehicle lifetime costs depend on the battery durability, an issue about which little is known except for the fact that usable lifetimes are quite different for different batteries. It should be noted that battery life depends on the desire of the battery system and its usage pattern. Also, there are tradeoffs between battery life and cost, specific energy, specific power, and user specification of end-of-life criteria. For example, a battery may have very different “life,” if the end-of-life criterion is set at 90 percent of initial energy density, or is set at 80 percent. Nevertheless, for almost any set of reasonable criteria for end-of-life that are acceptable to auto manufacturers, there are currently no advanced batteries that have demonstrated an average five-year life in the field, nor have any battery manufacturers been willing to warranty a battery for this period. Hence, even the prospect of five-year life in customer service is unproven and is an input assumption for most analyses of battery costs.

Cost per kilowatt-hour of storage capacity in table 3-9 is based on production rates of at least 10,000 modules per month and are estimated from the educated guesses of battery manufacturers, (except for the nickel-metal hydride battery where the cost controversy was noted earlier). The cost estimates in the table are based on both battery and auto manufacturer inputs. Although OTA has attempted to include only estimates that appear realistic given current knowledge, these estimates may still be unreliable as most battery types are not yet production ready.

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[87] M.L. Shemmans, ABB, personal communication, December 1994.

[88] EUCAR, see footnote 68.

[89] California requirements for 1998-1999 can be met with pilot production as the total sales requirements are low. The ZEV mandates have been adopted by New York and Massachusetts, however.

Hybrid Batteries and High Power Requirements

Most of the above discussion has focused on electric vehicle (EV) type batteries where specific energy is a major concern. Batteries used in hybrid vehicles do not necessarily need to store much energy (although some hybrids can resemble EVs) but must be capable for providing relatively high power for short duration. Bipolar designs, where the anode of one cell and the cathode of the next are mounted on opposite sides of the same plate or surface, can have high specific power--as much as three to five times that of conventional designs, owing to their high current capacity and low internal resistance. Although such designs have demonstrated specific power levels of 500 to 900 W/kg at the module level in the laboratory, even for a lead-acid type battery (see discussion on the bipolar lead-acid battery) many automanufacturers and battery experts believe that corrosion and cycle life present daunting problems for high power batteries. **Hence, batteries for hybrid vehicles are potentially more difficult to commercialize and may require a longer lead time than EV batteries.**

Fuel Cell Technology

Many researchers consider fuel cells to be the ultimate answer to power motor vehicles, because they combine the positive attributes of batteries--zero or extremely low emissions and quiet operation--with the quick refueling capability of internal combustion engines. A fuel cell is an electrochemical device that converts the chemical energy in a fuel to electrical energy directly without first converting the chemical energy to heat energy. As a result, the thermodynamic limitations imposed by the Carnot cycle are not applicable, and fuel cells can have theoretical efficiencies of more than 90 percent. In addition, if the fuel used is hydrogen, the energy conversion process is essentially pollution free, as fuel cells can convert hydrogen and the oxygen in the air directly to electricity and water. With other fuels, such as methanol or hydrocarbons, an external reformer may be necessary to first separate the hydrogen from the fuel the reforming process will generate small quantities of carbon monoxide and other pollutants, and substantial quantities of carbon dioxide.

For this analysis, aluminum-air and zinc-air cells are treated as fuel cells because they are mechanically recharged, although they are sometimes called batteries. These cells use aluminum or zinc as material inputs, and these are consumed and replaced. Zinc-air cells can be electrically recharged, but no practical system to accomplish this has been demonstrated at the module level.[90]

Aluminum-Air and Zinc-Air Cells

Aluminum-air cells and zinc-air cells are constructed like batteries except that the aluminum or zinc anodes are consumed as electricity is produced, and dissolve into an aqueous electrolyte. To “recharge” one of these cells, the anode and electrolyte are replaced and the old electrolyte is

90 More recently, a research group claims to have solved the problems of recharging and state that they have demonstrated over 100 charge-discharge cycles at the cell level. However, the rechargeable cell has poor recharging efficiency due to energy losses at the air electrode. Chris Borroni-Bird, personal communication, Chrysler Corp., Apr. 20, 1995.

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other types of cells are viewed as having more difficult problems in adapting to light-duty vehicle requirements. Solid oxide fuel cells, for example, operate at very high temperature (~1000°C), although their fuel flexibility and high-power density are attractive features. Alkaline cells are easily poisoned by $C0_2$ and require pure oxygen, presenting serious challenges for transportation use. Phosphoric acid fuel cells are relatively advanced, operate at relatively manageable temperatures of about 160° to 220°C, and can be considered as mature technology for large stationary source applications. Also, they recently have been adapted for use in buses (see Box 3-1). Their bulk and low-power density, however, are an important barrier to automotive use. PEM fuel cells operate below 100°C and are currently widely considered the only fuel cell candidate likely for car use in the near future, with the phosphoric acid cell being restricted to bus or heavy-duty truck use. For the longer term, solid oxide fuel cells and fuel cells that can directly transform methanol into electricity (direct methanol fuel cells) are strong candidates for light-duty vehicular use.

The PEM cell is essentially a sandwich composed of a hair-thin polymer membrane that serves as an ion-conducting electrolyte, between thin sheets of a porous, conducting material, coated with platinum catalyst, that serve as electrodes. One of these electrode/membrane/electrode assemblies may be less than one millimeter in thickness; these assemblies are stacked to form the fuel cell. Hydrogen is delivered to the anode, and oxygen (or air) to the cathode. The polymer membrane/electrolyte conducts protons but seines as a barrier to electrons. At the anode, hydrogen separates into hydrogen ions and electrons, aided by the platinum catalyst. When an electrical circuit is connected between anode and cathode, electrons flow through the circuit. The hydrogen ions flow through the membrane, combining with the returning electrons and oxygen at the cathode to form water. The cell operates at about 200°F, so that elaborate heat-management equipment is unnecessary.

A fuel cell system consists of a stack of individual cell "sandwiches," which produce the electricity; an air compressor to provide pressurized air to the fuel cell; a cooling system to manage waste heat; a water management system to keep the polymer membranes saturated and to remove the water created at the cathode; and a fuel source. The requirement for hydrogen fuel means that either hydrogen must be carried onboard the vehicle in a storage vessel, or it must be produced from a "hydrogen-earner" fuel such as methanol. In the latter case, hydrogen is produced by steam-reforming or partial oxidation of the fuel and the reformer should be considered as part of the overall system, especially in estimates of cost and system efficiency. Methanol is the preferred fuel for PEMs because reforming requires only moderate temperatures of about 300°C or less, whereas other fuels such as ethanol or natural gas require substantially higher temperatures, implying both higher expense and reduced system efficiency.

Some recent evaluations of PEM fuel cell prospects have been quite optimistic. Allison, for example, projects that a 60 kW system (60 kW is a reasonable output for a small car), including the reformer for extracting hydrogen from methanol, should cost about $3,000 in mass production, or about $46/kW.[95] Although the fuel cell cost does not include the cost of either

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95 Allison Gas Turbine Division, General Motors Corp., "Research and Development of Proton-Exchange Membrane (PEM) Fuel Cell System for Transportation Applications: Initial Conceptual Design Report," EDR 16194, U.S. Department of Energy, report prepared for Office of Transportation Technologies, Nov. 30,1993.

hydrogen storage or an electric motor, and thus should not be compared directly to the costs of an internal combustion engine drivetrain, costs this low would appear to make the fuel cell a viable competitor with the ICE--and it would be several times as efficient. General Motors projects the efficiency of a PEM cell to be 55 percent to 70 percent using hydrogen fuel or 40 percent to 55 percent with methanol as a hydrogen carrier. Energy density currently is about 200 W/kg, but GM hopes to raise this to 333 to 500 W/kg.[96] Mercedes Benz has recently demonstrated a prototype PEM cell that operates a van. Although the existing system occupies essentially all of the van's cargo space, Mercedes apparently believes it can have a production prototype ready within 5 years or so.[97]

The PEM fuel cell stack has been the subject of extensive research over the last five years, and some recent designs, especially by Ballard, have shown considerable promise. The current Ballard cell has a specific power rating of only 200 W/kg, equivalent to that of advanced lead acid batteries, and has demonstrated full load efficiencies in the range of 36 to 46 percent.[98] Although there have been some assertions that commercial PEM fuel cells can be available relatively quickly, most researchers suggest that a commercial model is still at least 12 years away, and such swift commercialization would require both continued government finding of research and rapid resolution of a number of remaining problems. Pessimistic assumptions on these factors leads to an estimate of 20 to 25 years for commercialization.[99] The goals are to double the specific power and reduce cost by an order of magnitude or more while increasing efficiency to more than 50 percent.

Current PEM fuel cells have been built with relatively high platinum loadings for the catalyst, and use expensive membranes which some believe are "over-specified" for automotive use. Moreover, the graphite bipolar plates are expensive. Highly conducting, corrosion resistant alternatives are needed to reduce costs in this area. Large reductions in platinum loadings--thus far achieved only in small laboratory cells--and cheaper membrane technologies also are required if the PEM fuel cell is to be manufactured at reasonable cost. Significant progress has been made in these areas, especially in reducing platinum loading at the laboratory cell level, although much remains to be done to scale up to an EV size stack. It is unclear whether cheaper membranes and plates will result in efficiency reductions, creating tradeoffs between competing goals. Current PEM fuel cells also require very pure water to hydrate the membrane, and, hence, startup at low temperatures poses difficulties with freezing.

Although the PEM stack fueled by hydrogen itself can be quite efficient (about 60 percent at its maximum efficiency point, about half of rated power), the accessory drives require power that detracts from overall system efficiency.[100] As noted above, the drives provide hydrogen to the anode, compressed air to the cathode, water to hydrate the membrane, and a cooling system to remove waste heat, all of which requires substantial power. For example, a 25 kW stack that is 50 percent efficient at rated power will generate 25 kW of heat to be removed by the cooling system,

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[96]General Motors briefing charts.

[97]Daimler-Benz, *High Tech Report,* March 1994.

[98]P. Howard, "Ballard Zero Emission Fuel Cell Bus Engine," paper presented at the 12th International EV Symposium, 1994.

[99]H.F. Creveling, "PEM Fuel Cell for Transportation Applications," paper presented at the Automotive Technology Development Contractors Coordination Meeting, U.S. Department of Energy, October 1993.

[100]C. Borroni-Bird, Chrysler Corp., "The Challenges Facing Fuel Cells for LDV Applications," presentation to OTA, Sept. 19,1993.

a requirement that implies some minimum water pumping--and power--requirements. Auto manufacturers believe that the focus of research to date has been on basic R&D for the stack but that not much has been done on system integration and in engineering the PEM fuel cell to adapt to the car. Even with a well-engineered hydrogen fueled PEM cell, manufacturers expect to attain system average efficiencies over the FTP driving cycle of only about 50 percent or less when installed in a car. This implies that "balance of plant" efficiency will be about 80 percent.

Efficiency will be still lower if methanol or another fuel is used instead of hydrogen. Current PEM fuel cells displayed by Mercedes and Ballard do use pure hydrogen as a fuel, but this arrangement creates important storage difficulties. The alternative of making hydrogen on board from methanol is also the subject of continuing research sponsored by the DOE. Large-scale hydrocarbon reformers are well developed technologically. The thermodynamics of methanol-steam reactions indicate that a minimum of **25** percent of the energy content of methanol is required for conversion to hydrogen and carbon dioxide.[101] The energy requirement is associated with the heat required for steam generation, methanol vapor generation, and reformer reaction heat. This heat can be supplied by the heat rejected by the fuel cell stack, however, so that it need not reduce overall system efficiency. Control of heat flows is a major challenge in designing a compact on-board reformer. In addition, the reformer introduces a lag in system response, as hydrogen must be supplied at a rate that varies with the power demand from the fuel cell. Although a battery can provide power for transient power demands in addition to providing instantaneous vehicle power from a cold start, this adds weight and complexity to the system. Reforming occurs over a catalyst that operates best at about 250° C, but this implies that the catalyst must be preheated before the reformer supplies hydrogen.

Another problem posed by the reformer is pollution created by the reforming reaction; some untreated methanol and CO will exit from the reformer and must be removed to avoid contaminating the fuel cell stack. Removing these gases is difficult and expensive, however. Typically, two packed catalyst beds are used to reduce these contaminants to very low levels. However, CO concentrations remain over 0.25 percent even after catalytic treatment,[102] and PEM cells are poisoned even by 10 ppm of CO. Further control is by a preferential oxidation (PROX) unit, where air is mixed with the reformer output and passed over a platinum-alumina oxidation catalyst. It is not yet clear whether the PROX unit can control CO to very low levels over a wide range of flow rates and demonstrate the durability required for vehicle use. Strategies such as an air bleed into the fuel mixture appear to prevent poisoning, but at some loss in efficiency. Alloy catalysts more resistant to CO poisoning are under development.

In summary, the use of a methanol-based system, instead of using pure hydrogen as a fuel introduces a range of difficulties. First, the system efficiency is degraded owing to the increased stack inefficiency as well as greater needs for the "balance-of-plant." Second, the time lag between power demand and hydrogen production indicate that a battery system will be required to provide power for transient accelerations, further adding to weight and complexity. The battery system will also be required to power the vehicle if instantaneous response from cold start is desired.

