Advanced Automotive Technology: Visions of a Super-Efficient Family Car

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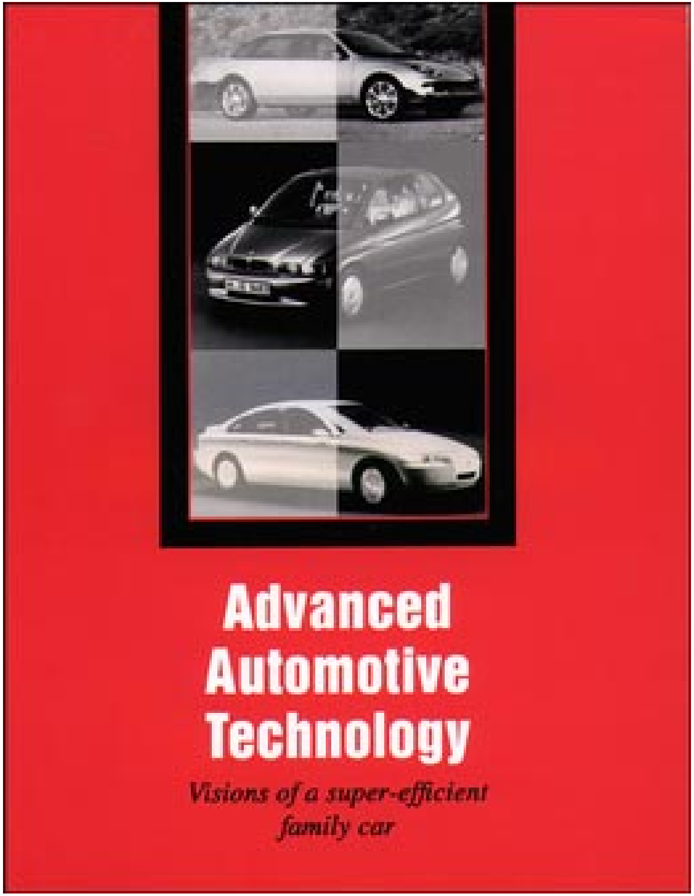

Foreword

This report presents the results of the Office of Technology Assessment's analysis of the prospects for developing automobiles that offer significant improvements in fuel economy and reduced emissions over the longer term (out to the year 2015). The congressional request for this study—from the House Committees on Commerce and on Science, and the Senate Committees on Energy and Natural Resources and on Governmental Affairs-asked OTA to examine the potential for dramatic increases in light-duty vehicle fuel economy through the use of "breakthrough" technologies, and to assess the federal role in advancing the development and commercialization of these technologies.

The report examines the likely costs and performance of a range of technologies and vehicle types, and the U.S. and foreign research and development programs for these technologies and vehicles (to allow completion of this study before OTA closed its doors, issues such as infrastructure development and market development---critical to the successful commercialization of advanced vehicles-were not covered). In particular, the report presents a baseline forecast of vehicle progress in a business-as-usual environment, and then projects the costs and performance of "advanced conventional" vehicles that retain conventional drivetrains (internal combustion engine plus transmission); electric vehicles: hybrid vehicles that combine electric drivetrains with an engine or other power source; and fuel cell vehicles. OTA has focused on mass-market vehicles, particularly on the mid-size family car with performance comparable to those available to consumers today. Based on our analysis, OTA is quite optimistic that very high levels of fuel economy-up to three times current averages—are *technically* achievable by 2015; attaining these levels at a commercially viable price will be a more difficult challenge, however.

This report is the last in a series on light-duty vehicles that OTA has produced over the past five years. Previous topics include alternative fuels *(Replacing Gasoline: Alternative Fuels for Light-Duty Vehicles);* near-term prospects for improving fuel economy *(Improving Automobile Fuel Economy: New Standards, New Approaches);* and vehicle retirement programs *(Retiring Old Cars; Programs To Save Gasoline and Improve Air Quality).* OTA also has recently published a more general report on reducing oil use in transportation *(Saving Energy in U.S. Transportation).*

OTA is grateful to members of its Advisory Panel, participants in workshops on vehicle safety and technology, other outside reviewers, and the many individuals and companies that offered information and advice and hosted OTA staff on their information-gathering trips. Special thanks are due to K.G. Duleep, who provided the bulk of the technical and cost analysis of technologies and advanced vehicles.

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Note: OTA appreciates and is grateful for the valuable assistance and thoughtful critiques provided by the advisory panel members. The panel does not, however, necessarily approve, disapprove, or endorse this report. OTA assumes full responsibility for the report and the accuracy of its contents.

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Chapter 1

Executive Summary

The automobile has come to symbolize the essence of a modern industrial society. Perhaps more than any other single icon, it is associated with a desire for independence and freedom of movement; it is an expression of economic status and personal style. Automobile production is also critically important to the major industrial economies of the world. In the United States, for instance, about 5 percent of all workers are employed directly (including fuel production and distribution) by the auto industry.[1] Technological change in the auto industry can potentially influence not only the kinds of cars that are driven, but also the health of the economy.

The automobile is also associated with many of the ills of a modern industrial society. Automotive emissions of hydrocarbons and nitrogen oxides are responsible for as much as 50 percent of ozone in urban areas; despite improvements in air quality forced by government regulations, 50 million Americans still live in counties with unsafe ozone levels.[3] Automobiles are also responsible for 37 percent of U.S. oil consumption,[4] in an era when U.S. dependence on imported oil is more than 50 percent[5] and still increasing. A concern related to automotive gasoline consumption is the emission of greenhouse gases, principally carbon dioxide, which may be linked to global climate change. The automobile fleet, which accounts for 15 percent of the U.S. annual total, is one of this country's single largest emitters of carbon dioxide.[6]

Recent technological improvements to engines and vehicle designs have begun to address these problems, at least at the level of the individual vehicle. Driven by government regulation and the gasoline price increases of the 1970s, new car fuel economy has doubled between 1972 and today,[7] and individual *vehicle* emissions have been reduced substantially.[8] Several trends have undercut a portion of these gains, however, with the result that the negative impacts of automobiles are expected to continue.

An important trend has been a 40 percent drop in the real price of gasoline since its peak in 1981.9 This decline has reduced the attractiveness of fuel-efficient automobiles for consumers and

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1 American Automobile Manufacturers Association, ***Facts and Figures*** 94 (Detroit, MI: 1994), p. 70. The number of workers employed by the industry is somewhat controversial because there are several alternative interpretations about which workers are in this category, and some of the data for specific sectors does not separate out automotive and nonautomotive workers, e.g. workers in petroleum refining. The value here includes motor vehicle and equipment manufacturing (which inadvertently includes workers making heavy trucks), road construction and maintenance workers, petroleum refining and distribution, auto sales and servicing taxicab employees, car leasing, and auto parking.

2 Here and afterwards *automotive* refers to automobiles and light trucks primarily used for passenger travel—vans, sport-utility vehicles, and pickup trucks. These vehicles use half of all the oil consumed by the U.S. transportation sector.

3 U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, ***National Air Quality and Emissions Trends Report, 1993, EPA-450/R-94-026*** (Research Triangle Park, NC: October 1994).

4 U.S. Department of Energy, Energy Information Administration, ***Annual Energy Outlook**, 1995,* DOE/EIA-0383(95) (Washington, DC: January 1995), tables A7 and Al 1.

5 For example, imports were 54 percent of total supply in August, 1994. U.S. Department of Energy, Energy Information Administration, *Monthly **Energy Review,*** DOE/EIA-0035(94/09)(Washington, DC: September 1994).

6 Energy Information Administration, see footnote 4, table A18.

7 S.C. Davis, *Transportation Energy Data Book: Edition 14,* ORNL-6798 (Oak Ridge, TN: Oak Ridge National Laboratory May 1994), table 3.35 and earlier editions.

8 The federal Tier 1 emissions standards represent emission reductions of about 97, 96, and 89 percent, respectively, from uncontrolled levels of hydrocarbons, carbon monoxide, and nitrogen oxides. Actual on-road reductions are not this high, however.

9 Davis, see footnote 7, table 2.16.

encouraged more driving; vehicle-miles traveled (VMT) have been increasing at 3 percent per year.[10] Expanding personal income[11] has meant that more new vehicles (especially less fuel efficient light trucks and vans) are being added to the fleet; there were approximately 15.1 million new light-duty vehicles purchased in 1994.[12] With more drivers and expected increases in individual travel demand, automotive oil consumption and carbon dioxide emissions are expected to increase by 18 percent from 1993 to 2010,[13] when U.S. oil imports are expected to reach 64 percent.[14] Although highway vehicle emissions have been dropping and air quality improving,[15] the rates of improvement have been slowed greatly by the increase in travel. Similar trends in automobile purchasing and use are occurring in other industrialized countries, even with motor fuel prices far higher than those in the United States, and the problems will be compounded as developing countries such as China continue to industrialize and expand their use of automobiles.

With these trends as background, it is clear that a major advance in automotive technology that could dramatically reduce gasoline consumption and emissions would have great national and international benefits. Such benefits would include not only the direct cost savings from reduced oil imports (each 10 percent drop in oil imports would save about $10 billion in 2010[16]), but also indirect savings such as:

- health benefits of reducing urban ozone concentrations, now estimated to cost $0.5 billion to $4 billion per year;[17]
- an "insurance policy" against sudden oil price shocks or political blackmail, the risk of which is estimated to cost $6 billion to $9 billion per year;[18]
- reduced military costs of maintaining energy security, which according to some estimates costs the United States approximately $0.5 billion to $50 billion per year;[19]
- potential savings from reduced oil prices resulting from decreased oil demand, conceivably tens of billions of dollars per year to the U.S. economy, and more to other oil-consuming economies; and

[10] Ibid, table 3.2.

[11] More precisely, higher personal income for the income segments who are most likely to purchase new automobiles. *Average* personal income has not risen.

[12] *Automotive News,* "1995 Market Data Book," May 24, 1995, p. 20.

[13] For light-duty vehicles. Energy Information Administration, see footnote 4, table A7.

[14] Ibid, table Al.

[15] For example, highway vehicle emissions of volatile organic compounds dropped by 45 percent and carbon monoxide by 32 percent between 1980 and 1993. During the same period nitrogen oxide highway vehicle emissions dropped by 15 percent. Ozone air quality standards attainment has fluctuated with weather, but has clearly been improving over the past 10 years, and carbon monoxide attainment has improved dramatically, with a several-fold drop in the number of people living in nonattainment areas. Council on Environmental Quality, *Environmental Quality: The Twenty-Fourth Annual Report of the Council on Environmental Quality* (Washington, DC: 1995) pp. *435,447.*

[16] At $24/bbl crude, ignoring the higher prices of product imports, total imports of 12.22 million barrels per day. Energy Information Administration see footnote *4,* table Al 1.

[17] These estimates of the cost of the short-term health effects only. The value of the risk of long-term chronic effects cannot be estimated. U.S. Congress, Office of Technology Assessment, ***Catching Our Breath: Next Steps for Reducing Urban Ozone, OTA-O-412*** (Washington, DC: U.S. Government Printing Office, July 1989).

[18] Congressional Research Service, Environment and Natural Resources Policy Division, "The External Coats of Oil Used in Transportation," June 3, 1992.

[19] Ibid

. increased leverage on the climate change problem, whose potential costs are huge but incalculable .20

Furthermore, if U.S.-developed advanced automotive technology were to penetrate not only the U.S. market but also the markets of other developed and developing countries, the benefits to the environment and the U.S. economy would multiply.

Many observers predict that the economic and environmental problems associated with continued high levels of world oil consumption will necessitate a transition to more environmentally benign, renewable fuels within the next 100 years. Such fuels might be, for example, electricity and hydrogen generated from renewable resources. These observers consider advanced automotive technology an important catalyst for this transition. In their view, internal combustion engines and their gasoline infrastructure would be transformed incrementally into more environmentally benign forms, such as fuel cells powered by hydrogen. In one such evolution, vehicles powered by gasoline-fueled internal combustion engines (ICES) would give way to hybrid electric vehicles (perhaps with multiple-fuel capability), in which the ICE would eventually be replaced by an advanced battery or fuel cell. Many analysts believe that the fuel cell, which combines hydrogen and oxygen to produce energy without combustion or its associated waste products, is potentially the most important energy technology of the 21st century-not only for vehicles, but also for electric power production in a wide range of stationary and mobile applications.[21]

Even advocates of such a technological transformation, however, would acknowledge that gasoline will be a very difficult fuel to displace because of its combination of abundance, low price, high energy content, and its long familiarity to engine designers. A major obstacle to any such transformation is that the full social costs of gasoline use are not included in its price (the true social cost includes the pollution damage and energy security cost discussed above, which some have estimated to be as high as several dollars a gallon[22]); nor are potential future social benefits of new technologies (e.g., reduced global climate change impact) valued in the marketplace so as to offset their higher costs. As a result, consumer demand is not providing an incentive for automakers to adopt technologies that could capture these social benefits. Rather, what incentives exist are coming from government, at both the state and federal levels.

There are now two key government drivers of vehicle innovation in the United States. One is California's Low Emission Vehicle (LEV) Program, one of whose provisions requires 2 percent of the vehicles produced by automakers with a significant share of the California market to be zero emission vehicles (ZEVs) by 1998, with the percentage rising to 10 percent by 2003.[23] This requirement has stimulated the three U.S. domestic automakers to form the U.S. Advanced Battery Consortium, a substantial cooperative research effort with other organizations to help produce batteries that would enable production of a commercially successful electric vehicle (the

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20 One of the potential impacts of global warming is an increase in the frequency of severe storms, each of which can cause many billions of dollars

and N. Lenssen, *Power Surge: Guide to the Coming Energy Revolution*, Worldwatch Environmental Alert Series (New York, NY: W.W. Norton& Co., 1994).

22 U.S. Congress, Office of Technology Assessment, *Saving Energy in U.S. Transportation*, OTA-ETI-589 (Washington DC: U.S. Government Printing Office, July 1994).

23 This works out to about 40,000 ZEVs produced in 1998 and 200,000 produced in 2003.

only near-term ZEV likely, according to current rules). Simultaneously, numerous electric vehicle (EV) development and commercialization efforts have begun, which are independent of, or only loosely affiliated with the existing auto industry.

The second is the newly created Partnership for a New Generation of Vehicles (PNGV), a research and development (R&D) program jointly sponsored by the federal government and the three domestic manufacturers. One of the program's three goals is the development of a manufacturable prototype vehicle within 10 years that achieves as much as a threefold increase in fuel efficiency while maintaining the affordability, safety, performance, and comfort available in today's cars.

OTA'S APPROACH

In this report, the Office of Technology Assessment (OTA) evaluates the performance and cost of a range of advanced vehicle technologies that are likely to be available during the next 10 to 20 years. Consistent with PNGV's goal of improving fuel economy while maintaining performance and other characteristics, a central emphasis of OTA's analysis is the potential to improve fuel economy. With the exception of nitrogen oxide (NO_x) catalysts for lean[24] and more efficient operation of piston engines, technologies whose primary function is to reduce tailpipe emissions are not a central focus of this study.

OTA's analysis of advanced vehicles is predicated on two critical vehicle requirements that strongly affect the study's conclusions and distinguish it from most other studies. The first requirement is that the advanced vehicles must have acceleration, hill-climbing, and other performance capability equivalent to conventional 1995 gasoline vehicles (the actual criteria used are 60 and 50 kW/ton peak power for, respectively, conventional and electric drivetrains, and 30 kW/ton continuous power for all drivetrain types) .25 This requirement is imposed first of all to enable a comparison of advanced and conventional technologies on an "apples to apples" basis, and also because advanced vehicles will have to compete head-to-head with extremely capable conventional vehicles in the marketplace. It is worth noting, however, that the exact power criteria used by OTA are not the only ones possible, that market preferences can change, and that the estimated advanced vehicle costs are quite sensitive to small changes in these criteria.[26]

The second OTA requirement is that the advanced vehicle be a mass-market vehicle produced in volumes of hundreds of thousands each year (as with PNGV, the actual target vehicle is a mid-size sedan similar to the Ford Taurus/Chrysler Concorde/Chevrolet Lumina). This requirement is imposed because advanced vehicles cannot have a major impact on national goals, such as

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[24]Current emission control systems require piston engines to operate *stoichiometrically,* that is, with just enough air to combust the fuel. *Lean* operation uses excess air, which promotes more efficient combustion but prevents the reduction catalyst for NO_x control from working-thus the need for a lean catalyst.

[25]Electric motors can match the acceleration performance of somewhat more powerful gasoline engines, at least at lower speeds, which explains the reduced peak power requirement for electric drivetrains. The performance requirements roughly correspond to a O to 60 mph acceleration time of 11 seconds and the ability to operate at 60 mph up a 6 percent slop-but the requirements should not be viewed narrowly as applying only to these precise conditions. Instead, they are ***placeholders*** for a variety of tasks that require high peak power or high **continuous** power, such as highway passing capability when the vehicle is heavily loaded or trailer towing.

[26] For example, electric vehicles that were used strictly as urban vehicles might not need 30 kW/ton continuous power.

reducing oil imports, unless they are able to penetrate the most popular market segments. Note that there are vehicles available in today's marketplace that attain more than 50 mpg fuel economy—but they are sold in such small quantities that they play essentially no role in the gasoline consumption of the fleet.

In examining hybrid vehicles,[27] OTA also focused its examination on vehicles that were not tied to the power grid-that could generate all of their needed electrical energy onboard using the power source as generator. This choice was made to provide maximum flexibility to the driver and minimum market risk to the automaker; that is, to make the hybrid resemble as closely as possible a conventional vehicle in operation. Some proposed alternative hybrids would operate more like electric vehicles (EVs) much of the time, recharging a large battery from the grid, with the engine providing a long-range cruise capability only. Hybrids of this sort might be able to achieve higher fuel economy values than the "autonomous" hybrids evaluated in this report, but they are less flexible in their performance capabilities.

Admittedly, these requirements establish an extremely high hurdle for new technologies to negotiate. Some critics of this approach may even say that OTA has predetermined its conclusions by deliberately setting criteria that new technologies cannot meet. Indeed, new technologies historically have not penetrated the automotive market by jumping full blown into the most demanding applications. Rather, technologies are typically introduced incrementally into niche vehicles in limited production. Only after the bugs are worked out and cost-effectiveness is proven do technologies move into mass-market vehicles. Similarly, the most likely mechanism for electric and hybrid vehicles to penetrate the market, at least initially, is in niches such as commuter vehicles or specialized urban fleets, which may have limited performance or range requirements.

OTA's concern in this study is less with the process by which advanced technologies may enter the market, however, than with the questions of how soon and to what extent these technologies could significantly affect national goals. It may well be, for example, that attractive, affordable, fin-to-drive electric commuter cars will be developed during the next five years that will attract a loyal following and sustain a small EV production industry. OTA's assumption, though, is that the powerful and versatile gasoline vehicles that constitute the majority of the U.S. market will only be displaced by advanced vehicles that have comparable power and versatility.

OTA'S METHODS

OTA's projections of advanced vehicle performance used approximate vehicle models based on well-known equations of vehicle energy use.[28] These models are "lumped parameter" models—that is, they use estimates of engine and motor characteristics and other variables that are averages over a driving cycle. Ideally, a performance analysis of complex vehicles such as hybrids should be based on detailed engine and motor maps that are capable of capturing the

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[27] Hybrids are vehicles that combine an electric drivetrain (including an energy storage device such as a battery) with an auxiliary power unit (e.g., engine, fuel cell).

[28] G. Sovran and M.S. Bohn, "Formulae for the Tractive Energy Requirements of Vehicles Driving the EPA Schedule," SAE Paper 810184, February 1981.

second-by-second interactions of all of the components. Such models have been developed by the auto manufacturers and others. Nevertheless, OTA believes that the approximate performance calculations give results that are adequate for our purposes. In addition, the detailed models require a level of data on technology performance that is unavailable for all but the very near-term technologies. Further details about OTA's methodology are given in appendix A.

OTA's cost estimates for advanced vehicles are based on standard industry methods that compute supplier costs to vehicle manufacturers and then apply markups to account for additional costs incurred by the manufacturer (handling, vehicle integration, warranty costs, and inventory costs), and dealer (e.g., shipping, dealer inventory costs, and dealer overhead). The cost estimates are based on assumptions about manufacturing volume, rates of return, and spending schedule (e.g., fixed cost spending over five years, 15 percent rate of return to vehicle manufacturers, 24,000 units per year for EVs 500,000 units per year for engines and transmissions).

DEALING WITH UNCERTAINTY

Forecasting the future cost and performance of emerging technologies is an extremely imprecise undertaking. This is particularly true in the advanced vehicle area, where the political and economic stakes are so high. For example, smaller companies seeking investment capital and concerned with satisfying existing investors have very strong incentives to portray their results as optimistically as feasible, and few companies are willing to discuss R&D problems and failures. Even Department of Energy research managers must sometimes act as advocates for their technologies to ensure their continued finding in a highly competitive research environment. The existence of government mandates for electric vehicles further complicates this problem: small companies, hoping that the mandate will create markets for their products, are strongly motivated to portray progress in the best possible light; the automakers affected by the mandates have, in contrast, an understandable stake in emphasizing the difficulties in achieving the mandates' requirements.

Another problem is that much of the research data are kept strictly confidential. Industry agreements with government laboratories have made even government test results largely off-limits to outside evaluators. For example, results of battery testing conducted by the national laboratories are now considered proprietary.

At the core of the problem, several of the key technologies are far from commercialization and their costs and performance are unknown. Furthermore, the research and development goals for some critical technologies require very large cost reductions and performance improvements that involve a great variety of separate technical advances. Consequently, cost and performance estimates are, implicitly or explicitly, based on a variety of assumptions about the outcome of several R&D initiatives. It is hardly surprising that such estimates vary greatly from source to source. In one case, for example, OTA has been assured by one reviewer that confidential data on batteries implies that our cost assumptions about near-term batteries are much too pessimistic; other reviewers with extensive access to test data and economic projections have told us that our cost projections for the same batteries are too optimistic.

Considering this wide range of claims, OTA developed its own "best guess" of technology performance and cost from test data in the open literature and opinions gathered from extensive interviews with experts from industry and the research community. Such an approach was necessary to reach any conclusions about the prospects for advanced automotive technologies. We also have attempted to define the assumptions behind our estimates, to make clearer comparison with others' estimates. Finally, we have cited relevant claims from various sources, to give the reader a sense of the range of uncertainty.

Where our estimates are seen as **pessimistic** *(example:* cost targets will be extremely difficult to meet), **they are likely to be more valuable as signposts of where attention must be directed if technologies are to be successfully commercialized, than as predictions that the technologies in question are unlikely to be successful.** And, where they are seen as **optimistic,** *especially* for the longer term *(example:* significant improvements will occur *in* internal combustion engines), **they are best taken as signs of a strong potential rather than as a definitive statement that these technologies are sure things.**

OVERVIEW OF RESULTS

OTA's general conclusions about advanced vehicle technologies are quite optimistic about the potential for excellent vehicle performance. They are considerably more cautious, however, about the speed with which technologies can be made commercially available and then introduced widely into the market, as well as about the likelihood that costs can be sufficiently reduced that no financial or regulatory incentives would be needed for market success.

Technical Potential

OTA concludes that the available broad menu of existing and emerging technologies offers a strong *technical* potential to substantially improve fuel economy. By 2005, assuming cost targets can be met, it will likely be possible to begin to introduce mass-market vehicles[29] into the new vehicle fleet that can achieve fuel economy from 50 **percent to 100 percent better than today's vehicles.** For example, some intermediate-size cars could be capable of achieving **from** 39 to 61 mpg (an increase from the current level of about 28 mpg), depending on their design and choice of drivetrain and other technologies. Within another decade, still higher levels of fuel economy may be possible-intermediate-sized cars capable of achieving 60 to 70 mpg or higher. **Much of this improvement (to about 40 mpg by 2005, and to over 50 mpg by 2015) should be achievable *without* a radical shift in vehicle drivetrains;** however, we believe that such radical shifts-for example, to hybrid-electric drivetrains--can yield significant added efficiency benefits (though at higher costs).

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[29] Like the Ford Taurus/Chevrolet Lumina/Chrysler Concorde trio.

Conventional vehicles are least efficient in city driving, and it is in this type of driving that advanced vehicles make the largest gains.[30] Some analysts believe that the actual mix of driving is changing away from the mix *assumed* in the standard Environmental Protection Agency (EPA) test of vehicle fuel economy, toward a higher percentage of urban, stop-and-go driving.[31] If this type of change in driving patterns is actually occurring—OTA has had no opportunity to examine this **issue-the fuel economy increases stated above--based on the standard driving cycle used in EPA fuel economy testing—might understate the on-road improvements made by the advanced technologies.**

Commercialization Potential

The commercial prospects for advanced technology vehicles will depend ultimately on their manufacturing cost and retail price, their operating and maintenance costs, and consumer attributes such as acceleration performance and range. According to OTA's projections, **advanced vehicles are likely to cost substantially more than their conventional counterparts, and the savings resulting from their lower fuel consumption will not offset their higher purchase prices.** Furthermore, although some analysts have claimed that operating and maintenance costs for advanced vehicles will be much lower than for conventional vehicles, evidence for such claims is weak.

These conclusions obviously raise valid concerns about the commercialization potential of advanced vehicles, especially given current consumer disinterest in fuel economy. Several factors, however, could improve commercialization prospects. First, ongoing research efforts to reduce manufacturing costs and to identify least-cost design alternatives for advanced vehicles might reduce vehicle prices below projected levels. Second, the prices of advanced vehicles could be reduced by limiting vehicle capabilities such as hill climbing ability or acceleration, or range (for EVs).[32] Third, consumer valuations of key characteristics of advanced vehicles, especially their improved efficiency and reduced emissions, could change (possibly as a result of another oil crisis); many consumers have shown by their current market behavior that they will pay substantial price increments for other "nonessential" vehicle characteristics that they value, such as four-wheel drive.[33] Fourth, government could boost commercialization prospects through economic incentives or regulations (e.g., gasoline taxes, feebates, and fuel economy standards).

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[30] For example, the 2015 median-case series hybrid is 161 percent more efficient than a 1995 mid-size vehicle on the city cycle, but only 96 percent more efficient than the 1995 vehicle on the highway cycle.

[31] J.D. Maples, University of Tennessee Transportation Center, Knoxville, "The Light-Duty Vehicle MPG Gap: Its Size Today and Potential Impacts in the Future," draft, May 28, 1993.

[32] Manufacturers have been reluctant to consider such limited capability vehicles, because they do not believe that large numbers of consumers will purchase them. There is an ongoing controversy about the willingness of auto purchasers to accept limitations on range, acceleration performance, and other vehicle attributes in exchange for features such as zero emissions.

[33] Although many purchasers of four-wheel drive vehicles require this capability, many four-wheel drive vehicles are never taken off the road and are rarely driven in the type of weather conditions where this capability may be essential.

Timing

Many in the automobile industry believe it is unlikely that rapid technological shifts will occur, as demonstrated by recent Delphi studies projecting an automobile fleet in 2003 that looks very much like today's.[34] In contrast, advocates of advanced vehicle technologies have tended to predict that such technologies can be introduced to the fleet in very short order. Indeed, the California ZEV initiatives assume that 10 percent of the state's new vehicle fleet can be EVs by 2003; the PNGV hopes to have at least a manufacturable prototype vehicle capable of achieving triple today's fuel economy by 2004; and several small manufacturers have exhibited prototype vehicles that they claim can be introduced at competitive prices as soon as sufficient financial support (or orders for vehicles) is obtained.

Predicting when a technology is ready for commercialization is particularly difficult because the act of commercialization is simultaneously a technical and a marketing decision—it hinges largely on a company's reading of the marketplace and on its willingness to accept risk, as well as on the actual state of the technology. Nevertheless, **OTA believes it is more realistic to be fairly conservative about when many of the advanced technologies will enter the marketplace. Also,** the history of market introductions of other technologies strongly implies that technologies will penetrate the mass market part of the vehicle fleet only after they have been thoroughly tested in smaller market segments—a process that can take from three to five years after initial introduction for incremental technologies, and more for technologies that require major design changes.

For example, even if the PNGV were fully successful—and OTA believes that its goals are extremely challenging-developing a manufacturable prototype by 2004 would likely yield an actual marketable vehicle no earlier than 2010. Furthermore, as noted, the first vehicles are likely to be small volume specialty vehicles, with entry into the true mass-market segments starting from three to five or more years later, depending on the market success of the new models. Finally, unless the first vehicles were overwhelmingly successful, the transformation of the new car and light truck fleets would take at least a decade. In other words, absent a crisis that would force a risky acceleration of schedules, **it might be 2020 or 2025 before advanced vehicles had thoroughly permeated the *new vehicle* fleet—and it would be another 10 to 15 years before they had thoroughly permeated the entire fleet.** Thus, major impacts of advanced technologies on national goals are decades away, at best.

DETAILED RESULTS

OTA's results focus specifically on a range of technology combinations in mid-sized automobiles, the heart of the light-duty fleet, including vehicles representing a continuation of current trends (business as usual); vehicles representing major improvements in conventional powertrains (advanced conventional); battery-powered EVs; hybrid vehicles that combine more

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34 Office for the Study of Automotive Transportation, ***Delphi VII Forecast and Analysis of the North American Automotive Industry, Volumes 2 (Technology) and 3 (Materials)*** (Ann Arbor, MI: University of Michigan Transportation Research Center, February 1994).

than one power source; and fuel cell vehicles. Two time periods were examined-2005 and 2015. The results of this analysis appear in tables 1-1 and 1-2.

Business as Usual

Assuming that gasoline prices rise very gradually in real dollars, to $1.50 a gallon[35] in 2015, OTA believes that new mid-size autos will gradually become more fuel efficient-reaching about 30 mpg by 2005 and 33 mpg in 2015[36]---despite becoming safer, roomier, more powerful, and cleaner[37] in this time period. The new car fleet as a whole would improve in fuel economy by about 25 percent during this period.

Because both the cost effectiveness of fuel economy technologies and customer preference for efficient vehicles will vary with gasoline prices, other gasoline price assumptions will generate different future fleet fuel economies. If gasoline prices were to reach $3 a gallon by 2015, OTA projects that new car fleet fuel economy would increase by 42 percent over 1995, to 39 mpg. In contrast, were gasoline prices to stagnate or decline in real dollars—as they have during the past decade or so---fuel economy improvements would be far less.

Furthermore, fleet fuel economy will depend on a host of additional factors (some of which are influenced by fuel prices) such as government safety and emissions regulations, consumer preferences for high performance, relative sales of autos versus light trucks (when considering the light-duty fleet as a whole), and so forth. OTA's estimate presumes no additional changes in regulations beyond what is already scheduled, gradually weakening demand for higher performance levels,[38] and no major shifts in other factors. Obviously, another set of assumptions would shift the fuel economy estimates.

Advanced Conventional

Auto manufacturers can achieve large fuel economy gains *without* shifting to exotic technologies such as fuel cells or hybrid-electric drivetrains. Instead, they could retain the conventional ICE powertrain by using a range of the technologies to reduce tractive forces (see box l-l) combined with advanced ICE technology (see box 1-2) and improved transmissions. If OTA's projections for technology prove to be correct, **a mid-size auto could achieve 39 to 42 mpg by 2005 and 53 to 63 mpg by 2015 using these technologies, at a net price increase to the buyer of $400 to $1,600 in 2005 and $1,500 to $5,200 in 2015.**

To achieve **53** mpg, the vehicle would combine a 2 liter/4 cylinder direct injection stratified charge (DISC) engine (with lean NO_x catalyst); optimized aluminum body, with the entire vehicle

[35] In 1994 dollars.

[36] Source: Department of Energy fuel economy model based on the cost-effectiveness of alternative technologies.

[37] It is expected that these vehicles will achieve California LEV emission standards or better by 2015.

[38] It is assumed that the steady increases in horsepower/weight and top speed and decreases in 0 to 60 mph acceleration time typical of the past decade will gradually slow down and cease.

weighing only 2,300 pounds (versus 3,130 today); continuously variable transmission; drag coefficient of 0.25, compared to today's average of about 0.33; and advanced, low rolling resistance tires. This vehicle would be likely to cost about $1,500 more at retail than the business as usual vehicle, which achieves 33 mpg.

Achieving 63 mpg requires materials technology likely to be more expensive than aluminum and more difficult to develop commercially-a carbon-fiber body weighing only 1,960 pounds, coupled with a small DISC engine, continuously variable transmission, and improved aerodynamic drag coefficient of 0.22;[39] the net price increase would be nearly $5,200 because of the expected high cost of the body. Although some developers have claimed that this type of materials technology is very close to commercialization, our evaluation indicates the opposite-the capability to mass-produce carbon-fiber composite automobiles does not currently exist, and extensive research will be required to design composite vehicle bodies to attain acceptable occupant safety.

Depending on the goals of policymakers, the less exotic of the year 2015 advanced conventional vehicles-with DISC engine and optimized aluminum body, achieving about 53 mpg at a net additional price of $1,500-might appear especially attractive. Because fuel economy gains achieve diminishing returns in fuel savings as fuel economy levels increase, this vehicle will attain most of the possible incremental fuel savings (from the business-as-usual vehicle) at much lower cost than alternative vehicles. For example, a hypothetical advanced hybrid vehicle attaining the PNGV goal of 80 mpg—which would likely cost several thousand dollars more than the business as usual vehicle-will use 125 gallons of fuel annually at 10,000 miles per year, compared with 303 gallons annually for the business as usual vehicle at 33 mpg. **The 53 mpg advanced conventional vehicle will use only 189 gallons annually—attaining 64 percent of the fuel savings of the 80 mpg vehicle at much lower cost.**[40]

Electric Vehicles

EVs are currently the only vehicles capable of satisfying the California zero emission vehicle mandates, which require that 2 percent of vehicles sold in California in 1998 have zero tailpipe emissions, rising to 10 percent by 2003. The future performance and costs of EVs are controversial Advocates such as California's Air Resources Board claim that EVs with satisfactory performance will soon be available whose life cycle costs are comparable to an equivalent gasoline vehicle (though probably not by 1998, when economies of scale have not been achieved). Skeptics, particularly the major auto manufacturers, claim that any EVs introduced in 1998 and a number of years thereafter will have limited range and much higher initial and operating costs than comparable gasoline vehicles.

39Most automakers are skeptical of the practicality of an aerodynamic drag coefficient this low for a mass-market vehicle, but there are some vehicle prototypes that appear to achieve this level without sacrificing critical features such as trunk space, ground clearance, and rear seat room.

40 At $1.50 a gallon gasoline, the advanced conventional vehicle's fuel savings of 114 gallons annually compared to the business as usual vehicle amounts to the equivalent of about $1,000 in initial purchase price, assuming a discount rate of 10 percent.

Although development of commercially successful mass-market EVs will require strong efforts with a number of different vehicle components, improving EV batteries is certainly the key task (box 1-3). With lithium batteries as the sole exception, however, the batteries under current development will not enable EVs to attain ranges comparable to conventional vehicles. Consequently, unless the lithium battery program is successful (which is unlikely before 2010), EVs must be able to overcome potential consumer resistance to range limits-an uncertain prospect for mass-market vehicles.

OTA examined mid-size EVs with a few different battery types and range requirements, but with performance matched to average conventional vehicles. A major source of uncertainty in our analysis was the operating capability of the various batteries under the stressful demands of vehicle operation. Much of the independent testing being conducted is under the auspices of the U.S. Advanced Battery Consortium, and even though DOE's national laboratories are doing the testing, the results are proprietary. Use of available public information led to the following vehicle projections:

1. In 2005, a mid-size EV powered by an advanced semi-bipolar lead acid battery with an 80-mile range would weigh over 4,400 pounds and cost about $11,000 more than the baseline (business-as-usual) vehicle. The vehicle would be much lighter—2,900 pounds—if equipped with nickel metal hydride (NiMH) batteries sized for a 100-mile range. Costs would be very high (about $18,000 over the baseline vehicle) if the batteries cost the expected $400/kWh; one developer claims it will achieve $230/kWh or less, however; a $200/kWh cost would reduce vehicle costs to about $9,000 over the baseline. As shown in table 1-1, the gasoline-equivalent fuel economy is 32 mpg for the lead acid-powered EV and 52 mpg for the NiMH-powered EV.[41]

2. EV characteristics may be much improved in 2015, owing to lighter body materials (e.g., optimized aluminum), better structural design, and further battery improvements. The incremental price for a lead-acid powered, 80-mile range mid-size EV would be about $4,200 over the baseline vehicle, and 200 mile EVs with either nickel metal hydride or sodium sulfur batteries will be available, though costly. If lithium polymer batteries are perfected by this date, a 300-mile mid-size EV is possible, at very uncertain cost. The equivalent fuel economies of the shorter-range vehicles are 51 mpg for lead acid and 82 mpg for a 100-mile range NiMH EV.

Because EV characteristics are so dependent on performance requirements, "low performance" EVs would be significantly less expensive-and more energy efficient, because of sharply lower battery weight—than those described here. For example, if range requirements were lowered to 50 miles from 80, the 2005 mid-size EV with semi-bipolar lead acid battery could be sold for a premium of only $3,600 over the baseline vehicle-versus more than $11,000 for the 80-mile range EV. The lower battery weight would reduce its energy consumption to about 0.156 kWh/km from 0.250 kWh/km—in "equivalent fuel economy" terms, raising its fuel economy from

[41]These values are dependent on the efficiency of power generation for recharge electricity. Here it is assumed to be 38 percent. If the power were obtained from combined-cycle natural gas plants, this efficiency could be as high as 50 percent.

31 mpg to about 50 mpg.[42] Further, reducing the peak power requirement by 20 percent (to 40 kW/ton) would save an additional $1,000.

Hybrid-Electric Vehicles

Hybrids are vehicles that combine two energy sources (for example, an IC engine and a battery) in a single vehicle, and use electric motors to provide some or all of the vehicle's motive force. The hybrid drivetrain offers several advantages: limited range becomes less of a problem, or no problem; a portion of inertia losses can be recovered through regenerative braking; and the engine can be operated near its optimum (most efficient) point.[43] A key *disadvantage* can be the added weight, cost, and complexity of the hybrid's multiple components.

A number of proponents have claimed that a hybrid configuration can yield fuel economy improvements of as much as 100 percent over an otherwise-identical conventional vehicle, and a number of experimental vehicles, including winners of DOE's "Hybrid Challenge" college competition, have claimed very high levels of fuel economy, up to 80 mpg. An examination of the actual vehicle results indicates, however, that the conditions under which high fuel economies were achieved are conditions that typically lead to high levels of fuel economy with *conventional* vehicles, and the test vehicles typically had limited performance capability. In OTA's view, the results reveal little about the long-term fuel economy potential of hybrids that could compete with conventional vehicles in the marketplace.

There are numerous powertrain and energy management strategy combinations for hybrid drivetrains, though many are ill-suited for high fuel economy or for the flexible service characteristic of current vehicles. OTA examined a limited set of hybrids designed to achieve a close performance match with conventional vehicles, combining IC engines with battery, flywheel, and ultracapacitor storage (see box 1-4) in series and parallel combinations (see box 1-5).

OTA found that hybrids of this sort could achieve 25 to 35 percent fuel economy improvement over an otherwise-identical vehicle with conventional drivetrain and similar performance *if* very good performance could be achieved from the storage devices and other electric drivetrain components. The importance of improving electric drivetrain components is paramount here. For example, a series hybrid *without* improved storage, that is, using an ordinary lead acid battery, would achieve *lower* fuel economy than the conventional vehicle, because the battery's lower specific power (power per unit weight) requires a larger, heavier battery for adequate performance, and because more energy is lost in charging and discharging this battery than would be lost with a more advanced battery. This latter result agrees with results obtained by several current experimental vehicles built by European manufacturers. **Perfecting high power density/high specific power[44] batteries or other storage devices is**

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42 Using the same assumptions as those in table 1-1.

43 That is, the engine can be run near its most efficient point most of the time, with the battery or other energy storage device absorbing excess power (when the vehicle's tractive loads are small) or providing extra power when needed (when vehicle loads are high, for example, during hard acceleration).

44 Power density is power per unit volume; specific power is power per unit weight.

critical to developing successful hybrids. Because the hybrid's fuel provides its energy storage, attaining high specific power and power density would allow the storage device to be much smaller and lighter--critical factors in maintaining usable space onboard the vehicle and improving fuel economy.

As noted, there are numerous strongly held views about the fuel economy potential of hybrids, ranging from the view that hybrids offer limited (if any) potential to a view that hybrids can yield 100 percent or higher fuel economy improvement with equal performance. European and Japanese automakers are particularly skeptical about hybrids. Those who are optimistic appear to be basing their position on the likelihood of radical improvements in the weights and efficiencies of batteries, motors and controllers, and other electric drivetrain components. OTA's analysis assumes that substantial improvements in these components will occur, but there clearly is room for argument about how much improvement is feasible.