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101 R.D. Sutton and N.E. Vanderborgh, "Electrochemical Engine System Modeling and Development" paper presented at the Automotive Technology Development Contractors Coordination Meeting, U.S. Department of Energy, October 1993.

102 Ibid

Third, the presence of CO and $C0_2$ in the input fuel stream poses significant problems for the fuel cell stack and removing these gases is relatively difficult. The result is that system efficiency and specific power and specific energy will be reduced so that the net fuel efficiency of the vehicle may not be much better than would be achieved with a diesel engine. The use of hydrogen derived from methanol reduces stack efficiency by *4* to 5 percent, and balance of plant efficiency could be reduced by another few percent. Simulations by Argonne National Lab suggest that a realistic system efficiency range for a methanol-based fuel cell is 38 to 47 percent at full load,[103] substantially under the 60 percent often quoted for the fuel cell. Part load efficiency could be higher or lower and is dependent on system design and "balance-of-plant" efficiency at different load factors. For systems using partial oxidation reformers and burning diesel or gasoline, overall system average cycle efficiencies could be less than 40 percent.[104]

Given the fact that the PEM fuel cell is just emerging from the basic research stage, it is difficult to estimate costs of a commercial model, as cost could vary greatly depending on the success in reducing platinum loadings; developing lower-cost membranes; reducing the size and cost of methanol reformers, or developing low-cost, high-energy-density onboard hydrogen storage; shrinking fuel cell "balance of plant;" and other R&D needs.[105] Researchers at Los Alamos National Laboratory estimated that current designs could cost $1,800/kW (manufacturer's cost) in volume production, but their most optimistic projection with future technology improvements was $40/kW (without methanol reformer).[106] GM/Allison has estimated that a total system cost of fuel cell and reformer could be $65/kW in volume production,[107] and some industry analysts hope to reduce costs still further. Some PEM cell manufacturers, however, suggest costs could come down by a factor of 5 (i.e. to $400/kW for the fuel cell system without hydrogen storage or methanol reformer).[108] Box 3-2 presents some basic arguments presented by fuel cell advocates in favor of their conclusion that fuel cell costs can be reduced to levels that will be competitive with internal combustion engines.

It is difficult to evaluate these cost estimates, because even those that present detailed costs for individual components cannot describe how the fuel cells will be manufactured and end up basically guessing what cell manufacture will cost; further, the bases for the component costs generally are unclear. Some of the estimates of low costs appear to be based on relatively rapid progress in achieving early cost and size reductions, but high rates of progress at this early stage of development are not unusual, nor do they guarantee continuation of this rate of progress. The rate of progress made by the Japanese in utility scale fuel cells, backed with hundreds of millions of dollars of research, probably should yield caution in assuming that attaining cost levels well below $100/kW is likely. Consequently, in OTA's view, the most optimistic estimates of future fuel cell cost--fuel cells at well below $65/kW--may be possible, but they require a substantial degree of good fortune in the R&D effort and are by no means inevitable.

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[103] R. Kumar et al., "Modeling of Polymer Electrolyte Fuel Cell Systems, paper presented at the Automotive Technology Development Contractors Coordination Meeting, U.S. Department of Energy, October 1993.

[104] Allison Gas Turbine, see footnote 95.

[105] C. Borroni-Bird, see footnote 100.

[106] T. Springer et al., "PEM and Direct Methanol Fuel Cell R&D," paper presented at the Automotive Technology Development Contractors Coordination Meeting, U.S. Department of Energy, October 1994.

[107] Allison Gas Turbine, see footnote 95.

[108] Ballard representative, personal communication, October 1994.

Methanol Fuel Cells

The *direct methanol* fuel *cell* **(DMFC)** uses methanol at the fuel cell anode, rather than reforming it to hydrogen in a separate reactor. The DMFC is a different category of fuel cells and can in principle, use an acid, alkaline or polymer electrode. Low temperature DMFCs are similar to the PEM fuel cell, and current research work at the Jet Propulsion Laboratory uses a solid acidic membrane similar to that used in the PEM fuel cell.

The DMFC suffers from two major problems. First, the methanol oxidation reaction is very slow at the 60° to 80°C operating temperature of such cells, even with the best available catalyst. Although there have been significant improvements in the reaction kinetics over the last three years, the PEM cell operated on hydrogen still provides about seven times more power per unit stack area than the DMFC, based on data from single cell testing.[109] Platinum loadings for the electrodes are also much higher than for the hydrogen PEM fuel cell, although there have been significant improvements recently[110] toward reduced loading requirements.

The second major problem is that methanol at the anode/membrane interface can diffuse and vaporize into the passing air stream at the cathode or react directly with the oxygen at the cathode catalytic surface. The vaporized methanol is a source of emissions and must be recaptured or flared, while methanol that oxidizes at the cathode lowers cathode potential and exacerbates waste heat removal problems. As a result, there are very large efficiency losses. Hence, considerable research is required before a fuel cell stack of reasonable efficiency can be built even as a prototype. DMFC researchers concur that it is too early to suggest whether and when it could be commercialized.

The ***direct methanol solid oxide fuel cell*** is a high temperature cell that eliminates some of the problems of the low temperature DMFCs. Although most solid oxide fuel cells operate at 800° to 1,000°C, Argonne National Laboratory is developing a novel design that could operate as low as 450°C.[111] Its advantages over the low temperature DMFC is elimination of methanol diffusion through the membrane, and no water management problems. This type of solid oxide fuel cell is at a very early stage of development, however, where only its technical potential has been established, and has not been demonstrated even at the cell level. The solid oxide ceil is potentially less expensive than other fuel cell types, but it is too early in the development phase to determine commercialization prospects.

Ultracapacitors and Flywheels

Ultracapacitors and flywheels provide additional means to store energy onboard vehicles. Ultracapacitors are devices that store electrical energy directly, rather than in chemical form as do energy fuels and batteries. They are double layer capacitors that store electrical energy in a

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109 A. Hammet and G.L. Troughton, "Electro Catalysis and the Direct Methanol Fuel Cell," *Chemistry and Industry, No. 13,* July 1992, pp. 480-483.

110 Springer et al., see footnote 106.

111 Argonne National Laboratory, "Direct Methanol Solid Oxide Fuel Cell for Transportation," Electrochemical Technology Program Brochure, 1994.

polarized liquid layer that forms when voltage is applied between two electrodes immersed in electrolyte. A key characteristic is their high power density--they can be discharged rapidly, and should be able to store and release electricity with high efficiency.

Flywheels, in contrast, store energy as the mechanical energy of a rapidly spinning mass, rotating on virtually frictionless bearings in a near-vacuum environment to minimize losses. The flywheel itself can serve as the rotor of a motor/generator, so that the flywheel can be accelerated (to store more energy) when excess electricity is available (e.g., from regenerative braking), or it can release its mechanical energy as electricity when a power boost is needed. The flywheel is also expected to have high storage efficiency.

Both types of devices are viewed primarily as sources of peak power required during vehicle acceleration or hill climbing, because they have very high specific power. Some advocates also view flywheels as capable of providing basic energy storage, though most analysts consider both devices to be impractical for this role because of their relatively low energy density and their tendency to "self discharge," that is, gradually lose energy when not in use. The DOE goals for advanced ultracapacitors are 15 Wh/kg specific energy and 1600 W/kg specific power with round trip efficiencies of 90 percent; [112] DOE has not yet set quantitative goals for flywheels.[113]

Ultracapacitors are being developed for the DOE by several contractors and the technologies include:

- carbon/metal fiber composites,
- monolith foamed carbon,
- doped polymer layers on carbon paper,
- thin-film lithium polymer, and
- ceramic metal oxides on metal foil.

Ultracapacitor cells of the carbon/metal fiber type have been constructed by Maxwell Labs, and their measured performance exceeds the near-term goals of the DOE program. Single cell organic electrolyte capacitors have shown the capability of providing peak power in excess of 2 kW/kg but have specific energy of about 7.5 Wh/kg (at 600 W/kg power) [114]--about 10 times more powerful than lead acid batteries of equal weight, but with only one-quarter of the energy storage capacity. Monopolar capacitor stacks are expected to be built in the near term, as there are no problems with scaling or sealing, but these stacks are bulky and could reduce the power and energy density by 25 percent or more from cell levels. Bipolar stacks offer lower internal resistance and weight, but sealing is a major problem. The bipolar stack can attain energy and

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[112] U.S. Department of Energy, Office of Transportation Technologies 'Hybrid Propulsion Program Plan," October 1994.
[113] Wi11iam Siegel, Department of Energy, personal communication, June 26, 1995.

[114] C. Murphy and W. Kramer, "DOE Ultracapacitor Program Overview," paper presented at the Automotive Technology Development Contractors Coordination Meeting, U.S. Department of Energy, October 994.

power densities 10 percent lower than those quoted for a cell. The basic cells have also exhibited long life (over 100,000 charge/discharge cycles) and have very low open circuit current loss, with self discharge to half the original voltage occurring in about four days. [115]

SRI International is developing a thin-film lithium polymer ultracapacitor, and it has projected a specific energy of 70 Wh/kg and a specific power rating of 50 kW/kg,[116] which corresponds to an order of magnitude increase over other ultracapacitor types. It is not clear whether such goals actually will be achieved.

Although the progress in ultracapacitor technology has been remarkable, it should be noted that the technology is still in the early development stage. It is difficult to forecast the performance and cost parameters for a "fill-scale" ultracapacitor that can contain 5 kWh of energy, for example. Many in the ultracapacitor industry believe that the DOE midterm goals of 10 Wh/kg energy density and a cost of $1/Wh could be attained in the next five to eight years, suggesting that a commercial product could be introduced in about 10 to 12 years. Peak power densities of over 2 kW/kg appears to be feasible for such devices, with storage efficiencies in the 93 percent to 95 percent range. [117]

Flywheel energy storage has been researched for decades, but recent progress has been attributed to improvements in materials and bearing technology. The energy stored by a flywheel is directly proportional to its mass but proportional to the ***square*** of its rotational speed, so the key to storing large quantities of energy is to increase speed--speeds of 100,000 rpm and higher have been contemplated. The flywheel can absorb and release energy very quickly, with the major limitation being the capability of the power electronics and stator to handle high peak power. Energy storage capability is limited by flywheel material properties, as well as safety considerations in the event of rotor failure (the cost and weight of the containment system increases with energy stored).

The only flywheel actually installed and tested in an automotive environment for which data are publicly available is a relatively low-performance system built by Magnet Motor MIX. The system uses a rotor operating at a maximum speed of 12,000 rpm, to provide performance levels of 750 W/kg power and about 5 Wh/kg energy, levels similar to those of an ultracapacitor. The system uses conventional bearings and has worked satisfactorily in an urban bus.[118]

Oak Ridge National Lab has constructed an experimental system using samarium-cobalt permanent magnets and a water cooled stator with a carbon-fiber flywheel rim. The estimated performance characteristics of such a system are 50 Wh/kg energy density and 1.5 kW/kg density power, indicating an energy density roughly comparable to an advanced Ni-Cd battery.[119] These figures, however, seem very high relative to other flywheels that have been built. American Flywheel Systems (AFS), in conjunction with Honeywell, claims even higher figures for its

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[115] E. Blank, "Ultracapacitors for Automotive Applications," paper presented at the Automotive Technology Development Contractors Coordination Meeting, U.S. Department of Energy, October 1994.

[116] CALSTART, letter to OTA, May 1995.

[117] Murphy and Kramer, see footnote 114.

[118] G. Reiner,"Experience with the Flywheel Storage System in Diesel Electric and Trolley Public Transport System," Flywheel Energy Systems Technology Workshop, November 1993.

[119] M. Belanger, "Workshop Summary and Observation" Flywheel Energy Systems Technology Workshop, November 1993.

flywheels with energy densities of over 130 Wh/kg, and power densities that can be tailored to over 1 kW/kg. AFS also claims that it could mass produce such flywheels for a cost of $250/kWh or less. Independent confirmation of AFS's claims is not available; AFS has displayed a prototype system on a car, but its performance is not reported publicly.[120]

Other flywheel manufacturers do not support AFS cost claims, but their own technology indicates that flywheels with similar performance can be built, though at high cost. For example, SatCon Technology Corporation is providing a special flywheel for Chrysler's Patriot race car, and has delivered a complete flywheel system (with conventional bearings) that weighs 59 kg and can store 4.3 kWh of energy,[121] while delivering very high-power pulses of 100 kW[122] (i.e., 73 Wh/kg and 1.7 kW/kg). Its engineering staff confirmed that this was an extremely costly system developed only for racing use. Its flywheel operates with tip speeds of 2,000 m/see, which requires very expensive, ultrastrong fibers. SatCon stated that commercial models (available in perhaps 5 to 10 years) would utilize much cheaper materials but operate at tip speeds of only 1,400 m/see, reducing the specific energy by 50 percent to about 35 Wh/kg.[123] Peak power could still be very high, in excess of 2 kW/kg, but this is a function of power system design. SatCon believes that, although magnetic bearings are desirable, they are not necessary for a short-term power storage device.

Not all the stored energy in a flywheel is recoverable; SatCon's flywheel operates between 30,000 and 60,000 rpm so that 75 percent of the total energy at 60,000 rpm is recoverable.[124] SatCon did not provide a cost figure but claimed that it could eventually meet USABC goals--a claim advanced by virtually all storage device developers, which makes it difficult to evaluate.