According to OTA's analysis, in 2005, a mid-size series hybrid combining a small 50 HP (37 kW) engine with a bipolar lead acid battery, with an optimized steel body, could achieve 49 mpg at an increased price of $4,900 over the baseline (30 mpg) vehicle. If the energy storage device were a flywheel and the body were aluminum-intensive, the hybrid could achieve 61 mpg, but at a substantially higher price, and the engine would have to be turned on and off several times during all but the shortest trips[45] —raising some concerns about emissions performance, because immediately after an engine is started emissions generally are higher than during steady operation.[46]

By 2015, a series hybrid with an improved bipolar lead acid battery (assuming this type of battery can be perfected) and an optimized aluminum body could be considerably more attractive---attaining 65 mpg at an estimated additional cost of about $4,600 to the vehicle purchaser. A similar vehicle with ultracapacitor or flywheel could achieve still higher fuel economies-71 and 73 mpg, respectively—but the earlier problems with turning the engine on and off would persist, and the price would likely be substantially higher than with the battery. The need to turn the engine on and off is a function of the limited energy storage and high cost/kwh of storage of the ultracapacitor and flywheel, so that improving these factors would reduce this need and improve emissions performance for these vehicles.

The projected fuel economy values for these hybrids is strongly dependent on improvements in the component efficiencies of the electrical drive system. Although the values projected by OTA are higher than those attainable today, PNGV and others hope to do still better—which would, in turn, yield higher vehicle fuel economy. For example, in 2015, an additional 4 percent increase in motor/generator efficiency would raise the lead acid-based hybrid's fuel economy from about 65 mpg to nearly 69 mpg; the same increase would raise the ultracapacitor-based hybrid's fuel economy from about 71 mpg to approximately 75 mpg. Similar improvements in other

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[45] The need to turn the engine on and off several times stems from the limited storage capacity of the flywheel. The engine has to be large enough to sustain the vehicle's requirementt for maximum continuous power, 30 kW/ton. At or close to its optimum output it will fill up the flywheel's storage capacity rather quickly during periods of low power demand, and then must be turned off---to be turned on again when the flywheel's energy is drawn down. Although turning the engine off might be avoided by throttling it back sharply, this would cause a substantial reduction in engine efficiency, and an increase in fuel consumption.

[46] Automakers have been working to reduce emissions following cold and hot starts, which should reduce the problems caused by turning the engine on and off.

components, such as the energy storage devices, could allow the ultracapacitor-based hybrid (and the flywheel hybrid) to achieve PNGV's goal of 82 mpg, which is triple the fuel efficiency of current mid-size cars.

An intriguing feature of many of these hybrids-specially those using batteries for energy storage is that they can operate in battery-only mode for some distance. For example, the 2005 and 2015 battery hybrids in tables 1-1 and 1-2 have battery-only *ranges* of 28 and **33** miles, respectively. This would allow them to enter and operate in areas (e.g., inner cities) restricted to EV operation. In addition, although these vehicles are designed to be independent of the electric grid, they could have the capacity to be recharged, allowing them to operate as limited-capability/limited-range EVs in case of an oil emergency—an attractive feature if the future brings more volatile oil supplies.

Although most U.S. developers appear to be focusing their efforts on series hybrids, OTA estimates that parallel hybrids that used their engines for peak loads and electric motors for low loads could achieve fuel economy gains similar to those of the series hybrids examined by OTA—25 to 35 percent. The development challenges of parallel hybrids appear to be more severe than those of series hybrids, however, because of this type of hybrid's unique driveability problems[47] and its requirements for stopping and restarting the engine when going back and forth between low and high power requirements.[48]

The hybrids discussed above are designed to compete directly with conventional autos—that is, they would perform as well and, being disconnected from the grid, have unlimited range as long as fuel is available. There are other configurations, or other balances between engine and energy storage, that could serve a different, narrower market. For example, vehicle designers could use a smaller engine and larger energy storage that would be recharged by an external source (e.g., the electricity grid) to achieve a vehicle that could serve as an EV in cities[49] and would have relatively long range. This design would not perform quite as well as the hybrids discussed above, however, and would have to be recharged after a moderately long trip.

California is considering allowing hybrids to obtain ZEV credits, if these vehicles meet a minimum EV range requirement. This would tend to push hybrid designs in the direction discussed above (small engine, large energy storage), and reduce the likelihood that those energy storage devices with low specific energy—such as ultracapacitors and possibly flywheels-will be attractive candidates for commercialization.

Fuel Cell Vehicles

Fuel cells are electrochemical devices that turn hydrogen directly into electricity without combustion, at high efficiency and with emissions only of water. For a fuel cell-powered vehicle,

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47 The wheels are driven by two different power sources that have different characteristics and will operate alternately or in tandem at different points in the driving cycle.

48 That is, as noted in box 1-2, the engine is turned on only when the power demand is too high for the battery/motor combination to handle, i.e. during hard acceleration, high-speed cruising, or hill climbing.

49 The "competitive" hybrids can operate as EVs also, though not as well as hybrids expressly designed to fit that role.

the hydrogen can either be carried onboard or produced from a hydrogen-rich fuel such as methanol.[50] Although there are several types of fuel cells, most analysts consider the proton exchange membrane (PEM) fuel cell as the best candidate for vehicle applications, because of its low-temperature operation and expected potential to achieve high power density and low cost. Achieving low cost and small size and weight remains a substantial development challenge, however. Current fuel cells cost thousands of dollars per kW and are too large to fit comfortably in a light-duty vehicle; researchers hope to reduce their costs to less than $40/kW and shrink their size to fit into a car without usurping its cargo space. In fact, recent fuel cell prototypes have demonstrated substantial success in size reduction.

While longer term prospects show promise, OTA considers it unlikely that a PEM fuel cell can be successfully commercialized for high-volume, light-duty vehicle applications by 2005, although fuel cell developers *are* hoping for early commercialization in larger vehicle applications (buses, locomotives); 2015, or perhaps a bit before, seems a more likely date for commercialization, *if* the many remaining development challenges are successfully met. By that year, an aluminum-bodied mid-size PEM fuel cell vehicle with methanol fuel and a bipolar lead acid battery for high power needs and cold start power might be capable of achieving about 80 mpg.[51] The price of such a vehicle is extremely uncertain. With current fuel cell designs, assuming that substantial cost reductions from current values are achieved and the designs are optimized and produced in large quantities, a mid-size car could cost $40,000 more than an equivalent baseline car. *If* fuel cell developers can cut costs to $65/kW or below for both fuel cell and reformer, the incremental price could be $6,000 or less. The incremental vehicle price could also be reduced substantially by relaxing the maximum continuous power requirement, thus allowing a smaller fuel cell to be used.[52] This conceivably might be a reasonable tradeoff for an urban commuter vehicle, but not for an all-purpose vehicle.

Small vehicular fuel cells are still at a relatively early stage of development, and system improvements have come rapidly. Successful commercialization, however, will depend on great improvements in a host of separate development areas—size and cost reduction of methanol reformers, development of low-cost, high-energy-density, onboard hydrogen storage; shrinkage of fuel cell "balance of plant"; reduction of platinum catalyst requirements[53]; and a good many others. Differing degrees of optimism about the likely success of these R&D efforts explain most of the differences among the various estimates of future fuel cell performance and cost. In OTA's view, the most optimistic estimates, such as fuel cell costs at well below $65/kW, are certainly possible but require a substantial degree of good fortune in the R&D effort-and the progress needed is unlikely to come quickly.

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[50] The onboard methanol-to-hydrogen reformer would produce emissions, but they would be small.

[51] Gasoline equivalent, in energy units, starting from methanol as the primary fuel.

[52] For example, by relaxing this requirement to 20 kW/ton (the equivalent of maintaining 60 mph up a 3 percent grade, versus the 6 percent grade allowed by 30 kW/ton), the incremental price at the higher fuel cell cost would be cut by 40 percent.

[53] Proved only at the individual cell level.

PERFORMANCE AND COST OF OTHER TYPES OF LIGHT-DUTY VEHICLES

Most of the results of OTA's analyses of mid-size autos apply similarly, on a percentage basis, to other auto size classes—such as subcompacts—and to light trucks. There are, however, some interesting differences. For example, the aerodynamics of different vehicle classes are subject to different constraints. Subcompacts are unlikely to attain as low a drag coefficient as mid-size vehicles because their short lengths inhibit optimum shapes for minimum drag. Pickup trucks, with their open rectangular bed and higher ride height have relatively poor drag coefficients, and four-wheel-drive pickups are even worse, because of their large tires and higher ground clearance. And compact vans and utility vehicles have short noses, relatively high ground clearance, and box-type designs that restrict drag coefficients to relatively high values. Although each vehicle type can be made more aerodynamic, it is unlikely that light-truck drag values will decline quite so much as automobile drag values can.

Another important difference is market-based—historically, introduction of new technologies on light-duty trucks has typically lagged by five to seven years behind their introduction in cars. Although this lag time might change, it is likely that some lag will continue to persist.

Differences in the functions of the different vehicle classes will affect fuel economy potential, as well. For example, the load-carrying function of many light trucks demands high torque at low speed, and may demand trailer-towing capability. The latter requirement, in particular, will constrain the type of performance tradeoffs that might be very attractive for passenger cars using electric or hybrid-electric powertrains.

Whereas OTA expects the business-as-usual fleet of automobiles to improve in fuel economy by about 24 percent between 1995 and 2015, the fuel economy of the light truck fleet is expected to increase a bit less than 20 percent. Prices will scale with size: for example, for hybrids, subcompact prices will increase by about 80 percent of the mid-size car's price increment, compact vans by about 110 percent, and standard pickups by about 140 percent, reflecting the different power requirements of the various vehicle classes.

LIFECYCLE COST---WILL THEY OFFSET HIGHER PURCHASE PRICES?

Although vehicle purchasers may tend to focus on initial purchase price more than on operating and maintenance (O&M) costs and expected vehicle longevity in their purchase decisions, large reductions in O&M costs and longer lifespans may offset purchase price advantages in vehicle purchase decisions. For example, diesel-powered vehicles typically cost more than the same model with a gasoline engine, and often are less powerful, but are purchased by shoppers who respect their reputation for longevity, low maintenance, and better fuel economy, or who are swayed by diesel fuel's price advantage (in most European nations), or both. Proponents of advanced vehicle technologies, especially EVs and fuel cell EVs, often cite their claimed sharp advantages in fuel costs, powertrain longevity, and maintenance costs as sufficient economic reasons to purchase them—aside from their societal advantages.[54]

A few simple calculations show how a substantially higher vehicle purchase price may indeed be offset by lower O&M costs or longer vehicle lifetime. Assuming a 10 percent interest rate and 10-year vehicle lifetime, for example, a $1,000 increase in purchase price would be offset by a $169 per year reduction in O&M costs. Since average annual maintenance costs for gasoline vehicles are $100 for scheduled maintenance and $400 for unscheduled maintenance over the first 10 years of vehicle life,[55] there is potentially a substantial purchase price offset if advanced vehicles can achieve very low maintenance costs. Similarly, an increase in vehicle price of about 25 percent—for example, from $20,000 to $25,000-would be offset by an increase in longevity of 5 years, assuming the less expensive vehicle would last 10 years.[56]

OTA's evaluation of lifecycle costs leads to the conclusion that their influence will offset sharply higher purchase prices *only under limited conditions.* For example, unless gasoline prices increase substantially over time, any energy savings associated with lower fuel use or a shift to electricity will provide only a moderate offset against high purchase price-primarily because annual fuel costs are not high in efficient conventional vehicles. In the mid-size vehicles OTA examined for 2015, for $1.50 a gallon gasoline, the *minimum* savings (NiMH EV versus baseline vehicle, savings of about $400 per year—see table 1-3) would offset about $2,300 in higher purchase price for the NiMH EV. In contrast, the EV may cost as much as $10,000 more than the baseline vehicle. Moreover, 51 percent of the fuel cost savings could be obtained by purchasing the 53 mpg advanced conventional vehicle, which costs only $1,500 more than the baseline vehicle.

Experts contacted by OTA generally agree that electric drivetrains should experience lower maintenance costs and last longer than ICE drivetrains.[57] The amount of savings is difficult to gauge, however, and may not be large because of continuing improvements in ICE drivetrains (for example, the introduction of engines that do not require a tune-up for 100,000 miles) and the likelihood that future electric drivetrains will undergo profound changes from today's,[58] with unknown consequences for their longevity and maintenance requirements. Moreover, battery replacement costs for EVs (and hybrids and fuel cell EVs to a lesser extent) could offset other savings,[59] although this, too, is uncertain because it is not yet clear whether battery development will succeed in extending battery lifetime to the life of the vehicle. Vehicles with hybrid drivetrains may experience no O&M savings because of their complexity. Finally, although analysts have claimed that fuel cell vehicles will be low maintenance and long-lived,[60] the very early

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[54]For example, see the lifecycle cost analyses in M. Delucchi, University of California at Davis, Institute of Transportation Studies, 'Hydrogen Fuel-Cell Vehicles" UCD-ITS-RR-92-14, September 1992; and U.S. General Accounting Office, *Electric Vehicles: Likely Consequences of U.S. and Other Nations Programs and Policies,* GAO/PEMD-95-7 (Washington, DC: December 1994).

[55]Delucchi, ibid

[56]Many vehicle purchasers will not actually make this economic calculation, however, because they do not foresee keeping the vehicle this long and its likely value at trade-in will depend on a host of factors besides its remaining lifetime. For advanced vehicles, technology change should be rapid during the period immediately following their introduction and technical obsol escence may negatively affect their trade in values.

[57]U.S. Congress, Office of Technology Assessment, Workshop on Advanced Automotive Technologies Apr. 19-20, 1995.

[58]For example, several-fold reductions in motor weight.

[59]An EV battery capable of 100 miles range can easily cost $10,000 at retail. There have been no public reports of any potential EV batteries having attained more than five years of operation in vehicle service.

[60]Delucchi, see footnote 54.

development state of PEM cells demands caution in such assessments, and we see little basis for them. In particular, fuel cells have a complex balance of plant,[61] a methanol reformer with required gas cleanup to avoid poisoning the fuel cell's catalysts, and a number of still-unresolved O&M-related issues such as cathode oxidation and deterioration of membranes.

EMISSIONS PERFORMANCE

Reductions in vehicular emissions are a key goal of programs to develop advanced technology vehicles. In California, it is the only explicit goal, although other considerations, such as economic development, are important. Furthermore, PNGV's original name was the Clean Car Initiative.

The drive to ratchet down the emissions of new vehicles is highly controversial. One reason is that most vehicular emissions come from older vehicles, or relatively new vehicles whose emission controls are malfunctioning. Automakers have long argued that new control requirements that raise the price of new vehicles have the effect of slowing new vehicle sales and, thus, reducing fleet turnover-the primary source of improved fleet emissions (and fuel economy) performance. Further, there is substantial disagreement about how much new controls will cost, and thus similar disagreement about their balance of costs and benefits.

Each of the advanced vehicles examined by OTA have emission characteristics that are different from current vehicles as well as from the baseline (business-as-usual) vehicles expected to enter the fleet, if there are no new incentives for significant changes in vehicle technology. A number of changes that will yield improvements to new vehicles' emission performance, however, already are programmed into vehicle development programs. Both the federal Clean Air Act and California's Low Emission Vehicle Program require significant improvements in the certified emission levels allowable for new light-duty vehicles, as well as an extension of the certified "lifetime" of required control levels from 50 thousand to 100 thousand miles. New requirements for onboard diagnostics to alert drivers and mechanics to problems with control systems, more stringent and comprehensive inspection and maintenance testing (including testing for evaporative emissions), and expansion of certification testing procedures to include driving conditions that today cause high emission levels should ensure that actual on-road emissions of average vehicles more closely match the new vehicle certification emissions levels.

The Advanced Conventional vehicles will most closely resemble the baseline vehicles' emissions performance. By 2015, however, these vehicles will have direct injection engines-either diesel or gasoline. These engines should have lower cold start and acceleration enrichment-related emissions than conventional gasoline engines. This should have a positive impact on emissions, although new regulations should force down such emissions even in the baseline case. A key uncertainty about emissions performance for these vehicles is the performance of the NO_x catalysts, which currently remain under development. Another area of concern, for the diesels, is particulate emissions performance; although new diesel designs have substantially reduced

61 Balance of plant is the machinery needed to support the basic fuel cell stacks, including air compressors, heat removal system, and watering system.

particulate emissions, these emissions levels are still considerably higher than those of gasoline vehicles.

The key emissions advantage of EVs is that they have virtually no vehicular emissions[62] regardless of vehicle condition or age-they will never create the problems of older or malfunctioning "super-emitters," now a significant concern of the current fleet. Because EVs are recharged with powerplant-generated electricity, however, EV emissions performance should be viewed from the standpoint of the entire fuel cycle, not just the vehicle. From this standpoint, EVs have a strong advantage over conventional vehicles in emissions of HC and CO, because power generation produces little of these pollutants. Where power generation is largely coal-based—as it is in most areas of the country-some net increases in sulfur dioxide might occur. However, Clean Air Act rules "cap" national powerplant emissions of sulfur oxides (SO_x) at about 9 million tons per year, which limits the potential adverse effects of any large-scale increase in power generation associated with EVs Any net advantage (or disadvantage) in NO_x and particulate emissions of EVs over conventional vehicles is ambiguous, however. All fossil and biomass-fueled power generation facilities are significant emitters of NO_x, and most are significant emitters of particulate, although there are wide variations depending on fuel generation technology, and emission controls. Analyses of the impact of EVs on NO_x and particulate emissions are extremely sensitive to different assumptions about which powerplants will be used to recharge the vehicles, as well as assumptions about the energy efficiency of the EVs and competing gasoline vehicles[63] and the likely on-road emissions of the gasoline vehicles. OTA estimates that the year 2005 lead acid EVs will most likely *increase* net NO_x on a nationwide basis, with the NiMH battery-powered vehicle about breaking even, but that the combined effect of increased NO_x controls on powerplants, a continuing shift to cleaner generating sources, and increases in EV efficiency will allow the more efficient EVs in 2015 to gain a small net reduction in NO_x emissions.[64]

Hybrid vehicles have been generally considered as likely to have significantly lower emissions than conventional vehicles because of their smaller engines and the supposition that these engines would be run at constant speed and load (for series hybrids). There have been various reports of hybrids attaining very low emissions—below ultralow emissions vehicle standards-in certification-type testing.[65]

One key advantage for some hybrids will be their ability to run in an EV-mode in cities, although their performance or range may be limited in this mode.[66] Other advantages are less certain, however. Hybrids will likely *not* run at constant speed, although their speed and load excursions will be less than with a conventional vehicle; they must cope with cold start and evaporative emissions essentially similar to a conventional vehicle; and their engines may be stopped and restarted several times during longer trips, raising concerns about increased emissions from hot restarts. In OTA's view, hybrid vehicles with substantial EV range have clear emission advantages in this mode, but advantages in normal driving are unclear.

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[6]EVs with unusual batteries will generate some emissions from deteriorating anodes and cathodes and vaporizing electrolyte.

[63]It is not uncommon for analysts to compare small, low-powered limited range EVs to large fill-powered gasoline vehicle clearly to the EVs advantage.

[64]The lead acid-powered vehicle has little or no reductions, but the NiMH-powered vehicle achieves about 30 to 40 percent reductions.

[65]Ward's Communications, *Ward's Engine update and Vehicle Technology,* various issues.

Fuel cell vehicles will have zero emissions unless they use an onboard reformer to process methanol or another fuel into hydrogen. Emissions from the reformer should be extremely low in normal steady-state operation, but there may be some concern about emissions during increased loads, or the potential for malfunctions. In particular, the noble metal catalyst needed for the reformer can be poisoned in the same manner as the catalyst on a gasoline vehicle.

SAFETY OF LIGHTWEIGHT VEHICLES

Several of the advanced vehicles examined by OTA will be extremely light. For example, one of the 2015 advanced conventional vehicles weighs less than 2,000 pounds. An examination of the basic physics of vehicle accidents and the large U.S. database on fatal and injury-causing accidents indicates that a substantial "downweighting" of the light-duty fleet will create some significant safety concerns, especially during the transition period when new, lighter vehicles mix with older, heavier ones. Any adverse safety impacts, however, are unlikely to be nearly so severe as those that occurred as a result of changes in the size and weight composition of the new car fleet in 1970 to 1982.[67] The National Highway Traffic Safety Administration concluded that those changes "resulted in (net) increases of nearly 2,000 fatalities and 20,000 serious injuries per year. " Many of those adverse impacts occurred because vehicles changed in size as well as weight, however, yielding reduced crush space, reduced track width and wheelbase (which increased the incidence of vehicle rollovers), and so forth. Reducing weight while maintaining vehicle size and structural integrity should have lower impacts.

The major areas of concern about vehicle "lightweighting" are the following:

- Passengers in lighter vehicles tend to fare much worse than the passengers in heavier ones in collisions between vehicles of unequal weight, because heavy vehicles transfer more momentum to lighter cars than vice-versa. During the long transition period when older, heavier vehicles would remain in the fleet, lightweight vehicles might fare poorly. Moreover, if the large numbers of light trucks in the fleet do not reduce their weight proportionately, the weight distribution of the fleet could become wider, which would cause adverse impacts on safety.

- Vehicle designers must balance the need to protect passengers from deceleration forces (requiring crush zones of lower stiffness), and the need to prevent passenger compartment intrusion (requiring high strength/high stiffness structure surrounding the passengers).[68] Lighter vehicles will have lower crash energy in barrier crashes or crashes into vehicles of similar weight, so they will require a softer front structure than a heavier vehicle to obtain the same degree of crush (and same protection against

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66 If the energy storage device is a battery, performance will likely be limited if the engine cannot be used. With a flywheel or ultracapacitor, having adequate power is not a problem, but the EV range will be very short, perhaps *no more than* a few miles.

67 Assuming that the weight reductions are purely based on materials substitution and structural redesign, not on size reduction.

68 Generally, the overall protective structure of the car has two components: a very stiff, very strong cage around the passenger compartment whose primary purpose is to maintain the integrity of the compartment; and a soiler, crushable structure surrounding it to absorb the energy of a crash and control deceleration forces. However, the roles are not truly independent; for example, the outer structure also works to avoid intrusion into the passenger compartment and the safety c-age may have to deform and dissipate crash energy in a very severe accident.

deceleration forces) in otherwise similar crashes (e.g., barrier crashes at the same velocity). Designing large, lightweight vehicles with soft structures that have acceptable ride and handling characteristics (structural stiffness is desirable for obtaining good ride and handling characteristics) and are protective against passenger compartment intrusion may be a challenge to vehicle designers. Additionally, the differential needs for stiffness among lighter and heavier vehicles may cause compatibility problems in multi-vehicle crashes.

- In collisions with roadside obstacles, lighter vehicles have less chance than a heavier vehicle of deforming the obstacle or even running through it, both of which would decrease deceleration forces on the occupants. Also, a substantial decrease in average vehicle weight might cause compatibility problems with current designs of safety barriers and breakaway roadside devices (e.g., light poles), which are designed for a heavier fleet.

- If weight reductions are achieved by shifting to new materials, vehicle designers may need considerable time to regain the level of modeling expertise currently available in designing steel vehicles for maximum safety.

There exist several safety design improvements that could mitigate any adverse effects caused by large fleetwide weight reductions—though, of course, such measures could improve fleet safety at any weight. Examples include external air bags deployed by radar sensing of impending accidents; accident avoidance technology such as automatic braking; and improvements in vehicle restraint systems (including faster acting sensors and "smart" airbags that can adjust to accident conditions and occupant characteristics). The latter would greatly benefit from further biomechanical research to improve our understanding of accident injury mechanisms.

Large fleet weight reductions also will intensify the need for the National Highway Traffic Safety Administration to examine carefully its array of crash tests for vehicles, to ensure that these tests provide incentives to maximize vehicle-to-vehicle compatibility in crashes.

A NOTE ABOUT COSTS AND PRICES

The price of advanced technologies is a controversial aspect of the continuing debate over the merits of several government actions promoting such technologies. These actions range from the alternative fuel vehicle requirements of the federal Energy Policy Act of 1992[69] to California's ZEV requirements to federal funding (in concert with industry) of PNGV. OTA's estimates of retail price differentials for advanced conventional vehicles are somewhat below industry estimates, while estimates for hybrid, fuel cell, and electric vehicles seem to be above some others prepared by advocacy groups. Part of the difference between OTA's estimates and others undoubtedly reflects the substantial uncertainty that underlies any efforts to predict future prices of new technologies. Other differences arise from the following sources:

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[69] Public Law 486, Oct. 24, 1992.

- OTA's relatively low incremental prices for advanced conventional vehicles rest partly on our assumption that the advanced technologies are competing with baseline technologies that are new models with newly designed assembly lines; the baseline vehicles are not simply continued production of an existing technology whose investment costs may have been filly amortized.

- OTA's relatively high prices for hybrid, fuel cell, and electric vehicles reflect in part OTA's assumption that these vehicles are competitive in performance with the baseline, conventional vehicles; other estimates often reflect lesser performing vehicles, which our analysis concludes would be considerably less expensive.

- Another source of price differences is OTA's assumption that vehicle prices must reflect an array of costs and manufacturer/dealer profits beyond the manufacturing costs for vehicle components. Some price estimates do not reflect these additional costs.

CONCLUSIONS ABOUT TECHNOLOGY COST AND PERFORMANCE

OTA's evaluation yields results that can be interpreted in either an optimistic or pessimistic manner. On the one hand, we conclude that reasonable success in technology development can yield vehicles with superior fuel economy—at least twice that of today's vehicles, and quite possibly even higher. Further, there is a good chance that the vehicles can avoid extreme performance tradeoffs and will be acceptable to most consumers in this regard. On the other hand, we believe that bringing technology costs down to the point where advanced vehicles can compete in price with conventional vehicles is a significantly more difficult challenge. Although we readily admit that projecting the future costs of new technologies is a *highly* uncertain business, we conclude that most of the advanced vehicles discussed here will likely cost the purchaser at least a few thousand dollars more than comparable conventional vehicles.

Higher vehicle prices could be a major stumbling block to commercializing advanced vehicles, even in exchange for improved fuel economy and lower emissions. In today's vehicle market, fuel economy is far less valued than comfort, safety, and performance, and reduced emissions will likely have little value to vehicle purchasers. Also, vehicle purchasers generally weigh purchase price far more heavily than fuel costs and, in fact, fuel savings are unlikely to pay for the efficiency improvements unless gasoline prices rise sharply. Consequently, without government intervention, the real market for these vehicles may be in Europe, Japan, and other areas where gasoline prices approach $3 or $4 a gallon, and yearly gasoline costs for a 30 mpg vehicle may be $1,000 or more.[70] It is worth noting, however, that these high prices have thus far stimulated only a modest differential in automobile fuel economy between the United States and the high-gasoline-price nations.

Alternatively, this price increment eventually may be reduced as greater experience is gained with the technologies or if breakthroughs occur in manufacturing methods or technology designs. Further, consumers have implicitly accepted price increases of this magnitude before-industry estimates of the price impact of current emission controls exceed $1,000 a vehicle, yet purchasers

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[70] Assuming 10,000 miles per year. European "per car" driving levels are below U.S. levels but are catching up.

of new vehicles and current vehicle owners appear to have accepted current emission control-based vehicle requirements.[71] Consequently, policies that promote the introduction of advanced technologies (through regulatory measures such as fuel economy standards, or other means) might well be accepted *even if costs are not greatly reduced below expected levels* if society values the fuel savings that would result as much as it has apparently valued the air quality protection afforded by current controls.

Finally, it is worth noting that the long-run incremental prices of some of the advanced vehicles are a few thousand dollars-a significant amount when comparing vehicles that are otherwise identical, but an amount close to the price of some automotive features (such as four-wheel drive) whose value to many purchasers appears to be mainly psychological. This implies that it might be possible to build a market for advanced vehicles by somehow shifting the market's valuation of some of the "nonmarket" benefits of these vehicles, such as striking a blow for energy security or improving the environment.

THE FEDERAL ROLE IN ADVANCED AUTO R&D

The federal government has played an active role in the research and development (R&D) of advanced automotive technologies for more than 20 years. From the Energy Policy and Conservation Act of 1975 through the Energy Policy Act of 1992, Congress has used a combination of mandates and R&D finding to promote the development of cleaner, safer, and more fuel efficient cars. With the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976, Congress authorized DOE to support accelerated R&D on electric and hybrid vehicles. Cumulative government finding for the DOE Electric and Hybrid Vehicle Program since 1976 has been $583 million;[72] however, annual finding has been highly variable and about half of this total has been spent in the past five years.[73]

State governments have also played an important role in automotive R&D, especially relating to auto emissions and air quality. The California LEV program (and its proposed adoption in several northeastern states) has not only stimulated joint research by the Big Three on advanced batteries and EVs, it also spawned a myriad of small companies aiming to produce EVs to meet the 1998 requirements. Japanese manufacturers interviewed by OTA indicated that they had largely abandoned EV research, until the California mandate forced them to renew it in earnest.

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[71]Actually, the only significant areas of complaint about vehicular emissions control programs appear to be the inspection and maintenance programss and fuel requirements--- *not* the onboard vehicular controls. To be fair, however, it is important to note that this acceptance was not immediatelywon. During the early years of the emissions control programs, when the new controls adversely affected vehicle performance, there were significant problems with consumer acceptance and disconnecting of control systems.

[72]Industry contractors also provided cost sharing of contracts, typically in the range of 5 to 20 percent.

[73]DOE officials interviewed by OTA attribute this rapid increase in funding to the 1991 California Low Emission vehicle program (especially the zero emission vehicle requ irements), which forced the major automakers around the world to accelerate the development of electric vehicles.

Partnership for a New Generation of Vehicles

The centerpiece of the current federal effort in advanced automotive R&D is PNGV, a joint initiative of the Clinton Administration together with the Big Three automakers,[74] announced in September 1993. PNGV is conceived as a joint government-industry R&D program aimed at the following three goals:

- Reduce manufacturing production costs and product development times for all car and truck production.
- Pursue near-term advances that increase fuel efficiency and reduce emissions of conventional vehicles.
- Develop a manufacturable prototype mid-size vehicle by 2004 that provides as much as three times the fuel efficiency of today's comparable vehicle, without sacrificing safety, affordability, comfort, or convenience.

In fiscal year (FY) 1995, program managers in the participating federal agencies estimated that the federal government spent about **$270** million for R&D that is relevant to achieving these goals,[75] with a requested increase t. $386 million in FY 1996 (see table 1-4).[76] PNGV is actually a "virtual" program, in the sense that it coordinates and refocuses the various existing agency programs and resources toward the PNGV goals. The effort involves numerous participants, including eight government agencies, the national laboratories, universities, the Big Three, and their suppliers and subcontractors. In FY 1995, about 41 percent of government finding for PNGV went to the Big Three or their suppliers, 23 percent to federal research labs, and 36 percent to other R&D performers.[77]

The Department of Energy (DOE) provides about 60 percent of federal finding for PNGV-related research (about $159 million in FY 1995), but may account for 90 percent of the federal finding for advanced vehicle development. Other agencies' contributions tend to be oriented toward improved components or materials processing technologies, or toward collateral areas, such as safety research. Within DOE, the Office of Transportation Technology's 20-year-old Electric and Hybrid Vehicle Program is the core of PNGV.

U.S. COMPETITIVE POSITION

The advanced automotive technologies considered in this report range from "advanced conventional" to "leapfrog" technologies. Broadly, these are distinguished by their relationship to

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[74] General Motors, Ford, and Chrysler are represented by their R&D consortium, the U.S. Council for Automotive Research (USCAR).

75 An exact estimate of federal funding is difficult to obtain, due to the lack of commonly accepted criteria for judging what is part of PNGV, and what is not. The $270 million figure is based on the estimates of program managers in federal agencies, which the industry participants feel is far too high. According to industry sources contacted by OTA, the *total* R&D expenditure of government plus industry may approach $270 million.

76 The National Institute of Standards and Technology's Advanced Technology Program anticipates about $30 million in new awards in FY 1996 that are not counted in current totals.

77 According to information supplied to OTA by the PNGV Secretariat.

the existing internal combustion engine/steel structure paradigm that has been evolving during the past 80 years. By advanced conventional technologies, OTA refers to evolutionary improvements to internal combustion engines and materials (e.g., direct injection of fuel variable valve timing, and substitution of aluminum for steel) that operate on the same physical principles as existing engines and materials, and require no major discontinuities of manufacturing methods.

By leapfrog technologies, OTA refers to use of powertrains and materials that are radically different from today's (e.g., electric drivetrains, composite structural materials). These generally operate on different physical principles compared with existing technologies, and may require new manufacturing methods and supporting infrastructures.

OTA found rather different attitudes toward these two categories of advanced vehicle technologies in the United States, Europe, and Japan.

Leapfrog Technologies

With support from federal programs going back over 20 years and culminating in PNGV, the U.S. R&D effort on leapfrog automotive technologies is currently the most comprehensive, best organized, and best funded in the world. No other country has collaborative R&D organizations comparable to USCAR, the DOE national laboratories, and PNGV, nor the regulatory aggressiveness of California's ZEV regulations. Using the PNGV budget of $270 million in FY 1995 as an estimate of federal spending, no other government comes within a factor of two of this level.

While other countries have specific areas of relative strength (e.g., the Japanese industry's expertise in advanced ceramics) the more comprehensive U.S. approach is likely to put U.S. companies in a strong position for leapfrog technologies. Whether this technological lead will be translated into early commercialization in the United States will depend on future government policies as well as how the vehicles perform and how much they cost relative to steadily improving conventional vehicles of the same generation.

Advanced Conventional Technologies

The U.S. car industry's attitude toward commercializing advanced conventional automotive technologies to improve fuel economy does not appear to be as aggressive as in some other countries, owing principally to differences in market forces. For example, German automakers have taken the lead in developing highly efficient direct injection diesel engines, whereas no U.S. manufacturer produces a diesel-powered passenger car for the U.S. market. In OTA's view, if NO_x emissions from these engines can be reduced through the use of improved catalysts, diesel-powered cars could make a comeback in the U.S. market. Based on their experience with building small, efficient diesels for passenger cars, European automakers may also be in an excellent position to exploit the use of compact diesel power plants in hybrid electric vehicles. This is a promising option currently being evaluated by the PNGV program.

The lean-bum gasoline engine is another advanced conventional technology that offers fuel efficiency improvements of around 10 percent at relatively low cost. This has been a technology targeted by several Japanese manufacturers in the Japanese market. As with the diesel, commercialization of the lean-bum technology in the United States will require the development of improved catalysts capable of reducing NO_x emissions. Japanese manufacturers apparently believe they can achieve many of the benefits of leapfrog technologies through evolutionary improvement in conventional technologies (such as lean-bum engines) at much lower cost. To date, no U.S. automaker has announced its intention to market a lean-bum engine vehicle.

These examples are not offered to suggest that U.S. automakers are ignoring these technological opportunities. Rather, they reflect differences in automakers' assessments of the cost-effectiveness of these technologies, given current fuel prices and consumer preferences in the United States. In fact, the Big Three have extensive in-house research programs on lean NO_x catalysts, and will build direct injection diesels for the European market through their subsidiaries in Europe. Further, federal finding for compact diesels, lean NO_x catalysts, and aluminum manufacturing technologies is requested to grow substantially in the FY 1996 budget (see below). The main lesson from this experience for leapfrog technologies is that even when the feasibility of these technologies is proven, commercialization will depend on the manufacturers' judgments of cost effectiveness and market acceptance.

U.S. R&D PROGRAM

The U.S. R&D program for leapfrog automotive technologies is technologically diversified and includes a mix of near-term and far-term options. **At** this writing, it is very uncertain which powertrains, energy storage systems, body designs, and materials will combine to give the best package of cost and performance in advanced light duty vehicles of the future. Indeed, depending on the desired vehicle function, location, and driving conditions (e.g., fleet or private, cold or warm climate, urban or rural), different combinations of technologies may be most appropriate. The federal R&D program is conscious of these uncertainties, and is structured to pursue several options simultaneously, so as not to miss promising opportunities.

Key Budgetary Changes in FY 1996

Although PNGV was initiated in 1993, FY 1996 is significant because it is the first real opportunity for the PNGV program to influence the budget priorities of the participating federal agencies. Table 1-5 gives a summary of some of the larger budget changes requested in FY 1996 for federal agency programs. At this writing, Congress is considering major cuts in programs that make up the PNGV, and few believe that any overall increases for FY 1996 are realistic. Nevertheless, the proposed increases are presented because they represent the government/industry consensus view of the key R&D problems that must be solved to achieve the PNGV goal of a threefold increase in fuel economy.

As might be anticipated, the largest requested increases in FY 1996 are in DOE's Electric and Hybrid Vehicle Program, which is the cornerstone of the PNGV effort. The areas of increase are high-power energy storage devices, fuel cells, and hybrid systems. Small piston engines and turbines for hybrids are requested for a significant increase at DOE, as are materials for lightweight vehicles; however, hybrid vehicle and composite materials programs in the National Institute of Standards and Technology (NIST) and the Advanced Research Projects Agency (ARPA) may face large cuts.

The priorities reflected in the federal budget request for FY 1996 appear generally consistent with the results of OTA's technical analysis. Research needs identified by OTA including the need for improved high-power energy storage systems, more cost-effective ceramic and composite manufacturing processes, and cost reduction of fuel cell systems, are all targeted for increases by DOE.[78] The opportunity noted by OTA for using a small, efficient direct injection diesel in a hybrid vehicle is also part of additional finding requested by DOE and EPA in FY 1996.

The finding priorities also tend to support recent statements by observers of PNGV that the most likely configuration of the PNGV prototype vehicle is a hybrid, powered in the near term by a piston engine, and in the longer term perhaps by a fuel cell. There are significant increases for contracts on hybrid energy storage devices, hybrid systems (including a hybrid development team at Chrysler), and fuel cells.

R&D Areas Likely to Require Increased Support in the Future

By its own acknowledgment, PNGV is a technology development program focused primarily on component and vehicle hardware to achieve its 80 mpg goal. At this stage, less attention is being given to several issues—including safety, infrastructure, standards development, and life-cycle materials management—that must be addressed before successful commercialization of an advanced vehicle. In each of these areas, the private-sector role is the dominant one, but government also has an important role to play. The upshot is that as the initial hardware problems with advanced vehicles are solved, substantial additional federal resources will have to be allocated to address the following issues.

- Safety. Advanced vehicles raise numerous new safety concerns stemming both from their lightweight structures and unconventional propulsion systems. Of course, the primary responsibility-and liability-for vehicle safety lies with the automakers. Government, however, has the responsibility to understand the issues and set appropriate safety performance standards. While DOE and National Highway Traffic Safety Administration (NHTSA) have made a good start in areas such as advanced batteries and lightweight materials, much more remains to be done.

[78] Note, however, that the contemplated cuts in NIST's Advanced Technology Program and ARPA's Electric and Hybrid vehicle program hit some research areas, such as composites manufacturing, particularly hard. If these programs are eliminated, they will more than offset proposed increases by DOE in composites processing funding.

- Infrastructure. Advanced vehicles cannot operate in a vacuum; they require a supporting infrastructure for refueling, servicing, recycling, and so forth, comparable to the existing conventional vehicle infrastructure. The infrastructure requirements of some advanced vehicles (e.g., battery electrics and fuel cell vehicles) would be rather different; for others (e.g., gasoline ICE-powered hybrids) the infrastructure might look very similar to today's.

  U.S. experience with programs aimed at promoting the use of alternatively fueled vehicles has shown that the lack of a convenient refueling infrastructure is a critical constraint. The infrastructure issue is Certain to constrain advanced vehicle development as well. Ultimately, the cost of developing a national infrastructure for advanced vehicles is the responsibility of fuel providers and the automakers. Experience with advanced fuel vehicle programs, however, has shown that the government has an important role to play in such areas as national standards development, federal fleet procurement, coordinating with states and localities to ensure an adequate concentration of vehicles in a given area, demonstration programs, and so forth.

  In the current budget, at most 1 percent of the hardware budget—perhaps a few million dollars-has been set aside for infrastructure considerations. As the most promising technological configurations of advanced vehicles become more evident, significant federal investments in supporting infrastructure are likely to be required.

- Standards. Today's light-duty vehicle fleet is largely uniform in terms of the structural materials and propulsion system technologies. With the prospect of a fleet of vehicles made of exotic structural materials, mix-and-match power plants and operation algorithms, and alternative fuels and fueling systems, manufacturers, consumers and regulators must each be assured of the safety, reliability, and performance of these vehicles and subsystems.

  Again, the primary responsibility for development of these standards will be private-sector organizations such as the Society of Automotive Engineers. The government, however, must also be able to set such standards as are necessary *to* fulfill its regulatory functions (examples include emissions testing standards, fuel economy standards, and standard procedures for handling emergency situations). Standards for safety and infrastructure have been mentioned above; an additional example would be the difficulty of setting a single emissions test procedure for hybrid vehicles that may differ widely in characteristics such as energy storage capacity, engine operating strategy, and so forth.

- Life Cycle Materials Flows. Lightweight vehicles with advanced powertrains will utilize a very different set of materials than do current autos. Because the auto industry is such a prodigious user of materials, any significant change would have wide-ranging ramifications for the entire life cycle of materials use, from extraction of raw materials to final disposal. For example, massive increases in the use of lead acid batteries to power EVs could result in significantly increased toxic emissions from battery recycling plants. While private industry must take steps to comply with the prevailing environmental regulations, it would be prudent for government to anticipate major problems with these changes in materials flows (e.g., supply disruptions, price impacts, hazardous waste streams, and recyclability issues) and conduct an appropriate R&D program to address these issues.

Future Role of Federal R&D Programs

As Congress debates the future of federal advanced vehicle R&D programs, several issues should be considered:

Issue 1: Should Congress continue to support advanced vehicle R&D?

During the past 20 years, government policies at the federal and state levels have been the principal impetus for leapfrog vehicle development. Auto manufacturers and their suppliers are anxious not to be blindsided by new technologies, but have had little market incentive to invest in developing leapfrog technologies on their own.[79] The rationale for this government involvement has been that the benefits offered by these vehicles—improved air quality, enhanced U.S. energy security-are social benefits that do not command higher prices in the marketplace.

Government policies to stimulate advanced vehicle R&D have been of two types: "carrots" such as R&D contracts or procurement subsidies for advanced vehicles; and "sticks" such as higher regulatory standards for emissions control and fuel economy. Regardless of one's view of California's ZEV regulations, for instance, it is undeniable that they have stimulated extensive research on batteries and fuel cells that would not have advanced in their absence. In addition, numerous small, entrepreneurial companies producing small numbers of electric vehicles and fuel cell prototypes are dependent on the ZEV regulations for their continued existence. The automakers, however, have fought bitterly against these regulatory mandates, claiming that they are forcing technologies into the marketplace before they are ready.

This lack of market demand for advanced vehicles seems unlikely to change in the foreseeable future absent a major oil price shock or other unforeseen developments. With real gasoline prices at historic lows, and urban air quality improving, car buyers care more about such attributes as good acceleration performance and carrying capacity than about increased fuel economy and reduced emissions. This is especially true if these attributes carry a higher price, as OTA's analysis suggests. Thus, if government wishes to continue to pursue the goal of super-efficient vehicles, it will likely need to continue its involvement, whether through R&D finding, mandates, or other incentives.

Issue 2: Is the federal advanced vehicle R&D effort coherent and consistent with national needs?

Government policies toward advanced vehicles have been driven by a diverse set of concerns including the desire to improve urban air quality, reduce oil imports and, more recently, to avoid global climate change. This diverse set of concerns has led to a patchwork of legislation and programs that attempt to address the concerns through different technical and economic approaches. The result has been a federal effort that has been poorly coordinated and that lacks clearly defined relationships to national needs.

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[79] Historically, industry cost sharing on government R&D contracts to develop risky, long-term technologies (e.g., gas turbines and fuel cells) has generally been less than 20 percent. In some recent program such as the DOE R&D contract with the automakers on advanced batteries and hybrid vehicles, industry cost sharing is around 50 percent.

Historically, for example, R&D on controlling vehicle emissions to address air quality issues such as those addressed in the Clean Air Act have been the province of EPA, while R&D on improving fuel economy to address energy security issues has been the province of DOE. While fuel economy and emissions characteristics are closely related in actual vehicle operation, R&D programs at EPA and DOE have not been well coordinated.

Many other examples might be cited. During the past 20 years, finding for R&D programs such as DOE's Electric and Hybrid Vehicle Program has fluctuated wildly, making it impossible to sustain a coherent effort to develop hybrid vehicles. And, although Congress outlined clear goals for bringing alternatively fueled vehicles into the fleet in the Energy Policy Act of 1992, federal tax policies favor some fuels at the expense of others, without regard for the fuels' relative energy content or desirability from an environmental point of view.

PNGV is clearly an attempt to address some of these issues, by coordinating government and industry R&D efforts toward achieving a commonly agreed-on set of goals; principally, the development of an 80 mpg prototype vehicle by 2004. Nevertheless, the 80 mpg target appears to have been chosen more for the technological innovations that will be required than for any direct relationship to national goals for reduced oil imports or reduced greenhouse gas emissions. While a super-efficient vehicle would clearly make important contributions to these goals, little thought has apparently been given to whether the 80 mpg target is the most cost-effective approach. For example, the same amount of imported oil might be displaced more cheaply through a combination of a 50 mpg target with a more aggressive alternative fuels program.

The point here is not that a high fuel economy target is wrong, but that appropriate planning and analysis are lacking that would enable an evaluation of the entire federal R&D program in the context of broader national goals for air quality, energy security, and reduced potential for global climate change. This analysis becomes especially important in a tight budget environment in which PNGV-inspired R&D programs maybe competing with other ongoing programs (e.g., alternative fuels and heavy duty vehicle research) for the same resources.

Issue 3: Is the federal R&D relationship with industry structured to encourage maximum innovation?

There is a continuing debate about the way federal R&D finding can best catalyze the emergence of advanced vehicle technologies. On the one hand, there are advantages to supporting work by the major automakers and their suppliers, because the automakers are in a position to rapidly commercialize a successful innovation in mass-market vehicles. On the other hand, many observers are concerned that federal efforts to develop leapfrog vehicle technologies rely too heavily on the existing industry, which, they argue, has a considerable stake in maintaining the status quo. In their view, more agile small and medium-sized companies are best able to commercialize novel technologies, particularly in niche markets that may be initially too small to attract the attention of the major automakers.

OTA's investigations for this study suggest that many small and medium-sized U.S. companies have developed innovative advanced vehicle technologies not currently being displayed by the automakers.[80] Most of these small companies recognize that successful commercialization of these innovations will require partnering with a large company in the industry. The automakers for their part recognize that small entrepreneurial companies have important contributions to make to solving the many challenging problems. These considerations suggest that the federal advanced vehicle R&D program should maintain a balance between small and large company participation to ensure maximum potential for a successful outcome.

Historically, DOE advanced vehicle technology programs have worked primarily with large companies: defense contractors, automotive suppliers, or the Big Three themselves. To the extent that small or medium-sized companies have participated, it has generally been as part of a subcontractor team. The Cooperative Research and Development Agreements with federal labs are also difficult for small companies to participate in, owing in part to the 50 percent cost-sharing requirements. PNGV, which is structured to work as a partnership under the leadership of the Big Three, seems likely to reinforce the large company orientation of the federal effort.[81]

Recently, other government programs, such as NIST's Advanced Technology Program, and ARPA's Electric and Hybrid Vehicle (EHV) program and Technology Reinvestment Project (TRP) have begun to provide significant funding to contractors outside the traditional auto industry, especially to small- and medium-size companies. The administration, however, has requested no finding for EHV in FY 1996, and substantial cuts in TRP and ATP are being debated in Congress. If these cuts are made as threatened, the federal program would become even more dependent on the traditional industry than it already is.

CONCLUSIONS ABOUT R&D

The more than 20-year federal involvement with advanced vehicle R&D provides an important perspective on current efforts to commercialize advanced automotive technologies. First, from the earliest days of these programs, the amount of time that would be required to commercialize advanced vehicle technologies was severely underestimated. For example, according to a projection made in the first annual report to Congress of DOE's Electric and Hybrid Vehicle Program, dated December 1977: "The technology of electric and hybrid vehicles is such that . . . advanced vehicles with advanced energy storage systems are not likely to appear before the early to mid-1980s." In fact, many of the technical challenges cited in those early reports, such as battery energy storage capacity, power density, and lifetime continue to be major challenges today.

Although most of the technologies involved in advanced vehicles (batteries, flywheels, motors, and controllers) have received government funding for decades, this finding has been highly

[80] Examples include superior regenerative braking systems and battery thermal management systems to enhance EV range in cold climates. The Big Three are no doubt working on these technologies, but may not be talking publicly about them.

[81] PNGV reviewers of this report noted that while 41 percent of government funds in FY 1995 involved contracts with the Big Three, more than two-thirds of that amount was passed through to suppliers. Thus, the fraction of PNGV funds flowing directly to the Big Three may be only 10 to 15 percent- It is more accurate to view the Big Three as directing and coordinating the flow of funds, rather than as the primary recipients. The PNGV steering committee has recognized the need to find ways to bring innovative ideas from entrepreneurs and small companies into the progran, and has published a document titled "Inventions Needed for PNGV."

variable, [82] and only in the last five years has there been a concerted attempt by both the auto industry and government to develop viable commercial vehicles. Thus, although the technologies are by no means "new," we still have little experience with how they perform as an integrated system in on-the-road vehicles, or with rapid, cost-effective manufacturing processes. At this writing, government finding for advanced vehicle R&D appears once again poised for a downturn, owing to budget cuts. PNGV has begun to define the R&D priorities for some of these technologies, particularly for hybrid vehicles; however, it will be difficult, if not impossible, to address these priorities and solve the many remaining problems without sustained, and even increased, finding,

82 For example, funding for DOE's Electric and Hybrid Vehicle program rose to a peak of $37.5 million in 1979, but dropped to $8.4 million in 1985. By 1995, it had risen again to about $90 million.

BOX 1-1: Reducing Tractive Forces

The tractive forces that a vehicle must overcome to stay in motion include:

- Aerodynamic drag, the force of air friction on the body surfaces of the vehicle. Aerodynamic drag averages about 30 percent of total tractive forces, and is highest during fast highway driving (drag is directly proportional to the square of speed,[1] so if speed doubles, the drag force quadruples). Drag forces may be reduced by reducing the frontal area of the vehicle, smoothing out body surfaces and adjusting the body's basic shape, covering the vehicle's underbody, and taking other measures that help air move freely past the vehicle;

  The efficiency of a vehicle's aerodynamic design is measured by the product of the drag coefficient C_D and the frontal area, which designers seek to minimize. The C_D of current U.S. automobiles averages about 0.33, with the best mass-produced vehicles achieving about 0.28. Experimental vehicles have achieved extraordinarily low CDS of 0.15 or better, but these low values have substantial costs in reduced passenger and cargo space,[2] added complexity and weight in cooling systems, low ground clearance, and so forth. Most automakers view a C_D of 0.25 as a feasible target for the next 10 to 20 years for an intermediate-sized sedan; this would yield about a 6 percent improvement in fuel economy from current average vehicles. Judging by some of the less-radical experimental vehicle designs, however, a more ambitious C_D of 0.22, yielding about a 7 percent improvement in fuel economy, appears to be possible. Most automakers are, however, skeptical of the feasibility of a C_D this low.

- Rolling resistance, the resistive forces between the tires and the road. These forces also average about 30 percent of total tractive force, and are of approximately equal importance in city and highway driving. Rolling resistance may be reduced by: 1) redesigning tires and tire materials to minimize the energy lost as the tire flexes, 2) lowering vehicle weight (see below), and 3) redesigning wheel bearings and seals. A major concern in tire redesign is to avoid compromising tire durability and handling capabilities.

  The rolling resistance coefficient (RRC), like the aerodynamic drag coefficient, is a measure of the resistance to a vehicle's movement—in this case, of the tires. Current mass-market (not performance-oriented) tires have RRCs of 0.008-0.010. By 2005, a 30 percent reduction in RRC, yielding about a 5 percent fuel economy improvement, should be possible with significant investments in research on tire design and materials and chassis technology. By 2015, an RRC of 0.005 may be possible, yielding a total 8 percent improvement in fuel economy over current levels.[3]

- Inertial force, the resistance of vehicle mass to acceleration or grade-climbing. This force is about 40 percent of total tractive forces, on average, and is largest in city driving and hill-climbing. Inertial force is reduced by making the vehicle lighter—a 10 percent weight reduction yields as much as a 6 percent reduction in fuel consumption, if performance is held constant and the vehicle design carefully handled.

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[1] To be precise, to the relative speed of the vehicle and the air. Thus, if a vehicle is moving into a headwind, the drag force is a function of the speed of the vehicle plus the windspeed.

[2] Vehicle designs that seek to minimize aerodynamic drag must have sharply sloped rear ends that reduce the height and width of the rear passenger space and the width of the trunk.

[3] The U.S. automakers believe OTA's values for fuel savings associated with rolling resistance reduction are too high, and propose a 3 to 4 percent reduction for a 30 percent RRC reduction and a 5 percent reduction by reducing RRC to 0.005.

Although major reductions in vehicle weight have occurred since the 1970s, there remains substantial further potential, by substituting lightweight materials—primarily improved high-strength steel, aluminum and, *possibly,* composites—and by structural redesign using supercomputers. The complexity of vehicle structural design to assure safety and the lack of industry experience with the new materials demand a careful program of testing and analysis, so that even aluminum will be introduced cautiously; an optimized design in a mass-market vehicle making full use of aluminum's unique properties—and, therefore, achieving maximum weight savings—must probably wait until after 2005. By 2005, the Office of Technology Assessment projects that a highly optimized steel body with aluminum engine could achieve a 15 percent weight reduction over 1995 norms; an aluminum intensive body (but not an optimized, "clean sheet" design) could achieve a 20 percent weight reduction, at a price increment of about $1,500 for a mid-size car. By 2015, an optimized aluminum design could achieve a 30 percent weight reduction, at a similar $1,500 price. /f the severe manufacturing challenges of mass producing carbon fiber composites are overcome, a 40 percent weight savings could be achieved, though probably at high costs (an estimated $2,000 to $8,000 for an intermediate auto). Such a 40 percent weight reduction might increase fuel economy by one-third.

BOX 1-2: Spark Ignition and Diesel Engines

Spark Ignition Engines

Although spark ignition (SI) engines have been the dominant passenger car and light truck powerplant in the United States for many decades, there are several ways to achieve additional improvements in efficiency---either through wider use of some existing technologies or by introduction of advanced technologies and engine concepts. Some key examples of improved technology, most having some current application, are:

- *Advanced electronic controls; improved understanding of combustion processes.* Improved thermodynamic efficiency through improved spark timing, increased compression ratios, and faster combustion.
- Use *of lightweight materials in valves, valve springs, and pistons, advanced coatings on pistons and ring surfaces, improved lubricants.* Reduced mechanical friction.
- *Increased number of* valves *per cylinder (up to five), variable timing for* valve *opening, deactivating cylinders* at *light loads,* variable *tuning of intakes to increase intake pressure.* Reduce "pumping losses" caused by throttling the flow of intake air to reduce power output.

Combining the full range of improvements in a conventional engine can yield fuel economy improvements of up to 15 percent from a baseline four-valve engine.

Besides improvements in engine components, new engine concepts promise additional benefits. The highest level of technology refinement for SI engines is the direct injection stratified charge (DISC) engine. DISC engines inject fuel directly into the cylinder rather than premixing fuel and air, as conventional engines do; the term "stratified charge" comes from the need to aim the injected fuel at the spark plug, so the fuel-air mixture in the cylinder is highly nonuniform. DISC engines are almost unthrottled; power is reduced by reducing the amount of fuel injected, not the amount of air. As a result, these engines have virtually no throttling loss and can operate at high compression ratios (because not premixing the fuel and air avoids premature ignition). DISC engines have been researched for decades without successful commercialization, but substantial improvements in fuel injection technology and in the understanding and control of combustion, and a more optimistic outlook for nitrogen oxide (NO_x) catalysts that can operate in an oxygen-rich environment make the outlook for such engines promising. The estimated fuel economy benefit of a DISC engine coupled with available friction-reduction technology and variable valve timing ranges from 20 to 33 percent, compared to a baseline four-valve engine.

Diesel Engines

Automakers can achieve a substantial improvement in fuel economy by shifting to compression ignition (diesel) engines. Diesels are more efficient than gasoline engines for two reasons. First, they use compression ratios of 16:1 to 24:1 versus the gasoline engine's 10:1 or so, which allows a higher thermodynamic efficiency. Second, diesels do not experience the pumping loss characteristic of gasoline engines because they do not throttle their intake air; instead, power is controlled by regulating fuel flow alone. Diesels have much higher internal friction than gasoline engines, however, and they are heavier for the same output.

Diesels are not popular in the U.S. market because they generally have been noisier, more prone to vibration, more polluting, and costlier than comparable gasoline engines. Although they have low hydrocarbon (HC) and carbon monoxide (CO) emissions, they have relatively high NO_x and particulate emissions.

| DISC engines' absence of throttling means that at low power, less fuel is injected with the same amount of air. This leaves a substantial concentration of oxygen in the exhaust, which cancels the effectiveness of conventional NO_x catalysts.

The latest designs of diesel engines recently unveiled in Europe are far superior to previous designs. Oxidation catalysts and better fuel control have substantially improved particulate emission performance. Four-valve per cylinder design and direct injection[2] have separately led to better fuel economy, higher output per unit weight, and lower emissions—though NO_x emissions are still too high. Compared with a current gasoline engine, **the four-valve indirect injection design will yield about a 25 percent mpg gain (about 12 percent gain on a fuel energy basis), while the direct injection** (DI) **design may yield as much as a 40 percent gain (30 percent fuel energy gain).**[3]

The new diesels are likely to meet California's LEV standards for HC, CO, and particulate, but will continue to require a NO_x waiver to comply with emission requirements. Although the four-valve design and other innovations (e.g., improved exhaust gas recirculation and improved fuel injection) will improve emissions performance and may allow compliance with federal Tier 1 standards, LEV standards cannot be met without a NO_x reduction catalyst. Although manufacturers are optimistic about such catalysts for *gasoline* engines, they consider **a** diesel catalyst to be **a** much more difficult challenge.[4]

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2 Most light-duty diesels are of indirect injection design. Air and fuel is injected into a prechamber where combustion starts, with further combustion taking place in the main combustion chamber. Although this design yields lower noise and NO_x emissions, it is less efficient than directly injecting the air and fuel into the combustion chamber.

3 The difference between the miles per gallon and fuel energy gains are due to diesel having an 11 to 12 percent greater energy content per gallon than gasoline. Some automakers are skeptical of the projected fuel economy improvement of the DI diesel because of its remaining emissions problems.

4 As a reference point, oxidation catalysts for diesels were commercially introduced in 1993, 18 *years* after their introduction for gasoline-fueled vehicles.

BOX 1-3: Battery Technologies

The battery is the critical technology for electric vehicles, providing both energy and power storage. 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.[1] Aside from increasing energy and power storage, other key goals of battery R&D are increasing longevity and efficiency and reducing costs.

Numerous battery types are in various stages of development. Although there are multiple claims for the efficacy of each type, there is a large difference between the performance of small modules or even full battery packs under nondemanding laboratory tests, and performance in the challenging environment of actual vehicle service or tests designed to duplicate this situation. Although the U.S. Advanced Battery Consortium is sponsoring such tests, the key results are confidential, and much of the publicly available information comes from the battery manufacturers themselves, and may be unreliable. Nevertheless, it is quite clear that a number of the batteries in development will prove superior to the dominant conventional lead acid battery,[2] though at a higher purchase price. Promising candidates include advanced lead acid (e.g., woven-grid semi-bipolar and bipolar) with specific energy of 35 to 50 Wh/kg, specific power of 200 to 900 W/kg,[3] and claimed lifetimes of five years and longer; nickel metal hydride with 80 Wh/kg and 200 W/kg specific energy and power, and claimed very long lifetimes; lithium polymer, considered potentially to be an especially "EV friendly" battery (they are spillage proof and maintenance free), that claims specific energy and power of 200 or more Wh/kg and 100 or more W/kg; lithium-ion, which has demonstrated specific energy of 100 to 110 Wh/kg; and many others. The claimed values of battery lifetime in vehicle applications should be considered extremely uncertain. With the possible exception of some of the very near-term advanced lead acid batteries, each of the battery types has significant remaining challenges to commercialization—high costs, corrosion and thermal management problems, gas buildup during charging, and so forth. Further, the history of battery commercialization demonstrates that bringing a battery to market demands an extensive probationary period: once a battery has moved beyond the single cell stage, it will require a testing time of nearly a decade *or more* before it can be considered a proven production model.

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[1] That is, when the vehicle needs a sudden burst of power, the battery will supply it while the engine generally will maintain near-constant output.
[2] With specific energy—energy per unit weight—of 25 to 28 Wh/kg, specific power of 100 W/kg at full charge, life of 2 to 3 years.
[3] Specific energy and power values based on data from tests on prototypes.

BOX 1-4: Nonbattery Energy Storage: Ultracapacitors and Flywheels

Ultracapacitors

Ultracapacitors are devices that can directly store electrical charges—unlike batteries, which store electricity as chemical energy. A variety of ultracapacitor materials and designs are being investigated, but all share some basic characteristics-very high specific power, greater than 1 kW/kg, coupled with low specific energy. The U.S. Department of Energy mid-term goal is only 10 Wh/kg (compared to the U.S. Advanced Battery Consortium mid-term *battery* goal of 100 Wh/kg). Other likely ultracapacitor characteristics are high storage efficiency and long life.

Ultracapacitors' energy and power characteristics define their role. In electric vehicles, their high specific power can be used to absorb the strong power surges of regenerative braking, to provide high power for brief spurts of acceleration, and to smooth out any rapid changes in power demand from the battery in order to prolong its life. In hybrids, they theoretically could be used as the energy storage mechanism; however, their low specific energy limits their ability to provide a prolonged or repeatable power boost. Increasing ultracapacitors' specific energy is a critical research goal.

Flywheels

A flywheel stores energy as the mechanical energy of a rapidly spinning mass, which rotates on virtually frictionless bearings in a near-vacuum environment to minimize losses. The flywheel itself can serve as the rotor of an electrical motor/generator, so it can turn its mechanical energy into electricity or vice versa, as needed. Like ultracapacitors, flywheels have very high specific power ratings and relatively low specific energy, though their energy storage capacity is likely to be higher than ultracapacitors. Consequently, they may be more practical than ultracapacitors for service as the energy storage mechanism in a hybrid. In fact, the manufacturer of the flywheel designed for Chrysler's Patriot race car, admittedly a very expensive design, claims a specific energy of 73 Wh/kg, which would make the flywheel a very attractive hybrid storage device. Mass-market applications for flywheels depend on solving critical rotor manufacturing issues, and, even if these issues were successfully addressed, it is unclear whether mass-produced flywheels could approach the Patriot flywheel's specific energy level.

BOX 1-5: Series and Parallel Hybrids

In a series hybrid, the engine is used only to drive a generator, while the wheels are powered exclusively by an electric motor. The motor is fed directly by the generator or by electricity from a storage device such as a battery (or flywheel or ultracapacitor)--or by both simultaneously when high power is needed. The storage device obtains some energy input from regenerative braking, and most of the input from the engine/generator; in some configurations, it could also be charged externally like an EV. Decisions about how well the vehicle must perform, whether the battery should be recharged externally or only by the engine, and when to use the battery or the motor/generator can lead to very different configurations, such as large engine/small battery and small engine/large battery.

In a parallel hybrid, both the engine *and* the motor can drive the wheels. This type of hybrid is generally acknowledged to be more difficult to develop than a series hybrid. U.S. automakers appear to be focusing their attention on series hybrids, although some European automakers do appear to favor parallel hybrids. Conceptually, however, the general strategy of a parallel hybrid is to downsize the engine, so that the maximum power requirement of the vehicle is satisfied by having both engine and motor operate simultaneously. The electric motor size required in a parallel hybrid is much smaller than that required in a series hybrid, because in the latter, the motor is the only source of power driving the wheels. If the vehicle is powered only by the electric motor when power demand is low, the engine will be needed only at higher loads, where it is most efficient.

TABLE 1-1: What Happens to a Mid-Size Car in 2005?

Vehicle type	Body material	Fuel economy, mpg[a]	Price change, $[b]	Comments
Business as usual	Baseline steel	30	Base	
Advanced conventional	Optimized steel 1st generation aluminum	39 42	+400 +1.600	
Electric vehicle (EV)	Optimized steel Optimized steel	31[c] 48	+11,400 +18,400 (9,300)	Lead acid battery NiMH battery (lower price assumes battery cost $200/kWh, based on developer claims)
Hybrid-electric	Optimized steel 1st generation aluminum	49 61	+4,900 +7,800/10,200	Bipolar lead acid battery energy storage Flywheel/ultracapacitor energy storage

[a]Environmental Protection Agency test values, unadjusted.
[b]All prices are the incremental retail price compared to the business as usual (base) vehicle of that year.
[c]Gasoline equivalent. Assumptions:

- 38 percent efficiency @ power station,
- 95 percent efficiency @ transmission,
- 94 percent efficiency @ refining and distribution of gasoline,
- 3413 Btu/kWh,
- 115,000 Btu/gallon of gasoline.

Lead acid EV efficiency is 0.250 kWh/km, NiMH efficiency is 0. 53 kWh/km.

NOTE: 1995 fuel economy = 28 mpg. To avoid misinterpretation: the values in this table represent OTA's best guess for mid-point values of performance and cost. In most cases, developers of the advanced technologies are intent on achieving better performance and lower costs than shown here. The values express OTA's conclusion that such achievements represent a substantial challenge; they do *not* imply that better performance and lower costs cannot be achieved.

SOURCE: Office of Technology Assessment, based on Energy and Environmental Analysis, Inc., "Automotive Techn og To Improve Fuel Economy o 2015," prepared for the Office of Technology Assessment, June 1995.

TABLE 1-2: What Happens to a Mid-Size Car in 2015?

Vehicle type	Body material	Fuel economy, mpg[a]	Price change,$[b]	Comments
Business as usual	Optimized steel	33	Base	
Advanced conventional	Optimized aluminum	53	+1,500	Direct Injection Stratified Charge engine
	Carbon fiber composite	64	+5,200	Price extremely uncertain
Electric vehicle	Optimized aluminum	51[c]	+4,200	Lead acid battery
	Optimized aluminum	82	+10,300/4,300	NiMH battery (lower value assumes battery cost $180/kWh, based on developer claims)
Hybrid-electric	Optimized aluminum	65	+4,600	Bipolar lead acid battery energy storage
	Optimized aluminum	71-73	+7,000/9,800	Flywheel/ultracapacitor energy storage
Fuel cell hybrid	Optimized aluminum	83[d]	+6,000/40,000	Lower price assumes major cost breakthroughs ($65/kW); energy storage by bipolar lead acid battery

[a]Environmental Protection Agency test value, unadjusted.
[b]All prices are the incremental retail price compared to the business as usual (base) vehicle of that year.
[c]Gasoline equivalent. Assumptions:

- 40 percent efficiency @ power station,
- 95 percent efficiency@ transmission,
- 94 percent efficiency@ refining and distribution of gasoline,
- 3413 Btu/kWh,
- 115,000 Btu/gallon of gasoline.

Lead acid vehicle efficiency is 0.167 kWh/km, NiMH efficiency is 0.103 kWh/km.
[d]Based on methanol/gasoline energy content--not primary energy.

NOTE: 1995 fuel economy =28 mpg. To avoid misinterpretation: the values in this table represent OTA's best guess for mid-point values of performance and cost. In most cases, developers of the advanced technologies are intent on achieving better Performance and lower costs than shown here. The values express OTA's conclusion that such achievements represent a substantial challenge; they do *not* imply that better performance and lower costs cannot be achieved.

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

TABLE 1-3: Annual Fuel Costs for Alternative Vehicles (mid-size automobiles in 2015)

Baseline (Taurus)	33 mpg	$535[a]
Advanced conventional	53 mpg	$333
Electric vehicle (EV) (lead acid)	0.27 kWh/mile	$223
EV (NiMH)	0.17 kWh/mile	$137
Series hybrid (lead acid)	65 mpg	$272
Proton exchange membrane fuel cell (methanol)	83 mpg (gasoline equiv)	$182

[a]The fuel economy values shown are Environmental Protection Agency (EPA) unadjusted values. Fuel costs are based on the assumption that on-road efficiencies are about 15 percent less. Each vehicle type will have a different adjustment factor, but it is not clear what those factors should be. For example, EVs will lose less energy from congestion effects (because they have regenerative braking and no idling losses), but will use substantially more energy to heat the vehicle--which is not accounted for in the EPA tests, where accessories are not used.

[b]Optimized aluminum body, direct injection stratified charged engine.

NOTE: Based on 10,000 miles per year, 7cents/kWh offpeak electricity, 75cents/gallon methanol. It is assumed that methanol price, including highway taxes, will approximate the energy-equivalent price of gasoline, for competitive reasons. The imposition of taxes equivalent to gasoline's tax burden yields a methanol price net of taxes of about 50cents/gallon, which is low by today's standards.

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

TABLE 1-4: PNGV-Related FY 1995 Appropriations by Technical Area and Agency ($ millions)

Technical area	DOC[a]	DOD[b]	DOE	DOI	DOT	EPA[c]	NASA	NSF	TOTAL
Lightweight materials	6.83	7.03	47.42	0.50				19.24	81.02
Energy conversion			70.47			2.75		0.85	74.07
Energy storage	0.04		0.47			2.00		2.69	**5.20**
Efficient electrical systems		1.20					1.00	15.41	17.61
Exhaust energy recovery			1.04				0.20		1.24
Analysis and design methods	1.50	**1.98**	**3.71**				2.20	1.85	11.24
Reduction of mechanical losses	0.25							1.25	1.50
Aero and rolling improvements			0.78						0.78
Advanced manufacturing	10.46	2.75	23.64					4.61	41.46
Improved internal combustion	0.58	11.02	7.04			2.90	0.25	3.02	24.81
Emissions control			3.78				1.35	2.07	7.20
Fuel prep, delivery, storage								0.15	0.15
Efficient heating, cooling, etc.			0.50					2.81	3.31
Crashworthiness								0.14	0.14
TOTAL	19.66	23.98	158.85	0.50	0.00	7.65	5.00	54.09	269.73

[a]In addition to the base of $19.7 million, DOC through the National Institute of Standards and Technology's Advanced Technology program has selected relevant projects with requested funding of $30.1 million. Contracts are not yet in place for these selected proposals.
[b]DOD numbers are based on program personnel contact and are still tentative.
[c]EPA numbers still in discussion.

NOTE: Numbers indicated in the table are specific to PNGV and identified as such. DOT program personnel indicate that an additional $20 million each year is spent on R&D related to PNGV with dual purpose; in FY96, $1 million of the $20 million will be targeted specifically for PNGV.

KEY: DOC = Department of Commerce; DOD = Department of Defense; DOE = Department of Energy; DOI = Department of the Interior; DOT = Department of Transportation; EPA = Environmental Protection Agency; NASA = National Aeronautics and Space Administration; NSF = National Science Foundation; PNGV = Partnership for a New Generation of Vehicles; R&D = research and development.

SOURCE: PNGV Secretariat.

TABLE 1-5: PNGV Budgetary **Changes in** FY **1996**

Agency/program	R&D area	FY 1996 dollars in millions, requested change (in percent)	Comments
DOC/NIST/ATP	**8** new projects on composite manufacturing initiated in FY 1995.	-lo (50%)	Requested budget does not include an expected **$30** million in new auto-related contracts to be negotiated in FY 19%. However, funding for ATP is controversial in Congress, and substantial cuts have been proposed.
DOD/ARPA/EHV	Hybrid and electric vehicle development	-15 (loo%)	Congressional add-on to ARPA budget in FY 1993, provides funds to seven regional consortia including small businesses. Funding zeroed out in President's FY 19% budget request.
DOD/ARPA/TRP	Advanced vehicle drivetrains	?	Supports development of "dual use" technologies; focus area on vehicle drivetrains designated in FY 1995. Funding for TRP is controversial in Congress, and large cuts have been proposed.
DOE/OTT/material technology	Composite and light metal manufacturing processes, recycling, and crashworthiness	+5 (42%)	Joint work with USAMP and national laboratories.
DOE/OTT/heat engine technologies	Develop gas turbine, spark-ignited piston, and diesel engines as hybrid vehicle APUs	+6 (48%)	Cost-shared work with industry, national labs.
DOE/OTT/electric and hybrid propulsion	Battery and other energy storage device development	+3 (lo%)	A $9 million increase for power storage devices for hybrids is offset by a $6 million decrease for advanced batteries.
DOE/OTT/electric and hybrid propulsion	Automotive fuel cell development	+19 (84%)	Increase equally divided between 15 percent cost-shared contracts with Big Three, and enabling research at national labs.
DOE/OTT/electric and hybrid propulsion	Hybrid vehicle development	+17 (45%)	Adds a third contractor team to existing teams at Ford and General Motors (presumably at Chrysler).
DOE/UT/hydrogen research and development	Production, storage, distribution, and conversion of hydrogen as fuel	-2 (22%)	Reduction comes from stretch-out of joint industry/lab efforts on near-term natural gas reforming and storage system.
EPA	Reducing emissions from four-stroke, direct-injection engines	+5 (65%)	Addresses a key problem with hybrids.

KEY: APUs = auxiliary power unit; ARPA = Advanced Research Projects Agency; ATP = Advanced Technology Program; DOC = Department of Commerce; DOD = Department of Defense; DOE = Department of Energy; EHV = Electric and Hybrid Vehicle program; EPA = Environmental Protection Agency; NIST = National Institute of Standards and Technology; OTT = DOE's Office of Transportation Technologies; TRP = Technology Reinvestment Project; USAMP = U.S. Advanced Materials Partnership; UT = DOE's Office of Utility Technologies.

SOURCE: Office of Technology Assessment, 1995; and U.S. Department of Energy, *FY 1996 Congressional Budget Request*, vol. 4, DOE/CR-0030 (Washington, DC: February 1995).

Chapter 2

Introduction and Context

This report evaluates the proposition that it is feasible to make rapid changes in automotive technology--away from current steel bodies and conventional drivetrains with gasoline engines, toward aluminum or composite bodies[1] and alternative powertrains, for example. In particular, the report concentrates on evaluating the technical promise, state of development, and potential costs of a range of automotive technologies--from advanced materials to hybrid-electric drivetrains to fuel cells--that would reduce vehicle fuel consumption and, in some cases, yield strong improvements in emission performance. The report also examines U.S. and foreign research and development (R&D) efforts directed toward preparing these technologies for the marketplace.

FORCES FOR INNOVATION

Promoting rapid technological change in the automobile industry is not a novel idea. Environmental groups pursuing twin goals of energy conservation and reduced vehicular emissions have promoted technological innovation for decades, for example, and the federal government has encouraged innovation in the industry in pursuit of similar goals.[2] Currently, there are some additional pressures for innovation. In particular, California's Low Emission Vehicle (LEV) Program requires automakers to begin producing vehicles with substantially reduced emissions; in particular, the LEV program requires 2 percent of the fleets of major automakers to be zero emission vehicles (ZEVs) by 1998, increasing to 10 percent by 2003. Some northeastern states also have adopted these regulations. In this time frame, only electric vehicles will be likely to satisfy the ZEV requirement.[3] Industry responses to the ZEV requirements include both an active campaign to discourage enforcement in California and several northeastern states that have followed California's example and a substantial cooperative research effort to help produce a commercially successful electric vehicle, including formation of an Advanced Battery Consortium with battery manufacturers, electric utilities, and the Electric Power Research Institute. Meanwhile, various development and commercialization efforts have begun independent of the established industry. These include market introduction of several vehicles (most based on conversion of conventional models, which involves removal of engines and transmissions and replacement with EV drivetrain components) and organizing of groups such as CALSTART, which is designed to promote a cooperative effort among California companies and others to design and manufacture electric vehicles and vehicle systems in California.

1 Or bodies of new high-strength steels, with extensive structural redesign aided by supercomputers.

2 Both the 1975 Corporate Average Fuel Economy Stndards and the Clean Air Act's emission standards were deliberately set high enough to be technology forcing.

3 Proposed modifications to the program ask that full-fuel-cycle emissions be considered. This would allow the ZEV requirement to be fulfilled by vehicles whose total fuel-cycle emissions (including emissions from production and distribution of the fuel) were equal to or less than the fuel-cycle emissions of electric cars-which would include the emissions of the powerplant that generates the recharge electricity.

Another force for innovation is the newly created Partnership for a New Generation of Vehicles (PNGV), an R&D program jointly sponsored by the federal government and the three domestic auto manufacturers. One of the program's three goals is the development of a manufacturable prototype vehicle within 10 years that achieves as much as a threefold increase in fuel efficiency while maintaining the affordability, safety standards, performance, and comfort available in today's cars. Although the Partnership has not yet defined any technology choices, it is clear that there will be a strong research emphasis on new materials and alternative powertrains, especially on hybrid electric configurations.[4]

Whether or not these forces for innovation will actually provide the impetus for an acceleration in the rate of technological change is uncertain, of course. Box 2-1 provides some perspective on the view that such an acceleration will be difficult.

CONGRESSIONAL CONCERNS

Congress has strong interests in future automotive innovation. First, the technologies and vehicle systems promise to increase substantially automotive fuel economy, which would reduce the oil use and carbon dioxide emissions of the U.S. and worldwide fleet of automobiles and light trucks. U.S. oil imports have recently reached 50 percent of total U.S. oil consumption, and the Energy Information Administration projects that imports will reach 60 percent by 2010, if technological improvement continues in a "business as usual" manner. These increases in import levels have strong implications for U.S. energy and economic security (see box 2-2), and a sharp decrease in these imports would represent an important benefit to the nation. Moreover, the spread of such technologies worldwide could ease pressures on global oil markets.

The reductions in carbon dioxide emissions may be a substantial benefit, as well. Carbon dioxide is a "greenhouse gas" that traps heat in the atmosphere. Scientists fear that increasing levels of greenhouse gases, particularly carbon dioxide, will cause substantial warming of the earth's atmosphere and extremely negative impacts on society (see box 2-3). The United States is the world's largest source of greenhouse gases, and its fleet of light-duty vehicles is responsible for about 15 percent of its total emissions. The United States is a party to international agreements that call for all nations to reduce their greenhouse emissions; a rapid shift to more fuel-efficient automotive technology would greatly simplify the task of complying with these international commitments.

Second, some of the advanced technologies may reduce emissions of hydrocarbons and nitrogen oxides and thus help reduce urban concentrations of ozone. Many U.S. citizens live in urban areas that still do not comply with national ambient air quality standards for ozone. Box 2-4 (at the end of this chapter) discusses several air quality and emissions issues associated with light-duty vehicles.

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4 Hybribs are vehicles that combine two or more power sources in one vehicle, for example, an internal combustion engine and a battery, with electric motors providing some or all driving forces to the wheels.

Third, Congress also has oversight responsibilities for federal expenditures of several hundred million dollars yearly for R&D on advanced automotive technologies. This oversight encompasses PNGV and other programs, as well as the Environmental Protection Agency's decisionmaking about the application of the Ozone Transport Commission and several northeastern states to adopt all or part of California's LEV program, including its ZEV mandates. Understanding the technical promise, state of development, and potential costs of the candidate technologies will be essential to exercising this oversight.

Fourth, the automotive industry and industries directly related to it[5] are a critical sector of the U.S. economy, employing an estimated 4.6 million people and accounting for 5 percent of all U.S. employment in 1991.[6] Motor vehicle manufacturers and suppliers generated annual shipments totaling $236 billion in 1992--4 percent of the Gross Domestic Product.[7] Sales of assembled vehicles and vehicle parts are fiercely competitive, with foreign-owned automakers capturing 25 percent of U.S. passenger car sales and 23.7 percent of the vehicle parts and accessories markets in 1991.[8] All three domestic manufacturers export vehicles, and both Ford and General Motors have major positions in the European market. Advocates of rapid innovation in the industry view the development of advanced technologies as critical to the domestic manufacturers' efforts to retain and increase U.S. market share and expand market share overseas. In fact, the White House's original press release for the PNGV stressed "strengthening U.S. competitiveness" as the key goal of this effort:

> The projects developed under this agreement are aimed at technologies that will help propel U.S. industry to the forefront of world automobile production. It will help ensure that U.S. jobs are not threatened by the need to meet environmental and safety goals and that world pursuit of such goals will translate into a demand for U.S. products, not foreign products. This means preserving jobs in a critical American industry.[9]

NATURE OF THE TECHNOLOGY

What types of vehicles would represent a technological "leapfrog" achieving very high levels of fuel economy coupled with significant reductions in emissions? Although formal technical efforts such as PNGV have not specified any particular pathway, a leapfrog vehicle would likely combine several changes from today's vehicles:

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[5] Industries directly related to the automotive industry include motor vehicle and equipment manufacturing, automotive sales and servicing petroleum refining and wholesale distribution road construction and maintenance, taxicabs, passenger car rental and leasing and automobile parking.