Researchers at Idaho National Engineering Laboratory and Argonne National Laboratory, as well as several automanufacturers, are substantially more pessimistic about the flywheel's prospects. They contend that rotor dynamics problems are very complex, and that maintaining rotor balance in a vehicle environment poses extreme challenges. After much advance publicity, the SatCon flywheel for the Patriot car has not yet been capable of sustained performance Mass production of rotors to extremely critical balance accuracy levels is also a difficult challenge, and several researchers believe that rotors operating at 100,000 rpm or more will never be commercially mass produced.

Electric Motors

An electric drive system uses a motor to convert electrical power to shaft power. Traditionally, direct current (DC) motors were used for variable speed applications, but the rapid development of power electronics now allows the use of alternating current (AC) motors in these applications. DC motors can further be classified into series-wound, shunt-wound, and separately excited, or

120 Ibid.
121 Total energy, not usable energy.
122 SatCon Technology Corp., "Flywheel Energy Storage Systems, brochure, n.d.
123 J.D. Hurley, Director, SatCon Corp., personal communication, December 1994.
124 However, redesign of the motor/generator to operate over a wider speed range could increase the energy recovery.

special types such as the switched reluctance motor. The major advantages of the series-wound or separately excited DC motors are that they are easy to control, which makes the control system relatively inexpensive, and that they are technologically mature. For high power applications, however, they are large, heavy, inefficient, and require maintenance. Consequently, they are considered unsuitable for modem EV's. Switched reluctance motors are still in the research stage, and are discussed later in this section.

AC motors can be classified as asynchronous (or induction type) or as synchronous. The asynchronous induction motor is the workhorse of industry in constant speed applications, and has also emerged a prime contender for EVs, as it requires almost no maintenance and can be manufactured relatively cheaply, although the variable speed electronic controls required for a vehicle application are expensive. In an EV application, the controller transforms the DC from the battery to AC (with a frequency from O to 400 Hz[125]). Pulse width modulation schemes use chopping frequencies typically in the range of 10 to 20 kHz. The system works well but requires high current owing to the relatively low-power factors (which are proportional to the phase angle between voltage and current waveforms). Asynchronous induction motors designed by Westinghouse for EVs have shown high efficiency, and peak motor plus controller efficiencies of 91 percent to 92 percent have been achieved.[126]

As induction motor size is reduced, "ripple" currents create higher losses, and one way to circumvent this problem is by operating with higher chopping frequency. DOE is sponsoring research into induction motors[127] that are half the size of the current best motors used in EV applications and use electronic controllers that operate at chopping frequencies of 80 kHz. However, available high-power electronic controllers of the IGBT (Insulated Gate Bipolar Transistor) type cannot operate at high frequency. Instead, MOSFET (Metal Oxide-Silicon Field Effect)-type controllers can be used, though at lower efficiency, or else more expensive control systems are required.

Synchronous motors can be further classified into the permanent magnet type and the electrically excited type. The latter type is considered to be too expensive for EV use, and most research has focused on the permanent magnet synchronous (PMS) motor. The use of these magnets allows the creation of a magnetic field without attendant electrical losses, so that these motors are very efficient at their best operating point. Recent breakthroughs in magnetic materials have allowed the development of very powerful lightweight permanent magnets, such as those made from samarium-cobalt alloys.[128]

Torque in an electric motor is proportional to the magnetic flux times current. Because the PMS motor has constant magnetic flux, it produces constant torque with increased rpm, and, hence, requires higher voltages to increase rpm. To reduce voltage requirements at higher motor speeds, flux must be reduced or else the motor rpm range is restricted. Many PMS motors used in EVs utilized a two-speed transmission to restrict the range of operating rpm. New methods have been developed to decrease the magnetic flux above certain rpm, however, either by designing the

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125 A hertz, or Hz in abbreviated form, is a unit of frequency equal to one cycle per second.
126 Westinghouse, brochures on EV motor controllers.
127 Siegel, see footnote 113.
128 Scheurer and Goubeau, see footnote 77.

stator winding to create a reverse magnetic force or by using electronic phase advance.[129] The field-weakening requirement reduces efficiency of such motors at high rpm, although such a solution is superior to using a two-speed transmission. One company, Unique Mobility, has developed lightweight PMS motors that are up to 93 percent efficient (peak), including the controller loss.[130] Unique Mobility also claims that its motors do not require a two-speed transmission, unlike earlier PMS designs, and such claims are supported by the BMW El design.

The switched reluctance motor has been a subject of intense research, as it has the potential to be very efficient and very cheap. Its design simplicity is an attraction, and it has the capability to operate with reduced power even if one winding fails. New designs are said to reach efficiency levels comparable to those of PMS motors.[131] The motors are still under development, however; current designs are still fairly bulky, and there is some lingering controversy about whether torque pulsation problems have been solved. **Most industry experts contacted by OTA do not believe switched reluctance motors can be commercialized before 2005, and some question whether they will ever be commercialized.**

Table 3-13 provides an auto manufacturer's subjective rating of the near-term candidates for EV propulsion motors, using 27 criteria.[132] If all criteria are equally weighted, then the **AC induction motor appears to be the choice with the best characteristics overall. PMS motors may be the choice, however, if efficiency, size, and weight are regarded as more important than low cost, simplicity, and durability.** These conclusions do not appear to be controversial with most of the EV supplier community.

There appears to be a widespread misconception that electric motor efficiency is always high, over 90 percent. Indeed, both the AC induction motor and PMS motor have displayed *peak* efficiency of over 90 percent--at times, as high as 96 percent.[133] However, efficiency is a function of load and speed, and peak efficiency is attained only at midspeed, high-load conditions. At low speed and low load, efficiency falls to 80 percent or less. Hence, a powerful motor used in an EV to provide high peak performance will operate at city speeds in the low efficiency part of its operating envelope. **Even low-powered EVs--which should be comparatively efficient in low-speed travel--have reported motor average efficiencies over the city cycle in the range of 65 to 75 percent.**[134]

Controller efficiencies have also improved but suffer at high current conditions typical of low-speed, high-load operation--a condition frequently imposed on urban EVs At high voltages (over 200 V), most controllers use the efficient IGBT-type power-switching transistors, although MOSFET-type transistors can be adequate at lower voltages. **Controllers generally have an efficiency of 94 to 95 percent (nominal), but their efficiencies are lower at high-current conditions.** It is now typical to plot the efficiency of the motor and controller together, and an

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[129] J. Lutz and C. Cambier, "Phase Advanced Operation of a PMS Motor Drive System," paper presented at the 12th International EV Symposium, December 1994.

[130] S. Ericksson, "Drive Systems with PMS Motors," *Automotive Engineering,* February 1995.

[131] IEEE Transactions on Power Electronic, January 1995.

[132] Daimler-Benz, presentation to OTA May 1994.

[133] Ericksson, see footnote 130.

[134] Data provided by Volkswagen and BMW to OTA.

example is provided in figure 3-5.[135] These plots, however, are sometimes generated for a constant input voltage, whereas the voltage from a battery declines with increasing current, causing motor efficiency to decline from published values at high loads.

Unlike IC engines that produce nearly constant torque over a wide operating rpm range, electric motors are designed to operate at constant torque from zero rpm to the motor design "base rpm" or "comer point," followed by operation at nearly constant power with rpm (in other words, torque declines as motor speed increases). Motors in EV applications are rated at peak output, which can be sustained for two to three minutes before overheating, and continuous output is usually restricted to 50 percent to 60 percent of peak output; these ratios are similar to the maximum peak output to maximum continuous output ratio required for a light-duty vehicle. The availability of high torque at low rpm allows a motor to match the characteristics of an IC engine with higher maximum or rated output at city speeds. For example, Westinghouse claims that its 100 HP electric motor provides better performance than a 125 HP V-6 engine up to 60 mph. At higher vehicle speeds, the motor's lower HP translates to reduced performance. It should be noted that an IC engine's performance also depends on the transmission ratios which determine the ratio of engine rpm to vehicle speed, so that the Westinghouse example is not necessarily applicable to all vehicles.

Although there are millions of multiple-kilowatt electric motors in operation today, there remains some disagreement about how much EV motor and controllers will cost. Current industrial-grade variable speed motor systems in the 10 to 20 kW range cost about $200/kW--far too expensive for EV use. However, motor manufacturers claim that these motors are a factor of six heavier than advanced motors for EV use, although it is unclear whether motor costs are driven primarily by material input costs. Discussions with motor manufacturers reveal that their *goal* is to match the cost of a current IC engine of similar performance capability. Based on confidential information provided by two motor manufacturers, the cost to the auto manufacturer of an induction motor/controller manufactured at high volume (~100,000 units per year) will be:

$$\text{Cost (\$)} = 300+30^* \text{ Peak kW}$$

Hence, **the cost of a 60 kW system (80 HP peak) is about $2,1OO.** This estimate is consistent with the DOE research goal of a $2,000 powertrain for a 75 HP system. Manufacturers stated that the motor itself costs about one-third of the total, or $700 in this example, and the controller costs two-thirds, or $1,400. **Motor manufacturers believe that this is a realistic cost goal, although these costs are almost an *order of magnitude* lower than current variable-speed drive motor costs.** PMS motors are expected to cost 15 to 20 percent more than induction motors of the same rating.

Others claim that even more substantial cost reductions are possible. For example, the DOE is sponsoring research into high frequency induction motors; preliminary estimates of motor plus controller costs are $600 to $700 for a 60 kW system.[136] Motor manufacturers do not believe these claims, as they feel there are problems with high-frequency motor drives that are not easily

135 Motor efficiency data provided by Ford.

136 W.L. Siegel, 'Electric and Hybrid Propulsion Systems Development" paper presented at the Automotive Technology Development Contractors Coordination Meeting, U.S. Department of Energy, October 1994.

resolved, and also believe that the cost of power electronics cannot be reduced as dramatically as claimed. Nevertheless, these claims suggest there may be a potential for significant cost reduction beyond even the aggressive goals of motor manufacturers.

OTA's vehicle price analyses for EVs and hybrids accepts the motor manufacturers' claims, but not the more aggressive DOE research goals, as the high-frequency motor concept has yet to be demonstrated in a practical application.

The weight of an EV-type induction motor and controller has the following relationship to output power:

$$\text{Weight (kg)} = 1.0 * \text{Peak kW} + 14$$

based on Westinghouse motor weight data. The weight of a 100 HP motor is remarkably similar to the weight of a modem OHC 4-cylinder engine (dressed) that provides 50 to 55 HP/L. PMS motors could weigh about 20 percent less, while the high frequency induction motors discussed above could possibly weigh 35 percent to 40 percent less than the weight indicated above.

If a motor with 30 percent lower HP is selected for equal performance, then weights for an induction motor electric drive are about 25 percent lower than the weight of the IC engine. In addition, elimination of the transmission results in a weight saving of about 70 lbs. These weight estimates are based on actual data on prototype motors and should be representative of future motor/controller weights for EVs.

As noted earlier, the efficiency of the electric motor and controller, averaged over the FTP city and highway cycles, can be very low. Currently, many EVs have reported efficiency for the motor/controller in the 75 percent range on the city cycle and about 80 to 82 percent on the highway cycle. Highly optimized prototypes have improved this efficiency to about 80 to 82 percent on the city and 80 to 90 percent on the highway. As noted, the higher performance requirements lead to lower efficiencies at city speeds. In this report, the efficiencies obtained by operating prototypes have been used to model *commercial* EVs and hybrids in 2005. By 2015, it is possible that efficiency could increase by another 3 to 4 percent, owing to reductions in losses in the power electronics and reduction of windage and eddy current losses in advanced motor designs. Such improvements are highly speculative, and alternative scenarios with and without these improvements are examined in the vehicle evaluation.

OTHER ENGINE AND FUEL TECHNOLOGIES

Overview

Numerous engine and fuel technologies have been suggested as powerplants and power sources for the future In general, most of the alternative fuels, with one exception, are hydrocarbon fuels ranging from natural gas to biomass-derived alcohol fuels, and most of these are being used commercially in limited scale in the United States. Although these fuels can offer significant advantages in emissions and small advantages in fuel economy over gasoline/diesel, their properties and benefits have received significant attention over the last decade, and there is a large body of literature on their costs and benefits. The one exception to this is hydrogen, which often is portrayed as the zero emission fuel of the future. Hydrogen's ability to fuel current and future automobiles is considered in this section.

Alternative engine technologies considered for the future include gas turbine and Stirling engines. (In this context, the two-stroke engine is considered as a "conventional" engine type, as it is similar in operating principles to four-stroke engines). The gas turbine engine, in particular, has received increased attention recently as a power source for hybrid vehicles. As a result, the potential for the gas turbine and Stirling engine in nontraditional applications is also discussed here.

Hydrogen

Hydrogen is viewed by many as the most environmentally benign fuel, because its combustion will produce only water and NO_x as exhaust components, and its use in a fuel ceil produces only water as a "waste" product. Because hydrogen, like methanol, must be derived from other naturally occurring compounds at substantial expenditure of energy, fuel economy evaluations of hydrogen vehicles should consider the overall energy efficiency of the hydrogen fuel cycle. Even if hydrogen is produced using electricity from photovoltaic cells, it maybe more efficient to use the electricity directly for transportation rather than through the production of hydrogen, depending on the location of the hydrogen production.