[6] American Automobile Manufacturers Association, *AAMA Facts and Figures, 94* (Detroit, MI: 1994), p. 70, citing U.S. Department of Commerce, Bureau of the Census. The employment figures include the truck and bus manufacturing divisions of Ford and General Motors

[7] U.S. Department of Commerce, International Trade Commission, "Motor Vehicles and Parts," *U.S. Industrial Outlook 1994* (Washington, DC: January 1994), Chapter *35;* and U.S. Department of Commerce, Economics and Statistics Administration, Bureau of the Census, *Statistical Abstract of the United States 1993,* 113th Ed. (Washington, DC: U.S. Government Printing Office, 1993), p. 442.

[8] Ibid, p. 617; and U.S. International Trade. Commission, *Trade & Industry Summary: Certain Motor-Vehicle Parts and Accessories,* USITC Publication 2751 (Washington, DC: March 1994).

[9] The White House, Office of the Press Secretary, "Historic Partnership Forged with Auto Makers Aims for 3-Fold Increase in Fuel Efficiency in as Soon as Ten Years," press release, Sept. 29, 1993.

1. *Materials.* Substantial changes in materials, especially those used for the vehicle structure and skin. Potential candidates are aluminum and composite materials as well as improved steel. A typical 3,000 pound family sedan might lose 600 or more pounds; some analysts claim that reductions could top 50 percent, although OTA does not agree.

2. *Aerodynam ics.* Reduction in aerodynamic drag, primarily from changing the shape of the vehicle and covering the underside. The aerodynamic drag coefficient of a sedan, where 0.3 would be considered quite good, would be reduced by several hundredths; some claim that values of 0.2 or below are achievable.

3. *Tires.* Tire rolling resistance would be reduced by 20 percent or more by adopting new tire designs that combine higher pressures and new structures and materials.

4. *New Powertrains.* A variety of new powerplants and powertrain/drivetrain combinations conceivably could supplant (or, more likely, compete with) current spark or compression ignition engine/transmission powertrains. These vary from two-stroke variations of current four-stroke engines that offer substantially reduced engine weight and size for the same power, to electric and hybrid-electric powertrains with power sources ranging from batteries to internal combustion engines to fuel cells. The electric and hybrid vehicles have an added advantage of being able to recapture part of braking energy, an especially valuable feature for urban vehicles.

DEALING WITH UNCERTAINTY

Attempts to project the potential performance, costs, and timing of a rapid introduction of new technologies are hampered by a range of critical uncertainties: several of the key technologies are far from commercialization and their costs and performance are unknown; industry choices of technology and vehicle configurations to be made available to the marketplace, and the timing of any offerings, depend on a range of complex tradeoffs (and on subjective judgments by key individuals) as well as on unknown consumer responses to any changes in vehicle cost and performance; and so forth. Both access to information and information distortion are problems, as well. Much of the research data are held strictly confidential, and industry agreements with government laboratories have made even government test results (for example, results of battery testing conducted by the national laboratories) largely off-limits to outside evaluators.

Moreover, many of the disseminators of technology information have little incentive to reveal any negative test results or other problem areas. For example, smaller companies seeking investment capital and concerned with satisfying existing investors have very strong incentives to portray their results in as optimistic a light as feasible, and few companies are willing to discuss R&D problems and failures. Even Department of Energy research managers must sometimes act as advocates for their technologies to insure their continued finding in a highly competitive research environment. The existence of government mandates for electric vehicles further complicates this problem: small companies hoping that the mandate will create markets for their products have a strong stake in portraying progress in the best possible light; the automakers affected by the mandates have, in contrast, an understandable stake in emphasizing the difficulties in achieving the mandates' requirements.

Despite these uncertainties, there exists enough information to construct a reasoned estimate of the *order of magnitude* of the potential costs and performance of many of the advanced technologies, to identify critical R&D problems that need to be solved to reduce costs or overcome other obstacles to commercialization, to examine some of the tradeoffs among alternative values that will be required, and to define some concerns that can be alleviated by advance attention and policy action. This report focuses explicitly on the technological potential for achieving large gains in fuel economy and emissions performance, the likely price effects of the new technologies and vehicle systems that would achieve the hoped-for gains, and the nature of continuing R&D programs aimed at commercializing these technologies.

STRUCTURE OF THE REPORT

Chapter 3 describes each of the major candidate technologies that may serve as components of an advanced vehicle. It identifies its state of development, major obstacles to its commercialization, and potential advantages and disadvantages, and evaluates claims for its likely cost and performance.

Chapter 4 then discusses the vehicle types that are candidates for introduction in the future. The chapter first briefly describes the energy requirements of light-duty vehicles and, broadly, the strategies available to reduce these requirements. It next projects the fuel economy performance, costs, emissions characteristics, and other characteristics of several alternative pathways of vehicle development for the years 2005 and 2015:

- **Business as usual vehicles with a level** of technology that appears likely to result from continued incremental improvement and no radical changes in oil prices or technology policy;

- **Advanced conventional vehicles that** use various advanced vehicle technologies without changing the **basic *nature*** of the drivetrain--that is, the vehicles retain spark-ignited or compression-ignited engines coupled to transmissions that transmit power to the wheels;

- **Electric vehicles** whose wheels are driven by electric motors , with the electricity provided by onboard storage in chemical (battery) or mechanical (flywheel) form;

- **Hybrid vehicles with an** electric drivetrain (possibly with a mechanical drivetrain as well) and two or more power sources (for example, an internal combustion engine and a battery); and

- **Fuel cell vehicles** that are essentially EVs or hybrids, with primary electricity supplied by an electrochemical device that transforms a hydrogen-bearing fuel (for example, hydrogen, methanol, natural gas) into electricity without combustion.[10]

The report next describes current research activities in the United States, Japan, and Western Europe. Its principal focus is on national and regional programs, and it discusses a range of issues associated with the U.S. government role in supporting automotive R&D. The report concludes with appendices that explain the methodology used by the Office of Technology Assessment to evaluate the performance and price impact of the vehicle systems.

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10 The fuel cells most likely to be used for light-duty vehicles require hydrogen as a fuel, so the vehicle must either store hydrogen or extract the hydrogen from a hydrocarbon fuel carried onboard. The latter process does require combustion, and generates small levels of combustion-related emissions.

BOX 2-1: Counterpoint: Forces Against Rapid Technological Change

There are excellent reasons why automobile manufacturers may hesitate to make large, rapid changes in vehicle technology, including shifts to electric drivetrains or alternative energy sources. First, the baseline fuel-gasoline-is in many respects an excellent fuel. Its petroleum feedstock is available in abundance, despite the jitters of the 1970s, and current worldwide proved reserves are higher today than 20 years ago. Worldwide oil prices, corrected for inflation, are at extremely low historical levels; even after adding refining costs, gasoline prices (before taxes) are lower than those of virtually any other processed liquid, including, in most cases, bottled water. Gasoline's energy content, about 125,000 Btu/gallon (higher heating content), is substantially higher than proposed alternatives such as compressed natural gas, ethanol, methanol, hydrogen, or electricity stored in batteries, and recent improvements in gasoline's composition have improved its emissions performance. Furthermore, engine designers' long familiarity with gasoline and its combustion properties provide it with a strong competitive advantage over alternative fuels.

Second, decades of experience with innovation has taught automobile designers that performance in the "real world" of spotty maintenance, wide ranges of driving patterns, unpredictable repair efficiency, and extremes of environmental conditions is often quite different from performance under test conditions, even when these conditions attempt to reproduce actual in-service conditions. All technological managers in the industry are familiar with the many notorious failures of innovative vehicle systems and subsystems such as the Chevrolet Vega's aluminum engine or Mazda's early rotary engine. In today's business environment, automobile purchasers have come to expect extremely high quality levels, and a major technological failure would likely exact a substantial penalty on a company's future market share. Further, in today's litigious environment, any adverse safety consequences, perceived or actual, stemming from a technological change could be extremely costly.

Third, the task-of designing a new vehicle is lengthy and expensive-generally five to seven years from concept to showroom, with a required investment of a billion dollars or more. If the model is a market failure, not only is the investment largely lost, but producing a replacement model for that market segment will take an additional several years. The daunting size of this task, as well as the financial risk it represents, tend to breed conservatism in the form of evolutionary rather than revolutionary design.

BOX 2-2: Energy Security, Economic Concerns, and Light-Duty Vehicle Fuel Use

The substantial dependence of the United States on imported oil to power its economy-especially its transportation sector-creates strong concerns about its economic security. Transportation consumes about 64 percent of U.S. oil use, and light-duty vehicles represent more than half of transportation's share. Consequently, the introduction of advanced, highly efficient vehicles, or any measure that would sharply reduce (or constrain the growth of) the fuel use of light-duty vehicles, will reduce energy security concerns and ease the economic impact of artificially high oil prices.

In practical terms, U.S. oil use exacts costs from the U.S. economy through three mechanisms:

- *Risks and costs of an oil disruption.* The political instability and hostility to Western interests of major sources of oil-primarily the oil producers of the Middle East-has caused severe supply disruptions, and may once again in the future. These disruptions have exacted sharp costs to the U.S. economy in the form of lost productivity, inflation, and unemployment; the Congressional Research Service has estimated these costs to be about $6 billion to $9 billion yearly.[1] The Strategic Petroleum Reserve has likely lessened the potential future costs of supply disruptions, but has itself incurred substantial investment and operating costs. An important point to note: because oil is easily transportable and all major oil markets are linked, price changes will affect U.S. oil prices regardless of how much U.S. oil is imported *or* domestically produced. The key to reducing the costs of an oil disruption is to reduce U.S. oil *use,* thus reducing the impact to the economy of a sudden rise in prices; reducing oil *imports* without reducing use, for example by increasing domestic production, will have less of a protective effect because it will not change the inflationary impact of a price rise (it may help the economy somewhat, however, if the incremental costs to consumers of higher oil prices are more likely to be recycled into the economy when the costs are paid to domestic, rather than foreign, producers).
- *Monopoly price effects.* Because the Organization of Petroleum Exporting Countries (OPEC) artificially restricts world production of oil, world oil prices are higher than they would be under free market conditions even at times of general price stability.[2] Higher oil prices reduce the amount of goods and services the U.S. economy can produce with the same resources and increase the amount of wealth U.S. citizens must shift to foreign oil suppliers. The amount of these effects has varied over the years as OPEC's market power has waxed and waned. The amount also depends on the extent to which dollars transferred to OPEC get recycled back to the United States in the form of purchases of our goods and services. In any case, however, the effects are tremendous-as much as a few trillion dollars since 1972.[3]
- *National security expenditures.* The United States spends large amounts-several tens of billion dollars annually–on military expenditures to protect oil supply, particularly for Middle Eastern flashpoints. Desert Storm cost more than $50 billion, though much of this was paid by U.S. allies, especially Saudi Arabia. There is substantial controversy about what portion of these expenditures should be "charged" to U.S. oil use, because U.S. strategic interests would be involved even without U.S. dependence on imported oil-inasmuch as Japan and Western Europe are themselves more dependent on oil imports than is the United States. There is little argument, however, over the proposition that U.S. oil imports raise the stakes for U.S. involvement in global oil security, and thus raise our costs.

U.S. economic interest is further involved in U.S. oil use and the potential for its reduction because of the market power associated with a large reduction. A substantial reduction in U.S. oil use would reduce world oil prices

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1 Congressional Research Service, Environment and Natural Resources Policy Division, "The External Costs of Oil Used in Transportation," June 3, 1992. Other authors have computed these costs to be somewhat higher or substantially lower; those computing low costs attribute much of the economic damage that followed past supply disruptions to government overreaction, especially in raising interest rates. See D.R. Bohi, *Energy Price Shocks and Macroeconomic Performance* (Washington, *DC:* Resources for the Future, 1989).

2 Estimates of what oil prices *would* be if the world market were competitive range around $7 to $11/barrel, implying that the world economy has been paying a premium of as much as $10/barrel or more for oil during the past 2 decades. D.L. Greene et al., Oak Ridge National Laboratory, "The Outlook for U.S. Oil Dependence," prepared for U.S. Department of Energy, Office of Transportation Technology, May 11, 1995.

3 Ibid.

because it would create, at least temporarily, excess production capacity. The magnitude of this impact is uncertain, however, because of disagreement about oil price's sensitivity to changes in demand and uncertainty about the ability of the Organization of Petroleum Exporting Countries to reduce production in response to a drop in oil use.

There have been substantial changes in oil markets and the world economy between the early 1970s and today. These changes can be summarized as a general shift to more flexible and responsive markets, with closer economic ties between oil producers and users, improved overall supply prospects, and improved capability for effective short-term responses to market disruptions. For example, oil production is more diversified than in 1973; the advent of the spot market and futures trading has made oil trade more flexible; OPEC investments in the economies of the Western oil-importing nations have created a strong disincentive for further market disruptions; and the end of the Cold War has removed an important source of tensions, These and other changes have generally improved U.S. and world energy security. Nevertheless, there are important reasons to remain concerned about energy security-the continued holding by Persian Gulf nations of the major share of the world's oil reserves and most of its excess oil production capacity; continued political instability in the area, although Arab-Israeli tensions have eased; and the existence of groups extremely hostile to the United States and the West in general. Further, even were the threat of new disruptions small, the costs exacted on the U.S. economy of OPEC monopoly behavior will continue as long as OPEC can maintain prices at artificially high levels. Thus, there remain extremely important reasons that both a sharp reduction in U.S. oil use and a decrease in the U.S. transportation sector's dependence on oil, should still be considered to offer an important societal benefit.

BOX 2-3: Greenhouse Emissions and Light-Duty Vehicles

Although air quality and energy security considerations have been the primary impetus for policy seeking to accelerate the development of advanced *automotive* technologies, these technologies also can play an important role in reducing emissions of carbon dioxide and other greenhouse gases. The administration has been sponsoring a greenhouse policy process called "Cartalk" that has brought together representatives of environmental organizations, automakers, and various transportation industries, as well as other interested parties in an effort to devise transportation policies that will reduce U.S. greenhouse emissions. It is OTA's understanding that policies to accelerate technology development have assumed a prominent role on Cartalk's agenda.

The "greenhouse effect"--a warming of the earth and the atmosphere-is the result of certain atmospheric gases absorbing the thermal radiation given off by the earth's surface and trapping some of this radiation in the atmosphere. The earth has a natural greenhouse effect, owing primarily to water vapor, clouds, and carbon dioxide ($C0_2$), that maintains its temperature at about 60°F warmer than it would otherwise be. What is now of concern to scientists is the potential for increasing levels of $C0_2$ and other gases to increase the earth's temperature even more-causing strong changes in sea level, storm frequency, rainfall patterns, and other conditions that would have enormous consequences on the manmade and natural environment. Although there are some continuing disagreements and uncertainties associated with these impacts, most atmospheric scientists accept the likelihood that global average temperatures will increase by 3° to 8°F, if global $C0_2$ concentrations double-a likelihood in the next century.

Worldwide emissions of $C0_2$ are so large-they were 6 billion metric tons of carbon in 1985[1]-that no one source can be singled out as a primary target. However, light-duty vehicle $C0_2$ emissions are large enough to make them an obvious target for reduction. The U.S. light-duty fleet accounts for about 63 percent of U.S. transport $C0_2$ emissions-about 3 percent of world $C0_2$ emissions, or about 1.5 percent of the world's total greenhouse problem. And, because most technology is "fungible''--easily transported and adopted-technological advances in the United States stand an excellent chance of spreading to the worldwide fleet, affecting still more of the world's total greenhouse problem. As a result, improvements in vehicle fuel economy are considered a key strategy in combating future global warming.

Generally, improvements in vehicle fuel economy will scale proportionately with reductions in greenhouse gas emissions. This is not true, however, if there is a fuel change, because vehicles using alternative fuels may have $C0_2$ and other greenhouse gas emissions that are strongly different from the emissions of gasoline vehicles. For example, electric vehicles have zero emissions, at least directly from the vehicle; the electric power used to recharge the vehicles will have $C0_2$ emissions determined primarily by the generation technology and fuel choice--from zero or negligible for nuclear power and hydroelectric power production, to levels high enough, for coal-powered generation, to raise total fuel-cycle emissions for electric vehicles to approximately the same or higher than fuel-cycle emissions for gasoline-powered vehicles.[2]

1 U.S. Environmental Protection Agency data.
2 M. Delucchi, University of California at Davis, results from GHG Emissions Mode1, personal communication, Dec. 7, 1993.

BOX 2-4: Air Quality Considerations

Improving air quality is a critical goal of most efforts to move advanced technology into the light-duty fleet. For example, California considers its zero emission vehicle (ZEV) requirements critical to its effort to achieve acceptable air quality. Similarly, reductions in vehicle emissions are one of the key Partnership for a New Generation of Vehicles goals; the administration's original name for the partnership was the Clean Car Initiative.

Vehicular emissions are an important source of an ongoing air quality problem-continuing widespread noncompliance with ambient health standards for ozone, primarily in urban areas. Currently, about 50 million people live in counties that exceed the National Ambient Air Quality Standard for ozone.[1] At high concentrations, ozone damages lung tissue, reduces lung function, and sensitizes the lung to other irritants; it also damages crops and natural vegetation. Ozone is formed by the atmospheric reaction of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight, and motor vehicles nationwide are responsible for about 32 percent of emissions of NO_x and 26 percent of VOC.[2]

Vehicles-especially diesel-powered vehicles-are also emitters of very small particulate that have been associated with severe adverse health impacts, including premature deaths. Further, NO_x emissions, of which vehicles are the major source, also form particles in the atmosphere. Although sulfur emissions from power generation are the single greatest source of particulate, vehicle emissions of particulate and particulate precursors occur closer to affected populations. Particulate emissions from heavy-duty diesels and gasoline vehicles will likely decline in the future, but the overall decline in small particulate concentrations may be slowed considerably, if diesel engines are used more widely in light-duty vehicles.

Why Vehicle Emissions Remain a Problem

Government regulations have succeeded in both reducing total emissions from highway vehicles (and other sources) and improving air quality. For example, highway vehicle emissions of volatile organic compounds dropped by 45 percent and carbon monoxide (CO) by 32 percent between 1980 and 1993. During the same period, nitrogen oxide highway vehicle emissions dropped by 15 percent. Ozone air quality standards attainment has fluctuated with weather, but has clearly been improving during the past 10 years, and carbon monoxide attainment has improved dramatically, with a severalfold drop in the number of people living in nonattainment areas.[3]

Vehicles remain a troublesome problem, however. Although "per vehicle" emissions have been drastically reduced, vehicle-miles traveled have doubled over the past 25 years, countering some of the improvement-and highway travel will continue to increase. In addition, although new cars certified at federal Tier 1 emissions standards achieve tested emission levels that are, respectively, 3, 4, and 11 percent of uncontrolled levels of hydrocarbon, carbon monoxide, and nitrogen oxides, actual on-road emissions are considerably higher than regulated levels, especially for hydrocarbons (HC) and CO. Reasons for this higher level of emissions include:

1. *Older cars still on the road.* Many older cars have less effective emission controls, and some have deteriorated systems.

2. *Tampering.* About 15 to 30 percent of all cars have control systems that have been tampered with.[4] Although today's computer-controlled engines and emission control systems have largely eliminated the drivability problems that spurred early tampering, some tampering continues to occur.

3. *Malfunctions.* Many vehicle owners ignore malfunctions of emission control components.

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[1] U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Quality and Emissions Trends Report, 1993, EPA-450/R-94-026* (Research Triangle Park NC: October 1994).

[2] Council on Environmental Quality, *Environmental Quality: The Twenty-Fourth Annual Report of the Council on Environmental Quality* (Washington, DC: 1995), p. 435.

[3] Ibid, pp. 435,447.

[4] J.G. Calvert at al., "Achieving Acceptable Air Quality: Some Reflections on Controlling Vehicle Emissions," *Science*, vol. 21, July 2, 1993.

4. ***Poor gasoline quality.*** Many U.S. gasolines have sulfur levels and/or vapor pressures that exceed specifications; and some brands do not contain adequate deposit-control additives.[5] High sulfur levels in gasoline reduce catalyst efficiency for all criteria pollutants; high vapor pressure yields high levels of evaporative emissions; and dirty valves, injectors, and combustion chambers raise carbon monoxide, hydrocarbon, and NO_x emissions.

5. *Off-test driving patterns.* The Environmental Protection Agency (EPA) emission control certification test does not include periods of high speeds, hard acceleration, or hill climbing, and automakers design their vehicles to comply with these tests. Auto designers meet the need for increased engine power during acceleration and hill climbing, however, by adjusting the air/fuel ratio to run "rich," that is, with excess fuel, which substantially increases hydrocarbon emissions during these periods.

6. *Limitations of current Inspection and Maintenance (I&M) Programs.* Although the I&M programs established in areas of noncompliance with air quality standards are designed to identify and correct those vehicles with higher-than-normal emissions, current programs are limited in effectiveness for several reasons:

- Because they test vehicles that are fully warmed up, they do not measure cold-start emissions, responsible for the majority of vehicle emissions.

- Because they do not use dynamometers, they cannot test emissions during acceleration, also a key element of total emissions.

- They measure exhaust emissions only, whereas evaporative emissions represent a growing share of total vehicle emissions.

- Some fraud exists, particularly in programs dependent on independent garages. In addition, some owners alter their vehicles' control systems to pass the test.

- Exemptions are granted when repairs exceed relatively low dollar amounts, although vehicles in need of expensive repairs often are the worst offenders.

Ongoing Emission Control Programs

The Clean Air Act Amendments have established numerous new programs designed to correct several of the aforementioned problems. First, emission standards for new vehicles have been made more stringent, and certification limits for emission controls have been extended to 10 years or 100,000 miles, up from the previous 5 years or 50,000 miles.

Second, new vehicles will be required to have electronic measuring systems that will provide warning when vehicle emission control systems malfunction. Third, new "reformulated gasolines''--gasolines that have been chemically altered to have lower Reid vapor pressure (to reduce evaporative emissions), increased content of oxygenated compounds (to reduce CO emissions), and other features that will reduce vehicle emissions-will be sold in noncomplying areas and other areas that "opt in" to this program.

Fourth, I&M programs are to be improved. EPA's initial definition of the act's "enhanced I&M" was a shift to more sophisticated tests using dynamometers and measuring evaporative emissions as well; the act also increased the

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5 Ibid. The authors cite a 1992 American Automobile Manufacturer Association survey of gasoline as concluding that 20 percent of commercial fuels exceeded established distillation cutpoints and 40 percent exceeded sulfur cutpoints, both contributing to high exhaust emissions.

repair bill amount for exemption to $450. Fifth, EPA is planning to change the current test procedures to account for off-cycle driving patterns.

In addition to the Clean Air Act requirements, the Energy Policy Act establishes a series of fleet requirements and economic incentives to increase the use of alternative (nonpetroleum) fuels. Qualifying fuels include natural gas, ethanol, methanol, propane, and electricity.

California has gone beyond the federal requirements by demanding the gradual addition to the new car fleet of vehicles meeting a set of emission standards that are more stringent than the new federal standards. The standards include a requirement for 2 percent of the new car sales of major auto companies to be ZEVs-–practically speaking, electric vehicles-by 1998, with the percentage increasing to 10 percent by 2003.

What Will In-Place Programs Accomplish?

The federal programs now in place appear to have a substantial potential to address the several problem areas that have prevented satisfactory control of vehicle emissions. The combination of reformulated gasoline and I&M targeting of evaporative emissions should greatly improve control of these emissions in noncomplying regions. Improved I&M programs, coupled with more stringent standards, onboard diagnostics, and increased emission control warranties for new vehicles, should reduce the number of "superemitters" among relatively new vehicles. Some past problems with misfueling catalyst-equipped vehicles with leaded fuel (which poisons the catalyst) will cease because leaded fuel is no longer available in the general market. Further, today's vehicles, with their sophisticated computer controls, are far less vulnerable to tampering problems. In addition, increased use of alternative fuels, especially natural gas and electricity, should have some positive effect.

The California emission programs, which may be adopted by some northeastern states, create the potential for sharp drops in the certified emission levels of the new car fleet. There has been substantial controversy about the most extreme of these measures, the ZEV and ultralow emission vehicle (ULEV) standards. Auto manufacturers have argued that attainment of ULEV standards will be extremely expensive ($1,000 or more for each vehicle), and that battery technology is not yet sufficiently advanced to allow enough vehicle range and battery longevity to satisfy consumers. Recent developments appear to have improved the prospects for attainment of ULEV levels at substantially lower cost for at least some classes of vehicles–the 1994 Toyota Camry came very close to ULEV certification levels, and Honda has recently announced attainment of these levels with a modified Accord, at a few hundred dollars per vehicle.[6] The potential for EVs is discussed in some detail in this report.

There are potential limitations to the effectiveness of some of the emission control programs. For example, some studies have shown that a significant percentage of vehicles that underwent repairs after failing I&M tests were inadequately repaired. Furthermore, EPA has recently backed off the I&M dynamometer requirements and central testing for states now using decentralized testing, and the survival of these requirements is in doubt. This may compromise the ability of the I&M program to ensure the identification and repair of noncomplying vehicles. And, although fuels such as natural gas and electricity will yield substantial "per vehicle" emissions reductions, it is far from clear whether the existing programs will result in widespread availability of these fuels.

Another issue, often raised by the auto manufacturers, is the extent to which the regulatory focus on obtaining higher and higher levels of control efficiency from new cars, with obviously diminishing returns, can backfire. The argument here is that it is the turnover of the fleet, driven by the sales of new cars and retirement of old ones, that is the most effective mechanism for reducing vehicle emissions. If greater emission control requirements cause vehicle prices to rise, this will slow turnover and impede this critical mechanism. Although this argument clearly is qualitatively correct, proponents of more stringent regulation argue that any negative effects will be small because: 1) emission control costs have dropped over time; 2) some technologies introduced primarily for emission control (fuel injection, improved engine controls) have substantially enhanced engine performance and reliability and, thus, have been an incentive for purchasing new vehicles, and; 3) there are limits to the length of time that vehicle owners will delay purchases, so that any slowdown in fleet turnover will be limited in duration.

[6] This cost assumes, however, that the vehicle is equipped with Honda's VTEC-variable valve control-technology. If this technology must be added, the price is substantially higher, but the vehicle owner gains a substantial boost in power and/or fuel economy.

The potential for continuing problems with identifying and fixing vehicles with high levels of emissions, and continuing problems with "off-cycle" emissions theoretically places a premium on new propulsion systems that offer low emissions without eventual deterioration, potential for malfunction, or high off-cycle emissions. The emissions performance of advanced technologies should be examined in this light.

An Added Concern: Small Particulate

Vehicle emissions of particulate have not been handled with the same urgency by regulatory agencies as nitrogen oxides, hydrocarbons, and CO, partly because particulate emissions have not generally been considered as a major health problem and partly because vehicle emissions are low and other sources (windblown soil, power generation) are so much greater. Recent studies, however, have found a strong statistical association between fine particulate (diameter less than 2.5 microns) and aerosols and mortality and morbidity rates. A recent study by the Harvard School of Public Health finds that death rates increase by as much **as 26** percent as fine particulate or sulfates rise from the least polluted of the six cities in their study to the most polluted-after adjusting for other causes of death such as smoking.[7]

Diesel engines have substantially higher particulate emission rates than gasoline vehicles, by about a factor of 10,[8] and their emissions have long been considered a problem because most are in the size range[9] where body defenses do a poor job of filtering, and they tend to be coated with organic compounds often associated with cancer. The newest generation of diesels have sharply reduced particulate emission rates, but these rates are still higher than those of gasoline vehicles. To the extent that diesel engines are used in advanced vehicles, and thus enter the fleet in large numbers, they may raise concerns about particulate air pollution.

7 D. W. Dockery et al., "An Association Between Air Pollution and Mortality in Six U.S. Cities" *New England Journal of Medicine,* **vol. 329, Dec.** 9, 1993, pp. 1753-1808.

8 K.A. Small and C. Kazimi, "On the Costs of Air Pollution from Motor Vehicles," ***Journal of Transport Economics and Policy,*** January 1995.

9 Over 90 percent are less than 1 micron in diameter. Tom Cackette, California Air Resources Board, personal communication, May 18, 1995.

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 Amory 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

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[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

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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.

201 5-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:

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

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

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:

[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 equal performance, 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 an equal power 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

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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.

Nickel-iron 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.

Nickel-metal hydride 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.

Sodium sulfur 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.

Sodium-nickel chloride 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.

Lithium-metal sulfide bipolar 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 usable 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.

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]

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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.

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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.

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

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 CO_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

[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

120Ibid.
121Total energy, not usable energy.
122SatCon Technology Corp., "Flywheel Energy Storage Systems, brochure, n.d.
123J.D. Hurley, Director, SatCon Corp., personal communication, December 1994.
124However, 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

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

[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;

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1 M. 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.

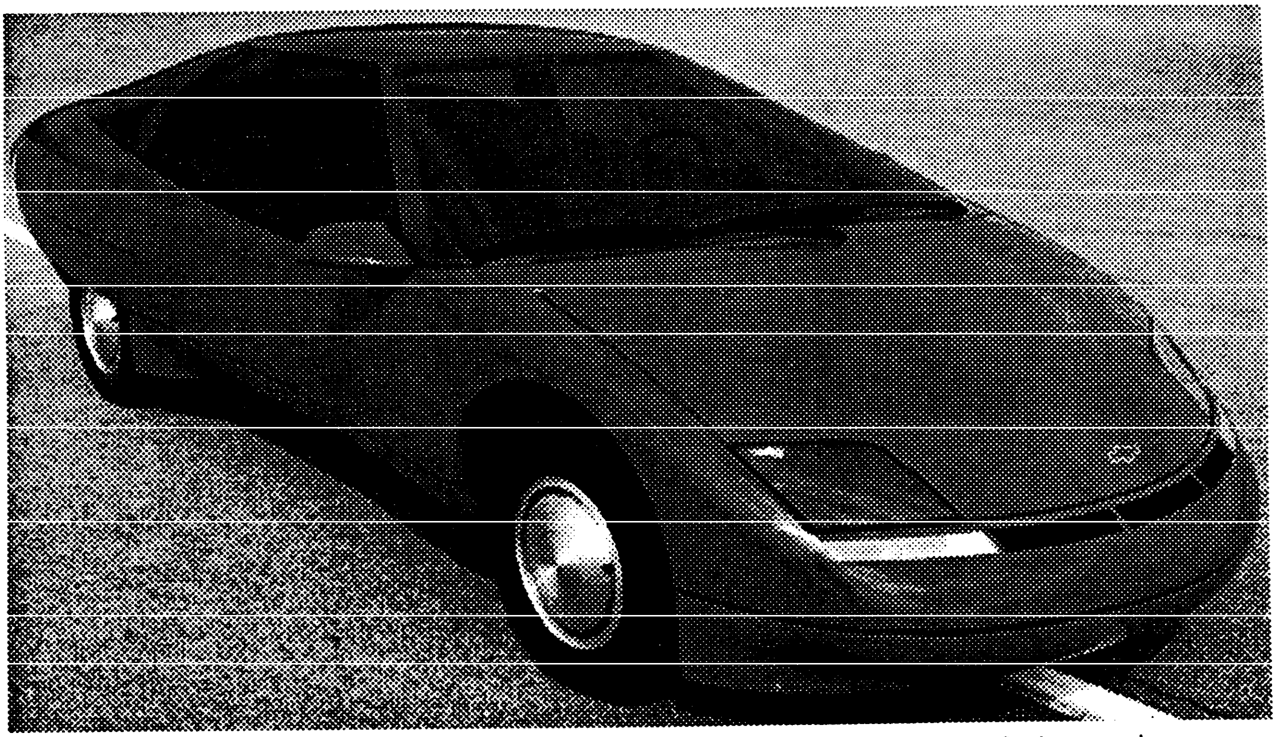
TABLE 3-13: Subjective Rating of Different Motors for EV Use

	Drive System With		
Feature	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		

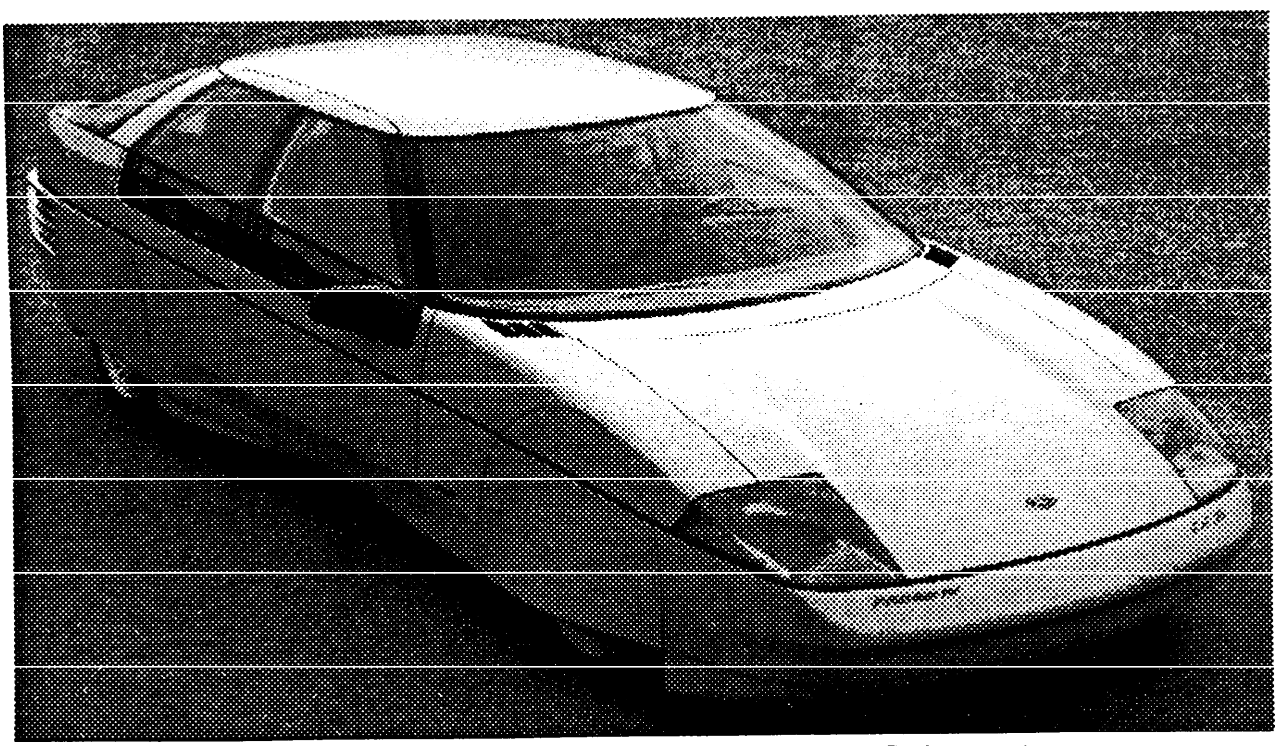
KEY: DC= direct current; PMS = permanent magnet synchronous; AC = alternating current.

SOURCE: Daimler-Benz.

FIGURE 3-1: Examples of Highly Aerodynamic Cars



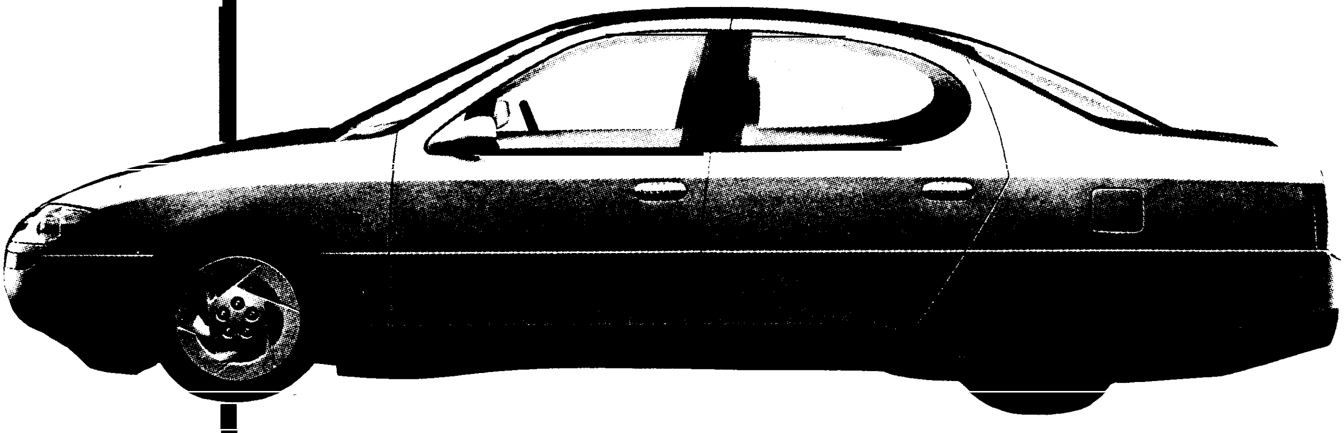
Chevrolet Citation IV — F ont eng ne f ont whee d ve 4 passenge 2 doo sedan

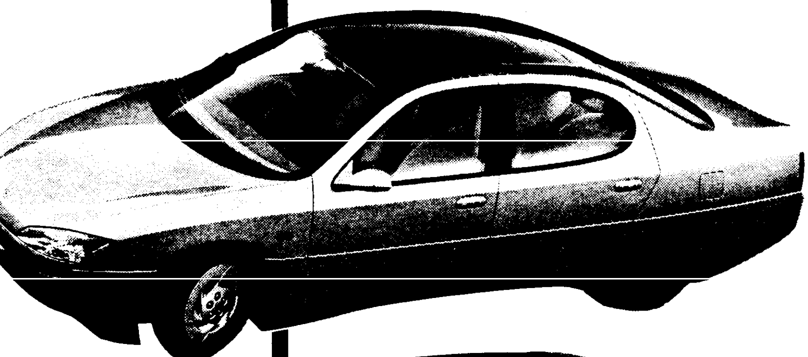


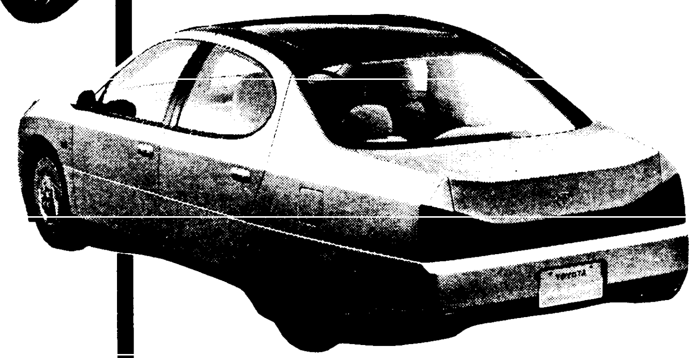
Ford Probe IV — F on eng ne f ont whee d ve 4 passenge 5 doo sedan

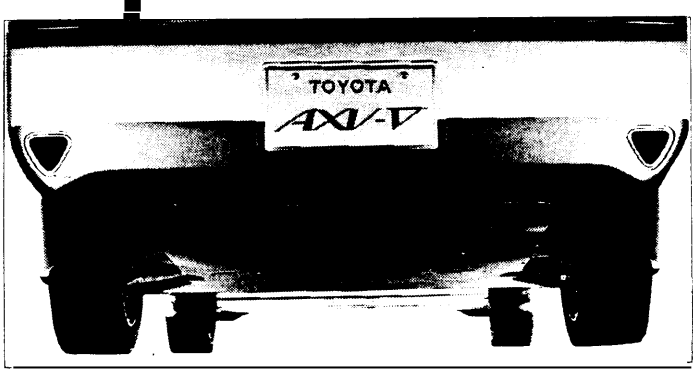
FIGURE 3-2: Design Features of **Toyota AXV-V**

AXV-V

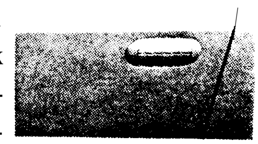








Side



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

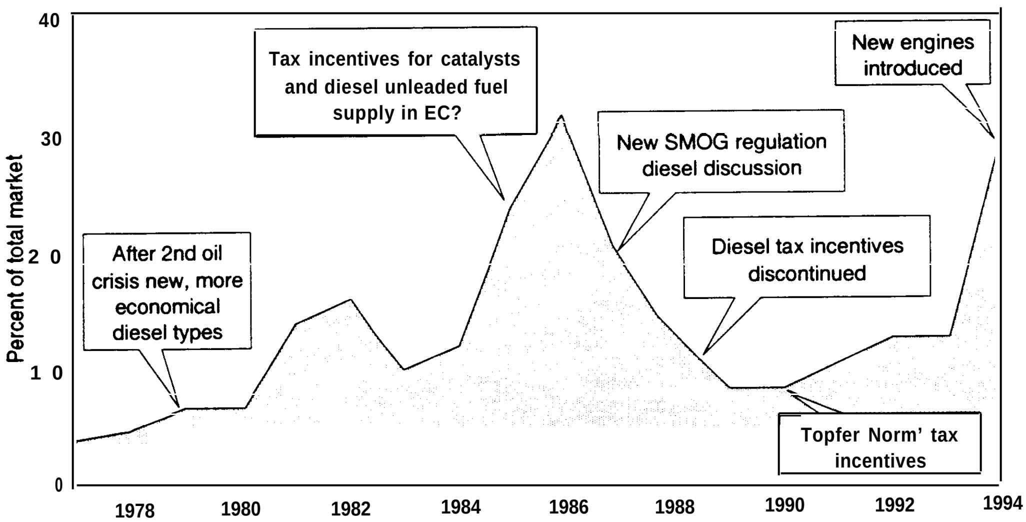
The entire underbody has a flat cover that sweeps up at the rear to maintain a smooth flow of air. Large spats in front of and behind all four tires also cut wind resistance. And a slit in the underbody cover beneath the exhaust pipe cools it with minimum drag.

Aluminum wheels

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

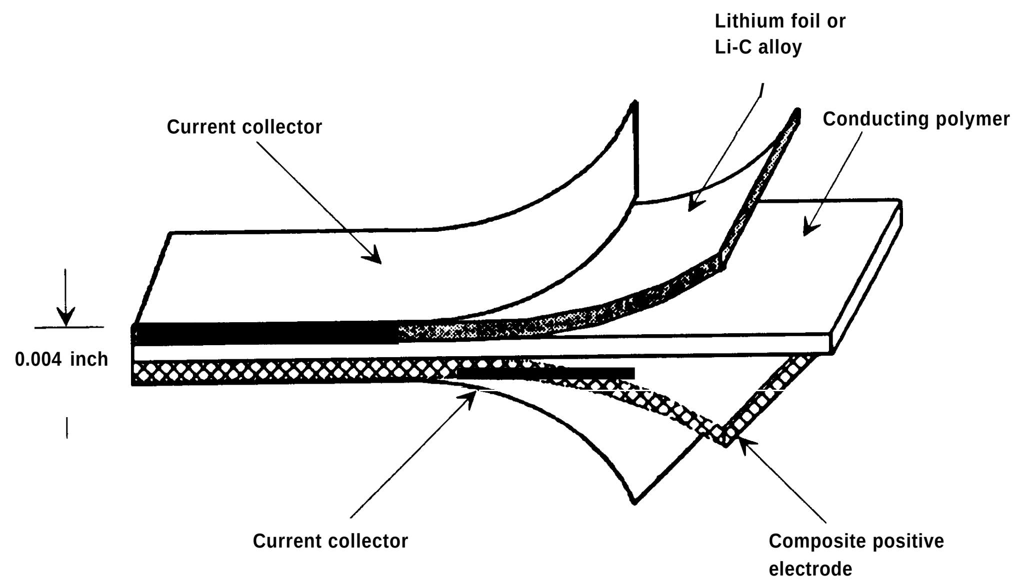
TOYOTA MOTOR CORPORATION
International Public Affairs, Tokyo Head Office

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



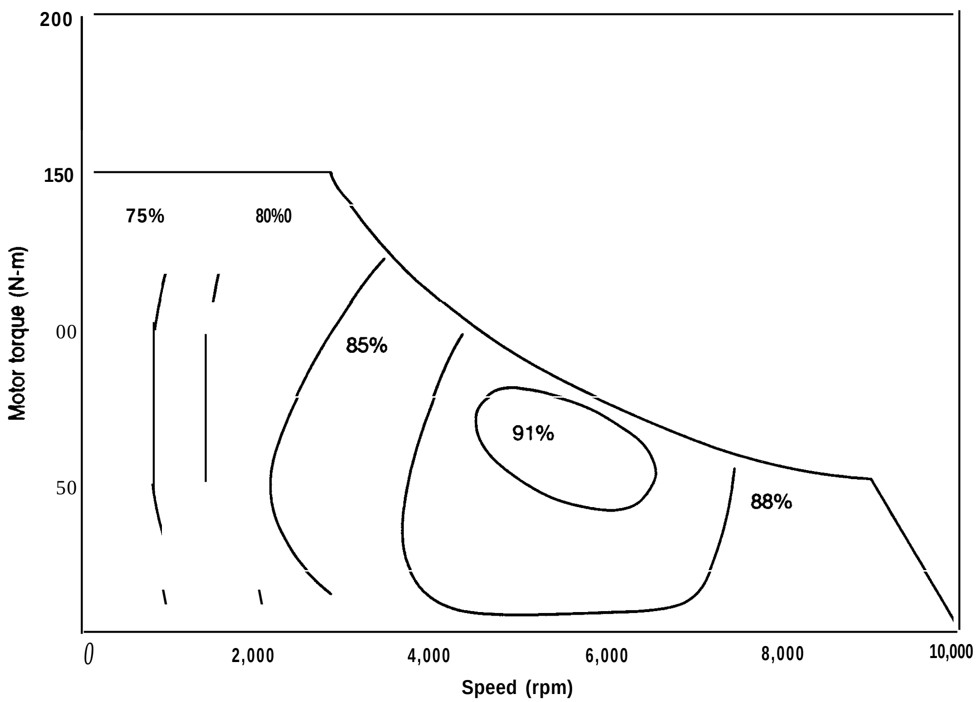
SOURCE: VDA.

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).

Chapter 4

Advanced Vehicles -- Technical Potential and Costs

This chapter discusses the potential for advanced light-duty vehicles that are capable of very high levels of fuel efficiency and excellent emissions performance, to be introduced during the next 10 to 20 years. The focus of this analysis is on *mass-market* vehicles (e.g., those produced in volumes of over 100,000 per year) because major reductions in U.S. oil use and vehicle emissions can be achieved only by drastically improving this class of vehicles.

As discussed below, the Office of Technology Assessment (OTA) chose to focus on "fill service" advanced vehicles that have comparable performance to conventional vehicles, rather than limited service or specialty vehicles that might be suitable for certain market niches (e.g., delivery vans, city-only commuter vehicles). The only exception to this is OTA's consideration of battery electric vehicles (EVs), which are certain to have a more limited range than conventional cars, at least for the next 10 to 15 years. Even in the EV case, however, the vehicles are required to have peak power (for acceleration) and continuous power (for grade climbing or other long-term, high-load conditions) comparable to conventional vehicles.

This comparable performance requirement implies larger electric motors and energy storage devices than are assumed in some other analyses, and may explain, at least in part, why OTA's price estimates are higher than those made by some other sources. By relaxing the power requirements, which are somewhat arbitrary, significant cost reductions can be achieved, making the "advanced" vehicles more price-competitive with conventional vehicles.

OTA's Methodology

OTA and its contractors gathered data for its analysis from several sources:

- a wide-ranging review of the literature, including papers given at recent conferences on automotive technology;
- a series of detailed interviews with the research and technical staffs of eleven auto manufacturers; [1]
- interviews with a range of manufacturers and researchers of advanced technologies; and
- published data on the fuel economy performance of existing commercial vehicles.

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[1] In Europe, interviews were conducted with VW, BMW, Mercedes-Benz and Porsche. In Japan, interviews were conducted with Honda, Nissan, Toyota and Mitsubishi, and with selected research laboratories and supplier industries. Interviews were also held with General Motors, Ford, and Chrysler in the United States.

To evaluate the performance and costs of advanced vehicles, OTA conducted a series of calculations based on physical principles and cost accounting methods. The performance calculations are explained in more detail in appendix A. Briefly, most vehicle fuel economy calculations follow the work of GM Research Laboratory scientists Sovran and Bohn,[2] who derived an equation for vehicle fuel consumption over the Environmental Protection Agency (EPA) test cycle. Fuel economy calculations for so-called parallel hybrids--vehicles that have two separate power sources driving the wheels--require more sophisticated computation, and OTA's estimates for these vehicles are rougher approximations than those of the others.

OTA's cost calculations derive a "retail price effect" (RPE) of new technologies--the *change* in retail price that would occur if a new technology is substituted for a baseline technology when designing a new vehicle--based on tracking variable and fixed costs from component supplier to vehicle assembler to sales outlet. This methodology uses an approach followed by industry and regulatory agencies. A primary assumption in the analysis is that the industry is competitive enough that manufacturers earn only the normal returns on capita1[3]--that is, they are not able to charge a premium because no one else has the technology. The estimated RPE may not correspond to a particular model because companies sometimes subsidize one model or size class with another; however, the RPEs should be good reflections of the industry average.

Types of Vehicles Examined

The discussion first establishes a baseline--vehicles believed to be representative of the mass-market fleets in 2005 and 2015 without shifts in energy policy, large changes in oil prices, or major technical breakthroughs. As will be seen, these vehicles are projected to be both more efficient than today's and superior in safety, acceleration performance, and other characteristics important to consumers. The projected improvements are based on an evaluation that they make market sense under an assumption of oil prices rising at a moderate pace, either because fuel savings are sufficiently high (at sufficiently low cost for the improvements) to attract consumers, or because the improvements add value to the vehicles in terms of performance and other customer attributes.

Four kinds of advanced vehicles are then discussed that might have the *technical* potential to enter the marketplace in this time frame, if very strong research and development efforts were pursued:

- *Advanced conventional vehicles. These* vehicles have conventional drivetrains--internal combustion engines (ICES) and transmissions--but each part of the vehicle is substantially improved from today's and is superior to what otherwise would be expected in this time frame.

[2] G. Sovran and M.S. Bohn, "Formulae for the Tractive Energy Requirements of Vehicles Driving the EPA Schedule," SAE paper 810184, February 1981.

[3] These returns reflect the oligopolistic nature of the auto industry, and are somewhat higher than they would be if the industry were perfectly competitive.

- *Electric Vehicles. These are* vehicles that rely on stored electrical energy (in batteries or, conceivably, in a flywheel) as their sole energy source. Electric motors drive the wheels.

- *Hybrid Vehicles.* Hybrids are vehicles that combine two energy sources in a single vehicle. For example, an ICE may be paired with a battery or flywheel. In a series hybrid, both energy sources are used to power one or more electric motors driving the wheels--the *engine is* connected to a generator whose output power can be fed into the battery and, in *some* configurations, directly to the motor as well. In a parallel hybrid, both the engine and electric motor(s) can directly drive the wheels.

- *Fuel Cell Vehicles. These are* vehicles powered by an electrochemical device called a fuel cell, which converts a replaceable fuel directly into electricity without combustion. Although considered separately, they are a type of electric vehicle, and they are also likely to be hybrids.

Four classes of vehicles--subcompact cars, mid-size cars, compact vans, and full size, or standard pickups--are modeled to capture the effect of size and fictional variations. These market classes were chosen as they represent the two most popular classes of cars and light trucks, respectively. Even with this size specification, however, manufacturers have the option of varying body rigidity, interior volume (within limits), safety and luxury options, and acceleration performance. In the last decade, all of these have increased significantly for almost every market class of car and light truck. For this analysis, the median 1995 characteristics of vehicles in each of the four segments are used as a reference, and these vehicles' attributes are held constant to define one maximum technology scenario. Other scenarios such as changed performance and increased body rigidity are discussed only qualitatively.

We have set performance requirements as follows: *Continuous power demand* (i.e., power output that must be sustained indefinitely) is set to a level that enables the vehicle to climb a 6 percent grade at 60 mph with a modest payload, which equates to about 30 kW (40 hp) per ton. Of course, such a long grade is encountered rarely, but this requirement is to cover numerous of other situations where the vehicle is fully loaded with five passengers and luggage, such as 55 mph climb up a 3 or 4 percent grade. *Peak power demand* is based on a O to 60 mph acceleration time under 11 seconds, with a nominal load. This equates to about 60 kW (8O hp)/ton for a normal gasoline drivetrain, but about 50 kW (67 hp)/ton for an electric drive because of an electric motor's excellent torque characteristics. We have required that peak power be sustained for over one minute, to cover situations where two highway "merge" cycles are required back-to-back, or the vehicle must climb a steep highway entrance ramp (for an elevated highway) and then have enough power to merge into 70 mph traffic. Hence, the 60 kW/ton and 30 kW/ton power requirements are to cover a wide variety of traffic conditions under full load, not just the example cases cited above, and most ICE-powered vehicles meet these performance levels.

Vehicle Attributes

This report focuses on vehicles that might essentially replace the conventional ICE-powered vehicles of our current light-duty fleet. There is some controversy about how well replacement vehicles must perform to be viable candidates in a competitive market. Some analysts claim that consumers are unlikely to accept vehicles that have important limitations in performance and range; others claim that consumers will accept limitations once they examine and better understand their actual travel patterns and requirements.

With the possible exception of electric vehicles, there are some configurations of each of the vehicle types examined that appear to have the potential to match or exceed the general performance characteristics of both current vehicles and the baseline vehicles that, if OTA's projections are correct, will form "the competition" in future years. OTA has chosen to focus on these "competitive" configurations of the vehicle types in this report, but the reader should recognize that other configurations that might underperform the baseline vehicles might have other advantages, particularly in cost. For example, the discussion of EVs concludes that designs with reduced range and performance can be built at prices that are considerably more competitive (in first cost) with conventional vehicles than are the more robust vehicles examined in detail.

The vehicles examined here are required to satisfy performance requirements for range, gradeability (ability to climb hills) and acceleration performance; these requirements determine such parameters as battery size and motor horsepower. Owners judge the value of their vehicles by a variety of characteristics, however, and these should be understood by those seeking to evaluate the competitiveness of new designs. For example, the vehicles adopted by the PNGV as targets--the Taurus, Lumina, and Concorde--as well as most other modem cars and light-duty trucks, are extremely versatile vehicles with robust performance. Although most of their use is for lightly loaded, short-distance travel (average auto occupancy is 1.4 occupants per car, average trip length is 9 miles[4]), they are also extremely competent as long-distance haulers--filly loaded with passengers and luggage.

There is substantial market evidence that this versatility is highly valued by vehicle buyers. Automakers have found themselves forced by consumer complaints and poor sales to upgrade performance on new models and have consistently found purchasers upgrading to more powerful engines although base engines appear adequate to handle most vehicle tasks. It appears that purchasers are selecting vehicle size and performance capability based on the most demanding 5 percent of their trips rather than the most common 95 percent--for example, the once or twice yearly family vacation rather than the daily commute or after-school carpool. *If this purchasing behavior remains the norm, it will have a substantial influence on the types of technologies introduced into the marketplace and the designs of the vehicles that carry them.*

This type of purchasing behavior cannot be assumed to be irreversible, of course. Consumer surveys performed by the University of California at Davis and others have found that potential vehicle purchasers who became more knowledgeable about their actual driving patterns often report they would be willing to purchase limited-capability vehicles (e.g., electrics) if cost were similar. Some researchers, however, contend that "stated preference" surveys of this type, where those being surveyed are reporting only their hypothetical behavior, are inherently unreliable and tend to overstate the likelihood of limited-capability vehicles being sold.

[4]P.S. Hu and J. Young, *Summary of Travel Trends: 1990 Nationwide Personal Transportation Survey,* FHWA-PL-92-027 (Washington, DC: Federal Highway Adminstration, March 1992).

OTA remains uncertain about the prospects for a large shift in consumer preferences toward vehicles with limited range or other performance limitations. Where possible, however, its analyses focus on vehicle designs that can match conventional ICE vehicles in overall performance. For example, as discussed below, there are virtually limitless variations on potential configurations for hybrid vehicles, but this report focuses on those hybrids with the fewest performance limitations.

Technologies Introduced Individually or in Combination

The vehicles examined here are *maximum technology* vehicles; that is, they combine a wide range of new advanced technologies in one vehicle. This is distinctly *not* in the mold of historic vehicle innovation, which has tended to be more incremental in nature. Generally, new technologies have been introduced singly, in limited-edition (often luxury) vehicles to test their readiness for the mass market in a way that limits risks to the automaker. Only after a few years of such "testing" are new technologies moved into the heart of an automaker's fleet. Thus, if the future is like the past, the vehicles examined here may be unrealistic in their capability to model real world events. The existence of the Partnership for a New Generation of Vehicles (PNGV), however, which is attempting to develop such a maximum technology vehicle, the technology-forcing nature of California's zero emission vehicle (ZEV) mandates, and the potential for future fuel economy regulations may make such vehicles more likely in the future.

Uncertainty in Technology Forecasting

There is now considerable literature evaluating the prospects for substantial advances in automotive technology. Unfortunately, a reading of this literature leaves the reader with a wide--and confusing--range of views about the likely timing, cost, and performance of advanced vehicles and vehicle technologies.

It is useful for the reader to recognize that the history of technology forecasting, and forecasting in the automotive arena, is rife with failure, particularly when forecasts are aimed at technologies that are clear departures from those in use at the time of the forecast. Many technologies that were forecast to be commercialized and to have made extensive inroads in market share have dropped from the menu of technology options by the target date of the projection. Others have been added to the menu despite widespread pessimism about their chances for commercialization or intensive penetration into the fleet. Reasons for incorrect technology forecasts include:

- the possibility that the market rejected the technology because of its expense or perceived disadvantages (high rates of failure, adverse effect on noise or ride quality, and so forth), and/or market preferences may have changed after the forecast was made;

- other technologies that are lower cost or have lower operating expenses may do a better job;

- the technical "context" that made the technology attractive or unattractive--the prevalent fuel or the nature of the technologies affecting or affected by the technology--may change;
- new regulations (for example, emission standards not easily complied with by the technology) can either hinder or enhance technology introduction;
- manufacturing the technology in large quantities can turn out to be more difficult and expensive than was expected, or improvements in manufacturing can do the reverse;
- problems may occur in the "real world" operating environment that are difficult to overcome (some automotive technologies fail because they require levels of maintenance that are difficult to *get* U.S. car owners to comply with, or because driving patterns place more severe strains on performance than were originally forecast by test results).

Moreover, when technologies enter the marketplace, their effect on vehicle performance may be considerably different from projected levels because of unforeseen changes in measured performance as the technology moves from the laboratory bench to prototype to production model. These changes may come from physical scaling effects that were not widely understood at the time of the forecast; from the need to change design to deal with an emerging problem; or even from design changes that deliberately trade off one performance characteristic against another (for example, sacrificing efficiency to achieve lower cost, or vice versa).

Forecasts also may go astray because of incorrect methodology--for example, not accounting for costs such as dealer markups and transportation costs (or not accounting for cost savings)--or simply by the acceptance of exaggerated claims (positive or negative) from sources with a financial or ideological stake in the technology or one of its competitors.

Considering the limitations of technology forecasting, OTA's forecast is meant to serve a limited purpose:

- to gain a rough estimate of the magnitude of fuel economy improvement potential over the next 20 years;
- to identify future policy challenges associated with advanced vehicles, such as potential for higher costs, difficult market challenges, potential safety problems; and
- to provide assistance in evaluating existing and proposed vehicle research programs.

ENERGY USE AND REDUCTION IN LIGHT-DUTY VEHICLES

Vehicles use energy primarily to produce power at the wheels to overcome three tractive forces that would otherwise prevent the vehicle from moving: aerodynamic drag forces, the force of air fiction on the body surfaces of the vehicle; rolling resistance, the resistive forces between the tires and the road; and inertial force, the resistance of any mass to acceleration. Moreover, if the vehicle is climbing a grade, its mass exerts a downward restraining force. In addition, the vehicle must produce energy to power accessories such as heating fan, air conditioner, lights, radio, and power steering. And, unless the engine is turned off, during idle and braking the engine energy is largely wasted because it is not being used to provide motive force.

To produce usable energy, the vehicle must take fuel energy and translate it to shaft power through the engine; most of this power is then directed through the remainder of the vehicle's drivetrain to drive the wheels. Generally, this is a relatively inefficient process. Energy is lost because moving parts in the engine create friction; because air and fuel must be pumped through the engine, causing aerodynamic and fluid drag losses; because much of the heat generated by combustion cannot be used for work and is wasted; and because slippage in the transmission causes losses. As discussed later, a conventional vehicle drivetrain generally will be able to transform about 14 (city) to 23 (highway) percent of the fuel energy into usable power at the wheels.[5]

In an attempt to reduce vehicle fuel consumption, vehicle designers can work to reduce all of the forces acting on the vehicle (the tractive forces), as well as the losses in turning fuel into motive power. Tractive forces may be reduced by smoothing out body surfaces to reduce aerodynamic drag, by redesigning tires to reduce their rolling resistance, or by making the vehicle lighter, through use of lighter materials and redesign of the vehicle structure and interior, to reduce inertia forces as well as to further reduce rolling resistance. Accessory losses may be reduced by improving the design of air conditioners, water and oil pumps, power steering, and other power equipment, or by reducing the work these accessories must do (for example, heating and cooling loads can be reduced by providing insulation and coating window surfaces with coatings that reflect unwanted solar radiation). Drivetrain losses may be reduced through various strategies--ranging from redesign of conventional engines and transmissions to shifting to alternative types of drivetrains that may offer increased efficiency.

Fuel consumption may also be reduced by sacrificing consumer amenities--reducing the size of the passenger compartment (and, consequently, the size and weight of the vehicle), using a less poweful engine that cannot provide the same acceleration (and that may cause greater noise and vibration), designing transmission shifts that achieve higher efficiency at the cost of more harshness, reducing the number of accessories such as air conditioning or power locks and windows, and so forth. Most modem attempts to reduce fuel consumption do not contemplate sacrificing these amenities,[6] but some types of vehicle redesigns may achieve higher efficiency only at the cost of such a sacrifice.[7] As discussed later, comparisons of vehicle fuel economy achievements should carefully consider of any differences in vehicle performance or amenities.

To obtain an idea of target areas for saving fuel the following are a few quantitative indicators for a typical mid-size car that gets 27.7 mpg on the EPA test cycle (22.7 mpg city; 38.0 mpg, highway):

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[5] Counting the energy not used for power during the time the vehicle is idling and braking.

[6] For example, the Partnership for a New Generation of Vehicles has as a key goal the development of an 80 mpg vehicle that essentially matches the performance of the current class of intermediate autos.

[7] With vehicles that rely on batteries or chemical fuels with low energy densities for energy storage, designers may have to sacrifice range to maintain efficiency.

- The engine efficiency--the fraction of fuel energy that emerges as shaft horsepower--is about 22 percent on the city part of the test and 27 percent on the highway, 24 percent composite. Strategies that increase engine efficiency, by changing the engine type, improving its design and components, or helping it to operate at its most efficient points attack the three quarters of fuel energy lost in the engines Raising engine efficiency from 24 to 25 percent would reduce fuel consumption by 4 percent.

- Of the energy that is converted by the engine to actual shaft horsepower:

  * 16 percent (city), 2 percent (highway), 11 percent (composite) is lost because it cannot be used when the vehicle is braking or idling. Systems that turn the engine off during braking and idle (engine off or electric drivetrains), or store the energy produced (hybrid systems can do this), can recover much of this 11 percent;

  * 10 percent (city), 7 percent (highway), 9 percent (composite) is lost by transmission inefficiencies. This is the target for improved transmissions or, for electric vehicles, avoiding the need for a transmission;

  * 11 percent (city), 7 percent (highway), 9 to 10 percent (composite) is used to power the accessories. Aside from conventional strategies to improve accessory efficiency or to reduce heating and cooling loads, electric vehicles have a different mix of accessories--some differences help (no oil pump), and some hurt (may need a heat pump to generate cabin heat);

  * 63 percent (city), 84 percent (highway), 71 percent (composite) is actually used to overcome the tractive forces on the vehicle.

- The three tractive forces play different roles at different speeds:

  * rolling resistance accounts for 28 percent of total tractive forces in the city, and 35 percent on the highway, 31 percent composite. Both improvement to tires and weight reduction work to reduce this large fiction of tractive forces;

  * aerodynamic drag accounts for 18 percent (city) and 50 percent (highway), 30 percent composite; and

  * inertia (weight) force accounts for 54 percent (city) and 14 percent (highway), 40 percent composite. Weight reduction directly attacks this force, or some of the energy used to overcome it can be recovered by regenerative braking.

BASELINE

The analytical model used to forecast baseline fuel economy is the Fuel Economy Model (FEM), used by the Department of Energy (DOE) Energy Information Administration as one of the submodels in the National Energy Modeling System (NEMS). The fuel economy is forecast as a function of input fuel prices, personal income and Corporate Average Fuel Economy (CAFE) standards, and its methodology is summarized in appendix A. The FEM incorporates both

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[8]Note that thermodynamic limitations prevent a substantial part of the energy loss from being "accessible" to saving.

technological and econometric models to estimate technological improvements by size class and performance and size class mix choices by consumers.

Under OTA's assumptions about future gasoline prices and economic growth--prices increasing to $1.55/gallon by 2015, from $1.15/gallon in 1994, in constant (1994) dollars[9] (growth rate of about 1.5 percent per year), personal income growing at 0.9 percent per year--the model projects a **fuel economy of 34.0 mpg for domestic cars and 24.9 mpg for domestic light trucks in 2015, which is a 24 percent increase relative to 1995.** These increases are expected to be attained even in the absence of new fuel economy standards or other measures aimed at increasing automotive efficiency. Details on the four vehicle classes are provided below.

In general, a number of new technologies are expected to be gradually introduced into the fleet during the 1995 to 2015 period, simply because the technologies are relatively cost-effective, and for competitive reasons. For example, high-strength, low-alloy steel optimized structures should be used widely by 2005, while plastic parts (mostly non-load bearing) will be widespread by 2015. Drag reduction to C_D levels of 0.28 will be commonplace for cars by 2015 and a significant fraction will be at C_D levels of 0.25. Four-valve engines will almost completely replace two-valve engines in cars by 2005, and in light trucks by 2015. Variable valve timing of both the "two stage" type and fully variable type will be widespread. Major technological changes to the four classes considered for 2005 and 2015 are summarized in table 4-1.

The general trends in technology adoption are quite similar across classes, although the compact van and pickup truck classes lag the two-car classes technologically. This is based on the historical fact that introduction of new technologies into the light-duty truck (LDT) fleet has typically lagged by five to seven years behind their introduction in Cars.[10] Table 4-2 has the fuel economy forecast for each class along with vehicle weight and horsepower. Fuel economy of the cars is expected to increase by about 24 percent between 1995 and 2015, while the light-truck fuel economy increase is a little less than 20 percent.

These overall fuel economy increases hide the fact that technologies contribute about 10 percent additional fuel economy that is lost to changes in other vehicle attributes. Safety standards and customers' choices of safety equipment such as antilock brakes and traction control will add 60 to 80 lbs per vehicle, affecting subcompacts disproportionately in weight. These safety improvements are expected to cause a 1.5 to 2 percent decrease in fuel economy. The forecast also assumes that federal Tier II standards will essentially equal low emission vehicle (LEV) standards and be in place by 2005. Unless there are significant improvements in technology, **LEV standards will cause about a 2 percent fuel economy penalty.** Consumer demand for size, luxury, and performance will increase both weight and horsepower of the vehicle. In the OTA baseline, **increases to body rigidity and size within each market class will contribute to a 6 percent increase in weight (over what it would be otherwise), and a 4 percent decrease in fuel economy.** Finally, the model predicts that, **if fuel prices rise as projected, performance increases will likely be restrained and lead to only a small 2 percent reduction in fuel economy.**

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[9] Based on U.S. Department of Energy, Energy Information Administration, *Annual Energy Outlook, 1994* (Washington, DC: February 1994), baseline case.

[10] Energy and Environmental Analysis, Inc., "The Fuel Economy Model: Documentation Report to EIA," October 1993.

The projections of fuel economy changes are quite sensitive to assumptions about future gasoline prices. **If fuel prices were twice the base-case levels, to $3.10 per gallon in 2015, fleet fuel economy climbs to 39.0 mpg for cars and 28.5 mpg for light trucks,** although one-third of the difference in fuel economy over the base case is attributable to changes in sales mix. In effect, of the 6 mpg difference for cars between the base case and the high fuel price scenario, about 2 mpg is attributable to consumers switching to smaller cars. The differences between the two scenarios are much smaller in 2005 owing to the reluctance of automakers to accelerate model life cycles (which would cut profits) and limits on the rate that new technology can be introduced.

Table 4-3 shows the approximate changes in drivetrain efficiency, weight, forces on the vehicle, and fuel economy of a "best-in-class" mid-size car in 2015. This car is projected to attain a 25 percent reduction in fuel consumption, or a 33 percent increase in fuel economy, which is about **9** percent better than the average increase for the fleet.

The changes relative to current 1995 cars and light trucks are easier to understand in a qualitative form. The vehicles in each size class will be somewhat roomier, and their bodies will be stronger and more rigid. Along with other safety improvements such as dual air bags, side impact restraints, roof crush strength improvements, antilock braking system, and traction control, these improvements imply that the vehicles will be much safer than today's vehicle, if driven in similar conditions. Engines will be much smaller in displacement (by 20 to 30 percent), and most of these cars will feature variable valve timing, although only about 35 to 40 percent of light trucks will have this technology. However, the smaller engines will produce nearly equal torque and 20 percent more power (at high rpm) relative to today's engines, so that maximum performance will be actually enhanced, with some loss in "elasticity," or the ability to accelerate without shifting gears. The use of five-speed automatic transmissions and even some continuously variable transmissions should, however, make the loss almost invisible to most drivers. In other words, **the 2015 cars will be better in most respects such as roominess, safety, performance, and fuel economy relative to current cars, and their emissions will meet the California-mandated LEV standards.** Hence, the cost increases need not be justified on the basis of fuel savings alone, but also on the basis of perceived and real quality improvements.

ADVANCED CONVENTIONAL VEHICLES

The baseline projection suggests that considerable technological improvements will occur in all cars even in the absence of any intervention in market forces. This section characterizes the maximum potential of conventional technology in 2005 and 2015, using the technology benefits described in the sections on individual technologies.

Attaining these high levels of technology would require some form of intervention in the market to become a reality. In this context, we have constructed two scenarios for each date, one using the mean or manufacturers' average estimate (designated as "m") of technology benefit, and the second using the most optimistic benefit estimates (designated "o") obtained from the auto manufacturers (virtually all of the data on conventional technologies was obtained from auto manufacturers).

Many of the available advanced technologies are relatively cost-effective, and design and technology changes to reduce aerodynamic drag, tire rolling resistance, engine friction, and transmission loss are expected to be adopted even in the baseline scenario, although the reductions are not as large as those postulated in this maximum scenario. Other technologies such as four-valves/cylinder, variable valve timing, advanced fuel injection, and variable-tuned intake manifolds are likely to be adopted for reasons of performance, drivability, and low emissions potential, although the market penetrations of these technologies are expected to grow slowly over the next two decades. This section examines the **fuel economy potential of a hypothetical "best-in-class" car, if all technologies that are fully developed and available for commercialization are adopted in such a way as to maximize fuel economy, while keeping interior volume and performance constant at 1995 levels.**

Because this analysis is not based on costs, cost-effectiveness, or on vehicle life-cycle considerations, the best-in-class vehicle in all four market classes uses the same set of technologies with only a few exceptions (as discussed below). Hence, focusing in on one market class and describing the changes in detail provides a comprehensive picture of the changes to all classes considered. The intermediate car class is selected for this description, and the most popular car in this class, the Ford Taurus, is the 1995 benchmark, or reference, vehicle. The current vehicle has an interior volume of 100 cu ft and trunk volume of 18 cu ft. It is powered by an overhead valve (OHV) two-valve V-6 that produces 140 horsepower, and has a peak torque of 165 ft. lb @ 3,250 rpm. It uses a four-speed automatic transmission with lockup torque converter, an axle ratio of 3.37, and a relatively steep overdrive ratio of 0.67. The Taurus weighs 3,130 lbs and is tested at 3,500-lb inertia weight. Its composite fuel economy is 28.0 mpg, which is 1.5 to 2 mpg higher than many other competitors in its class. Its performance is characterized by its O to 60 mph time of about 10.4 seconds (based on car enthusiast magazine tests). The Taurus has a remarkably high ratio of highway to city fuel economy of about 1.69, probably as a result of its low numerical overdrive ratio. This number is usually closer to 1.5 in most cars.

Table 4-4 traces the hypothetical evolution of a mid-size car equivalent to the Taurus under the two scenarios for 2005 and 2015. The greatest difference between the baseline and the advanced technology scenarios is in material substitution and the resultant weight. Four weight-reduction scenarios were considered for this analysis. The assumptions involved in each case are described in more detail in box 4-1, along with the approximate material compositions of the vehicles. [11] The 2005(m) vehicle is made of steel, but substantial weight has been removed by optimizing the design and using an aluminum engine. It weighs 15 percent less than the current Taurus. The 2005(0) vehicle uses considerable aluminum in the body as well, but the design does not take full advantage of aluminum's properties and achieves only a 20 percent weight reduction. For 2015, the (m) vehicle's aluminum body is optimized and attains a 30 percent weight savings, whereas the (o) vehicle has a carbon fiber composite structure yielding a 40 percent weight reduction from the current Taurus. The costs of these material changes range from modest ($200 to $400) for the steel redesign and aluminum engine to high ($2,000 to $8,000) for the carbon fiber Taurus.

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[11] Energy and Environmental Analysis, Inc., "Domestic Manufacturers Light Duty Truck Fuel Economy Potential to 2005," prepared for Martin Marietta Energy Systems, January 1994.

In other respects, the 2005 scenario projections are relatively mundane. In 2005, the 3.0L V-6 engine is expected to be replaced by a 2.3L, four-valve four-cylinder *engine* with variable valve timing,[12] and the four-speed automatic transmission will be replaced with a five-speed automatic. There are no differences in the assumptions on the types of drivetrain technologies for 2005 between the mean and optimistic scenarios, but the benefit for each technology is different, leading to different fuel economy estimates. In many respects, the 2005 hypothetical vehicle is not technologically very different from the baseline 2015 vehicle. The 2015 baseline vehicle, however, is expected to use a 2.5L V-6 and offer better performance and comfort than the 2005 hypothetical vehicle, which explains the difference in fuel economy.

For 2015, the mean scenario includes the weight projections discussed above, and includes the use of a direct injection stratified charge (DISC) engine with variable valve timing. This assumes of course, that lean nitrogen oxide (NO_x) catalyst technology is perfected to meet a NO_x standard of 0.2 g/mile. The reduced weight results in a small displacement engine, and the **resultant fuel economy estimate is 53.2 mpg.** It is also possible that the direct injection diesel can meet this stringent emission standard by 2015, and OTA has estimated its fuel economy at 59.0 mpg on diesel fuel The high efficiency of the DISC engine essentially narrows the difference between gasoline and diesel versions to almost identical levels on an energy content basis as diesel has about 12 percent more energy per gallon than gasoline. **The optimistic 2015 scenario forecasts a hypothetical vehicle with a carbon fiber body and a small displacement DISC engine, and is estimated to attain 63.5 mpg.**

Price differentials (over prices of the 1995 Taurus) of the vehicles are calculated using the methodologies described in appendix B, and are mid-range estimates. Uncertainties in incremental price are about ±10 percent for 2005 estimates and ±20 percent for the 2015 (m) estimates. The 2015(0) price estimates are extremely uncertain owing to the wide variations in potential future price estimates for carbon fiber based body construction. These estimates do not include the cost of emission control and safety related equipment (which do not vary across scenarios), with one exception. For the 2015 cases, the incremental cost of the lean-NO_x catalyst for the DISC and diesel *is* included, because the conventional engines in the baseline will not require such a catalyst.

Improvements to other market classes (subcompact, van, pickup) are quite similar to those for the hypothetical Taurus, allowing for some variation in baseline technology. For example, the absolute drag coefficients for the compact van and pickup truck are different from those for cars, but the percentage reductions relative to the base are quite similar. The only major exception to this similarity in technology improvements is for the pickup truck; owing to its greater weight, meeting a 0.2 g/mi NO_x standard is considered very difficult and, hence, the DISC is adopted only in the “optimistic” scenario for 2015.

While estimates of intermediate car fuel economy of 53 to 65.5 mpg in 2015 may seem remarkably high, there *currently* are some highly fiel-efficient cars that rival this type of performance. For example, VW **produces a 1.9L turbocharged direct injection (DI) diesel car**

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[12]Low speed performance is kept constant by controlling the variable: Torque x Axle Ratio / Weight to the baseline level, based on Torque at 2000 RPM, an engine speed typical of 30 mph in second gear or 45 mph in third gear. This leads to an axle ratio of 3.18, which would normally be very low for a 4-valve engine. However, in this ease. the VVT is optimized for low speed torque making the low axle ratio possible.

with a fuel efficiency of almost 55 mpg[13] **(European 1/3 mix cycle) on a car of weight similar to that estimated for the hypothetical Taurus in 2015.** If the DISC engine turns out to be as efficient as the DI diesel (as is widely expected), the estimates of 53.2 and 59.0 mpg seem quite reasonable and possibly conservative. Costs and fuel economy for all four classes of vehicles examined in all scenarios are shown in table 4-5.

An important point to note is that these hypothetical maximum scenarios hold size, performance, and (implicitly) vehicle features constant over time--that is, the 2005 and 2015 Taurus vehicles are identical in size, performance, and features to the 1995 Taurus. However, OTA expects size, performance, body rigidity, and other features to *increase* over time; consequently, except for their higher fuel economy, vehicles in these scenarios are less desirable than the ones in the baseline. Changing the attributes of body rigidity, size, and performance to levels equivalent to those defined under the "baseline" scenario will reduce fuel economy by 6 to 7 percent from the values shown in table 4-5. In other words, **the advanced 2015 Taurus would obtain a fuel economy of about 50 (DISC) to 55 (DI diesel) mpg, if its performance and other features matched the 2015 Taurus baseline.**

The emissions of these advanced technology vehicles are expected to meet California LEV levels. In 2005, the engine technology forecast is quite similar to the "baseline scenario" technology forecast for 2015, and smaller displacement engines with VVT on light-weight cars (relative to the baseline) actually have an advantage in meeting LEV standards. The 2015 scenario assumes that DISC engines and the diesel can meet LEV standards through the use of a lean NO_x catalyst. Because direct injection engines, both diesel and gasoline, have lower cold start and acceleration enrichment related emissions than conventional gasoline engines, their overall impact on in-use emissions is expected to be positive.

ELECTRIC VEHICLES

EVs substitute a battery (or other device capable of storing electricity in some form) and electric motor for the gas tank/ICE/transmission components of a conventional vehicle. As discussed earlier, the key drawback of EVs has been the inability of batteries to store sufficient energy to allow a large enough range capability.

Although batteries can store only a small fraction of the energy in the same weight and volume of gasoline, EVs may gain back some of this disadvantage because of several efficiency advantages. First, conventional ICE vehicles use about 10.8 percent of their fuel during braking and at idle when the engine contributes no useful work; electric motors need not work during EV braking and idling. Second, most of the accessories used in an ICE-powered car, such as the water pump, oil pump, cooling fan, and alternator can be eliminated if battery heat losses are not high, as motor and electronics cooling requirements do not require much power. In addition, the hydraulic power steering in a conventional vehicle *must* be replaced by electric power steering, which consumes only a fraction of the power of conventional systems.[14] The reduction in

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[13] See chapter 3 discussion of diesel engines.

[14] And consumes *no* power on an EPA dynamometer test where the steering is not used.

accessory use saves as much as 9.5 percent of fuel consumption on the EPA test cycle. (Real world fuel efficiency and range are considered following the discussion of the EV's efficiency on the EPA test) And although the EV may need some power for the brakes, this requirement is probably small owing to the use of regenerative braking, as described below.

Third, some of the energy lost during braking can be recovered by an EV, because the motor can act as a generator when it absorbs power from the wheels. The energy can be stored in the battery and later released to drive the motor. As noted earlier, the energy lost to the brakes in a conventional car is about 35 percent of total tractive energy. For various reasons--transmission and generator losses, battery charge/discharge loss, requirement for some conventional braking capacity--the actual energy recovery is considerably less than this.[15] Actual systems in the Toyota EV[16] and the Cocconi CRX,[17] which have the best regenerative braking efficiencies reported, provide range increases of about 17 to 18 percent maximum. An 8 to 10 percent range extension is more typical of current EVs, such as the BMW El.

Fourth, the motor is quite efficient in converting electrical energy to shaft energy, with cycle average efficiencies for good motors in the 75 to 80 percent range in the city cycle, as opposed to gasoline engines, which have an efficiency of only 20 to 23 percent on the fuel economy test cycle.

There are several factors working in the opposite direction. Losses from the primary energy source to energy delivered to the vehicle--critical for concerns about greenhouse gas production--generally are much higher for EVs than for gasoline vehicles, because electricity generation efficiency is quite often low (about 34 percent for a conventional coal-fired powerplant), and electricity generation may add another 10 percent in losses. Additional losses occur at the battery charger, in losses in discharging the battery, and in battery internal self discharge, wherein the battery (or flywheel, or ultracapacitor) gradually suffers losses over time. Another important factor is that EVs may be much heavier than an ICE-powered vehicle of similar performance (and have lower range[18]), because battery size is critical to range and power--the added weight then creates higher rolling resistance and higher inertia losses (of which only a portion are regained from the regenerative braking).