Because hydrogen is a gas at normal temperatures and pressures and has very low energy density, it has serious storage problems on-board a vehicle. There are essentially four different ways to store hydrogen, which are as a:

- compressed hydrogen gas,
- cryogenic liquid,
- reacted with metals to form a hydride, and
- adsorbed on carbon sieves.

Compressed hydrogen gas can be stored in high-pressure tanks (of advanced composite material) at pressures of 3,000 to 6,000 pounds per square inch (psi). To store the equivalent of 10 gallons of gasoline, a tank at 3,000 psi must have a volume of 150 gallons, and the tank weight is approximately 200 lbs.[137] Doubling the pressure to 6,000 psi does not halve the tank volume because of increasing tank wall thickness and the nonideal gas behavior of hydrogen; at 6,000 psi,

137 Daimler-Benz, "Hydrogen: An Alternative Fuel," n.d.

the tank volume is 107 gallons, and its weight is 225 lbs. Increasing tank pressure leads to greater safety problems and increased energy loss for compressing the hydrogen; at 6,000 psi, the energy cost of compression is approximately 10 to 15 percent of the fuel energy. Realistically, pressures over 6,000 psi are not considered safe,[138] and tank capacity over 30 or 40 gallons would seriously compromise the room available in a car. Hence, compressed hydrogen gas storage in a car would have the energy equivalent of only about 3.0 gallons of gasoline for a 6,000 psi tank of a size that could be accommodated without seriously impairing trunk room.

Liquid storage is possible because hydrogen liquefies at -253°C, but a highly insulated--and, thus, heavy and expensive--cryogenic storage tank is required. A state-of-the-art tank designed by BMW accommodates 25 gallons of liquid hydrogen.[139] It is insulated by 70 layers of aluminum foil with interlayered fiberglass matting. The weight of the tanks when fill is about 130 lbs, and hydrogen is held at an overpressure of up to 75 psi. The total system volume is about five times that of an energy equivalent gasoline tank (gasoline has 3.8 times the energy content of liquid hydrogen per unit volume), and the weight is twice that of the gasoline tank. Heat leakage results in an evaporation loss of 1 to 2 percent of the tank volume per day. Although the container size for a 120-liter tank would fit into the trunk of most cars, there are safety concerns regarding the venting of hydrogen lost to evaporation, and crash-safety-related concerns. [140] There is also an important sacrifice in overall energy efficiency, because the energy required to liquefy hydrogen is equal to about one-third the energy content of hydrogen.

Metal hydride storage utilizes a process by which metals such as titanium and vanadium react exothermally (that is, the reaction generates heat) with hydrogen to form a hydride. During refueling, heat must be removed when hydrogen is reacting with the metals in the tank; when the vehicle powerplant requires fuel heat must be supplied to release the hydrogen from the tank. For these reasons, the entire tank must be designed as a heat exchanger, with cooling and heating water flow ducts. The hydrogen used must also be very pure, as gaseous impurities impair the chemical reactions in the metal hydride tank Moreover, the weight of metal required to store hydrogen is very high: to store the energy equivalent of 10 gallons of gasoline, the tank would weigh more than 500 lbs.[141] The main advantages of the system are safety and low hydrogen pressure. The overall process is so cumbersome, however, that it seems an unlikely prospect for light duty vehicles, although such systems can be used in buses and trucks.

Adsorption in carbon sieves was thought to be a promising idea to increase the capacity of compressed gas cylinders, although there is a weight penalty. However, most recent work on carbon sieves have concluded that the capacity increase is significant only at pressures in the 1,000 to 1,500 psi range; at 3,000 psi or higher pressure, carbon sieves appear to offer no benefit over compressed gas cylinders. 142 Because a pressure of 5,000 psi or more is desirable, it does not appear that this technology is of use for on-board storage.

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[138]J. Zieger, "Hypasse - Hydrogen Powered Automobiles," paper presented at the 10th World Hydrogen Conference, June 1994.

[139]D. Riester and W. Strobl, " Current Development and Outlook for a Hydrogen Fueled Car," paper presented at the 8th World Hydrogen Energy Conference, June 1992.

[140]In the event of a spill, contact with the liquid hydrogen (during the brief period before it would evaporate) would be extremely dangerous.

[141]Daimler-Benz, see footnote 132.

[142]J. Bentley et al., "Development of Advanced Hydrogen Storage Systems for Transportation Application," paper presented at the Automotive Technology Development Contractors Coordination Meeting U.S. Department of Energy, October 1994.

Hydrogen can be used directly in engines or in fuel cells. When used in conventional IC engines, the combustion properties of hydrogen tend to cause irregular combustion and backfires.[143] To prevent this, BMW has used very lean mixtures successfully, with the added benefit of no measurable emissions of NO_x and an improvement in peak energy efficiency of 12 to 14 percent. Because of hydrogen's low density, however, operating lean results in a power reduction of about 50 percent from the engine's normal capacity. BMW uses superchargers to restore some of the power loss,[144] but a larger engine is still required, and the added weight and increased fiction losses could offset much of the energy efficiency gain. Mercedes Benz has solved the low power problem by operating at stoichiometry or rich air fuel ratio at high loads, coupled with water injection to reduce backfire and knocking potential. The Mercedes approach results in significant NO_x emissions, however, and the engine requires a three-way catalyst to meet ULEV NO_x standards. Overall engine efficiency is not much different from gasoline engine efficiency owing to compromises in spark timing and compression ratio.[145]

The use of hydrogen in a compression-ignition (diesel) engine has also been attempted by directly injecting liquid hydrogen into the combustion chamber. Cryogenic injectors operating on low lubricity liquid hydrogen poses difficult engineering problems, however, and automanufacturers doubt whether a commercially viable system can ever be developed.

Gas Turbine Engines

The gas turbine, or Brayton cycle, engine has largely replaced piston engines in most small aircraft, and has been investigated extensively for use as an automotive powerplant for the last three decades. The engine of interest for automotive applications has a cycle that first compresses intake air, then mixes fuel with the air and ignites it, and finally expands the air to ambient pressure. The hot, high velocity air turns a turbine that operates the compressor for the intake air. Output power can also be taken directly from the same shaft as the compressor, or the engine's exhaust can be directed to another turbine to extract output power.

As a replacement for the internal combustion piston engine, the gas turbine offers exceptional smoothness, low emissions potential, and multifuel capability. It suffers, however, from other serious problems that make it difficult to use as an automotive engine. The engine has very poor part-load performance because the characteristics of turbomachinery are such that high aerodynamic efficiencies are attained only in a narrow operating range. The simple "single shaft" design, where the compressor and turbine and power takeoff are all on the same shaft, is not well suited to automotive uses, where speeds and loads vary. The more complex two-shaft turbine offers better performance in automobiles at significant increase in cost. Part-load efficiencies can only be made high by a recuperator or regenerator that transfers heat from the exhaust to the compressed intake air before combustion, which recaptures some of the energy remaining in the exhaust. Overall engine efficiency increases with increasing combustion temperature, which is limited by the materials used in the turbine. Since 1979, DOE has funded the development of

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[143] Daimler-Benz, see footnote 132.
[144] BMW, "Hydrogen Drive - Current Factbook," 1993.
[145] Daimler-Benz, see footnote 132.

advanced ceramic recuperators, and ceramic turbine blades capable of operating at very high temperature.

A simple, all metal single shaft gas turbine engine of 150 HP attains relatively low efficiency because of the low compression ratios employed (3:1), low turbine inlet temperature of 1,300°C, and the heat loss in the exhaust. Typically, these efficiencies are in the range of 30 to 32 percent.[146] To improve efficiencies to over 40 percent, regenerators have been widely used. The regenerator is usually a ceramic matrix that rotates through both the hot turbine exhaust and cooler intake air from the compressor, transferring heat from exhaust to intake air. A major problem area with regenerators is the dynamic seal between the turbine exhaust and compressor discharge air, which tends to leak, leading to a substantial reduction in performance.[147] An alternative is the fixed boundary heat exchanger, or recuperator. This eliminates leakage, but size, weight, and cost are problems with regenerators that have persisted even after a decade of research.

An additional way to increase efficiency, by another 5 to 7 percent, is through use of ceramic parts in the "hot" section of the turbine, allowing higher temperatures. The development of durable and reliable ceramic components is the focus of much research and such components could be available commercially by 2005.

To date, the best automotive gas turbine cannot yet match the efficiency of a gasoline engine over the entire drive cycle, and many now believe that it is <u>never</u> likely to exceed this moving target of gasoline engine efficiency in an automotive environment.[148] Even <u>ceramic gas turbines</u> of about 80HP now under development have project <u>goals</u> of reaching a 40 percent efficiency (peak),[149] a level already attained by current production diesels.

More recent research has focused on the use of the ceramic gas turbine as a hybrid vehicle powerplant, where it operates at constant rpm to drive an electric generator. If the generator speed is increased to that of the turbine shaft, the size and weight of the generator can be reduced by nearly a factor of 10 for equal output, and the gearbox between the turbine and output shaft is eliminated. Such an approach has been used by Volvo in its High Speed Generation concept included in the Volvo ECC prototype hybrid vehicle.[150] The HSG unit features a single-stage radial compressor and turbine, which operates at speeds up to 90,000 rpm with an output of 56 HP. The gas turbine engine uses a recuperator to maximize energy efficiency. Anecdotal information suggests that the Volvo gas turbine engine operates with an efficiency of about 35 percent, but there are no data on the durability of the recuperator seals or the efficiency and durability of the high rpm electric generator.

It is unlikely that small gas turbines (20 to 40 kW) can have an efficiency of much more than 35 percent, because the 1aws of fluid dynamics affect the scaling laws for gas turbines. As the engine

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[146] Ford Motor Co., "Conceptual Design Study of Automotive Gas Turbine," report prepared for the National Aeronautics and Space Administration, 1979.

[147] R. Mackay, "Gas Turbine Generator Sets for Hybrid Vehicles," SAE paper 920441, 1992.

[148] C.A. Amman, "The Automotive Engine - A Future Perspective," GM Research Publication, GMR-6653, n.d.

[149] M. Bauer, "The European Ceramic Gas Turbine Programme -AGATA," Automotive Technology Development Contractors Coordination Meeting, U.S. Department of Energy, October 1994.

[150] Volvo ECC publicity brochure, n.d.

is made smaller, turbine and compressor tip leakage, boundary layer effects, and aerodynamic friction become a larger part of overall loss, so efficiency of small turbines is lower than the efficiency of large ones of the same design and materials. In addition, it appears that it will be extremely difficult to manufacture a ceramic gas turbine with a recuperator as cheaply as a conventional IC engine. For example, even in light aircraft, where the requirements are well suited to a turbine engine, spark-ignition piston engines are preferred over turbines in virtually all applications under 300HP because of their higher efficiency and far lower cost.

At this point, it appears unlikely that a ceramic gas turbine can compete with IC engines on the basis of efficiency or cost. The turbine's high specific power and power density, lack of vibration, and low emission potential may, however, make it an attractive engine candidate in some applications, especially in hybrids where its poor part-load performance is irrelevant. Although it would probably be less efficient than a diesel, it would be smaller and lighter than a diesel of equal power, and have substantially lower emissions. Some companies such as NOMAC are developing "low" technology, low cost gas turbines that could potentially compete on costs at the expense of efficiency.

Stirling Engines

Stirling engines operate on a thermodynamic cycle that resembles the ideal heat engine cycle, or the Carnot cycle. For any given maximum temperature limitation, the Carnot cycle represents the most efficient cycle theoretically possible under the second law of thermodynamics. In addition, it uses a continuous combustion process, which can have low emissions. Stirling cycle engines are external combustion engines, that is, they have a working fluid that does not come into direct contact with combustion, but instead is heated through a heat exchanger. Those Stirling cycle engines built to date utilize hydrogen as a working fluid. Hydrogen is heated at constant high pressure in a specially designed heater head, expanded through a piston expander, recompressed and reheated in the head to complete the cycle.

DOE funded the development of Stirling engines from the late 1970s to the mid-1980s before terminating its program. The engines proved to have both cost and reliability problems. For example, hydrogen containment, especially at high pressure and temperature, requires sophisticated seals, which are expensive and failure prone, in the piston compressors and expanders. The heater head exposes the coils containing high-pressure hydrogen to high continuous temperatures. Very-high-temperature-capable alloys containing rare earth materials such as cobalt and vanadium are required, and the heater head is both complex and costly to manufacture.[151] The Stirling engine also does not have high part-load efficiency, and requires a long warmup time owing to the thermal inertia of the heater head. After nearly a decade of development, prototype engines did not demonstrate fuel efficiency levels even equal to that of a gasoline IC engine.

[151] W.H. Haverdink, "Assessment of an Experimental Stirling Engine Powered Automobile," paper presented at the Automotive Technology Development Contractors Coordination Meeting U.S. Department of Energy, October 1984.

The Stirling engine is potentially better suited to constant speed/load applications, and could conceivably have peak efficiency as high as 45 percent,[152] but the high combustion temperatures result in high NO_x emissions without catalytic aftertreatment. Even if an efficiency of *45* percent were reached, the costs of the hydrogen seals and heater heads cannot be easily reduced. For these reasons, it appears very unlikely that Stirling engines will be a cost competitive automotive powerplant, even in constant speed applications.