Considering the fill range of energy losses, an EV may well be less efficient on a primary energy basis than a conventional vehicle of equal size and acceleration performance, especially if

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[15]For the motor to convert braking energy to electricity, transmission loss and motor loss in generator mode must first be considered. Typically, transmissions for electric motors are simple drive gears, and can be 95 to 96 percent efficient. Motors operated in reverse generator mode typically have cycle average efficiency in the 80 to 84 percent range. Hence, only 78 percent of the braking energy can be converted to electricity, which is about 27.0 percent of traction energy. The storage and retrieval of electricity in a battery causes further loss, but this is very dependent on the battery type, and its efficiency in terms of absorbing power pulses. This efficiency is only 80 percent or lower for lead acid and nickel-cadmium batteries, so that regenerative braking recaptures only 0.82 x 0.95 x 0.80 x 0.35, or 21.8, percent of tractive energy. This assumes that all of the braking can be done regeneratively but this is not true in practice, since the motor is connected to only two wheels, leaving the other two wheels to be braked conventionally (proper handling during hard braking requires that all four wheels be braked for stability).

[16]K. Kanamaru, "Toyota EV-50: An Effort To Realize Practical EVs," paper presented at the 12th International Electric Vehicle Symposium December, 1994.

[17]A. Burke, Institute of Transportation Studies, University of California at Davis, "Dynamometer and Road Testing of Advanced E1ectric Vehicle," 1995.

[18]Matching the range of a similarly sized ICE vehicle may well be impossible for an EV, because the ability to increase battery size is limited by the effect of the added weight on motor and structural weight. Consequently, "fair" comparisons of EVs and ICE vehicles may try to match acceleration performance, especially at low speeds, but rarely try to match range.

the ICE vehicle is particularly fuel efficient. One such primary energy comparison between a BMW El and VW Polo diesel,[19] which are comparable in size, is shown in figure 4-1. In this comparison, the overall BMW El motor efficiency is very low, at 66 percent rather than 75 to 80 percent; if this were changed to 80 percent, then the EV would have the same primary energy efficiency as the diesel car.

The BMW comparison also shows some real world effects of energy loss owing to battery heating--the battery is a high-temperature Na-S battery--and includes accessory losses. Internal self discharge or battery heating losses reduce efficiency in inverse proportion to miles driven per day. Accessories such as the power steering and power brake consume a few hundred watts of power typically, but the air conditioner, heater, and window defrosters are major drains on power. Some EVs, such as the GM Impact, have replaced the conventional air-conditioner or heater with a heat pump which increases accessory load to 3 kW.[20] A typical advanced EV will consume about 12 to 15 kW at 60 mph (see table 4-6[21]), so that accessory load represents a substantial fraction of the total power demand of the vehicle. Thus, **with these accessories on, highway range can be reduced 20 to 25 percent; range in city driving can be reduced 50 percent.**

Cold or hot temperatures also impact the battery storage capacity, so that the range reductions owing to accessory power loss are only one part of the picture. In very cold weather, alkaline batteries and lead-acid batteries have significantly lower energy storage capacities, as discussed earlier. Peak power is also affected, so that both range and acceleration capability suffers. At 20°F, the effect of accessory loads is also very high, as it is not unusual to need headlights, wipers, defroster, and passenger heating in such situations. The combined effect of reduced battery capacity and higher loads can reduce the range in city driving by as much as 80 percent. In hot weather, the battery can be power limited owing to the difficulty of removing the heat created when high power is demanded from the battery, and internal self discharge of batteries can also be higher. Unfortunately, hard data on battery losses in hot weather is not available publicly.

The analysis of overall vehicle weight, and the tradeoffs among range, performance, and battery weight are especially important for an electric vehicle. Generally, adding more battery weight allows greater vehicle range and power. However, there is a limit to this relationship: as battery weight increases, structural weight must also increase to carry the loads, and a larger--and heavier--motor is required to maintain performance. This weight spiral effect leads to rapidly declining benefits to each additional battery weight increment, and finally to zero benefit.

It is possible to examine these tradeoffs by using energy balance equations similar to those used for ICE engines, coupled with some simplifying assumptions about motor output requirements for normal performance requirements (50 kW/ton of vehicle weight to allow normal levels of acceleration and hill climbing), and using a “best-in-class” specific traction energy measured in kilowatt hours per ton-kilometer (kWh/ton-km), that is, assuming the vehicle being analyzed attains the energy efficiency of the best available EVs with regenerative braking, which is about 0.1 kWh/ton-km.

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[19]K. Scheurer et al., "The Electric Car: An Attractive Concept for City Traffic," BMW Publications, 1993.

[20]K. Scheurer, "The BMW E-1, A Purpose Designed EV," paper presented at the 11th International EV Symposium, September 1992.

[21]At 60 mph or 97 km/hr, an average fuel consumption of 0.15 kWh/km implies a power use of 97* 0.15 = 14.6 kW.

Figure 4-2 shows the relationship between battery weight and range As range approaches six times the specific energy of the battery, battery weight gets impossibly large, because the added weight of the battery does not provide enough energy to increase range while maintaining performance.

What does this figure say about the relationship between battery weight and range for a particular vehicle? If an EV were made by using a 1995 Taurus as a "glider," with beefed-up structure and suspension if necessary, **obtaining a 90-mile range with an advanced semi-bipolar lead acid battery**[22] **would require 1,600 lbs of battery, and the total weight of the car would increase from the current 3,100 lbs to 5,240 lbs** (in reality, useful range would be only about 70 miles since lead acid batteries should be discharged only to 20 percent of capacity).[23] In contrast, a nickel-metal hydride (Ni-MH) battery, with an S_E of 72 Wh/kg, of the same weight will provide a range of more than 150 miles. **The weight of nickel-metal hydride battery to provide a 100-mile range is 957 pounds, while the car weight falls to 3,305 lbs, illustrating the importance** of weight compounding effects in an EV.

The second constraint on the battery size is that it must be large enough to provide the peak-power requirement of the motor, or else some peak-power device such as an ultracapacitor or flywheel may be necessary. Using the same assumptions as before (about vehicle power requirements and energy efficiency): to obtain a range of 100 miles, the specific power capability of the battery divided by its specific energy must be at least 3.125 hr^{-1}, or else the power requirement becomes the limiting factor on battery size. If the range requirement is doubled to 200 miles, then the minimum ratio declines to 1.56 hr^{-1}. For a 100-mile range, only the advanced semi-bipolar lead-acid battery meets this requirement, with an S_P/S_E ratios of almost 5, while the Ni-MH battery has a ratio of about 3. The existing "hot-battery" designs provide ratios of only 1.25, while more recent advanced designs provide ratios closer to 2. The important point of this discussion is that **doubling the specific energy (e.g., by substituting a battery with better energy storage capability) does not automatically lead to half the battery size, if the battery's power capability is inadequate to provide "average performance." Relaxing the performance requirement reduces the required ratio, illustrating that hot batteries with good specific energy but low specific power are best applied to commercial vehicles, where range is more important than performance. One alternative is to include peak-power devices such as ultracapacitors** with these batteries to provide adequate peak power.

In evaluating the characteristics of EVs in each of the four market classes, OTA made several assumptions about EV production. We assumed that each EV make/model could be manufactured on a "conversion" assembly line to produce 2,000 vehicles per month (24,000 per year), implying total EV sales (across all models and manufacturers) of at least several hundred thousand vehicles per year. This assumption is required to establish economies of scale, and the assumption that EVs will be based on "gliders" (conventional vehicles stripped of their drivetrain and modified as necessary) is required to establish that the vehicle body technology will be similar to the

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[22] Assumed specific energy, S_P, of 42 Wh/kg.

[23] When battery weight equals body weight on the graph, the value of R/S_E is 3.6. With an S_E of 3.6, the semi-bipolar battery will obtain a range of 150 km (42 x 3.6) or 90 miles when zero engine body weight (theoretical weight of the body with a weightless powertrain and secondary *weight* reductions accounted for) equals battery weight- For a current (1995) mid-size ear like the Taurus, the zero engine body weight is about 730 kg or 1600 lbs. Methodology to use these values is described in appendix A

technology of the baseline vehicles. Total investment in assembly line equipment, tooling, development, and launch is estimated at $60 million for this type of facility based on recent DOE studies[24] and is amortized over a four-year cycle. It should be noted, however, that total costs are dominated by battery costs, so that EV cost is not greatly affected by modest errors in the $60 million estimate.

GM and BMW, among others, have displayed purpose designed EVs, which are vehicles designed from the start to be electrically powered. It is unclear, however, how the design and engineering costs for such vehicles can ever be amortized over their likely low production rates, and GM officials have publicly stated that the $250 million invested in the Impact to date will never be recouped.[25] The advantage of purpose designed EVs is that design decisions about items such as lightweight materials would tend to be different depending on whether the end result was a gasoline-powered vehicle or an electrically powered one; EV designers would favor energy efficiency to a greater extent than gasoline vehicle designers. Building EVs from gliders based on OTA's advanced vehicle designs eliminates these differences, however, as these designs also are geared toward maximum energy efficiency.

Table 4-7 shows the battery and total vehicle weight, energy efficiency, and incremental price of several EVs in each market class in 2005. In each case, the level of body technology and tire technology is identical to the level used in the advanced conventional vehicle scenarios, and **prices are calculated as an increment over the advanced conventional vehicle in the same scenario, consistent with the "glider" approach to manufacturing** EVs. **Note that the vehicles' price increments over the business-as-usual vehicles (which may be the better comparison) would be higher than the values given in the table.**

In 2005, an EV powered by an advanced semi-bipolar lead-acid battery with an 80-mile range appears to be a viable though expensive prospect for the subcompact and intermediate car, but less viable for the compact van or a standard pickup truck. **The EV version of the intermediate car is about $11,000 more than the gasoline-powered car, which is consistent with the results of some other studies.[26] In going from gasoline to electricity, weight increases from less than 1,300 kg (2,860 lbs) to over 2,030 kg (4,400 lbs). An** EV pickup truck could weigh over 6,400 lbs, rendering it an unrealistic proposition. Very significant weight reductions would occur, if the battery used were a Ni-MH design and range restricted to about 100 miles. Incremental prices are almost twice that for the lead acid battery-powered EV if the Ni-MH battery costs the expected $400 per kilowatt hour.[27] However, if Ovonic's claims for the Ni-MH battery[28] prove correct, the EVs powered by the Ni-MH battery at $200/kWh would be lower in cost than those powered by the lead-acid battery (at $150/kWh) owing to the weight compounding effects, and the incremental vehicle price would be about $8,800.

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[24] Energy and Environmental Analysis, Inc., 'Characteristics of Alternative Fuel Vehicles: Imputs to the AFVTM," prepared for Martin Marietta, 1995.

[25] "Shocker at GM: People Like the Impact," ***Business Week,*** Jan. 23, 1995, p. 47.

[26] Sierra Research, "The Cost-Effectiveness of Further Regulating Mobile Source Emissions," prepared for the American Automobile Manufacturers Association, Febuary 1994.

[27] Although this is nearly three times the lead acid battery's cost, there are some cost savings in the vehicle structure and motor because of the Ni-MH battery's lighter weight.

[28] See the section on batteries in chapter 3.

Table 4-8 shows how the costs were calculated for the year 2005 mid-size EV. Battery and motor/controller costs are as specified in chapter 3, while incremental costs of electric power steering and heat pump air conditioner over conventional systems were derived from supplier quotes.[29] Those "costs" are the costs to an auto manufacturer buying the components at a sales volume of 20,000 to 25,000 per year for this model, but there is an implicit assumption that total battery and motor sales across all models is over 100,000 units per year. Costs of engine, transmission and emission control systems are based on earlier studies by Energy and Environmental Analysis, Inc. for DOE, adjusted for inflation. Analysis of fixed costs is based on the formula presented in appendix A. Note that learning curve effects are *included in* the costing of batteries, motors, and controllers, but there is no learning curve effect for assembly.

Computations **for a range of 200 miles were performed with the Ni-MH and sodium sulfur (Na-S) batteries; only the Na-S battery appears to be a realistic proposition from a weight standpoint. However, the Na-S battery-powered EV is estimated to cost from $27,000 to $54,000 more than an advanced conventional vehicle, depending** on vehicle type; the EV powered by Ni-MH would cost even more if the projected $400/kWh proves correct.

These prices could be lowered significantly, if the range and power criteria were relaxed. Using the same methodology as for the analysis above, **a lead acid battery-powered subcompact EV can be produced for an incremental price of about $3,000, if range is relaxed to 40 miles and power degraded to about 40 HP/ton.** Hence, many of the disagreements about future EV prices can be resolved on the basis of vehicle performance and range assumptions, or owing to the fact that some estimates cite "cost" instead of price. In fact, Renault and Peugeot have chosen the limited-range, low-performance EV to reduce incremental prices to about $3,000, consistent with this estimate. The Citroen AX EV, for example, has a range of about 45 to 50 miles and a top speed of about 55 mph, with poor acceleration.[30]

Table 4-9 shows the EV characteristics for 2015. As body weight is reduced with new materials technology, and modest battery improvements to increase specific energy are expected to occur by 2015, the weight compounding effects provide for more reasonable prices by 2015. Incremental price for an intermediate-sized lead acid-powered EV with a range of 80 miles and with reasonable performance is estimated at less than $3,200 over a similar conventional car with advanced technology, while a Ni-MH powered version could retail for $2,750 to $8,830[31] more and offer a range of 100 miles. In a more optimistic scenario, even a 200-mile range is possible with Ni-MH batteries at price differentials of about half the 2005 levels, while sodium sulphur batteries can also provide this range for about half of the 2005 price differential, although this is still expensive at nearly $18,000. If the lithium polymer batteries succeed in meeting U.S. Advanced Battery Consortium (USABC) expectations, however, an EV with a 300-mile range could become available at an incremental price of $10,400 for a mid-size car, even after accounting for the fact that these batteries are likely power limited and will need ultracapacitors to provide the peak power requirements for acceleration. These price estimates clearly explain the reason for the interest in the lithium polymer battery. To model the case where the battery is

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[29] Private communications with AC-Delco representatives.

[30] N. Bureau, "Electric Peugeot 106 and Citroen AX Vehicles in Customer Hands in La Rochelle," paper presented at the 12th EV Symposium, California, December 1994.

[31] The lower value corresponds to an assumed battery cost of $180/kWh, the upper value to assumed cost of $360/kWh.

power limited, we have sized the battery to be able to indefinitely sustain a 60 mph climb on a 6 percent grade, and provided for peak acceleration power capability to be sustained for two minutes.

All of these estimates are based on a set of assumed performance levels and OTA's best guesses about future battery costs and component efficiencies. Ongoing research programs, such as the USABC, have as their goals improving EV component costs and efficiencies to values below OTA's values, and success at achieving these clearly would impact EV price and performance. Moreover, some EV advocates have concluded that vehicle purchasers can be convinced to purchase vehicles with generally lower performance than current vehicles, in particular with lower range. To examine the implications of R&D success and shifts in vehicle purchasing behavior, we estimated the effects of battery cost reductions, performance reductions, range reductions, and component efficiency changes on the 2005 lead acid-battery-powered, intermediate-size EV. Range reductions have a very large effect on vehicle cost and battery requirements; reducing the range to 50 miles (real) reduces EV incremental price to $3,170 (from about $11,000), and reduces battery size to less than 40 percent the size required for a range of 80 miles. Reducing performance levels (with a range of 50 miles) provides only modest reductions in battery weight, but reducing motor and controller costs reduces incremental price to $2,130. If battery costs fall to $100 per kWh from $150, vehicle incremental price is reduced to $960, and including the maximum level of component efficiency of motor/controllers and drivetrain reduces vehicle incremental price to $410. Hence, **it is theoretically possible to build a reduced range EV for a very low incremental price in 2005, if the most optimistic assumptions were used in all facets of the analysis.** Even if range were kept at 80 miles, incremental price would be $4,125, if very optimistic assumptions regarding performance, component efficiency and battery cost were used. These findings are summarized in table 4-10, but it is emphasized that the base attributes represent what OTA believes to be the most likely outcome of current R&D trends.

OTA's analysis of EV performance and costs shows that the following four factors have significant influence on the analysis results.

- *Range.* Vehicle weight and costs increase nonlinearly with range increases.
- *Battery specifications. The* usable specific energy and power strongly affect battery size for a given range and performance level. Power requirements can set the minimum size for a battery in many applications.
- *Performance requirements.* Relaxing the continuous and peak performance requirement has only a small effect on battery and motor requirements, where batteries are sized for range, but can have a large effect, if batteries are power limited.
- *Component efficiency.* Assumptions regarding the overall efficiency of the drivetrain (including motors, power controllers, and gears) as well as the battery charge/discharge efficiency can affect the results, with very optimistic assessments reducing casts by as much as 30 percent over the median estimates.

In summary, the analysis finds that in 2005, mid-size EVs with a range of 80 to 100 miles and reasonable performance would be priced about $11,000 **more than an equivalent**

advanced conventional midsized car, assuming no subsidies. A reduced (50-mile) range EV can be offered for a price of only $3,000 more than an advanced conventional car. EVs with a range of 200 miles however, are expected to be too heavy and unrealistically expensive in 2005.

By 2015, incremental prices for an intermediate-size EV with a 100-mile range could come down to the $3,000 range. A 200-mile range intermediate-size EV would still probably be priced about $24,000 more than an equivalent conventional car, unless the lithium polymer cell battery becomes a reality. If this were the case, it is possible that an EV with a 300-mile range could be priced about $12,000 more than an equivalent intermediate car. ***Note, however, that these comparisons are to OTA's advanced conventional cars, which have costly body structures (especially the 2015 optimistic case, with a carbon fiber composite body).***

Public estimates of EV prices are often not well documented in terms of the assumptions regarding battery size, vehicle size, vehicle range, and performance, which are all *critical* to the value of price obtained. For example, a major study for the Northeast Alternative Vehicle Consortium [32] used cost numbers with no specific estimate of motor size and rating, and used a fixed battery capacity (21 kWh) regardless of vehicle weight. In addition, the methodology used to convert cost to price does not follow standard costing guidelines; for example, a fixed amount of the investment is amortized each *year* instead of being allocated to each *EV* produced, so that as production rises, unit costs fall. Other studies, such as one by the California Air Resources Board[33] ignores the difference between cost and price, which understates EV prices dramatically. **Many estimates of very low EV costs from environmental or conservation groups are, indeed, referring to manufacturer costs rather than vehicle prices, or do not control for range or performance.** It is **quite possible that, if these calculations were made more explicit in terms of assumed** EV size, range, and performance, and the methodology were corrected to transform cost to price, then much of the difference in price estimates could be easily explained.

Emission Effects

The key emissions advantage of EVs is that they have virtually no vehicular emissions[34] regardless of vehicle condition or age--they will never create the problems of older or malfunctioning "superemitters," which are now a significant concern of the current fleet. Because EVs are recharged with power-plant-generated electricity, however, EV emissions performance should be viewed from the standpoint of the entire fuel cycle, not just the vehicle. From this standpoint, EVs have a strong advantage over conventional vehicles in emissions of hydrocarbons (HC) and carbon monoxide (CO), because power generation produces little of these pollutants. Where power generation is largely coal-based--as it is in most areas of the country--some net increases in sulfur dioxide might occur. However, Clean Air Act rules "cap" national powerplant

[32]International Environment and Resource Program, "Near Term EV Costs," prepared for Northeast Alternative Vehicle Consortium October 1994.

[33]Air Resources Board, "Technical Support Document: Zero Emission Vehicle Update," April 1994.

[34]EVs with unsealed batteries will sometimes generate emission from deteriorating anodes and cathodes and vaporizing electrolyte.

emissions of sulfur oxides (SO_x) at 10 million tons per year--limiting the potential adverse effects of any large scale increase in power generation associated with EVs.

Any net advantage (or disadvantage) in NO_x and particulate emissions of EVs over conventional vehicles is dependent on several factors. All fossil and biomass-fueled power generation facilities are significant emitters of NO_x, and most are significant emitters of particulate, although there are wide variations depending on fuel generation technology, and emission controls. Analyses of the impact of EVs on NO_x and particulate emissions are extremely sensitive to different assumptions about which powerplants will be used to recharge the vehicles, as well as assumptions about the energy efficiency of the EVs and competing gasoline vehicles[35] and the likely on-road emissions of the gasoline vehicles.

Aside from the magnitude of emissions, location plays an important role in impacts--although some forms of pollution tend to travel long distances, generally pollution emitted close to population centers will have a greater impact on human health than does pollution emitted far away. Most electric power plants are located out of major urban areas, while most gasoline vehicles are operated within urban areas. Because of this, use of EVs generally sharply reduces emissions of NO_x, SO_x, and particulate as well as HC and CO in urban areas. The increases in SO_x and particulate *emissions* by use of EVs occur primarily out of urban areas. The increases in SO_x, NO_x, and particulate emissions in remote areas may cause less damage to human health, since human exposure to air pollution is low in remote areas; however, long range transport of fine particulate, including sulfates formed from SO_x emissions, is widely recognized as a major health concern, so a fair risk assessment should include a careful examination of pollution transport issues.

As noted, EV emission reductions are affected significantly by several important factors. First, electric generation mix is a dominant factor. In regions where clean fuels or renewable fuels are used for electricity generation (such as hydropower and natural gas), EVs are expected to achieve large emission reductions. In regions where less benign fuels such as coal are used, use of EVs achieves lower emission reductions. For example, nationwide, 51 percent of electricity is generated from coal, 13 percent from natural gas, 18 percent from nuclear, 3 percent from oil, and 11 percent from hydropower and other renewables.[36] In California, about 36 percent of electricity is generated from natural gas, 5 percent from oil, 47 percent from nuclear and hydropower, and only 12 percent from coal.[37] Because of the difference in generation mix between the United States and California, EV emission reduction benefits in California are much greater than in the United States as a whole.

Even where alternative studies are examining the same region, there may be sharp differences in the power mix assumed because the mix of generating plants likely to be used to add power when EVs need recharging may be quite different from the area's overall mix. The area's mix reflects primarily the power generated during the daytime, when power demands peak; the EV mix

[35] It is not uncommon for analysts to compare small, low-powered limited range EVs to large full-powered gasoline vehicles, clearly to the EVs' advantage.

[36] Energy Information Administration, ***Annual Energy Outlook, 1995,*** DOE/EIA-0383(95) (Washington DC: January 1995), table A8.

[37] California Energy Commission data, supplemented by other sources.

reflects those plants that will be dispatched during the night over and above the normal nighttime baseload.

Second, EV per-mile electricity consumption is important in determining per-mile EV emissions and net emissions reductions. Although existing EV technologies have relatively high per-mile electricity consumption and fuel-cycle emissions, future, more efficient, EV technologies may well lead to substantial reductions in EV electricity consumption and corresponding improvements in the emissions "balance" between EVs and competing gasoline vehicles.[38]

Third, the level of emission control in power plants is a key determinant of EV fuel-cycle emissions. Eventually, old power plants with fewer controls will be retired, and new plants that are subject to stringent emission requirements will come into service with low emissions. Thus, future EVs will automatically have lower fuel-cycle emissions.

Finally, the estimates of gasoline vehicle (GV) emissions are critical. Most past studies of EV emissions impacts used either emission standards or computer model-estimated emissions to represent GV emissions. It is well known now that emission standards and most previous estimates of on-road emissions are substantially lower than actual on-road emissions. Use of low baseline GV emissions will cause underestimation of EV emission reductions. OTA used an existing computer model--EPA's Mobile5--to project gasoline emissions, and our estimated gasoline vehicle emissions are likely to be somewhat low. Another problem with some past studies was the use of gasoline vehicles for comparison that were relatively inefficient, and thus had correspondingly high-fuel-cycle emissions. This analysis compares EVs with gasoline vehicles that are identical to the EVs except for their powertrain and energy storage, that is, EVs with aluminum bodies are compared with gasoline vehicles with aluminum bodies.

Using a fuel-cycle model developed for the project,[39] OTA evaluated and compared the fuel cycle emissions of EVs and the corresponding advanced conventional vehicles sharing the same efficiency characteristics (except powertrain). In calculating GV emissions, the federal Tier 2 standards are assumed to be implemented. For EVs a national electric generation mix is used, assuming most recharge will occur at night and use surplus off-peak (baseload or intermediate) power.[40] The use of the national mix here certainly underestimates EV emission benefits in areas like California that have relatively clean power.

The 80 to 100-mile range 2005 MY EV technologies, using lead acid and Ni-MH battery technology, almost eliminate emissions of HC and CO, and achieve 50 percent to 70 percent reductions in emissions of very fine particulate, PM10.[41] These high PM10 emission reductions, which are different from the results in many previous studies, are owing to the very high GV fuel

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[38] Battery research is aiming to improve substantially the charge/recharge efficiency and specific energy (energy storage per unit of weight) of EV batteries both of which will have a great impact on EV energy requirements and emissions (better energy storage will yield a lighter, more efficient vehicle if range is unchanged).

[39] M.Q. Wang, Argonne National Laboratory, "Fuel-Cycle Energy Requirements and Emissions of Advanced Automotive Technologies," draft prepared for the Office of Technology Assessment, July 5, 1995.

[40] Assumed generation mix: coal, 50 percent; natural gas, 30 percent; nuclear, 10 percent; oil, 5 percent; and hydropower, 5 percent. This mix reflects the assumption that much nuclear and hydropower generation capability is already fully subscribed and will not be available for dispatch to recharge EVs

[41] PM10 refers to particulate matter below 10 microns in diameter, that is, fine particulates.

cycle PM10 emissions estimated in this study.[42] The EVs cause 200-400 percent *increases* in per-mile SO_x emissions. Also, the lead acid EV causes an increase in NO_x of nearly 90 percent, with the Ni-MH EV causing a small increase.

The 2015 EV results are somewhat better. Again, both the lead acid and Ni-MH almost eliminate emissions of HC and CO, and they achieve a 60 percent to 70 percent reduction in PM10 emissions. SO_x emissions still increase, as they must considering the high forecasted coal use in power generation, but the increases are basically cut in half from the 2005 results. The changes in NO_x emissions vary substantially with the battery technologies, with Ni-MH achieving nearly a 30 percent reduction, while the Pb-acid still causes NO_x emissions to increase, by 20 percent.

These results are generally in line with the results of other studies except for the NO_x results. Past studies often have projected a more uniform reduction in NO_x emissions from the use of EVs,[43] though this is by no means universal. OTA's projections for gasoline vehicles' NO_x emissions may be optimistic, however. Unless there are strong improvements in inspection and maintenance programs, and excellent success for projected changes in EPA's certification testing program (designed to reduce emissions during vehicle acceleration and other high-load conditions), gasoline vehicles may have substantially higher on-road emissions than projected in this analysis--especially as they age. Given the virtual certainty of obtaining low EV fuel cycle emissions, these results indicate that EVs generally will yield significant emissions benefits on a "per-vehicle" basis.

HYBRID VEHICLES

As noted in the introduction to this section, hybrid vehicles combine two energy sources with an electric drivetrain, with one or both sources providing electric power to the motor. This section examines hybrids that incorporate an internal combustion engine as one of the energy sources, with batteries, flywheels, or ultracapacitors also providing electric energy to the motor. Moreover, although gas turbines can be used in a hybrid, turbines of the size optimal for 1ight-duty vehicles are unlikely to be more efficient than piston engines of the same performance capacity; consequently, only piston engines are considered in this section. Other combinations of energy sources, such as a fuel cell and a battery, can also be used in a hybrid, however.

The conceptual advantage of a hybrid is that it gains the range provided by an engine using a high-density fuel, but avoids the energy losses associated with forcing the engine to operate at speed/load combinations that degrade its efficiency. In other words, the engine can run at nearly constant output, near its optimum operating point, with the other energy source providing much of the load-following capability that undermines the engine's efficiency in a conventional vehicle.

The term hybrid is applied to a wide variety of designs with different conceptual strategies on the use and size of the two drivetrains. One form of classification for hybrids is a division into so-

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[42] Based on estimates that refineries producing the gasoline fuel have relatively high emissions of PM10.
[43] Wang, see footnote 39.

called series and parallel hybrids. In a *series hybrid,* the power generated by the ICE is always converted to electricity, and either stored (in a battery, flywheel, or ultracapacitor) or used directly to drive a motor, which is connected to the vehicle's wheels. In a *parallel hybrid,* the engine or the motor, or both, can drive the wheels directly. The two design types are shown schematically in figure 4-3. Although both systems have advantages and disadvantages, most manufacturers who have displayed prototype hybrid vehicles have selected the series design. The exception is VW, and its engineers believe that series designs are being displayed largely because they are very easy to develop, but are inefficient for reasons explained later. Another classification method is according to whether the vehicles require externally supplied electrical power (as an EV does), or can operate solely on gasoline, and these are labeled as *nonautonomous* and ***autonomous*** hybrids, respectively..

For either the series or parallel type hybrid, the ICE and the electrical system can be of widely different sizes. In both hybrid types, one extreme would be to have the engine act as a "range extender" by charging the battery (or other electricity storage device) while the electric drivetrain is quite similar in size to that of a pure EV. With this type of setup, sizing the engine's maximum output close to the vehicle's average power demand during highway cruise (e.g., 15 to 20 kW/ton of vehicle weight) would allow the range of the vehicle to be similar to that of a conventional car. Moreover, unless there were an abnormally long hill climb, the battery state of charge could be maintained at near constant level. At the other end of the spectrum, an engine could be large in size and the battery or power storage device made relatively small, so that the engine could be employed to provide peak power for acceleration and battery recharging capability. Obviously, there are infinite combinations in between the two extremes. The amount of energy stored in the battery or other storage device, as well as the device's peak-power capability, are key determinants of how the engine and storage device will interactively supply power to the drivetrain under any arbitrary driving cycle. Autonomous hybrids of either the parallel or series type usually utilize larger engines than nonautonomous ones.

The hybrid vehicle concept is neither new nor revolutionary. The earliest hybrids were built in 1917, and DOE funded a large research program in the late-1970s and early 1980s. Many of the same arguments and analyses in vogue now in support of hybrid powertrains were voiced after the two oil crises of the 1970s.[44] The Jet Propulsion Laboratory and General Electric developed studies, published in 1980, that estimated that a mid-sized car could attain 33 mpg on the city cycle, which was about 40 to 50 percent better than vehicles of that era. A prototype in the early 1980s demonstrated about 50 percent improvement in fuel economy relative to a early-1980s conventional vehicle of the same size, though it had lower performance.[45]

More recently, several papers[46] have claimed that hybrid vehicles using lightweight body construction, can provide a fuel economy increase of about 100 percent, while one paper claims an improvement potential of several hundred to several thousand percent for a hybrid configuration with a carbon fiber body, superb aerodynamics, and improved tires.[47] Moreover, PNGV contractors have discussed charts where some form of hybrid powertrain (undefined) was

[44] General Electric, "New Term Hybrid Vehicle Program," report No. SRD-79-134, 1979.
[45] General Electric, "Hybrid Vehicle Program: Final Report," report No. SRD-83-031, November, 1993.
[46] E.g., A. F. Burke, "Hybrid Vehicles," ***Encyclopedia of Energy and Technology*** (New York, NY: John Wiley, 1995) pp. 1709-1723.
[47] A.B. Lovins et a1., "Supercars: The Coming Light Vehicle Revolution," ECEEE Conference Proceedings, June 1993.

by itself (that is, without changes in body construction, aerodynamics, and tires) to provide a 100 percent benefit in fuel economy,[48] and this value currently is the target for the DOE hybrid program. DOE has also sponsored several college-level competitions, called the Hybrid Vehicle Challenge, where colleges have displayed hybrid vehicles of both the series and parallel type that have attained relatively high fuel economy levels. For example, the 1994 entries from University of California at Davis and the University of Maryland have claimed fuel economy levels of 75 to 80 mpg at constant speed (-40 to 50 mph) in small or compact cars.[49] Given these demonstrations and programs, **there is a widespread belief among many observers that hybrid powertrains can easily achieve 100 percent improvements in fuel economy, and that even higher benefits are possible in the future. An added attraction is that hybrids can potentially act as limited-range electric vehicles, and thus can be zero emission vehicles in select urban areas.**

This positive view of hybrids is by no means unanimous. On the other side of the argument, several auto manufacturers and EV manufacturers have told OTA that hybrid drivetrains produce small or no benefits to fuel economy .50 Several series hybrids displayed by BMW,[51] Mercedes, and Nissan,[52] for example, have displayed virtually no benefit in fuel economy relative to gasoline engine-powered vehicles of similar performance. VW has developed parallel hybrids using a diesel engine and a small electric motor that have displayed good diesel fuel efficiency but high electricity consumption. The VW Golf hybrid requires that batteries be charged from the grid, and they are not charged by the engine. In the Federal Test Procedure, this hybrid attained 80 mpg of diesel fuel but also consumed 0.122 kW/km (about 0.20 kW/mi) of electrical energy .53 This electric energy consumption is similar to that of a comparable EV.

Series Hybrids

In a series hybrid, the engine is used only to drive a generator, while the wheels are powered exclusively by an electric motor. A battery (or flywheel or ultracapacitor) is used to store energy, obtaining some energy input from regenerative braking, and most of the input from the engine/generator. The motor can be powered either directly by the engine/generator, by the battery, or by both simultaneously (at high-power demand). Strategy considerations about when to use the battery or the motor/generator lead to decisions about the relative power output of each unit and the energy storage capacity of the battery.

The popular vision of a series hybrid has a small engine operating at constant output, providing the average power needed over the driving cycle, with a battery, flywheel, or ultracapacitor providing additional power when needed, such as for acceleration *or* hill-climbing. When the

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[48]P.G. Patil, "Partnership for a New Generation of Vehicles," Automotive Technology Development Contractors Coordination Meeting, U.S. Department of Energy, October 1994.

[49]S.A. Merit and K. Wipke, "The 1994 Hybrid Electric Vehicle Challenge," Automotive Technology Development Contractors Coordination Meeting, U.S. Department of Energy, October 1994.

[50]Office of Technology Assessment project team meetings with automobile manufacturers in Europe and Japan, May/June 1994.

[51]S. Friedman and K. Scheurer, "On The Way to Clean(er) Vehicles," SAE paper 94C052, 1994.

[52]Nissan, personal communications June 16, 1994.

[53]W. Josefowitz and S. Kohle, "The Volkswagen Golf Hybrid," paper prepared for the 1lth International EV Symposium, September 1992.

vehicle's power needs are below the engine output, the excess energy goes to recharge the storage device.

A careful examination of the vehicle's energy requirements and the characteristics of the available power sources is necessary to show whether the popular vision will work in practice. First, examining an engine's power characteristics does make it clear that the engine should be used to provide the total energy for driving, while the battery or other storage device should be sized to provide peak power. Although an ICE does have high specific power (power output per kilogram of engine weight) under normal operation, keeping the engine at its peak efficiency point sharply limits specific power. That is, a typical engine operating at its best efficiency point produces only about 40 percent of its peak output.[54] Such an engine, combined with a generator, radiator, and other engine components, would weigh 7.5 to 8.5 kg/kW and have specific power about 117 to 130 W/kg.[55] In contrast, advanced lead acid batteries of the semi-bipolar or bipolar type provide specific power of over 300 W/kg for a 30-second rating, while ultracapacitors and flywheels can provide 2,000 W/kg or more. That is, the storage devices can have higher specific power than the engine itself.

Second, the storage mechanisms are limited in the amount of power they can provide, which has important implications for engine sizing and operations. The battery, for example, is capable of providing peak power in short bursts only, because of heat removal requirements. Ultracapacitors are limited by their low specific energy; they would have to be very large to provide high power for a long period. Consequently, while the storage devices can be used to satisfy high-power requirements that last a short period, **the engine itself must be sized large enough to take care of any high-power requirements that may be of long duration. Consistent with the analysis for** EVs OTA has imposed the requirement that the vehicle be capable of sustaining a long climb of a 6 percent grade at 60 mph.[56]

Sizing the hybrid's engine in this manner--to provide enough power to climb a long hill--implies that the engine, when operating at its most efficient speed, is providing a higher average power output than needed for most driving. This means that much of the time the engine is operating, it will be charging the battery or other storage device. When the storage device becomes fully charged, the engine must be turned off and the vehicle operated in the following manner:

- As long as power demands are moderate, the vehicle operates as an EV, until the storage is drawn down far enough to allow the engine to be turned on again. Depending on the energy storage capacity of the buffer, then, the engine might be turned off and on several times (for low-energy storage, such as with an ultracapacitor) or possibly just once during an average drive (with battery storage). The engine must be turned on well before the buffer is drained of its energy, however, because the buffer must still be available to provide a power boost, if needed.

- During the period when the engine is turned off, it will have to be restarted, if there is a demand for power that exceeds the capacity of the buffer. In a hilly area, the engine may need to be restarted often.

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[54] The peak efficiency point occurs at 40 to 45 percent of peak rpm and 70 to 80 percent of maximum torque.
[55] Assuming the engine weighs about 2 kg/kW of peak output, or 2.2 to 2.6 kg/kW including radiator, exhaust system, and catalyst.
[56] This requirement is a placeholder for a number of long-duration, high-power requirements such as trailer towing or long-duration climbs at lower grades but higher payloads.

This operating mode is far more complex than implied by most discussions of series hybrids, which often give the impression that the engine runs at one speed during the entire trip, with the buffer providing occasional bursts of power on demand. Moreover, the need to turn the engine on and off may have important implications for pollution control.

The imposition of a 6 percent grade-climbing ability at 60 mph, when coupled with the requirement that the engine run at constant output, has a startling impact on engine size and vehicle design. This grade-climbing capability requires about 30 kw/ton of vehicle and payload weight. Because attaining a desirable O to 60 mph acceleration time of about 12 seconds requires about 50 kW/ton of vehicle and payload (for a vehicle with an electric drivetrain), the batteries (or other storage devices) must supply (50-30) kW/ton for peak accelerations. Given these specifications, a mid-size Taurus hybrid would have the following characteristics:

- Vehicle curb weight: 1843 kg
- Engine output (nominal): 61.3 kw
- Battery peak output: 40.9 kw
- Battery weight: 136.2 kg
- Battery type: semi-bipolar lead acid, 300 W/kg.

The engine must be a 3.3L four-valve engine rated at 155 kw at its normal peak. **The amazing result is that the engine must actually be substantially more powerful than that of the current Taurus.** The reason, of course, is that the engine of the current Taurus already operates near the maximum efficiency point at a 6 percent grade climb at 60 mph. Hence, if the engine of the hybrid electric vehicle (HEV) is sized in the same proportion, it must be larger to provide the increased power to overcome the weight associated with the motor, battery, electrical system, and generator, which adds 800 lbs to the weight--and the larger engine also adds to the vehicle's weight. **The result is that the Taurus hybrid weighs over** 900 **pounds more than the current Taurus.**

This is only one of the unattractive aspects of limiting engine operation to only one output level. Another problem is that on the FTP city cycle, the engine operates for a very brief duration. The 23-minute cycle requires about 2.3 kWh of energy at the motor to cover the cycle, which means that the engine needs to run about 1.1 minutes,[57] and be shut off the rest of the time. Hence, cold-start fuel consumption will add a significant penalty to total fuel consumption. Interestingly, because the battery is capable of storing 5.7 kwh, the vehicle could be run as an EV over the entire FTP cycle, if it started with the battery fully charged--though its performance would be quite limited.

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[57] Time of running = energy required/power output of the engine = 2.3 kWh/61.3kW * 0.8 percent (where 61.3 * 0.8 is the electrical output of the engine in kW stored in the battery) * 6O minutes/hour.

The above analysis clearly indicates that **restricting the engine in a series hybrid to operating only at its most efficient point is not a practical strategy; the theoretical advantage in efficiency is overwhelmed by both the requirement for a very large engine and the energy and emissions penalties from turning the engine on and off during operation. A more practical alternative is to use a smaller engine running at its most efficient point** *most of the time*, with short-term high-power needs met by the battery (or other storage device) and longer-term power needs, such as hill climbing, met by allowing the engine to increase its output. In other words, if high-peak loads persist for over 20 or 30 seconds, the control logic can allow the engine to provide more power rapidly (albeit with lower efficiency) so that the batteries are not taxed too heavily. To avoid too large an efficiency loss, the engine can be constrained to stay within 10 percent of the maximum efficiency--a constraint that still allows a substantial increase in available power. The only disadvantage of this strategy is that the battery must be somewhat bigger, to provide maximum peak short-term power with the engine operating at lower power than the previous, larger engine. Even this has some benefits, however, because the larger storage capacity of the battery reduces the need to turn the engine on and off, thus reducing the adverse emission consequences.