Waste Heat Recovery

With spark ignition and compression ignition engines, much of the heat energy of the fuel is lost to the cooling system, oil, and to the exhaust. Recovery of a portion of this waste heat is an obvious solution to improve efficiency, but the low temperature of the waste heat makes it very difficult to recover any energy in a cost-effective way. The coolant and oil temperature are so low (less than 100°C) that no practical system has been devised to recover this energy. Exhaust heat is a much better target, but the temperature and quantity of heat fluctuates rapidly is urban driving conditions.

Recovery of the waste heat has been explored by using a Rankine cycle (steam engine) or by turbocompounding. The Rankine cycle could convert the water in the cooling system to steam by using exhaust heat, and expand the steam to provide useful work. Because of the relatively low temperatures of the exhaust (250°C), the theoretical (or Carnot cycle) efficiency is limited to about 40 percent--that is, a maximum of 40 percent of this waste heat can be recovered. The complexity of a heavy steam engine in series with the spark ignition engine, however, has always outweighed the potential fuel efficiency benefit. Turbocompounding is a simpler heat recovery method where a turbine (connected to the engine output shaft) recovers the waste pressure energy in the exhaust. Owing to the low engine load in urban driving and in highway cruise, there is very little pressure energy to be recovered in a passenger car or light truck engine, but this system can be useful in heavy-truck diesel engines.

One of the more sophisticated attempts to recover energy was by Toyota. In this application, the existing cooling system was replaced by a system in which a chlorofluorocarbon working fluid evaporated into a vapor. Power was recovered from the vapor by means of a scroll expander (that is, an expander that uses a helical-shaped blade rather than vanes to capture the energy of the expanding vapor). Theoretical analysis predicted that, at low speed, a fuel economy improvement of 7 to 8 percent was possible at an ambient temperature of 25°C when such a system was fitted to a small Toyota with a 1.5 litre engine.[153] In actuality, the system installed by Toyota attained only a 3 percent benefit, because an unmodified (from production) cylinder head created pressure losses, and the scroll expander efficiency was also lower than expected.[154] Of course, the waste heat recovered is sensitive to the ambient temperature, with heat recovery decreasing to near zero

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[152] J. Corey et al., "Design Description of an Automotive Stirling Engine with Competitive Manufacturing Costs," paper presented at the Automotive Technology Development Contractor Coordination Meeting U.S. Department of Energy, October 1994.

[153] H. Oomori and S. Ogino, "Waste Heat Recovery of Passenger Car Using a Combination of Rankine Bottoming Cycle and Evaporative Engine Cooling System," SAE paper 930880, 1993.

[154] Ibid.

at ambient temperatures of 45°C (113°F). Improved systems could provide a benefit of 5 to 6 percent under urban driving conditions at 25°C, and as much as 10 percent at winter conditions.

Waste heat recovery from the exhaust alone could be a possibility for engines operating at near constant output, as is theorized for some hybrid vehicle types. Mitsubishi[155] has experimented with a turbocompound system where the turbine drives an auxiliary generator and obtained a 7 percent increase in output. Another possibility is a thermoelectric generator, which converts heat directly into electricity. DOE is supporting the development of a thermoelectric generator with **Hi-Z** Technology,[156] Inc. for heavy-duty truck applications. Data presented by Hi-Z indicates that the power output of the current design of the thermoelectric generator is very low, (about 1kW) in conjunction with a 250HP ***engine*** at fill power, which is only a 0.5 percent increase in output. Mitsubishi confirms that these generators provide only about 100W of power in a light-duty vehicle application, so that currently they do not appear to be cost effective.

IMPROVEMENTS TO AUTOMATIC TRANSMISSIONS

The transmission in a vehicle matches the power requirements of the automobile to the power output available from an engine or motor; the automatic transmission's selection of different gears keeps the engine operating in speed ranges that allow high levels of efficiency to be achieved. Most modem transmissions operate at efficiencies of over 85 percent on the city cycle and 92 to 94 percent on the highway cycle. The efficiency losses that do occur are caused primarily by:

- ***Hydraulic losses in the torque converter*** (current automatic transmissions use a hydraulic system to transmit the engine power to the drivetrain).

- ***Designs that avoid the operating point that would maximize fuel economy. If fuel*** economy were the only concern, the optimum point would maximize torque and minimize engine speed (rpm), which reduces throttling and fiction losses. Designing the transmission for maximum efficiency leaves little or no reserve power, however, so that even modest changes in road load horsepower may require a downshift-and frequent downshifts are considered undesirable for customer satisfaction. In addition, operating at too low an rpm causes excessive driveline harshness and poor accelerator response.

Improvements to current transmissions can occur in the following areas:

- reduction in flow losses in the torque converter for automatic transmissions;

- increase in the ratio spread between top and first gear;

155 Mitsubishi, presentation to OTA, June 1993.

156 J.C. Bass, "Engine Test of Thermoelectric Generator," paper presented at the Automotive Technology Development Contractors Coordination Meeting U.S. Department of Energy, November 1994.

- increase in the number of gear steps between the available limits (that is, moving to five or more speeds in an automatic transmission), with continuous variable transmissions (CVTs) being the extreme limit; and

- electronic control of transmission shift points and torque converter lockup.

All of these improvements have been adopted, in some form, by automakers, but their penetration of the fleet is incomplete and, in some cases, further technical improvements are possible. For example, Mercedes-Benz and Nissan have recently (1993) introduced a five-speed automatic transmission, while GM introduced a six-speed manual transmission. Product plans reveal that such transmissions are likely to be more widely adopted by 2005. CVTs have been introduced in Europe and Japan, and in the United States in one car model that has been since discontinued.

Torque converter improvements

Redesign of the torque converter to reduce flow losses will yield improved fuel economy. Toyota has introduced a new "Super Flow" converter in its Lexus LS400 vehicle.[157] The new converter was computer designed to optimize impeller blade angle and blade shape to reduce loss of oil flow. In addition, new manufacturing techniques were developed for the impeller to increase rigidity. As a result, Toyota claims the converter efficiency is the world's best, and is 3 percent to 5 percent higher than other torque converters.[158] Such an improvement is expected to provide a 0.5 percent benefit in composite fuel economy.

Greater number of gears

Increasing the number of transmission gears can be used to provide a wider ratio spread between first and top gears, or else to increase the number of steps with a constant ratio spread for improved drivability and reduced shift shock. In addition, the wider ratio spread can be utilized to provide higher performance in the first few gears while keeping the ratio of engine speed to car speed in top gear constant, or else to maintain the same performance in the first few gears and to reduce engine speed in top gear. Because the manufacturer is able to select among these tradeoffs, different manufacturers have chosen different strategies in selecting gear ratios; therefore, any fuel economy gain from increasing the number of gears is dependent upon these strategies.

Five-speed automatic transmissions have only recently been commercialized in Japan and Europe. Nissan has provided a comprehensive analysis of the effect of numbers of gears and choice of first gear and top gear ratios on fuel economy.[159] They found declining benefits with increasing numbers of gears, with little or no benefit above six gears. With a first gear ratio of 3.0 (similar to that of current automatics) they found no benefits in fuel economy in using overdrive

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[157] T. Kondo et al., "Toyota "ECT-i", A New Automatic Transmission with Intelligent Electronic Coolant System," SAE paper 900550, 1990.
[158] Ibid.
[159] N. Hattori et al., "A New 5-speed Automatic Transmission for Passenger Cars," SAE paper 900551, 1990.

ratios lower than about 0.7. Increasing the first gear ratio to about 4.0, however, provided better standing start performance. The Nissan production five-speed transmission uses a 3.85 first gear ratio and a 0.69 overdrive ratio for a 5.56 ratio spread. At constant performance, Nissan showed fuel economy gains in the 3 percent range.[160] Mercedes, the only other manufacturer to have introduced a five-speed automatic, confirmed that the fuel economy benefit over a four-speed automatic was in the 2 to 3 percent range. Ford estimates that their planned five-speed automatic would provide a 2.5 percent fuel economy benefit at current performance levels, but could have much smaller benefits at other levels.

A 2.5 percent fuel economy benefit appears representative of a five-speed automatic over a four-speed automatic. With either a six-speed or seven-speed transmission, complexity and weight increases appear to offset fuel efficiency benefits.

A continuously variable transmission (CVT) offers an infinite choice of gear ratios between fixed limits, allowing optimization of engine operating conditions to maximize fuel economy. Currently, Subaru is the only manufacturer that has offered a CVT in a small car in the United States. Although there are several designs being tested, the CVT that is in production features two conical pulleys driven by metal belts. The position of the belts on the conical pulleys determines the gear ratio between input and output shafts. Under steady-state conditions, the metal belt system can be less **efficient** than a conventional system, but the fuel used over a complete driving cycle is decreased because of the optimized speed/load conditions for the engine. Nissan and Ford have developed CVTs using rollers under radial loads that may be more efficient than metal belt designs.

Shift performance of the CVT should be equal to, or somewhat better than, conventional automatic transmissions, with its main benefit the absence of shift shock associated with discrete gear changes. However, a CVT can produce unexpected changes in engine speed--that is engine speed dropping while the vehicle speed is increasing--which may deter consumer acceptance. Moreover, attaining acceptable startup vehicle performance could require the use of a lockup torque converter or a conventional planetary gear set, or both, which would add to cost and complexity. Nevertheless, developments in the metal belt system coupled with weight reduction of future cars are expected to enhance the availability of the CVT for use in all classes of cars and trucks in the 2005 time frame.

During the early 1980s, CVTs were expected to provide substantial fuel economy benefits over three-speed automatic transmissions. Researchers from Ford[161] showed that an Escort with a CVT of 82 percent efficiency would have a fuel economy 14 percent higher than the fuel economy with a three-speed automatic; at a CVT efficiency of 91 percent, the fuel economy benefit was computed to be 27 percent (91 percent was considered to be an upper limit of potential efficiency). Similarly, Gates Corporation installed a CVT in a Plymouth Horizon and found a fuel economy improvement of 15.5 percent over a conventional three-speed automatic with lockup, at almost identical performance levels.[162] Design compromises for drivability, however, as well as improvements to the base (three speed) automatic since the time these papers were published

160 Ibid

161 R.R. Radtke et al., "Optimization of a CVT with Emission Constraints," SAE paper 810107, 1981.

162 Steig R., and S. Worley, "A Rubber Belt CVT for Front Wheel Drive Cars," SAE paper 820746, June 1982.

(1982), have resulted in lowered expectations of benefits. A more recent test conducted by the Netherlands Testing Organization on a Plymouth Voyager van with a 3.3 LV6 and a four-speed automatic replaced by a Van Doorne CVT showed fuel economy benefits of 13 percent on the city cycle and 5 percent on the highway cycle for a 9.5 percent improvement (over a four-speed automatic).[163] These figures, however, may be unrepresentative of more average applications as supplier companies usually provide the best possible benefit estimates. The current consensus among auto manufacturers is that the CVT will be 4 to 8 percent more efficient than current four-speed automatics with lockup. A 6 percent improvement, including the benefit of the electronic control required to maximize CVT benefits, would be consistent with the measured results from the Subaru Justy CVT sold in the United States.

The benefits for the CVT, however, are associated with current engine technology. Reduction of fuel consumption is associated with two effects: reduced friction losses owing to lower engine rpm, and reduced pumping losses owing to operation at higher load. In the future, engines equipped with variable valve timing and direct injection stratified charge engines will have much lower pumping losses than current engines, thus reducing part of the CVT fuel economy reduction potential. Typically, this would reduce the benefits of CVTs to about half the value estimated for current engines, or to approximately 3 percent.

Electronic transmission control (ETC)

ETC systems to control shift schedules and torque converter lockup can replace the hydraulic controls used in most transmissions. Such systems were first introduced in Toyota's A43DE transmission in 1982. The benefit of the ETC system lies in the potential to maximize fuel economy by tailoring shifts and torque converter lockup to the driving schedule. Domestic auto manufacturers, however, claim that the measured benefits are small, because most modem nonelectronic transmissions have been optimized for the FTP test cycle. In 1994, more than half of all vehicles had ETC. Although several electronically controlled transmissions are available, "paired sample" comparisons are impossible as no example is available of the same car/engine combination with nonelectronic and electronic transmissions. Regression studies across different models of similar weight and performance show a 0.9 percent advantage[164] for the electronic transmission. However, it appears there is potential for greater improvement with some loss of smoothness or "feel."

Estimates by Ross and DeCicco[165] have claimed very large benefits for ETC by following an aggressive shift profile, and they estimate fuel economy benefits as great as 9 percent. These benefits have been estimated from simulation models, although detailed documentation of the input assumptions and shift schedule followed is unavailable. Clearly, shifting very early into a high gear (such as by shifting from second gear to fourth gear directly) and operating the engine at very low rpm and high torque can produce significant gains in fuel economy--but at a great cost

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[163] E. Hendricks, "Qualitative and Quantitative Influences of a CVT on Fuel Economy and Vehicle Performance," SAE paper 930668, March 1993.

[164] H.T. McAdams, "Projection of Automotive Fuel Economy to the Year 2000: Critique of the Berger-Smith-Andrews Methodology," rep@ prepared for Martin Marietta Energy Systems, July 1991.

[165] M. Ross and J. DeCicco, "An Update Assessment of Near-Term Potential for Improved Automotive Fuel Economy," ACEEE publication, May 1993.

to drivability and vibration. Operating the engine at very low rpm leads to conditions known as "lugging" that causes a very jerky ride. Current industry trends, however, are to maximize smoothness, so that it is difficult to envision a strategy similar to the one advocated by Ross and DeCicco being introduced without incentives strong enough to override performance and comfort considerations.

Prices

Prices for a five-speed automatic transmission over a four-speed automatic are $100 to $125, as obtained from actual data for transmission applications. Prices for commercial CVTs are expected to be virtually identical to prices for four-speed automatics, according to Van Doorne.

BOX 3-1: Box Fuel Cell Use in Urban Buses

Both the phosphoric acid fuel cell and proton exchange membrane (PEM) fuel cell can utilize hydrogen as a fuel, and many current working prototypes of fuel cells use pure hydrogen as an input or obtain hydrogen by steam-reforming methanol or by partial oxidation of methanol. The phosphoric acid fuel cell has been developed by H-Power Corporation and fitted to an urban bus. The low-power density of the fuel cell requires that the bus carry batteries to supply power for peak loads, with the fuel cells charging the battery at low loads. The fuel cell used in the bus delivers a net power of 47.5 kW, and has a net efficiency of 42 percent at rated load, and 46 percent at its maximum efficiency point which occurs at about 50 percent load. ' The need to carry a large battery (and its supporting equipment) for operation during fuel cell warmup and acceleration transients makes the overall system, including electrical controls, expensive and bulky. Moreover, the methanol reformer is also expensive and contributes to the overall inefficiencies in the fuel cell system. H-power claims that the transit bus in which this system has been installed has an overall energy economy level similar to or slightly better than the diesel bus with the same body and performance level.[2]

Ballard Power Systems Inc. has converted a diesel-powered bus to use a PEM fuel cell with compressed hydrogen as its fuel. The 1993 version uses a fuel cell that produces 120 kW at 160 to 280 volts. Range is 100 miles and the fuel cell itself takes up the space of three rows of seats. The vehicle can attain 45 mph top speed and accelerates from zero to 30 mph in 20 seconds.[3] This vehicle achieved several firsts for PEM fuel cell systems: higher power by a factor of more than 10 than previous air-breathing systems; highest voltage; cold, unassisted startup in less than four seconds; and virtually instantaneous power response.[4] In 1993, Ballard projected commercialization of a fuel cell-powered 75-passenger bus with 350 mile range by 1998, though no price was discussed.[5]

Ballard currently is developing a 275 HP PEM fuel cell engine designed to be installed into the standard engine compartment of a full-size 40-foot heavy duty bus (a New Flyer D40LF Low Floor model).[6] The fuel will be hydrogen from compressed storage and oxygen from air compressed by an electrically driven on-board compressor. The goals of this phase of Ballard's commercialization program are to obtain a 250-mile range and top speed of 60 mph, with zero to 30 mph acceleration in 19 seconds and gradability of a starting capability at 20 percent grade and maintenance of 20 mph on an 8 percent grade.[7]

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[1] A. Kaufman, "Phosphoric Acid Fuel Cell for Buses, Automotive Technology Development Contractor Coordination Meeting U.S. Department of Energy, 1994.

[2] Ibid.

[3] "Innovative Fuel Cells Power Canadian ZEV Transit Bus," *Ward's Engine and Vehicle Technology Update,* July 15, 1993.

[4] P.F. Howard and C.J. Greenhill, "Ballard PEM Fuel Cell Powered ZEV Bus," SAE paper 931817, August 1993.

[5] Ibid.

[6] P.F. Howard, Ballard Power Systems Inc., "Ballard Zero Emission Fuel Cell Bus Engine," 1995.

[7] Ibid.

BOX 3-2: Arguments in Favor of an Inexpensive PEM Fuel Cell

A number of advocates of light-duty vehicle applications for fuel cells believe that fuel cell vehicles can eventually have lifecycle costs that are fully competitive with gasoline-fueled vehicles. The basis for this contention is, generally, that the materials and manufacturing costs of fuel cell systems will be relatively inexpensive in mass production, and that maintenance costs will be low and system longevity high because of the inherent nature of fuel cell operation.

Critical fuel cell materials consist of the platinum catalyst, the flow field plates (currently made of graphite), and the polymer electrolyte membrane. An important generic argument in favor of the potential for achieving large cost reductions is that all of the current manifestations of these components were developed for completely different applications. Developers believe that a process that takes specific fuel cell requirements and designs the components for those requirements, with reduced costs a key goal, should readily succeed in lowering costs.

The catalysts on the Gemini space missions cost about $57,000 for a 40 kW fuel cell, with catalyst loading about 35 mg/cm^2. Ballard's 1993 fuel cell bus had catalyst loadings of about 4 mg/cm^2, and catalyst loadings of 0.1 mg/cm^2 have been achieved in individual cells at Los Alamos National Laboratory. If the latter loadings can be transferred to a complete system, catalyst cost will clearly not be a problem for fuel cells. However, substantial further development and testing will be needed to establish this low a catalyst loading. In particular, for methanol-based systems, a catalyst system with very light platinum loading might be very sensitive to carbon monoxide poisoning.

According to Los Alamos National Laboratory, graphite flow field plates currently cost about $270/kW and could eventually cost about $14/kW in mass production,[1] an unacceptably high cost if fuel cell first cost is to approach internal combustion engine costs. Fuel cell developers hope to use less expensive materials, e.g., aluminum or plastics, to drastically reduce costs.[2] And the polymer electrolyte membranes, which now cost about $170/kW,[3] are made in small quantities and may be made to higher specifications than are necessary for a fuel cell. Developers hope to utilize mass-production techniques used to manufacture other thin film materials, as well as redesign of the membrane specifications, to reduce costs by an order of magnitude or more.[4]

Fuel cell advocates believe that fuel cell manufacture will not involve close tolerances and thus should not be high in cost. Further, advocates argue that the fuel cell stack is basically composed of large numbers of identical elements-in sharp distinction from internal combustion engines (ICES), which are composed of large numbers of unique elements-that should increase the probability of obtaining substantial reductions in fuel cell fabrication and assembly costs. Fuel cell cost projections reviewed by OTA's contractor did not, however, contain descriptions or evaluations of fuel cell mass production procedures, and important production issues remain to be resolved, for example, sealing.[5] Consequently, claims that manufacture will be at low cost, or the use by estimators of (fabrication cost)/(materials cost) ratios appear premature.

Finally, some analyses of fuel cell vehicle life-cycle costs project very low operating and maintenance costs, and high system life times, based on claimed advantages including:

- lack of moving parts in the fuel cell stack;

1M. Wilson et al., Los Alamos National Laboratory, "A Polymer Electrolyte Fuel Cell Stack for Stationary Power Generation," paper presented at the DOE Hydrogen Program Review Meeting Apr. 18-21, 1995, Coral Gables, FL These estimates are not Universally accepted; Chris Borroni-Bird of Chrysler believes that Los Alamos' estimated current cost is substantially too low, and that mass production with current designs and materials would yield a $130/kW cost (personal communication Aug. 11, 1995). Ken Dircks of Ballard agrees that current coats are much higher than $270/kW, and characterizes the $14/kW estimate as a reasonable target given new materials and design and mass production (personal communication, Aug. 22, 1995).

2 J.M. Ogden et al., "A Technical and Economic Assessment of Renewable Transportation Fuels and Technologies" prepared for the Office of Technology Assessment, May 27, 1994, table 4.5.

3 Wilson et al., see footnote 1.

4 Ogden, see footnote 2.

5 Borroni-Bird, see footnote 1.

- inherent simplicity of a fuel cell compared to an internal combustion engine, which has hundreds of moving parts;
- operation of PEM fuel cells at temperatures below 10O°C, i.e. much lower than ICE operating temperatures;
- lack of a need to control explosive events, in contrast to ICES; and
- PEM cells' chemically benign operating environment.

As discussed in the text, OTA believes that the costs of PEM cells will clearly be reduced substantially as research and development efforts continue and economies of scale are realized with mass production at the high volumes typical of the auto industry. The extent of these cost reductions-whether they will approach the two orders of magnitude that are needed for market viability-remains highly uncertain, however.

TABLE 3-1: Lightweight Materials: Relative Component Costs and Weight Savings

Cast applications	Relative materials cost (per pound)	Relative component cost	Weight savings (Percentage)
Cast iron (base)	1.0	1.0	Base
Cast aluminum	1.8-2.2	1.0	50-60
Cast magnesium	3.0	1.0	65-75
Body structural applications			
Mild steel (base)	1.0	1.0	Base
High-strength steel	1.1	1.0	10
Aluminum	4.0	2.0	40-50
Glass fiber-reinforced polymers	3.0	0,8a	25-35
Carbon fiber-reinforced polymers	10[b]-30[c]	1.25-2.25[a]	50-65

a Assuming low-cost resin transfer molding process is developed; with current processes, relative component costs would be two times higher.
b Assuming 50 percent carbon fiber at $6 per prod.
c Assuming 50 percent carbon fiber at $20 per pound.

SOURCE: National Materials Advisory Board, ***Materials Research Agenda for the Automotive and Aircraft Industries,*** NMAB-468 (Washington, DC: National Academy Press, 1993).

TABLE 3-2: Mechanical Properties of Some Alternative Automotive Structural Materials

	Density (gm/cc)	Tensile Strength (ksi)	Elastic Modulus (msi)
Low carbon steel	7.5	40-70	30
Aluminum sheet	2.7	**20-37**	10-12
Sheet molding compound	1.6-2.6	8-25	1.3-2.3
E-glass composite[a]	2.1	150	3-7
S-glass composite[a]	2.0	280	4-8
Kevlar composite[a]	1.4	290	11
Carbon/graphite composite[a]	1.6-1.8	145-330	**6-20**

[a] Unidirectional composite.

SOURCE: Roy M. Cuenca, Center for Transportation Research, Argonne National Laboratory, briefing for the U.S. Department of Energy, Office of Transportation Technologies, Oct. 28, 1993.

TABLE 3-3: Weight Distribution in the Ford Taurus (circa 1990)

System/subsystem	Weight	Percentage
Body-in-white	826	25.5
Hinges, locks, gauges, etc.	33	1.0
Body electrics	23	0.7
Moldings/ornaments	30	0.9
Trim/insulation/seals	207	6.4
Seats	107	3.3
Glass	81	2.5
Radio, lighter, mirrors, etc.	21	0.7
Paint/coatings	10	0.3
Total body	**1,338**	**41.2**
Base engine	444	13.7
Engine accessories	160	4.9
Engine electrics	38	1.2
Emission controls	30	0.9
Fuel storage system	24	0.7
Exhaust system	33	-1.0
Catalytic converter	30	0.9
Total engine system	**759**	**23.4**
Transmission	134	4.1
Clutch and controls	7	0.2
Final drive	110	3.4
Total transmission system	**251**	7.7
Total powertrain	**1,010**	**31.1**
Frame	99	3.1
Suspension	153	4.7
Steering	60	1.8
Brakes	154	4.7
Wheels/tires/tools	181	5.6
Fender shields/bumpers	90	2.8
Chassis electrics	41	1.3
Accessories	4	0.1
Total chassis	**782**	**24.1**
Fluids	115	3.5
Total vehicle	**3,245**	**100.0**

SOURCE: Office of Technology Assessment, 1995.

TABLE 3-4: **Manufacturer's Projection of Potential Improvements in Light-Truck C_D**

Vehicle type	Potential best	Current average
Pickup 2WD	0.38-0.40	0.47
Pickup 4WD	0.41-0.43	0.50
van 2WD	0.30-0.31	0.39
Utility 2WD	0.35-0.36	0.43
Utility 4WD	0.38-0.40	0.46

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995.

TABLE 3-5:
Summary of Long-Term Fuel
Efficiency Benefits from Advanced Technology

	Fuel consumption impact (%)	
	Manufacturers mean	Optimistic
4-valve engine with simple variable resonance intake	Base	Base
2-valve engine	+4	+5
4V with camphasing +VRI	-2	-3
4V with 2-position VVLT +VRI	-6	-9
4V with full VVLT + VRI	-8	-11
4V with full VVLT + cyl. shutoff + VRI	-lo	-13
4V + VVLT + lean bum + VRI	-12	-15
DISC (+ VVLT ?)	-15	-19
Friction: roller cams	-1	-2
Piston/rings/crankshaft	-1.5	-4

KEY: VRI = variable resonance intake manifold; VVLT = variable valve lift and timing; DISC = direct injection stratified charge; + indicates increased fuel consumption, - a decrease.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995.

TABLE 3-6: **Estimated RPEs for DISC Engines**

Engine	Without VVLT	With VVLT
4-cylinder	$500-$550	$750-$850
6-cylinder	$650-$700	$1,125-$1,250
8-cylinder	$850 -$900	$1,350 -$1,500

KEY: RPE = retail price effect; DISC= direct injection stratified charge; VVLT = variable valve lift and timing.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995.

TABLE 3-7: Retail Price Effects for Friction Reduction Components in Four-Valve Engines

	4-cylinder	6-cylinder	8-cylinder
Roller cams	**$17.20**	**$24.20**	**$31.20**
Lightweight valve/springs	31.20	**45.20**	**59.20**
Pistons	10.20	13.70	17.20
Piston coatings	6.70	8.45	10.20
Total	$65.30	$91.55	$117.80

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995.