For the same Taurus example, we have the following HEV specification:[58]

• Vehicle curb weight	1385 kg
• Engine peak output	44.7 kW
• Continuous output	19.0 kW
• Engine plus generator weight	167 kg
• Battery	
peak output	59.1 kW
energy stored	8.3 kWh
weight	197 kg
type	**Semi-bipolar lead acid**
• Motor	
output	79.3 kW
weight	**80 kg**

In other words, **the hybrid with a relaxed engine-operating strategy appears much more reasonable.** Its **engine is now quite small, with a 44.7** kW peak **rating and displacement of 1.0 litres, and total vehicle weight** very similar to the current Taurus. **On the urban cycle, the engine** would be *on* **28 percent of the time, and shut off during the rest of the cycle. On the highway** cycle, the engine is on for 62 percent of the time, and the engine would be operating continuously at 70 mph cruise on level ground. This is favorable for fuel efficiency because the engine would be operating at its near optimal point, and energy can flow directly from generator to motor without going through the battery.

The effects on fuel consumption can be estimated with reasonable accuracy using the methodology presented in appendix A. The major assumption here is that the engine can be operated at close to optimal efficiency, or else be turned off. The computation, described in box

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[58]Assumptions: engine weighs 2.3 kg/kW, generator weighs 1.0 kg/kW, peak specific power of the engine/generator combination is 284 W/kg.

4-2 and table 4-11, shows that urban fuel economy for the HEV "Taurus" is 32.7 mpg, highway fuel economy is 41.2 mpg, and composite fuel economy is 36.1 mpg, which is about 30 percent better than the current Taurus. Most of the **improvement is in the urban cycle, with only a small (8.4 percent) percentage improvement on the highway cycle--not a surprising result because engine efficiency is quite high at highway speeds.**

The 30 percent improvement is an *optimistic value* for current technology, since the efficiencies of every one of the components have been selected to be at 2005 expected values, which are higher than the actual observed range for 1995. It also assumes the availability of a semi-bipolar battery that can produce high-peak power for acceleration. In the absence of such high-peak power capability, fuel economy drops precipitously. **If a normal lead acid battery with a peak-power capability of 125 W/kg is used, composite fuel economy is only 24.5 mpg, which is almost 12 percent lower than the conventional Taurus.** These findings are in good agreement with the observed fuel efficiency of some HEVs with conventional lead-acid batteries. As noted, both Nissan and BMW reported lower fuel economy for their series hybrid vehicles, which used nickel-cadmium batteries with specific peak power of 125 to 150 W/kg.[59]

Table 4-12 presents detailed assumptions and results for analyses of several series hybrid vehicles that might be ready for introduction by the years 2005 and 2015. For these vehicles, ICES were combined with bipolar lead acid batteries, ultracapacitors, or flywheels using the same flexible operating regime evaluated above. The main focus of the results should be on the last five rows in the table, which lists urban, highway, and composite fuel economy, range as a pure EV with the engine off, and the amount of time the storage mechanism can put out maximum power if it begins with a full charge.

In **2005, improvements to engine peak efficiency, higher battery peak-power, and body-weight reductions are expected to provide significant improvements to the fuel efficiency of an HEV with battery storage (using a bipolar lead acid battery); fuel economy increases to 48.5 mpg.** This however, is only a 25 *percent* improvement in fuel economy over the 2005(m) scenario vehicle using the same body, aerodynamic, and rolling resistance improvements. The reduction in fuel economy benefit relative to the advanced conventional car--the benefit in 1995 was 30 percent--occurs primarily because engine technologies such as variable valve timing (VVT) and lean-bum help part-load fuel efficiency *more* than peak efficiency. Hence, a crucial advantage of the series hybrid--maintaining engine efficiency close to the highest point--is steadily eroded as part-load efficiencies of the IC engine are improved in the future.

Several of the HEVs evaluated in table 4-12 can, if necessary, operate for a while as an EV, though with reduced performance and limited range. With a bipolar lead acid battery, for example, the 2005 series hybrid has a range of about 28 miles maximum, or 22 miles realistically. The use of an ultracapacitor, if it is sized only to provide peak power requirements for acceleration, reduces the range to less than one mile, owing to the ultracapacitor's high power-to-energy ratio. In fact, if sized this way, the ultracapacitor stores only 0.1 kWh, so that it can deliver the required peak acceleration power of 40 kw for only eight seconds, which clearly is impractical. In OTA's

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[59]S. Friedman and K. Scheurer, "On The Way to Clean(er) Vehicles," SAE paper 94C052, 1994; and Nissan, personal communication with Energy and Environmental Analysis, Inc., June 16, 1994.

analysis, the ultracapacitor size is tripled from the size needed for power. The result--peak acceleration capability of 24 seconds and EV range of 2.4 miles--still seems inadequate, however, because the ultracapacitor will not be able to support long, repeated accelerations, which maybe necessary on the highway, and *on* most trips the engine would have to be shut down and restarted several times, which may adversely affect emissions.

If flywheel storage becomes commercially practical by 2005, the composite fuel economy of an ICE/flywheel hybrid will be similar to that of the ultracapacitor-based hybrid--about 60 mpg. With the flywheel sized to provide the necessary 40 kW of peak power, it can provide this power level for about 54 seconds or allow travel in an EV mode for about five miles. The peaking capability may be on the margin of acceptability, though it is doubtful whether there will be enough power for rapidly repeated accelerations. In OTA's analysis, the flywheel size is doubled from the size required just to meet peak power requirements.

By 2015, the use of a lightweight aluminum body with low drag and low rolling resistance tires, and the use of a high-efficiency engine permits the HEV with a bipolar battery to be 280 lbs lighter than the advanced conventional vehicle, although the engine must be a 0.7 litre, two-cylinder engine with the attendant noise and vibration problems of such engines. The advanced bipolar lead acid battery, rated at 500 W/kg of specific power, weighs only 82 kg. Even so, **the fuel efficiency of the vehicle at 65.3 mpg is less than 23 percent better than the equivalent 2015 advanced vehicle with a conventional drivetrain. The ultracapacitor and flywheel-equipped vehicles are estimated to be even lighter and more fuel efficient at 71 to 73 mpg, but the problems of energy storage still persist. Assuming that the ultracapacitor meets the** DOE long-term goal of a specific energy storage capacity of 15 Wh/kg, it can still provide peak power for only about 25 seconds starting from a fully charged condition, if sized for peak power. Similarly, a flywheel sized for peak power can provide this peak power for only 65 seconds. Such low values makes it impossible for a vehicle to have repeatable acceleration characteristics, if they are subjected to two or three hard accelerations in the duration of a few minutes. As done in OTA's analysis for 2005, the flywheel capacity is doubled and the ultracapacitor size is tripled to provide sufficient energy storage, with resulting cost and weight penalties. **At their expected levels of energy storage, ultracapacitor's would have to be substantially oversized (with respect to their power capability) to be used with an HEV, as even a tripling of ultracapacitor size provides peak power for only about one minute from a fully charged state.** ***At this time, a high peak-power lead-acid battery appears to be a better storage technology for a series HEV than an ultracapacitor or flywheel, although the battery will be less efficient*** **If developers can substantially increase the specific energy storage capability of ultracapacitors and flywheels, however, they will become far more practical as hybrid vehicle energy storage devices.**

The estimated fuel economies attained by the hybrids are sensitive to the assumptions about the efficiency of the electric drivetrain components. Although the component efficiencies assumed in the above analysis are superior to the best current values, the PNGV is aiming at still higher efficiencies. A sensitivity analysis of the results displayed in table 4-12 indicates that improving motor/generator efficiencies by increments of 2 percent will boost fuel economy by a similar percentage. For example, for the 2015 lead acid hybrid, a 2 percent boost in engine efficiency raises vehicle fuel economy from 65.3 to 66.9 mpg; an additional 2 percent boost raises it to 68.5

mpg. Similarly, a 2 percent engine efficiency boost for the ultracapacitor hybrid raises fuel economy from 71.2 mpg to 73.1 mpg, with an additional 2 percent boost yielding 74.9 mpg.

Emissions

Advocates have promoted series hybrids both for their efficiency advantages *and* for their potential as ultralow-emission vehicles. Popular opinion is that an HEV engine's constant speed/load operation should greatly facilitate attainment of extremely low emissions. This ignores the fact that 75 percent of all emissions in a conventional car occurs in the first two minutes after cold start. Cold start also occurs in HEV operations, although the use of electrically heated catalysts becomes easier with the large HEV battery. It has been noted, however, that Honda is already close to certifying a conventional car to ULEV levels, so that the advantages of HEVs in those terms appear minimal. In addition, since the HEV's engine is on for a small fraction of the time (-27 percent) during the urban cycle, cold-start emissions will be a much larger fraction of total emissions--as much as 90 percent. Owing to high-load operation, cold-start NO_x could be a problem at LEV standards.

A second factor affecting emissions is the strategy of turning the engine off when the battery or other storage device becomes fully charged. Ideally, in the EPA urban test, the engine would be turned on only once, run for 370 seconds (27 percent of 1,372 seconds), and then kept off with the vehicle running as an EV. This is possible because the current FTP has only one strong acceleration mode that should logically occur when the engine is on, so that the engine need not turn on again to provide adequate power. The energy storage device would then have to sustain the vehicle for the other 73 percent of the time, which requires an energy storage capacity of over 2 kWh. As table 4-12 indicates, the ultracapacitor and flywheel fall short of this goal although *both devices are deliberately sized well above the minimum size needed to provide adequate power*. This implies that, with these devices, the engine must be restarted more than once during the emissions test, with attendant hot-start emissions and catalyst cool-down problems as well as engine rotational inertia losses. Hence, HEV emissions may actually be *more* difficult to control than emissions from a conventional vehicle, if electrical energy storage capacity is limited.

Automakers and suppliers are working on new controls that could greatly reduce problems with hot restarts. For example, there are recent developments in quick light-off catalysts and insulated manifolds that could minimize the emission effects of hot restarts to the point where multiple engine shutdowns and restarts would no longer be a significant emissions problem. For these reasons, we conclude that **the suitability of ultracapacitors (and, possibly, flywheels as well) for use in hybrid vehicles will depend on the development of controls that can greatly reduce emissions from engine hot restarts.**

Aside from emission certification tests, "real-world" emissions of hybrids can also be a concern. Although certification emission levels can be low if the engine is operated infrequently on the FTP, frequent high acceleration rates and high speeds may cause much more frequent engine operation in real life, on average, than on the FTP, with significantly higher emissions than certification levels. Such emission effects could be addressed by the proposed FTP test revisions which will include high speeds and high acceleration rates during the test. Engine malperformances can cause high emissions as in regular cars, but the hybrid design may reduce intentional maladjustment or tampering as engine operation is at near constant speed/load. Malperformance-related issues are a major concern for regulatory agencies, however, especially as the vehicles age, and the hybrid may offer no benefit over conventional vehicles in this arena. Hence, **hybrids may have no significant benefit in emissions relative to conventional vehicles, with the possible exception of their capability to act as limited-range EVs in specific urban areas.**

Other Studies

The results presented here are radically different from these presented by some analysts, and a comparison of the assumptions employed is provided here for a few selected papers. A recent paper by Mason and Kristiansson[60] of Volvo showed low fuel economy levels for all types of hybrids and claimed that series hybrids were more efficient than parallel hybrids. The analysis presented in the paper incorporated several assumptions that do not appear defensible, for example:

- Engine efficiency under urban driving was assumed to be 10 percent, and 20 percent for highway driving for conventional vehicles. A 30 percent efficiency was used to model the series hybrid, and the incorrect large difference in efficiencies explains the poor results for the parallel hybrids.
- Weights for alternative configurations of hybrids were not calculated, but were *assumed* to be equal to the conventional vehicle. This leads to gross error in some cases. ‘
- A very rigid operating strategy was dictated by assuming that the vehicle would behave as an EV for the first 30 miles, and as a hybrid for the next 60 miles.
- The issue of engine sizing and on/off operation were not addressed.
- The battery was expected to supply the worst-case requirements for power unaided by the engine, which dictated the need for an excessively large battery.

As a result of what we consider as unrealistic input assumptions, the fuel economy for a mid-sized HEV was estimated at about 34 mpg for a series hybrid and 19 mpg for the parallel hybrid.

Some analysts have obtained substantially more optimistic results than OTA. One analyst has published studies on hybrid vehicles for the past 15 years, and has used a relatively sophisticated model (SIMPLEV) to estimate their benefits. In recent work, he has reported fuel efficiency benefits for series hybrids of 40 to 60 percent on the city cycle and in the 30 percent range for the highway cycle.[61] Direct comparisons between this analyst's simulations and OTA's results were facilitated by a special run of his model using values quite similar to those used by OTA for vehicle characteristics. His results provide for a direct comparison of the results of the two modeling methods for a hybrid using an ultracapacitor for energy storage (see table 4- 13).

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[60] W. Mason and U. Kristianson, "Hybrid versus Pure EVs Which Gives Greater Benefits," SAE paper 94C017, 1994.

It appears the OTA results are very similar to the SIMPLEV results on the highway cycle but differ significantly on the city cycle. The reason maybe partly because there is no hot or cold-start fuel penalty in the SIMPLEV model, partly because OTA assumes that the engine operates around but not exactly at the optimal bsfc, and partly because of OTA's assumed lower regenerative braking efficiency.

Another researcher[62] estimates a 100 percent fuel economy improvement from a series hybrid configuration, in a comprehensive analysis that fortunately uses a mid-size car for its starting point, facilitating comparisons with OTA's analysis. Many of the assumptions in the analysis do not appear to be consistent with OTA's stated objective of obtaining vehicle performance that rivals that of conventional vehicles. Among the major differences are:

- The small engine operates at a single point and provides 35 kW of power. Its efficiency is rated at 36.5 percent, which is higher than any engine of that size available today.
- The entire energy storage is by an ultracapacitor that stores only 0.5 kwh. This is similar to the ultracapacitor scenario considered by OTA, but the paper does not address the issue of sustained acceleration or gradability, or multiple hot restarts.
- Generator efficiency is assumed at 96 percent, and the engine operates 11 percent of the time on the FTP.
- The efficiencies of electric storage, motor, and transmission are combined and are assumed to be 80 percent. In OTA's analysis, the battery, motor and transmission combined efficiency is around 0.68.
- All inertia loss is assumed to be braking loss, and braking energy recovery is 90 percent. In OTA's analysis, the value of recovered inertia loss is less than 60 percent.
- Cold start and hot restart fuel consumption penalties are ignored.

This researcher also combines the hybrid configuration with a lower weight, lower air drag, and lower rolling resistance design and calculates a fuel efficiency of 83.1 mpg. The car weight, drag, and rolling resistance are roughly comparable to the 2005(0) scenarios used here, for which OTA calculates a 61 mpg fuel economy.

A third paper[63] concludes that a subcompact car can attain several hundred mpg based on an unusually optimistic set of input assumptions;

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[61] A. Burke, "Electric-Hybrid SuperCar Designs Using Ultracapacitors," preprint of paper to be presented at 30th IECEC Conference, August 1995.

[62] M. Ross and W. Wu, "Fuel Economy of a Hybrid Car Based On a Buffered Fuel: Engine Operating at its Optimal Point," SAE paper 95000," February 1995.

[63] Lovins, et al., see footnote 47.

- Car weight (total) would be 580 to 400 kg, less than half of what is estimated by OTA even with carbon fiber construction.

- Drag co-efficients are reduced to 0.14 to 0.10, about half the best levels forecast by OTA.

- Switched reluctance motors that drive the wheels directly are assumed to have an average efficiency over the EPA test cycle of 93 percent. This is an unusally high average value for a motor.

- Accessory loads on the engine would be reduced to zero.

- Regenerative braking efficiency is assumed to have very high (>75%) recovery of inertia losses.

If these input assumptions were used by OTA in our analysis, we would obtain fuel economy levels of over 100 mpg. However, the above analysis does not specify the size and power of the motors or engine, and it is unclear what such a vehicle's performance would be with any payload.

Aside from theoretical analyses, some actual hybrid vehicles have been built and tested. For example, a number of series hybrid vehicles have been developed by universities. These vehicles have been reported to have achieved high fuel efficiencies, but OTA's examination of the actual data showed that the efficiencies achieved *were* not unusually high. At a constant speed (40 to 50 mph), the best car showed about 60 mpg, while many cars achieved 20 mpg or lower. The best series hybrid vehicle (Michigan State) was a converted Ford Escort that had low performance relative to our benchmark of 50 kW per ton of weight plus payload; its power rating was only 22.8 kW per ton, implying that it had less than half the power level required to be equivalent to an average car in today's fleet.[64] In addition, the constant speed 40 mph mode is one where even a *conventional* Escort can attain 50 mpg (the Escort's highway fuel economy on the EPA test is over 45 mpg) while providing much better performance. **Rather than proving the potential for high fuel economy, these early hybrid demonstrations have shown how difficult it is to gain *any* benefit in fuel economy from shifting to a hybrid drivetrain.**

Parallel Hybrids

In a parallel hybrid, both the engine and the motor can drive the wheels. The close coupling between engine and motor duty cycles makes the parallel hybrid difficult to analyze without a detailed simulation model that computes efficiencies as a function of operating speed/load for each of the two prime movers. Conceptually, however, the general strategy of a parallel hybrid is to downsize the engine, so that the maximum power requirement of the vehicle is satisfied by having both engine and motor operate simultaneously. The motor size required in a parallel hybrid is much smaller than that required in a series hybrid, because in the latter, the motor is the only source of power driving the wheels.

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[64] Merrit and Wipke, see footnote 49.

There are two possible operating strategies for a parallel hybrid:

1 Use the electric motor for base (light) loads, while using the engine to provide power at higher loads. Depending on vehicle load requirements, the engine is turned on and off.

2. Use the engine for the light load and the electric motor for short-term peak loads. In this case, the engine operates steadily.

VW has chosen the first approach, and has used a small electric motor with 9 kW peak output to aid a diesel or gasoline engine. The motor is used exclusively at all loads below 7 kW, corresponding to a cruise speed of 40 mph on a level road; the engine is started instantaneously when more power is needed. This vehicle, based on the VW Golf, consumes 2.8 litres of diesel per 100 km, and 15.8 kWh of electric power, on the FTP urban cycle.[65] If the electricity were generated (for example) at 34 percent energy efficiency at the wall plug from primary fuel **the hybrid would have a fuel consumption of 4.05 litres/100 km diesel equivalent, which is 35.8 percent better fuel economy than the conventional Golf diesel.**

Project staff had an opportunity to drive the hybrid Golf, and the impression was that the vehicle behaved quite differently (uncomfortably so) from a conventional auto. In particular, the transitions between electric motor operation and engine operation during city driving were disconcerting, although this impression may disappear with driving experience or with a more advanced design. For this type of vehicle, the diesel is the more suitable engine because its hot restart occurs in half a revolution of the engine, whereas hot restart on a gasoline engine is slower and could have significant emission penalties. With a diesel engine, however, emissions over the driving cycle are reduced significantly. **It seems possible that a diesel-based parallel hybrid using this operating strategy might be capable of meeting the ultralow emission vehicle (ULEV) standard.**

In the second type of strategy, where the ICE is on continuously (except possibly at idle, where it could be turned off) and the electric motor is used for peak loads, most of the fuel economy gains are associated with engine downsizing, at least on the FTP cycle, where hard accelerations are not required. For a "type 2" parallel hybrid, the electric motor power and battery storage capacity are relatively small; coupled with the smaller engine, the overall vehicle weight should decrease.

Two alternative specifications for mid-size parallel hybrid vehicles that provide near equal performance (at speeds below 70 mph) to the baseline vehicle are shown in Table 4-14. The first hybrid uses a 2.0-litre engine and a flywheel for energy storage, while the second uses a 1.0 litre engine with a battery for energy storage. Either type of strategy can be incorporated with both hybrid vehicles. **The type 2 strategy of using the engine for peak loads could provide fuel economy gains of approximately 25 to 30 percent in the first vehicle, and 30 to 35 percent in the second, compared with equivalent vehicles with conventional drivetrains. However, drivability and hot restart problems (with a gasoline engine) with these configurations could be daunting. The fuel economy gains are estimated to be half as much using a type 2**

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[65] Josefowitz and Köhle, see footnote 53.

strategy where the engine is on all the time; however, emissions and drivability for the type 2 hybrid should be much easier to perfect. The type 2 hybrid may make more sense if simplicity, reliability, and low cost are more important than attaining maximum fuel economy.

The percentage changes in fuel economy should be generally applicable to all size classes examined, given the inaccuracies inherent in our simple methodology. Available data from existing simulations provided by Chrysler[66] are consistent with the estimates provided above.

Data from parallel hybrid vehicles in the most recent "HEV challenge" were also examined. It is interesting to note that the winning cars in this event have almost always used a parallel design, and series hybrids have fared poorly. The University of California at Davis achieved the best fuel economy (by far) in the road rally segment. Its vehicle used only 0.45 gallons of gasoline and 8.51 kwh of electricity to cover 134.86 km[67]--a "gasoline equivalent" fuel economy of 69.32 mpg if the electricity generation efficiency is about 34 percent. Although this is an impressive attainment for a student competition, **this is not a uniquely high fuel economy** (several conventional vehicles attain equivalent fuel economy on the EPA highway test), **and the vehicle itself is limited in its capabilities.** The vehicle is basically an EV with a small engine that is started *only* when the battery is discharged by over 50 percent or when the vehicle is traveling faster than 70 mph. Range as a pure EV is 60 miles, and about 180 miles as a hybrid with available battery power; after 180 miles, the battery must be recharged or the vehicle can limp home powered only by the engine, which produces 15 kW (20 hp). Although the vehicle's total power output with fully charged battery and engine available is 60 kW (which provides almost exactly 50 kW/ton of peak power for acceleration[68]), the power drops off once the battery is depleted to 50 percent DoD. Hence, **vehicles such at the UCDavis hybrid demonstrate that high levels of fuel economy can be obtained while overcoming some of the range limitations of pure EVs--but these vehicles are far from the "full capability" hybrids that OTA examines in this report.**

Prices

Prices for the series and parallel hybrids were computed using a methodology similar to the one employed for EVs. Battery costs and motor costs are identical to those used for EV cost estimates. The generator is assumed to be less expensive than the motor owing to its restricted speed range, and we have estimated costs at $25/kWh (peak). Ultracapacitor and flywheel costs are as outlined in chapter 3 and are DOE *goals* rather than real cost estimates. Investments were estimated at $200 million (incremental) for an HEV facility designed to produce 100,000 vehicles/year.

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[66] Chrysler, presentation to OTA, September 8, 1994.

[67] E. Chattot et al., "The Continuing Development of a Charge Depletion HEV, Aftershock, at UC-Davis", SAE Paper 95000.

[68] Actually, a parallel hybrid will require greater 50 kW/ton of available peak power to match OTA's power requirement, because part of the power for peak acceleration is provided by the vehicle's electric motor, at 50 kW/ton required and part by the engine, at 60 kW/ton required.

Incremental prices (relative to the advanced conventional vehicles) for the mid-size series HEVs are as shown in table 4-15, for the different energy storage devices. The bipolar lead acid battery is the cheapest solution, as both flywheel and ultracapacitor are relatively expensive for energy storage, which becomes a limiting constraint in our analysis. By 2015, costs are very low because large cost savings are realized from eliminating the advanced DISC engine and continuously variable transmission (CVT).[69] The subcompact car price will increase by about 80 percent of the costs shown above, compact vans by 110 percent, and standard pickups by 140 percent.

Prices for parallel hybrids are only slightly lower than those for a series hybrid, but OTA did not estimate them in as much detail. Costs are lowered for the Case 1 type hybrid owing to the absence of a separate generator, and the use of a small flywheel energy storage system, but are increased by the need for a larger engine and transmission. In Case 2, the engine size is similar to that of the series hybrid, as is the battery size. The motor is smaller, and the vehicle does not need a separate generator, but this is partially offset as a transmission is not eliminated. Hence, we expect costs to be similar to that for a series hybrid, but they may be slightly lower depending on the specific strategies chosen. The same scaling laws should apply for the different classes within the range of accuracy of this analysis.

FUEL CELL VEHICLES

Two types of fuel cells are considered in this section, the zinc air cell and the proton exchange membrane (PEM) cell fueled with methanol. The zinc air cell is very much like a high specific energy/low specific power battery, so that all of the equations derived for EVs (see appendix A) are directly applicable. The PEM/methanol fuel cell is power limited, not energy limited, because a regular gasoline tank size can carry enough methanol for a range of over 300 miles. Hence, PEM ceils can be sized according to requirements for short-term peak power (that is, rapid accelerations) or maximum continuous power (long hill climbs). In the latter case, the PEM/methanol cell will require additional electric storage in the form of a flywheel, battery, or ultracapacitor to provide an occasional power boost, and this combination is sometimes called a fuel cell hybrid.

The zinc-air fuel cell has a high specific energy of over 200 Wh/kg, but a low specific power of less than 100 W/kg. The vehicle power requirements demand either a very large fuel cell, or a smaller cell coupled with a peak power device such as an ultracapacitor or flywheel. As is true of the hybrid vehicle, the issue of ultracapacitor sizing for repeatability of acceleration performance is an important consideration. A second consideration is the 6 percent grade-climb requirement, which defines the continuous power requirement of 30 kW/ton. Because the zinc air cell has such a low specific power, the cell weight needed to provide even the continuous power requirement is too high, and the cell too expensive, for commercial viability in 1995 and 2005. However, the

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[69] The benefits of the DISC engine are essentially negated by the series hybrid configuration, since the engine operates close to its moat efficient point at all times, and the DISC technology improves *part load* efficiency. Consequently, a less expensive engine will give the same efficiency. The transmission is not needed in the hybrid configuration.

reductions in vehicle body weight by 2015 make it possible to meet the 6 percent grade climb requirement with a zinc-air cell of reasonable size.

OTA's analysis shows that the (mechanically recharged) zinc-air fuel ceil can provide a 200-mile range and reasonable performance--but *not* the capability for a sustained 60 mph, 6 percent hill climb--for a car (subcompact) price increment of less than $10,000 in 2005 (see table 4-16). This, of course assumes that a zinc reprocessing infrastructure is developed. The zinc-air system's inability to sustain the 6 percent grade climb specified for EVs, however, implies that a direct comparison with a battery-powered EV would be unfair. The zinc-air fuel cell becomes even more cost effective with incremental prices in the range of $8,700 to $11,900 for cars and $13,000 to $19,000 for trucks by 2015, while providing a 200-mile range and being able to sustain a 6 percent grade climb.

The zinc-air fuel cell or battery is "recharged" by mechanically replacing the electrolyte and zinc anodes, so that a zinc refueling infrastructure must be developed; no estimate of the refueling infrastructure costs and zinc reprocessing facility requirements are included here. The vehicle energy consumption estimates shown in table 4-16, however, take into account the electric energy efficiency of the zinc-processing facility.

Use of zinc-air fuel cell vehicles may be limited from a practical standpoint to commercial, centrally fueled fleets. It is not clear that the cells can be "topped off, " which makes their range limitations onerous for private users. Moreover, the air handling systems that scrub intake air free of carbon dioxide may require frequent maintenance, which is impractical for such users.

In evaluating PEM fuel cell vehicles, we have *assumed* that the fuel cell can be packaged to fit into a car without interfering with passenger or trunk space. Such an assumption is necessary since current fuel cells, even those powered by hydrogen, are quite large in volume.

OTA does not expect that a PEM fuel cell for light-duty vehicles can be commercialized by 2005. The vehicle evaluated for 2015 uses a fuel cell sized to provide the continuous power requirement of 30 kW/ton, while ultracapacitors or batteries are used to provide peak power requirements of 50 kW/ton. Fuel cells attain maximum efficiency at about 40 to 50 percent of maximum power, so that the most efficient operating strategy is to operate much as an engine-powered hybrid that operates near its optimum bsfc point, unless high continuous power is required. Two vehicles are examined, one using a semi-bipolar lead acid battery for peak power and cold-start energy storage, and the second using an ultracapacitor; in both cases, body materials, aerodynamics, and rolling resistance correspond to the 2015 (m) scenario for vehicle technology.

Table 4-16 shows the results for a mid-size car, for the two cases. The ultracapacitor is sized to provide about one minute of peak-power availability and is, therefore, energy storage limited. Nevertheless, the two scenarios provide nearly equivalent results in all areas except one--the battery offers superior range as an EV or in cold-start conditions. Costs are highly dependent on the fuel cell/reformer cost. At $650 per kW for the combination, the incremental RPE for the fuel cell vehicle over a 2015(m) conventional mid-size vehicle is close to $40,000. Even at $65/kW, the incremental price is $4,500 to $5,000. Fuel economy has increased to the low 80 mpg range in gasoline equivalent terms. This is in line with the fact that a methanol-PEM cell is not substantially more efficient than an advanced ICE, gasoline or diesel, at its best operating point, so the fuel economy figures for hybrids are relatively similar whichever prime mover is used.

CONCLUSIONS ABOUT PERFORMANCE AND PURCHASE PRICE

Detailed analysis of potential improvements in fuel economy for a range of vehicle sizes indicates that, in percentage terms, similar levels of increases can be expected for the different vehicle sizes, if the same kind of efficiency improvements are added. Using a mid-size car as an example, and holding its space, acceleration performance, and other comfort features constant at 1995 levels, it appears likely that a fuel efficiency level of about 53 mpg with a gasoline ICE, or 59 mpg with an advanced diesel engine can be attained in the year 2015 by using a combination of advanced engine technology, improved materials and structural design, better aerodynamic design, and improved tires. Such vehicles would cost $2,500 to $3,000 (in constant 1994 dollars) more than a current mid-size vehicle. If very optimistic estimates are used for technology, an additional 10 mpg may be available, but costs may increase to over $6,000, largely owing to this hypothetical vehicle's carbon-fiber construction. OTA is somewhat skeptical that mass-produced carbon-fiber auto bodies will be practical in this time frame.

A mid-size electric vehicle would not have the same range capability but could be designed to match a conventional mid-size vehicle's performance and other attributes. Such a vehicle in volume production could cost as little as $2,600 over the 53 mpg advanced conventional vehicle, if powered by advanced lead acid batteries, and have a range of 80 miles. If nickel metal hydride batteries can be produced cheaply ($180/kWh), an electric vehicle using them would be much lighter, and have a range of 100 miles at about the same additional cost as a lead acid battery-powered vehicle. Many observers believe that actual costs of the nickel metal hydride battery will be twice as high as the most optimistic estimate, causing incremental vehicle price to about $8,800. There is also the possibility of a 300-mile-range EV if lithium polymer batteries are successfully manufactured, and such a mid-size EV could potentially be made for about $10,000 more than the 53 mpg advanced mid-size car. EV prices are quite sensitive to range or performance assumptions, or both, so that relaxing the requirement to match conventional vehicle performance characteristics can reduce EV prices. In particular, reducing range requirements will sharply reduce EV prices.

Hybrid vehicles offer the range of a conventional vehicle with potentially superior fuel economy and the ability to operate as an electric vehicle with limited range. OTA chose to analyze only autonomous hybrids--that is, vehicles that recharge their electrical storage systems through their prime mover (engine, fuel cell), not from an external source (e.g., the utility grid). **Autonomous hybrids will be fuel efficient only if a good high-power storage medium (with specific power >400 W/kg) is available that can be charged and discharged with high efficiency. No** such medium exists now, but there are numerous potential candidates under development much as the bipolar battery, ultracapacitor and flywheel. OTA's analysis shows that a hybrid mid-size car with basically the same performance capability as a current mid-size vehicle can attain about 65 mpg using a battery, and about **72** mpg using an ultracapacitor or flywheel in 2015, using body technology similar to the 2015 advanced conventional mid-size car. Cost is estimated at about $3,200 over the 2015 advanced conventional vehicle, if a battery is used, and about $6,000 to

$8,000 more if an ultracapacitor or flywheel is used. The battery version is preferable because such a hybrid can be operated as an EV with a range of 25 to 30 miles, compared with five miles with an ultracapacitor, or 10 miles with a flywheel. When not operated as an EV, a hybrid vehicle may not have any emissions advantage over the advanced conventional vehicle.

OTA estimates that a PEM fuel cell hybrid vehicle, using hydrogen from methanol reformed onboard, could attain a fuel economy of about 80 mpg, if its structural and other characteristics matched the 2015 advanced conventional vehicle. Such a vehicle probably could not be commercialized in a mass-market vehicle before 2015 or so. Currently, the PEM fuel cell's power density and cost are ill-suited to a light-duty vehicle, and considerable improvements are required. If fuel-cell costs decrease by *one order of magnitude* from current levels, a mid-size car powered by a PEM fuel cell/battery hybrid drivetrain could be available for about $39,000 over an advanced conventional vehicle in 2015. If costs came down by *two orders* of magnitude, the vehicle price increment could decrease to less than $5,000, but the potential for such large decreases is highly uncertain. Even if such price decreases were possible, the marginal fuel economy benefit over an ICE hybrid is small--the fuel cell vehicle's zero emission potential appears to be its primary value.

LIFECYCLE COSTS

Cost and price analyses in this report have focused primarily on vehicle purchase price. Although vehicle purchasers have tended to weigh initial purchase price extremely heavily in their buying decisions, there are strong reasons to examine differences in operating and maintenance (O&M) costs, as well as differences in trade-in value or vehicle longevity, or both, in attempting to measure the commercial potential of advanced vehicles. First, there *is* evidence that many vehicle purchasers strongly consider lifecycle costs in choosing vehicles. For example, diesel-powered vehicles traditionally have been more expensive and less powerful than otherwise-identical gasoline vehicles, but diesels are extremely popular in Europe because of their lower maintenance costs, greater longevity, and lower fuel costs. Similarly, they enjoyed a period of popularity in the United States when diesel fuel prices were below gasoline prices and public concern about oil prices was high. Second, differences in O&M costs among the alternative vehicles examined here are likely to be much larger than the differences among current vehicle alternatives. For example, the limited lifespan of the batteries in EVs and HEVs and their high costs imply that owners of these vehicles must contend with one or more payments of thousands of dollars for battery replacement during their vehicle's lifetime. Also, there are sharp differences in "per unit of energy" prices for the various fuels--gasoline, diesel, electricity, methanol, and hydrogen--considered here, which, coupled with substantial differences in fuel efficiency, will cause overall fuel charges for the different vehicles to vary considerably.

A few simple calculations show how a higher vehicle purchase price may be offset by lower O&M costs or longer vehicle lifetime. Assuming a 10 percent interest rate and 10-year vehicle lifetime, a $1,000 increase in purchase price would be offset by a $169/year reduction in O&M costs. Similarly, an increase in vehicle price of about 25 percent--such as from $20,000 to $25,000--would be offset by an increase in longevity of five years, assuming the less expensive vehicle would last 10 years.

In OTA's analysis, the alternative vehicles are essentially identical in size, aerodynamic characteristics,[70] body material and design, tire characteristics, and types of accessories. Consequently, the primary physical differences among the different vehicles are powertrain components (engine, transmission, electric motors and controllers, energy storage devices, and any peak-power devices), some differences in accessories depending on availability of waste heat, and any differences in body structure, suspension system, and tires caused by differences in powertrain weight.

Based on these differences among the vehicles, corresponding differences in operation and maintenance costs are likely to arise primarily from:

- battery replacement costs,
- differences in maintenance costs between electric drivetrains and ICE drivetrains,
- differences in longevity between electric and ICE drivetrains, and
- differences in energy costs.

Battery Replacement Costs

A battery for a mid-size EV with significant range (80 miles or longer) can cost $10,000 at retail, and the high-power density battery a hybrid vehicle would use is likely to cost at least a few thousand dollars. Although the long-term PNGV goal for battery lifetime is 10 years, no current EV battery has yet demonstrated a life of five years. If EV and hybrid batteries do not last the lifetime of the car--which seems likely--the substantial expense of battery replacement will play a weighty role in lifecycle O&M costs.

Differences in Maintenance Costs and Longevity Between EV and ICE Drivetrains

There is a widespread belief among analysts that electric drivetrains will prove to be substantially more robust than ICE drivetrains, requiring less maintenance and lasting longer. OTA's interviewees in the industry readily agreed that maintenance costs (both scheduled and unscheduled) would be lower in vehicles. with electric drivetrains. This view is based on experience with EVs in Europe and elsewhere and extrapolation of the characteristics of drivetrain components in other settings, such as electric motor use in factories. The value of this experience as a predictor of future performance may be compromised somewhat, however, by the substantial differences in component characteristics between future electric vehicles and current and older vehicles (e.g., future electric motors will be much lighter), and the harsh environment that EV and HEV components must endure (unlike a factory environment). Also, low EV

[70] In reality, there *would* likely be differences in aerodynamics among the different types of vehicles. The drivetrain differences might allow more or less flexibility in aerodynamic design depending on cooling requirement and the ability, or lack of it to use conformal shapes for energy storage and for the basic power system.

maintenance will be achieved only if the power electronics, sensing, and computer control systems in these vehicles (which may be more extensive than in conventional vehicles) are relatively maintenance-free--not a foregone conclusion. Finally, many of the batteries that are candidates for EVs are not sealed and maintenance-free.

Maintenance costs for ICEVs typically are low for scheduled maintenance, on average about $100/year for the first 10 years[71]; unscheduled[72] costs may be closer to $400/year for that time period.[73] These costs maybe changing with technological change, however. Engines and emission control systems are becoming more complex, incorporating monitoring and control of more parameters (e.g., valve timing) and adding components such as additional catalytic converters for controlling cold-start emissions. New engines now being introduced into the market, however, do not require tuneups for 100,000 miles and generally have fewer parts than the engines they replace; in addition, automakers are succeeding in improving quality control to the point that they can offer extended warranties for up to 100,000 miles at real costs (to them) of only a few hundred dollars.

Because hybrid vehicles (HEVs) combine elements of ICE and electric drivetrains, clear differences in maintenance costs between ICEVs and HEVs are more difficult to predict. Series hybrids, which have no multispeed transmission, are less complex than parallel hybrids and may retain some maintenance advantages over ICEVs. This potential advantage will depend on whether the smaller engines in series hybrids, with limited speed ranges and gentler load changes within these ranges, will require substantially less maintenance than conventional ICES; which seems likely. On the other hand, parallel hybrids may enjoy no clear advantages, or may have higher maintenance requirements, because they retain an engine and transmission and add a complete electric drivetrain.

Fuel cell vehicles (FCEVs) are basically EVs with the fuel cell stack and hydrogen storage system or methanol reformer (with methanol fuel system) substituting for the larger EV battery, or hybrids with the fuel cell/fuel system providing the base power and a battery, flywheel, or other storage device providing peaking power and cold start capability. Fuel cells have fewer moving parts and a less severe operating environment than ICES, and some analysts have concluded that fuel cells will require little maintenance. One analyst, for example, estimates that fuel cell stacks will cost less than $40/yr to maintain.[74] It appears premature, however, to draw such conclusions. The fuel cells considered here have a fairly complex “balance of plant,” and a methanol reformer, with required gas cleanup to avoid poisoning the fuel cell’s catalysts, will be similarly complex. Problems such as oxidation of the graphite cathode and deterioration of membranes must be solved. Further, vehicle designers may make tradeoffs--for example, choosing lower quality membranes to reduce first cost--that might add to fuel cell maintenance requirements.

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[71]Maintenance costs will be higher if owners follow the dealers recommended maintenance schedules, which typically call for much more maintenance than recommended by owner's manual.

[72]Costs cannot be scheduled even if they are regular, e.g., brake repairs.

[73]M. Delucchi, University of California at Davis, *Hydrogen Fuel Cell Vehicles,* UCD-ITS-RR-92-14, September 1992, table B-3.

[74]Ibid. Delucchi estimates that the annual levelized maintenance costs of mid-size FCEVs will be $390, compared to $430 for EVs and $520 for ICEVs.

Differences in longevity between conventional ICEVs and advanced vehicles depend on both the longevity of the alternative drivetrains and the importance of drivetrain deterioration in future decisions about vehicle scrappage. It is not really clear that, for the vehicles analyzed here, drivetrain condition is likely to be a critical determinant of scrappage decisions. For example, although material shifts in vehicle skins and structures should improve the longevity of these components, deterioration of body parts may still remain a problem. Vehicles will either have aluminum or composite-based skins and structures, or their steel equivalents will likely have excellent weathering characteristics to compete with these materials. Manufacturers of composites, however, must solve some problems of delaminating that have occurred in aircraft, and even aluminum oxidizes, albeit slowly. There have been some legitimate concerns about the repairability of aluminum and composites, which raise the possibility that moderate accidents--a not-infrequent occurrence--could lead to early retirement of future vehicles. This is extremely unlikely, however, as materials that are not easily repaired will not be commercially successful.