TABLE 3-8: Fuel Consumption/Economy Benefits of Diesel Engines Relative to Gasoline Engines

	Fuel consumption (percentage)	Fuel economy (percentage)
Indirect injection (IDI), (naturally aspirated)	12-13	13-15
Turbocharged IDI	19-20	24-26
Turbocharged DI	28-30	40-45

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995.

d

TABLE 3-9: Fuel Economy Comparison at Equal Performance: Gasoline vs. Diesel (miles per imperial gallon)

Type	Manufacturer	Model	Engine	Trans	E.C.E. city	90 km/hr	120 km/hr
IDI/NA	Fiat	Tipo	1.4 L gas	M-5	31.7	52.3	38.7
			1.6 L diesel	M-5	42.2	57.6	42.2
			Benefit %		33.1	10.1	9.0
	Ford	Escort	1.3 L gas	M-5	34.9	52.3	38.8
			1.8 L diesel	M-5	43.5	64.2	47.1
			Benefit %		24.6	22.7	18.3
	Peugeot	306	1.6 L gas	M-5	31.4	52.3	39.8
			1.9 L diesel	M-5	40.4	61.4	44.8
			Benefit %		28.7	17.4	12.6
	Nissan	Primera	1.6 L/4V gas	M-5	30.1	54.3	42.2
			2.0 L diesel	M-5	39.2	62.8	44.1
			Benefit %		30.2	15.6	9.7
IDI/Turbo	Fiat	Tempra	1.6 L gas	M-5	27.4	48.7	28.7
			1.9 L diesel	M-5	46.3	62.8	47.9
			Benefit %		69.0	29.0	23.8
	Ford	Escort	1.6 L gas	M-5	31.0	49.6	40.9
			1.8 L diesel	M-5	38.2	58.9	41.5
			Benefit %		23.2	18.8	1.5
	Peugot	306	1.8 L gas	M-5	27.2	47.9	37.2
			1.9 L diesel	M-5	37.7	64.2	45.6
			Benefit %		38.6	34.0	22.6
IDI/Turbo	BMW	320i	2.0 L gas	M-5	24.8	41.5	34.0
			2.4 L diesel	M-5	32.1	57.6	43.5
			Benefit %		29.4	38.8	27.9
			2.0 L gas	A-5	23.3	46.3	36.7
			2.4 L diesel	A-5	30.1	57.6	44.1
			Benefit %		29.2	24.4	20.1
	Volvo	940	2.0 L gas	M-5	23.3	39.2	29.4
			2.4 L diesel	M-5	28.8	49.6	35.8
			Benefit %		23.6	26,.5	21.8
			2.0 L gas	A-4	21.6	38.2	29.7
			2.4 L diesel	A-4	28.8	47.9	34.9
			Benefit %		333	25.4	17.5
DI/Turbo	**VW**	Golf	1.8 L gas	M-5	30.4	52.3	39.2
			1.9 L diesel	M-5	50.4	74.3	52.3
			Benefit %		65.8	42.1	33*4
		Passat	1.8 L gas	A-4	25.4	42.8	34.4
			1.9 L diesel	A-4	34.5	52.3	39.2
			Benefit %		34.5	523	592
		Audi[a]	2.6 L gas	A-4	20.9	37.7	30.7
			2.5 L diesel	A-4	34.4	61.4	43.5
			Benefit %		64.6	62.9	41.7

[a]Gasoline engine has higher performance.

KEY: IDI = indirect injection.

SOURCE: *U.K. Fuel Economy Guide, 1994.*

TABLE 3-10: U.S. Advanced Battery Consortium Battery Development Goals

Criterion	Mid-term goal	Long-term goal
Power density, W/L	250	600
Specific power, W/kg	150 (200)	400
Energy density, Wh/L	135	300
Specific energy, Wh/kg	80 (100)	200
Life, years	5	10
Cycle life (to 80% depth of discharge)	600	1000
Power/capacity degradation. %	20	20
Efficiency, %	75	80
Recharge time, hours	<6	3 to 6
Self discharge, %	15/48 hours	15/month
Price., $/kWh	< 150	<100

SOURCE: U.S. Advanced Battery Consortium.

TABLE 3-11: Battery Technology

Technology	Sponsor[a]	Developer[a]	Status (mid-1994)
Bipolar lead acid	CARB SCAQMD EPRI	Arias Pinnacle Batelle	Prototype module
Woven grid lead/acid	EPRI	BDM Electro-Source	Pre-production
Common vessel lead/acid or nickel-cadmium	None	Acme Electric	Laboratory
Nickel-cadmium (prismatic)	None	SAFT Eagle Pitcher ACME	Pre-production
Zinc-bromine	Exxon DOE	Powercell SEA	Full-size prototype
Lithium polymer	USABC DOD	ADL SAFT Grace	Laboratory
Nickel metal hydride	USABC	SAFT Ovonic Maxwell	Full-size prototype
Sodium-sulphur	USABC DOD	Silent Power ABB Hughes	Full-size prototype
Nickel-iron	EPRI	Eagle Pitcher	Pre-production
Zinc-air	DOE ILZRO Arizona Public So. Cal. Edison	Westinghouse “ Lawrence Livermore DEMI SRI	Full-size prototype
Aluminum-air	ALCAN	Alu Power Eltech	Full-size prototype
Lithium/metal sulfide	DOE USABC	Westinghouse SAFT Argonne	Laboratory
Lithium ion	DOE DOD	Lawrence Livermore Sony	Laboratory
Sodium/nickel chloride	German Govt	AEG Diamler-Benz	Full-size prototype
Ultracapacitor (not a battery)	DOE	Lawrence Livermore SRI Maxwell Auburn Pinnacle	Laboratory

[a]Not a comprehensive listing.

KEY: ABB = Asea-Brown Boveri, Inc.
ADL = Arthur D. Little
AEG = AEG Corp.
ALCAN = Aluminum Corporation
BDM = BDM Technologies, Inc.
CARB = California Air Resources Board
ILZRO = International Lead-Zinc Research Organization
SCAQMD = South Coast Air Quality Management District
SRI = SRI International
USABC = United States Advanced Battery Consortium

SOURCE: National Institute of Standards and Technology, “Advanced Components for Electric and Hybrid Vehicles," Special Publication 860, 1993.

TABLE 3-12: Current State-of-the-Art for Batteries (expected values in parenthesis)

Types	Specific Energy Wh/kg @ c/3	Specific Power W/kg @ 20% DoD	Status[a] in mid-1994	Estimated costs per kWh (volume production)
Advanced lead acid	40	200	4	125-190
Bipolar lead acid	(45)	(500+)	2	175-190
Nickel cadmium	55	175	4	500-600
Nickel iron	50	100	4	400-500
Nickel-Metal hydride	70	200	3	400-500[b]
Sodium sulfur	110 (130)	125 (200)	3	250-300
Sodium nickel chloride	90	140	3	350-450
Bipolar lithium metal sulfide	(125)	(190)	2	(350-450)
Lithium polymer	(200+)	(80-100)	1 or 2	unknown
Lithium ion	100-110	200-250	1	unknown

[a]Status: 1 - ce1l for lab tests; 2- module for lab tests; 3- prototype EV battery; 4-pilot production.
[b]Ovonic has claimed it can manufacture these batteries at substantially lower costs.

KEY: e/3 = The constant discharge rate that would drain the battery in three hours; DoD = depth of discharge.

NOTE: *Usable* specific energy is different from values shown above.

SOURCE: Energy and Environmental Analysis, Inc.

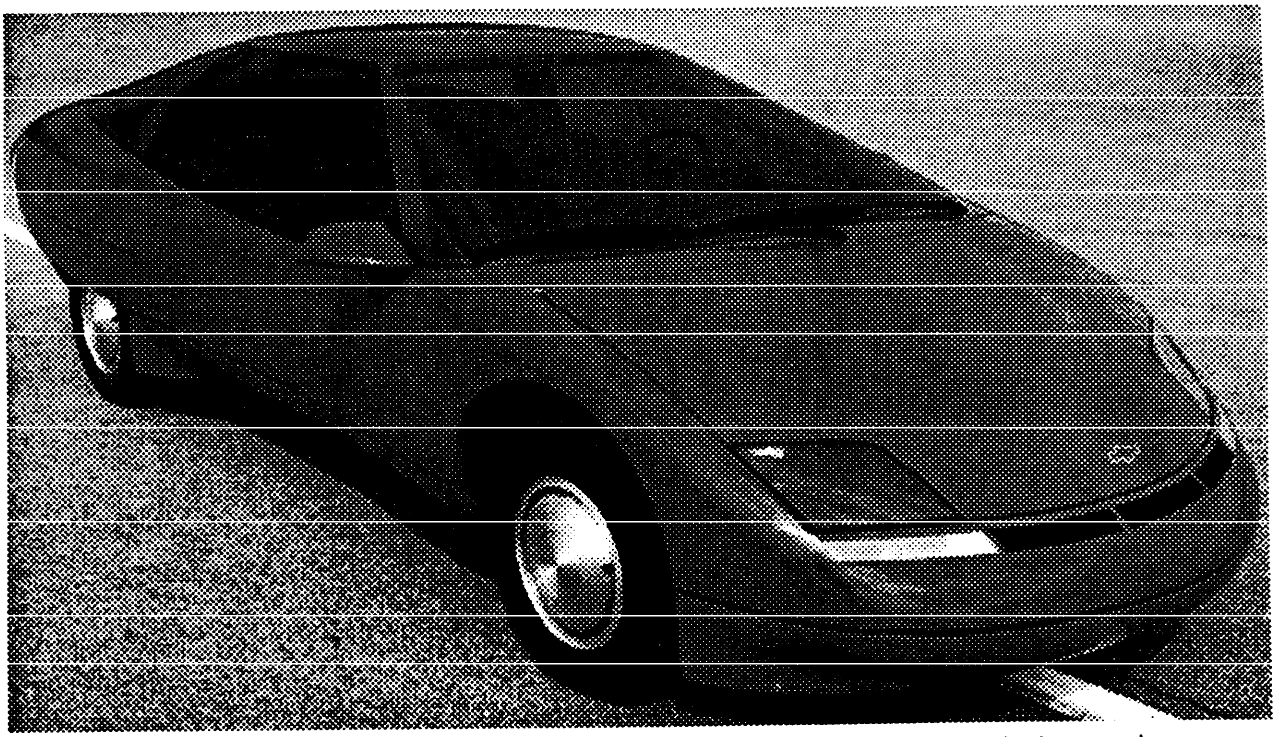
TABLE 3-13: Subjective Rating of Different Motors for EV Use

Feature	Drive System With: DC-motor, separately excited	PMS-Motor	AC induction motor
Maintenance	0	2	2
Efficiency	0	3	1
speed limit	0	2	3
Volume	0	3	2
Weight	0	3	2
Maximum torque	3	2	2
Moment of inertia	0	3	3
Allowed rotor temperature	0	0	2
Cooling possibilities	0	3	2
Complexity of electronics	3	0	1
Torque control	3	3	1
National power limitation	3	3	0
Installed inverter power	3	0	1
Electromagnetic field loss	3	0	1
Rotor losses	0	3	0
Excitation losses	0	3	1
Field weakening	3	0	2
Slip rings, brushes	0	3	3
Stator winding simplicity	1	3	2
Centrifugal rotor bandage	1	3	3
Power factor	3	2	1
Temperature dependence	3	0	3
Stability of magnets	3	0	3
cost of magnets	3	0	3
Construction simplicity	1	1	3
Automatic mass production	1	1	3
Tooling cost	0	0	3
	0 = poor 1 = average 2 = good 3 = excellent		

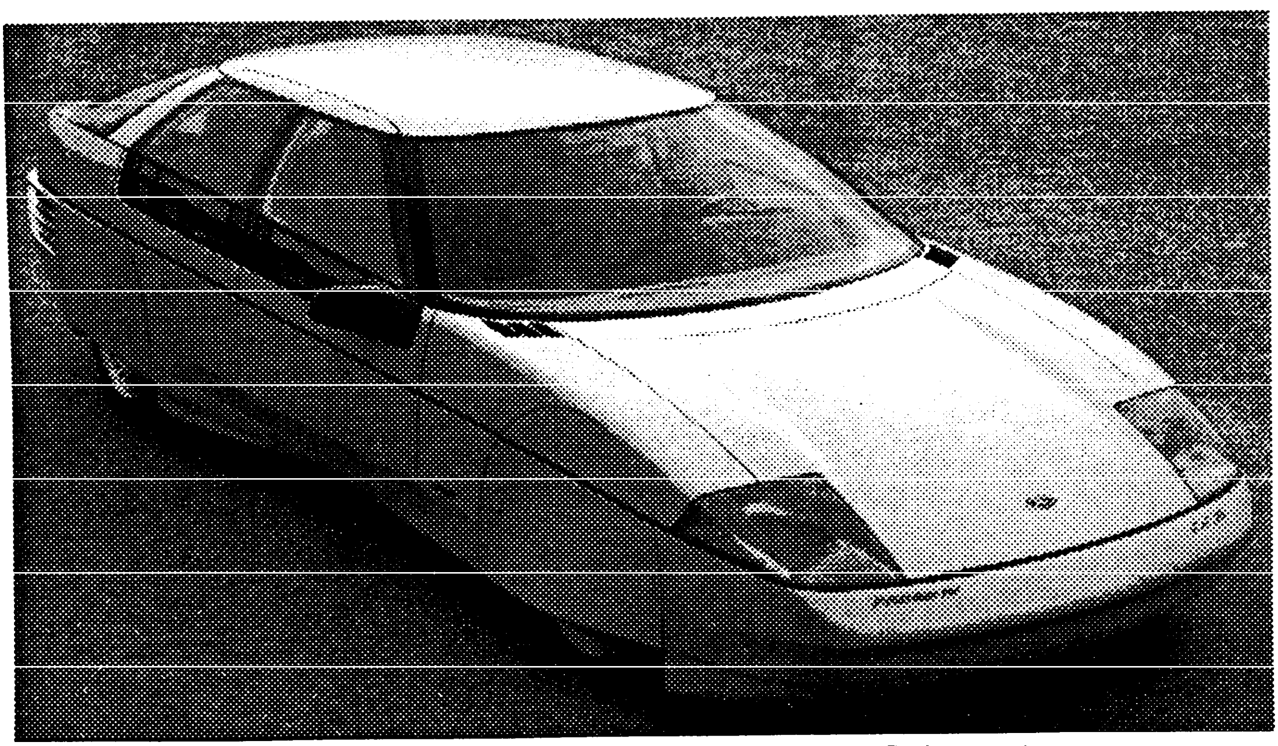
KEY: DC= direct current; PMS = permanent magnet synchronous; AC = alternating current.

SOURCE: Daimler-Benz.

FIGURE 3-1: Examples of Highly Aerodynamic Cars

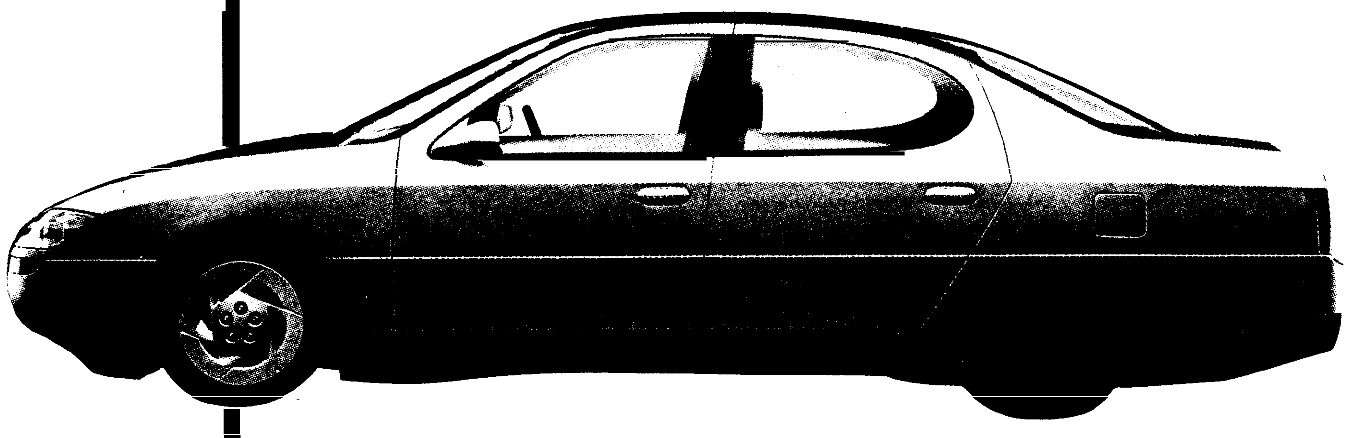


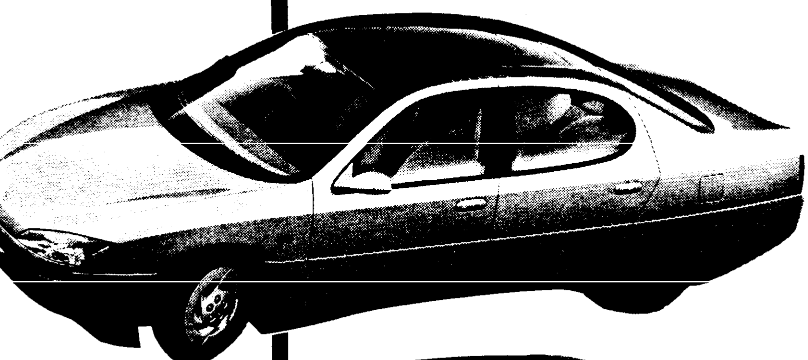
Chevrolet Citation IV — F ont eng ne f ont whee d ve 4 passenge 2 doo sedan

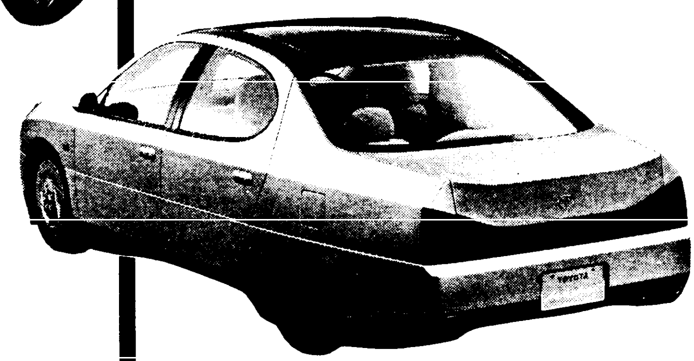


Ford Probe IV — F on eng ne f ont whee d ve 4 passenge 5 doo sedan

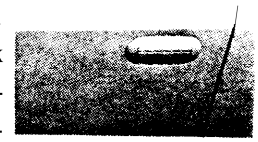
FIGURE 3-2: Design Features of **Toyota AXV-V**







Side



The flat door cross-sections and sham lines sweeping from front to back are both firm and futuristic. In addition, door handles and window pillars are flush with the surface, while fender skirts cover the rear tires to assure a smooth flow of air.

Rear

The driver can see the trailing edge of the trunk lid. The rear fenders taper toward the rear end, the rear window is sloped, and the trunk lid is truncated to reduce trailing vortex, a major cause of drag.

Cabin

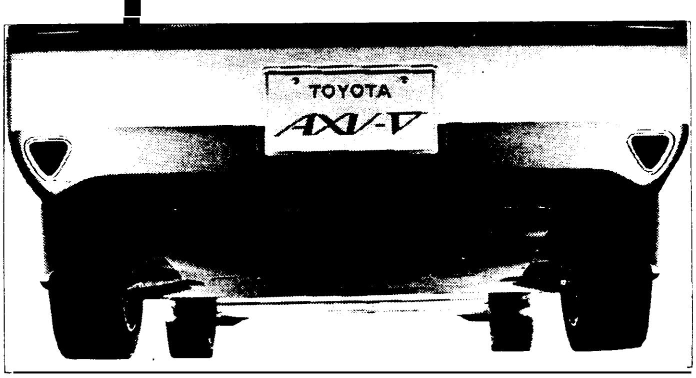
The cabin has been placed as far forward as possible. The large window area increases the feeling of space inside. And the shapes of both the windshield and the rear window are designed for superior aerodynamics.

underbody

The entire underbody has a flat cover that sweeps up at the rear to maintain a smooth flow of air. Large spats in front of and behind all four tires also cut wind resistance. And a slit in the underbody cover beneath the exhaust pipe cools it with minimum drag.

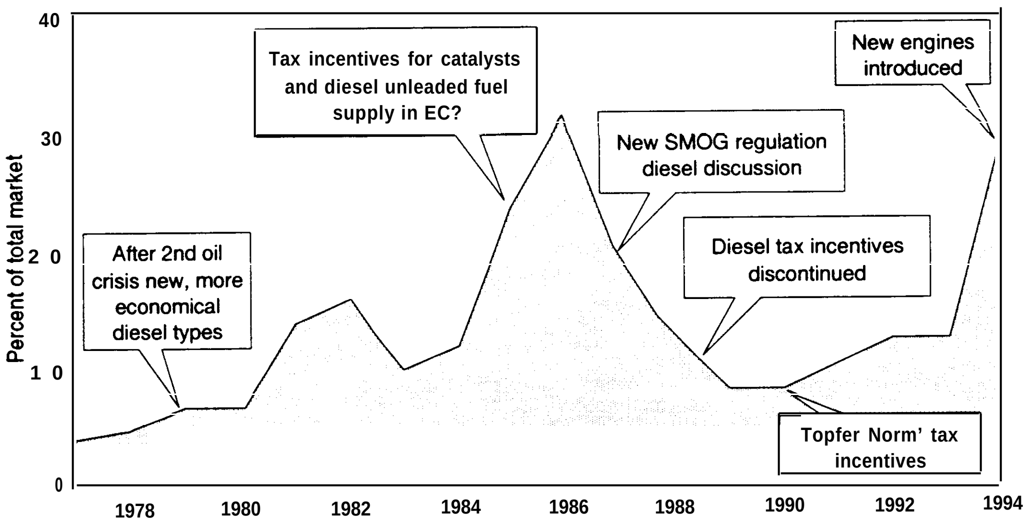
Aluminum wheels

Aerodynamically designed aluminum wheels with large, flat outer surfaces further reduce drag.



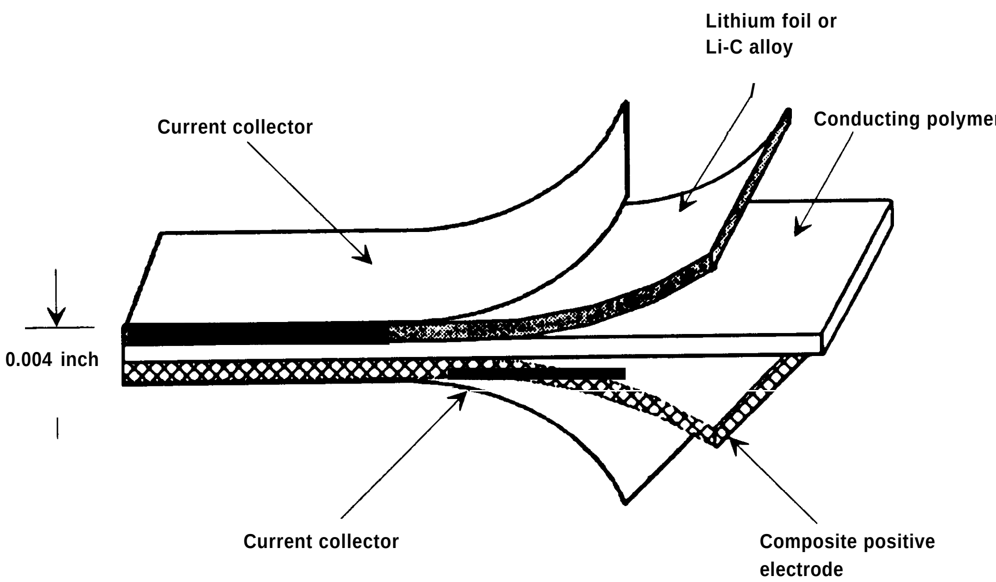
TOYOTA MOTOR CORPORATION
International Public Affairs, Tokyo Head Office

Figure 3-3: Development of Diesel Market Share in Germany



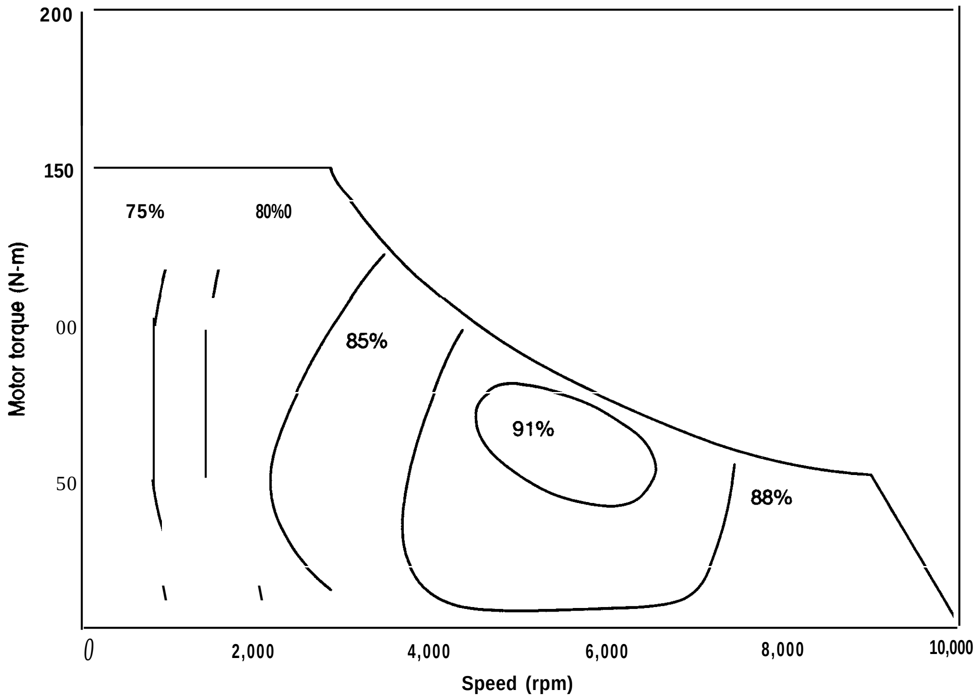
SOURCE: VDA.

Figure 3-4: Lithium Battery Technology: Lithium-Polymer Electrolyte Battery



SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies to Improve Fuel Economy to 201 5," prepared for the Office of Technology Assessment, June 1995, p. 6-14.

Figure 3-5: Efficiency of Induction Motor and Controller



SOURCE: A motor manufacturer (confidential).