Delucchi estimates that the average lifetime of EVs and FCEVs will be about one-third longer than ICEVs--160,000 miles compared to 120,000 miles.[75] This differential seems possible but not compelling; the level of uncertainty is, again, extremely high. As for ICE-powered hybrids, the added complexity coupled with reduced stress on the engine might best be interpreted as implying that vehicle longevity may be similar to that of the conventional ICEV, and possibly even shorter.

Trade-In Value

Automotive marketers pay significant attention to trade-in value in their advertising campaigns when the vehicles being promoted have values that are sharply higher than fleet averages. This attention implies that the industry believes that expected trade-in value is an important element of purchase decisions--not surprising considering the comparatively short periods that the average vehicle remains in the hands of its first owner.

Over the long term, when advanced technology vehicles become commercially accepted and widespread in the fleet, and technologies become relatively mature, there should be little difference in patterns of trade-in values among alternative vehicle types, except as a direct result of different expected vehicle lifetimes. There is a good chance, however, that trade-in values for advanced vehicles will fall short of fleet averages for a number of years for two reasons:

- Many early vehicles will serve niche markets; the buyer pool for used vehicles would then be limited, depressing prices;
- For a number of years following commercialization, innovation of drivetrain technologies should be rapid, making older vehicles less attractive in comparison.

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[75] Ibid.

Energy Costs

Differences in energy prices coupled with differences in energy efficiency will yield some significant differences among alternative annualized energy costs of the different vehicles.

OTA has assumed a baseline retail price of gasoline of $1.50/gallon (in 1995 dollars) in 2015. This choice is somewhat arbitrary, but reflects a future of relatively plentiful supplies of oil, with pressures generated by sharply higher worldwide vehicle populations alleviated by continued advances in oilfield technologies, some use of alternative transportation fuels,[76] and widespread availability of nonoil fuels (including nuclear and other nonfossil sources) for power generation.[77]

The series of vehicles evaluated in this report for 2015, their fuel consumption, and yearly fuel costs (based on 10,000 miles per year, 7 cents/kWh offpeak electricity, $.75 per gallon methanol[78]) are shown in table 4-17.

At the assumed prices of fuels and electricity, the relative advantage in fuel costs of moving beyond the 53 mpg advanced conventional vehicle is relatively small, about $200/year in the best case (EV with Ni-MH batteries). This conclusion would change substantially, of course, with higher gasoline prices and lower electricity prices. At European gasoline price levels of $4.00/gallon and electricity prices of 5 cents/kWh, the owner of the advanced conventional vehicle would pay nearly $800/year more than the owner of the Ni-MH-powered EV, and about $730/year more than the owner of the lead acid-powered EV.

Conclusions

If advanced vehicles yield substantial savings over conventional vehicles in O&M costs, and also last significantly longer, they will be cost-effective even if their initial purchase price is a few thousand dollars greater than conventional vehicles. Although experts contacted by OTA generally agree that electric drivetrains should experience lower maintenance costs and last longer than ICE drivetrains, the magnitude of savings is difficult to gauge because of continuing improvements in ICE drivetrains and the likelihood that future electric drivetrains will undergo profound changes from those of today. Further, battery replacement costs could overwhelm other savings, although this, too, will be uncertain until battery development matures. Finally, vehicles with hybrid drivetrains may experience no O&M savings because of their complexity; and, although analysts have claimed that fuel cell vehicles will be low maintenance and long-lived,[79] the very early development state of PEM cells demands caution in such assessments, and there is little obvious basis for them.

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[76] Obviously, the relative success of advanced technologies for light-duty vehicles, including EVs, could begin to play a depressing role in oil prices by 2015, although this role might primarily be anticipatory (that is, giving buyers a psychological advantage over sellers) rather than physical (depressing oil demand) at this relatively early date.

[77] The choice has evoked reactions from study reviewers ranging from indifference (presumably acceptance) to sharp disagreement, with most of the disagreement from those who foresee much higher oil prices in this time frame.

Unless gasoline prices eventually increase substantially, any energy savings associated with lower fuel use or a shift to electricity will provide only a moderate offset against high purchase price--primarily because annual fuel costs are not high in efficient conventional vehicles. In the mid-size vehicles OTA examined for 2015, for $1.50/gallon gasoline, the *maximum* savings (NiMH battery-powered EV versus baseline vehicle) would offset about $2,300 in higher purchase price for the EV.[80] OTA expects the Ni-MH EV to cost about $10,000 more than the baseline vehicle, although the sharp reductions in cost projected by one battery developer--Ovonics--would reduce this to about $4,000.

SAFETY OF LIGHTWEIGHT VEHICLES

Although some of the vehicles examined by OTA will weigh as much or more than current conventional vehicles, many will weigh substantially less. For example, the advanced conventional vehicles in the year 2015 will weigh approximately 30 to 40 percent less than current conventional vehicles. In other words, a mid-size car with a current weight of 3,250 pounds conceivably could weigh less than 2,000 pounds in 2015, if maximum weight reductions are sought.

Strong concerns about vehicle safety would likely accompany such dramatic weight reductions. Weight reductions of lesser magnitude have been associated in the past with significant increases in fatality and injury rates in the U.S. fleet; the National Highway Traffic Safety Administration (NHTSA) concluded that changes in the size and weight composition of the new car fleet from 1970 to 1982[81] "resulted in increases of nearly 2,000 fatalities and 20,000 serious injuries per year"[82] over the number that would have occurred had there been no downsizing occurred. Moreover, during the early 1990s, the congressional debate on proposed new fuel economy standards was strongly influenced by claims and counterclaims about the potential adverse effects on vehicle safety of size and weight reductions that supposedly would be forced by the standards. It would be surprising if future attempts to speed the commercialization of these lighter weight designs were not accompanied by a renewal of the safety debate.

Much of the "accepted wisdom" of automotive safety comes from the statistical analysis of the nation's database on automobile accidents, especially from the Fatal Accident Reporting System and other government data repositories. Unfortunately, attempts to determine the impact of weight reduction on car safety suffer from the close association of vehicle weight with wheelbase and other size measures (including the amount of crush space) that also impact safety. In other

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[78] We have assumed that methanol price, including highway taxes, will approximate the energy-equivalent price of gasoline, for competitive reasons. The imposition of taxes equivalent to gasoline's tax burden yields a methanol price net of taxes of about 50¢/gallom which is low by today's standards.

[79] Delucchi, see footnote 73.

[80] For a 10 percent discount rate, assumed 10-year vehicle lifetime. This calculation assumes near constant miles driven over time for the new vehicles. Historically, vehicles tend to be driven most when they are new, with mileage dropping off quite rapidly as they age. Were these vehicles to fit the historic pattern, our calculation of a $2,300 offset would be much too low because in a discount calculation, early savings count more than later ones, and the more efficient vehicle would save more money on energy in its first few years than it did in later years. However, the increasing reliability and longevity of modern vehicles appears likely to shift annual driving patterns in the direction of more uniform mileage overtime.

[81] For new cars involved in fatal collisions, median curb weight shrank by 1,000 lbs, wheelbase by 10 inches, and track width by 2 to 3 inches.

[82] U.S. . Department of Transportation National Highway Traffic Safety Administration, 'Effect of Car Size on Fatality and Injury Risk," 1990.

words, analysts often have a hard time determining whether it is weight or size (or even some other measure) that is the primary determinant of safety, because large cars are usually heavy cars, and small cars are usually light. One analysis concluded that weight was the more important factor in vehicle safety.[83] This conclusion has been disputed by others, who claim that extremely lightweight vehicles can be made as safe as heavier ones.

The Role of Weight in Accident Prevention and Crashworthiness

An examination of the role that vehicles play in maintaining occupant safety can be instructive in determining the potential impact of sharp weight reductions. The vehicle must do the following:

1. Aid the driver in keeping the vehicle on the roadway.

2. If the vehicle leaves the roadway, avoid a rollover.

3. In a crash, absorb crash forces in such a way that no intrusion of the passenger compartment occurs.

4. Also, control the deceleration of the vehicle so that it occurs in as uniform a way as possible, over as long a crush distance[84] as possible.

5. Finally, prevent the passenger from crashing against interior surfaces and/or minimize damage if he does, prevent ejection of the passenger, and control the way deceleration forces affect the passenger.

Weight plays a different role in each of these vehicle tasks. In (l), weight may be protective in keeping vehicles from being adversely affected by crosswinds, but directional stability and handling are affected far more by wheelbase, suspension, and steering system design, tire design and maintenance, and other nonweight-related factors.

In (2), rollover can be weight-related because in lightweight cars, the payload will have a greater effect on the height of the center-of-gravity than it will in heavier cars. This effect maybe positive or negative depending on vehicle design, and specifically on the location of the payload vis-à-vis the location of the empty vehicle's center-of-gravity. However, rollover propensity is primarily a function of wheelbase, track width, suspension design, and overall vehicle design; a small increase in track width can compensate for any increase in rollover propensity that might occur from "lightweighting" a vehicle.

In (3) and (4), the role of weight is complex. The ability of the vehicle structure to control crash forces and prevent penetration of the passenger space *for a given set of forces on the vehicle* is dependent on vehicle design and the strength, rigidity, and deformation characteristics of the structure--not specifically on weight. Thus, it would appear at first glance that substitution

[83] L. Evans and M.C. Frick, General Motors, "Car Size or Car Mass: Which Has Greater Influence on Fatality Risk," 1992.
[84] Crush distance is the amount of length that the vehicle can give up to compression and energy absorption through controlled collapse.

of stronger materials, or materials with better energy absorption characteristics, should allow weight reduction without compromising a vehicle's crashworthiness, or even with an improvement in crashworthiness, with proper design. In virtually all accidents, however, vehicle weight does play an important role, because it determines the forces on the vehicles and their relative decelerations.

In a head-on collision between two vehicles of different weights but identical designs, the heavier vehicle will drive the lighter one backward, and the passengers in the lighter car will experience higher decelerations. The precise balance of forces depends on how the car structures collapse. If the heavier car is twice the weight of the lighter one, if they collide head-on while each traveling at 30 mph and become entangled, the law of conservation of momentum dictates that the heavier car would end up traveling 10 mph in the same direction it was going, while the lighter car would wind up going backward at 10 mph. The change in speed of the lighter car (30+10, or 40 mph) would be twice that of the heavier one (30-10, or 20 mph). Because deceleration is proportional to the change in velocity divided by the amount of time the velocity change requires, the passengers in the lighter car would experience about twice the deceleration experienced by the passengers in the heavier car. Consequently, passengers in light cars are at increased danger in multi-vehicle collisions. Although a widespread shift to lighter vehicles will eventually lessen the danger by reducing each vehicle's exposure to heavier vehicles, the continued existence of freight-carrying vehicles on roadways would prevent this problem from being cancelled out.

Light vehicles are also at a disadvantage in collisions with deformable obstacles. Deceleration forces *on* passengers are directly proportional to the distance they travel during the deceleration--this distance is the sum of the few inches an airbag may allow them to move forward, the foot or so that the front end of the vehicle will crush in a controlled, relatively uniform manner,[85] and any distance that the obstacle deforms. Because a heavier car will cause a larger deformation in an obstacle than a lighter car (all else being equal), the distance of deceleration will be greater for the heavier car--and the deceleration forces on the passengers will be smaller. This difference could be dramatic, if the heavier car actually knocks over the obstacle (e.g., a collapsible light post or a tree) and the lighter car is stopped by it.

This issue has great importance to the design of the many thousands of manmade roadside objects--e. g., signposts, lampposts, cable boxes, and crash barriers--that can either pose hazards or play a protective role to vehicles that have left the road. Current designs for these objects aim at directing vehicles to safety or at breaking away in high-energy collisions. The existing array of roadside objects, however, have been designed for the current and past fleet, and may pose significant dangers to lightweight vehicles. In-fact, the fleet downsizing that followed the 1972 oil embargo encountered significant problems with breakaway designs formulated for the pre-1972 fleet,[86] and these problems could easily be repeated with another round of fleet lightweighting, unless significant planning is accomplished and capital investments are made.

Weight plays a role even in two-vehicle collisions where the weights of the vehicles are similar, or in collisions into rigid, impenetrable barriers. In such collisions, the vehicles' front structures

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[85] Vehicle structures cannot collapse in a completely uniform manner, so that deceleration-and deceleration forces on passengers-varies over the brief period of the crash.

[86] "Emerging Roadside Safety Issues," *TR News, vol. 177,* March-April 1995.

must absorb all of the initial kinetic energy of the vehicles. Since kinetic energy is proportional to mass, heavier vehicle(s) must absorb more impact energy than lighter vehicles in the same types of crash. This has both positive and negative implications. First, assume that the differences between the heavy and light vehicles are differences in materials and design, and that their bodies are equally stiff and strong. Given the higher forces, the heavier vehicles will experience a greater depth of crush and greater crash duration, yielding reduced deceleration forces on their passengers--a substantial benefit. The heavier vehicles, however, may run a somewhat greater risk of intrusion into the passenger compartment, if the accidents are unusually severe. Although making the front end of lighter vehicles less stiff would address part of this problem, this would leave these vehicles more vulnerable in accidents involving heavier vehicles and higher speeds, and might adversely affect handling characteristics.

Finally, in (5), the design of passenger restraint systems and the interior space itself is the critical factor, although an unrestrained passenger will crash against the interior with a velocity that is dependent on the velocity change of the vehicle--which is weight-related in a multiple-vehicle collision.

What Accident Statistics Tell Us

Safety analysts have exhaustively studied accident statistics to gain a better understanding of the relative roles of various vehicle characteristics in passenger safety. It is clear from these studies and from physics, as noted above, that occupants of lighter vehicles are at a basic disadvantage to those of heavier vehicles in two-vehicle collisions. However, if most vehicles in the fleet are made lighter, the *relative* weights of vehicles in most collisions will not change. Consequently, a key issue here is whether reducing the weight of most vehicles in the fleet while maintaining basic structural integrity will adversely impact vehicle safety--beyond the adverse impact caused by those remaining vehicles that retain higher weight (older vehicles and freight trucks).

Some analysts have argued that weight reductions will have strongly negative impacts on fleet safety even in accidents where the role of weight is ambiguous--for example, in accidents where two (lighter) vehicles collide with each other. In the current fleet, in accidents where two cars of identical weight collide with each other, the occupants have an injury risk roughly proportional to the weights of the vehicle pairs; occupants of 2,000-pound vehicles colliding with each other would have roughly one and one half times the risk of occupants of 3,000-pound vehicles in a similar collision.[87] This seems to imply, at face value, that weight reductions will increase injuries. The basic problem with all such interpretations, however, is that they are derived from data on a vehicle fleet in which car size and car mass are strongly related to one another. In other words, in today's fleet, if a car is lighter, it is also smaller--and has a smaller front end with which to absorb the energy of a crash. Consequently, some portion of the greater risk of lighter cars will be associated with their size (and perhaps structural strength) rather than their weight. The dilemma for analysts is figuring out the relevant importance of each.

Some analyses have identified vehicle mass as the more important factor than size.[88] A recent study concludes, however, that virtually all of the variation in injury risk for accidents such as "collisions between cars of equal weight" can be explained by the differences in car *length* among different pairs of equal weight vehicles.[89] In other words, the study found that, in today's fleet: 1) lighter cars generally are smaller cars with smaller crush zones, 2) small cars generally are scaled down versions of large cars, that is, cars' overall design do not vary much with size, and their overall energy absorption characteristics do not vary either, so that 3) for the same accident severity, the deceleration imposed on the occupant compartment is inversely proportional to car length.

Even if the second study is correct, there still are important categories of accidents, as discussed above, where weight will play a protective role--by reducing the velocity change and deceleration of the vehicle in a collision. Consequently, at best, a reduction in the weight of light-duty vehicles will have some adverse impacts on the safety of the light-duty fleet, even if crush space and structural integrity are maintained--especially during the time when heavier light-duty vehicles remain in the fleet, but perhaps permanently in collisions with freight vehicles and off-road obstacles. Also, the net impact of weight reduction on barrier crashes and crashes into vehicles of similar weight remains unclear. Quantifying this impact will require substantial analysis of available accident statistics, and perhaps the collection of additional data, to determine the relative importance of each accident type and the impact of vehicle weight on that type.

Design Solutions

Various design solutions have been proposed to compensate for the automatic momentum disadvantage experienced by lightweight cars in collisions. Because crush space is a critical factor in passenger safety, designs that increase crush space can compensate somewhat for the increased velocity change experienced by lightweight cars in collisions. Although increased crush space can be achieved by structural design, an interesting possibility is to deploy an external air bag immediately before a crash.[90] Such a bag, deployed by a radar warning of the impending crash, would create a substantial temporary addition to crush space. The availability of low-cost radar systems and strong, flexible materials for the bag make this system an interesting one that may

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[87] Evans and Frick, see footnote 83.

[88] Ibid

[89] D.P. Wood et al., "The Influence of Car Crush Behaviour on Frontal Collision Safety and on the Car Size Effect," SAE paper 930893, 1993.

[90] C. Clark, "The Crash Anticipating Extended Air Bag Bumper Systems," paper presented at the 14th International Technical Conference on the Enhanced Safety of Vehicles, Munich, Germany, May 23-26, 1994, cited in B. O'Neill, Insurance Institute for Highway Safety, memo to Policy Dialog Advisory Committee on Greenhouse Gas Emissions from Personal Motor Vehicles, Jan. 12, 1995.

bear increased attention. As a possible adjunct to such a system, automatic braking activated by the same radar signal could reduce crash severity.

Another interesting design solution proposed by the Swiss involves building the lightweight vehicle with an extremely stiff "impact belt" around the exterior of the vehicle.[91] The idea here is that, in case of a collision with a heavier vehicle, the rigidity of the vehicle shell would cause the front of the heavier vehicle to deform substantially. In essence, the lighter vehicle uses the crush space of the heavier vehicle as its own crush space, and the heavier vehicle absorbs most of the kinetic energy released in the crash.[92] This design also includes very strong and stiff side beams that prevent intrusion of the car door into the passenger compartment during a side impact, avoiding the main cause of severe injuries during this type of collision.[93]

This type of design demands that restraint systems and interior padding bear much of the task of dealing with deceleration, especially in accidents where the vehicle strikes largely immovable objects. Although the structure does not eliminate crush space--it does deform in a crash--it reduces crush space and will increase the deceleration forces on passengers in many crashes.[94] It also demands that heavy cars be built with lower rigidity in their front and rear structures, so they can absorb most of the kinetic energy of crashes with lighter vehicles.[95] Another concern of this type of design is its potential to increase the aggressivity of light cars in collisions into the sides of other vehicles. Of particular concern is the incidence of vehicle-to-vehicle crashes where ***both*** vehicles are of this design. In such collisions, deceleration forces on the passengers would be substantially higher than in collisions between vehicles of more conventional design. Thus far, the Swiss have focused this design on very small vehicles, and this maybe where the design makes the most sense--when there simply is no room for much crush space. In OTA's view, this type of design, if used in standard-size vehicles, would be likely to create more problems than it eliminates.

Improvements in restraint systems will increase safety in *all* vehicles. In particular, crash sensors with very fast response times allow more time for deploying airbags and thus allow deployment to be less aggressive. This might mitigate some of the injuries that rapidly deploying airbags have been known to cause. Also, so-called "smart" restraint systems potentially may deploy the air bag differently depending on crash severity, position of the vehicle occupant, and characteristics of the occupant (e.g., size, sex, age), yielding greater protection.

Additional Issues

OTA's workshop on the safety of lightweight vehicles identified numerous additional issues. First, regardless of whether or not lightweight vehicles adopt any kind of "impact belt" design,

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[91]R. Kaeser et al., "Collision Safety of a Hard-Shell Low-Mass Vehicle," Accident Analysis and Prevention, vol. 26, No. 3, 1994, pp. 399-406.

[92]Ibid.

[93]Ibid. Although passengers are likely to strike the door whether or not the doors are pushed in or the entire vehicle is pushed sideways as a unit, the impact forces are far lower in the latter case.

[94]In a very small vehicle that would not have much crush space to begin with, this type of design has fewer tradeoffs. However, the vehicles we are considering here are lighter but not smaller than conventional vehicles.

[95]Ibid.

vehicle compatibility problems may pose a major challenge to lightweight vehicle safety design. A concern here was that current barrier tests might force even the heaviest vehicles to have stiff front ends, making them quite dangerous. to all of the other, lighter vehicles on the road. Thus far, however, NHTSA has found that application of the barrier tests to heavier vehicles--such as full-size pickups and vans, as well as heavy luxury cars--has tended to force them to *soften* their front ends, making them less aggressive to other vehicles.[96] Nevertheless, NHTSA might want to take special care that its current frontal crash requirements will create maximum fleet safety, if another round of vehicle weight reductions occur. Further, in adopting new side impact standards, NHTSA should take care to examine the impact of such standards on the feasibility of moving to new lightweight designs.

Another compatibility issue may be with roadside hardware such as collapsible light posts and vehicle barriers. Lightweight vehicles may pose problems for this hardware, because it is designed to give or collapse under impact forces that may be above the levels achieved by some of the smaller vehicles.

As discussed elsewhere (discussion on advanced materials), current vehicle structural modeling depends on extensive experience with steel structures. Shifting to aluminum or composites will provide a substantial challenge to vehicle safety designers, one that may take some time to overcome. Before the requisite knowledge is obtained, automakers may be forced to “play it safe” with designs that do not take full advantage of the properties of nonsteel materials.

Many safety advances in the past occurred because biomechanical research identified injury mechanisms and provided the data that allowed engineers to design restraint systems, padding, and collapsible vehicle structures (e.g., steering wheels) to appropriate human tolerances.[97] Such research also has led to the design of improved crash dummies that have greatly improved the value of crash testing. Further improvement in understanding of injury mechanisms would be especially valuable, if substantial vehicle weight reduction occurs and adds increased risks to the vehicle fleet. Unfortunately, biomechanical research is funded at a relatively low level in NHTSA and is extremely limited elsewhere.[98] This conceivably may limit the industry’s ability to respond fully to the challenges presented by lightweight advanced vehicles.

Finally, current safety standards focus on designing to protect unbelted occupants as well as belted ones. Some analysts believe that requirements to protect unbelted occupants compromise the ability of vehicle designers to provide maximum protection for belted occupants.[99] This issue may become more intense with extensive reductions in vehicle weights, and the potential for higher accident intensities that would occur- with such reductions. This is a complex issue that OTA is not prepared to address at this time, but it is well worth a careful examination.

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[96] Ken Hackney, National Highway Traffic Safety Administration, personal communication, May 1995. Their original, rigid designs resulted in very high passenger decelerations in the barrier tests.

[97] Transportation Research Board, *Safety Research for a Changing Highway Environment; Special Report 229* (Washington, DC: National Research Council, 1990).

[98] Ibid.

[99] U.S. Congress, Office of Technology Assessment Workshop on the Safety of Lightweight Vehicles, Sept. 12, 1994.

BOX 4-1: Four Weight Reduction Scenarios for a Mid-Size Car

About 70 percent of today's passenger car is comprised of iron and steel. The largest steel component is the body (25 to 28 percent), and the largest iron component is the engine (12 to 15 percent). A typical material composition of a mid-size passenger car would be 55 percent steel, 15 percent iron, 5 percent aluminum, 8 percent plastics, and 17 percent other. Substitutions of lightweight materials for iron and steel yield a primary weight savings plus a secondary weight savings derived from downsizing of supporting components, engine size reduction, and so forth. For vehicles that are completely redesigned (that is, all but the 2005 "optimistic" vehicle) a secondary weight savings of 0.5 pounds per pound of primary weight is assumed for equal performance. For the 2005 "optimistic scenario" vehicle, a secondary weight savings of 0.25 pounds per primary pound is assumed.

For the 2005(m) scenario, the vehicle is an optimized steel design that has an aluminum engine. Because of the automakers familiarity with steel auto manufacture, it is assumed that 10 years is long enough to implement a complete vehicle redesign. Through a clean sheet design approach with high-strength steels and advanced manufacturing processes, curb weight is reduced 11 percent, with an additional 4 percent reduction from the aluminum engine, for a total of 15 percent, compared with an unsubstituted baseline. Composition changes to: steel, 51 percent; iron, 8 percent; aluminum, 12 percent; plastic, 10 percent; and other, 19 percent. The estimated cost increase of $200 to $400 for the intermediate sedan is scaled according to weight for the other size classes.

For the 2005 optimistic scenario, the vehicles have an aluminum-intensive body and an aluminum engine. However, it is assumed that by 2005, there is insufficient time to solve all of the design and manufacturing issues associated with a clean sheet aluminum design with maximum substitution and full secondary weight reductions. A 20 percent weight reduction below baseline is achieved assuming secondary weight savings of 0.25 pounds per pound of primary weight. Composition changes to: steel, 29 percent; iron, 8 percent; aluminum, 31 percent; plastic, 12 percent; and other, 20 percent. The cost increase is estimated at $1,500 for the intermediate sedan and scaled according to weight for the other size classes.

In the 2015(m) scenario, the vehicle has maximum use of aluminum with a clean sheet design. Curb weight savings over the baseline are 30 percent. Composition shifts to: steel, 16 percent; iron, 1 percent; aluminum, 43 percent; plastic, 15 percent; and other, 25 percent. The cost increase for the intermediate sedan is estimated at $1,200 to $1,500, and this figure is scaled by weight to yield the cost increases for the other size classes. Although the vehicle contains more aluminum than the 2005 vehicle, which will tend to raise costs, the cost increase is about the same as in 2005, due to increased manufacturing experience with aluminum and the advantage of a clean sheet design to take advantage of the properties of aluminum.

In the 2015(0) scenario, the vehicles have a carbon fiber composite structure with aluminum engine and appropriate secondary weight savings that yield 40 percent reduction in curb weight compared with today's baseline. Composition changes to: steel, 15 percent; iron, 1 percent; composite, 22 percent; aluminum, 19 percent; plastic, 16 percent; other, 27 percent. The cost increase is estimated at $2,000 to $8,000 for the intermediate sedan, and this range is scaled by weight for the other size classes. The weight breakdown for an intermediate size vehicle by material is shown in the table below.

Material Weight Distribution for Lightweight Mid-Size Cars, Model Years 2005 and 2015

	2005(m)	2005(o)	2015(m)	2015(o)
steel	1,838	775	366	294
Iron	501	214	23	20
Aluminum	167	829	984	373
Plastic	211	321	343	314
Other	401	535	572	529
Carbon fiber	~0	-Q	~0	431

SOURCE: Office of Technology Assessment, 1995.

BOX 4-2: Calculating the Fuel Economy Effects of Converting a Taurus to a Series Hybrid with Flexible Engine Operation

Shifting the drivetrain to a series hybrid configuration saves energy in several areas. First, because there is no idling of the engine, the 16 percent of fuel consumed during idling on the city cycle and 2.0 percent on the highway cycle is saved. Second, accessory power demand is not likely to be reduced in a hybrid, as an engine running at or near its optimal brake-specific fuel consumption point rejects much more heat to the coolant, and, hence, cooling fan and water pump requirements will increase, but the engine itself is much smaller. Accessory fuel consumption will be reduced by the improvement in efficiency. Third, the use of regenerative braking will reduce tractive energy requirements by an amount similar to that for an EV.[1] Fourth, the use of an electric motor drive eliminates the transmission and improves drivetrain efficiency. Finally, by operating at or near its optimal point, the engine brake specific fuel consumption is greatly reduced.

On the negative side, a small engine (with smaller cylinders) is inherently less efficient owing to the higher surface/volume ratio of its combustion chambers. In the Taurus example, the engine would be a 1.0 litre four-valve four-cylinder engine, rather than the 3.0-litre two-valve V-6 used. Although some have discussed using one-or two-cylinder engines, their noise and vibration characteristics are so poor that only a four-cylinder engine is thought to be acceptable in a mid-size car (even the three-cylinder Geo Metro engine is considered quite rough in automotive circles). Hence, peak efficiency is reduced by 2 to 3 percent relative to a two-litre four-cylinder or three-litre 6-cylinder engine. The generator also must be sized for peak continuous output of 45 kW (e. g., for long hill climbs) while operating most of the time at 19 kW, making it heavier and less efficient under the standard operating mode.

Detailed analysis of the efficiency without a comprehensive simulation model requires some assumptions regarding average generator and motor efficiency. To provide an optimistic view of hybrid potential, we chose a set of "2005 best" values for component efficiencies, as follows:

. Generator efficiency at 19 kW	91 percent
at 45 kW	94 percent
. Motor efficiency	
urban cycle	82 percent
highway cycle	90 percent
. Drivetrain gear efficiency	
urban	94 percent
highway	96 percent

The motor and generator efficiency values are 3 to 4 percent higher than those of the most efficient current motors and generators. Engine efficiency was assumed at slightly off-peak value of 33 percent (in reality, this is higher than the peak efficiency of small engines today). A cold-start related fuel economy loss of 5 percent was also used on the urban cycle. The calculation is detailed in table 4-11.

[1] The battery for a hybrid vehicle will be designed to emphasize high power capability rather than high energy storage, in contrast to an EV battery. Therefore, even though the hybrid's battery will be substantially smaller than an EV battery, it should have relatively good capability to absorb the energy pulse from regenerative braking.

TABLE 4-1: Forecast of Advanced Technology Penetration in the Base Case
(Percentage of new vehicle fleet)

Technology	Subcompact		Intermediate		Compact van		Standard Pickup	
	2005	**2015**	**2005**	**2015**	**2005**	**2015**	**2005**	**2015**
Advanced HSLA bodies	**31.4**	**33.5**	**29.0**	**31.1**	**18.6**	**31.8**	**21.4**	**36.6**
HSLA + high-plastics body	13.0	25.3	12.3	24.4	0	14.5	0	16.2
High-aluminum body	0	5.0	0	10.5	0	0	0	0
Drag, C_D= 0.31[a]	46.8	21.6	37.4	0	64.9	0	56.6	0
Drag, C_D= 0.28[a]	45.0	48.9	61.6	61.6	35.1	69.8	43.4	61.5
Drag, C_D= 0.25[a]	0	28.9	0	38.4	0	29.7	0	38.5
5-speed auto/CVT	24.6	36.7	27.5	42.0	21.6	59.5	18.4	36.8
4-valve/cylinder	100.0	100.0	83.4	100.0	88.2	98.0	29.4	80.0
Variable valve timing	22.0	75.2	23.5	82.0	5.0	34.1	0	39.0
Lean bum	0	4.0	0	0	0	0	0	0
Tires C_R = 0.0085[a]	40.0	43.8	45.3	46.0	57.5	37.1	73.5	20.0
Tires C_R = 0.0075[a]	4.4	37.2	2.7	52.0	6.3	62.9	8.1	80.0
Low friction metal components	98.4	79.1	100.0	72.9	96.0	95.0	100.0	92.8
Titanium/ceramic components	0	20.9	0	27.1	0	5.0	0	7.2
Accessory improvements	29.0	40.5	43.0	60.9	17.5	52.1	23.4	69.0

[a]Values are for cars, but equivalent reduction from base available for trucks.

KEY: HSLA = high-strength, low-alloy steel; CVT = continuously variable transmission; C_D = drag coefficient; C_R= rolling resistance coefficient.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-18.

TABLE 4-2: Forecast of Vehicle Characteristics: Baseline Scenario

		2005	2015
Subcompact			
Price	Base	307	872
FE (mpg)	33.5	37.2	41.3
Weight (lb)	2,315	2,410	2,360
HP	101	108	126
Intermediate			
Price	Base	492	1,044
FE	27.0	29.8	33.4
Weight (lb)	3,190	3,230	3,150
HP	151	159	169
Compact Van			
Price	Base	363	804
FE	23.6	25.6	28.5
Weight (lb)	3,680	3,760	3,725
HP	153	160	172
Full-size pickup			
Price	Base	287	866
FE	18.0	18.9	21.2
Weight (lb)	4,250	4,400	4,350
HP	193	204	209

KEY: FE= fuel economy; HP = horsepower.

NOTE: Price refers only to incremental price of fuel economy technology and performance but does not reflect cost increases associated with safety and emission standards.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-19.

TABLE 4-3: 2015 Best-in-Class Mid-size Car Baseline Scenario

	Change from 1995 (in percent)
Weight reduction	10
Drag reduction	22
Tire rolling resistance reduction	20
Total reduction in traction force	15.4
Increase in engine efficiency (includes friction reduction)	12[a]
Increases in transmission efficiency	2
Reduction in accessory power	25
Decrease in (idle and braking) fuel consumption	35
Total fuel consumption decrease	25

[a]This is percentage increase in efficiency or:
(Efficiency 2015 - Efficiency 1995)/Efficiency 1995 * 100.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-21.

TABLE 4-4: Hypothetical Mid-size Car with Advanced Technology

	1995	2005(m)	2005(0)	2015(m)	2015(m)	2015(0)
Weight (lbs)	3,130	2,840	2,675	2,290	2,405	1.960
Engine:						
Size	3.0L	2.3L	2.2L	2.0L	2.4L	1.7L
Type	OHV V-6	OHC 4V/VVT	OHC 4V/VVT	DISC4V/VVT	4V/TDID5L	DISC 4V/VVT
Horsepower	140	168	158	144	132	122
Peak torque	165	160	154	140	140	111
Torque @ 2,000 rpm	155	150	143	129	130	109
Transmission	L-4	L-5	L-5	CVT	CVT	CVT
Axle Ratio	3.37	3.20	3.18	3.09	3.09	3.18
C_D	0.32	0.28	0.26	0.25	0.25	0.22
C_D	0.0105	0.0085	0.0080	0.0070	0.0070	0.0065
0 to 60 time (sec.)	10.4	9.1	9.1	9.2	10.0	9.2
Fuel economy (mpg)	28.0	38.8	41.7	53.2	59.0	63.5
Incremental price ($)	Base	920	2.100	2.550	2.870	6.250

KEY: CVT = continuously variable transmission; DISC = Direct Injection Stratified Charge Gasoline Engines; DSL = diesel; L = liter; m = Mean assumptions about new technology; o = Optimistic assumptions about new technology; OHC = overhead cam; OHV = overhead valve; TDI = Turbocharged Direct Injection Diesel Engine; VVT = variable valve timing.

SOURCE: Energy and Environmental Analysis, Inc., “Automotive Technologies To Improve Fuel Economy to 2015,” prepared for the Office of Technology Assessment, June 1995, p. 10-25.

TABLE 4-5: Conventional Vehicle Potential
Best-in-Class

		Subcompact	Intermediate	Compact van	Standard Pickup
	Baseline	**Honda Civic**	**Ford Taurus**	**Dodge Caravan**	**Ford F-150 4x2**
1995	FE	38.8	28.0	23.3	19.1
	Price	0	0	0	0
2005(m)	FE	49.05	39.0	32.3	33.5
	Price	$800	$920	$965	$1,080
2005(0)	FE	54.84	41.7	34.8	24.6
	Price	$1,700	$2,100	$2,330	$2,500
2015(m)	FE	67.30	53.2	45.0	31.6
	Price	$2,150	$2,550	$2,760	$2,870
2015(m) (diesel)	FE	74.94	59.0	50.9	39.5
	Price	$2,450	$2,870	$3,070	$3,630
2015(0)	FE	78.80	63.5	51.4	37.7
	Price	$4,850	$6,250	$7,000	$8,050

KEY: FE= fuel economy; m = median of technology estimates; o = optimistic technology estimate.

NOTE: Incremental prices do *not* include cost of emission and safety standards.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-30.

TABLE 4-6: Specifications of Some Advanced Electric Vehicles

Vehicle Type	Total weight (kg)	Motor output peak (hp)	Fuel consumption (kWh/km)	P (hp/kg)	E (Wh/kg-km)
GM Impact	1.348	137	0.115	0.091	0.086
Cocconi Honda CRX	1,225	120	0.103	0.087	0.084
BMW E-1	880	45	0.133	0.044	0.151
Chrysler Van	2,340	70	0.300	0.028	0.128
Ford Ecostar	1,405	75	0.188	0.040	0.134
Honda CUV-4	1,680	66	0.155	0.036	0.093

KEY: P = performance rating of vehicle + payload; E = specific efficiency of vehicle.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-39.

TABLE 4-7: 2005 Electric Vehicle Characteristics

		Subcompact	Intermediate	Compact van	Standard pickup
2005(m)					
Lead acid	Battery weight	586.7	776.2	880.0	1,137.3
	Total weight	1,500.0	2,003.1	2,275.2	2,838.5
Range = 80 miles	F/C	0.195	0.260	0.295	0.368
	Price	$8,090	$10,920	$14,000	$19,200
Nickel-metal hydride	Battery weight	234.2	389.3	441.4	570.4
	Total weight	1,027.0	1,377.2	1,565.5	1,921.5
Range = 100 miles	F/C	0.124	0.166	0.189	0.232
	Price	$14,590	$19,510	$23,750	$37,790
2005(0)					
Nickel-metal hydride[a]	**Battery weight**	1,057.4	1,381.4	1,586.1	2,058.1
	Total weight	2,229.1	2,928.2	3,368.7	4,264.1
Range = 200 miles	**F/C**	0.269	0.354	0.407	0.515
	Price	$56,600	$74,100	$86.800	$113.600
Sodium sulfur	Battery weight	292.2	381.7	**438.2**	**587.8**
	Total weight	991.2	1,311.0	**1,511.9**	**1,858.1**
Range = 200 miles	F/C	0.124	0.164	**0.189**	**0.233**
	Price	$31,600	$41,400	$49,300	**$64,950**

[a]Unrealistic Scenario.

NOTE: F/C is electricity consumption at outlet, (assuming charger efficiency of 94 percent), in kWh/km. Weight in kg; Range is nominal range in city driving; Price is incremental price over the same size conventional vehicle for that year. In each case, performance was controlled to “average” levels of 65 brake horsepower per ton, based on electric motor output, with weight based on curb weight plus nominal payload. Payload was set at **150, 180, 200, and 360** kg for the subcompact, intermediate car, compact van, and standard pickup, respectively. Lead acid batteries are discharged only to **80 percent depth of discharge, others to 100 percent for full range.**

SOURCE: Energy and Environmental Analysis, Inc., “Automotive Technologies To Improve Fuel Economy to 2015,” prepared for the Office of Technology Assessment, June 1995, p. 10-44.

TABLE 4-8: Computation of Incremental Costs and RPE for 2005 Mid-size EV

Component	Size	Cost basis[a]	Cost/price
Battery (lead acid)	34.9 kw-hr	$150/kw * 34.9 kwh	$5,240
Motor/controller	105.9 kw	$300 + (30/kw * 105.9 kw)	3,480
Electric power steering	..	$65	65
Heat pump air conditioner	..	$300	300
Total electric system	--	--	*9,085*
Engine	125 kw	$400 + $18/kw * 125 kw	2.650
Transmission	5-spd auto	$300 + $2/kw * 125 kw	*550*
Emission controls	Evap + Exhaust	$300	300
Net savings	--	--	*3,500*
Total variable cost (v)	--	--	5.585
Unit fixed investment (F)		See appendix B	900
RPE	--	(1.4 v+F) * 1.25	10.900

[a]The costs are much lower than current costs and include the "learning curve" effects for batteries, motors, and controllers. Battery charger cost not included.

KEY: RPE = retail price effect.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-46.

TABLE 4-9: 2015 Electric Vehicle Characteristics

Battery type		Subcompact	Intermediate	Compact van	Standard pickup
2015(m)					
Lead acid	Battery weight	393.5	515.1	590.3	779.8
	Total weight	1,079.7	1,429.8	1,644.5	2,077.0
Range =80 miles	F/C	0.140	0.185	0.213	0.269
	Price	$2.260	$3.175	$5.720	$9.050
Nickel-metal hydride	Battery weight	209.8	229.6	314.7	415.8
	Total weight	782.6	967.8	1,198.9	1,488.2
Range = 100 miles	F/C	0.095	0.117	0.145	0.180
	Price	$6,150	$6,800	$11,540	$16,740
2015(0)					
Nickel-metal hydride	Battery weight	611.1	788.4	898.4	1,197.8
	Total weight	1,377.8	1,790.9	2,045.9	2,634.5
Range = 200 miles	F/C	0.167	0.216	0.247	0.318
	Price	$25,560	$33,090	$39.750	$54.550
Sodium sulfur	Battery weight	220.6	284.5	324.2	432.3
	Total weight	746.0	975.8	1,117.1	1,396.2
Range = 200 miles	F/C	0.093	0.122	0.140	0.175
	Price	$18.080	$23.450	$28,765	$39,900
Lithium polymer	Battery weight	116.4	150.2	171.1	228.2
	Capacitor weight	60.0	80.0	100.0	120.0
Range = 300 miles	Total weight	637.5	838.5	969.5	1,185.9
	F/C	0.075	0.099	0.115	0.140
	Price	$8,720	$11,370	$13,500	**$19,200**

NOTE: F/C is electricity consumption at outlet, (assuming charger efficiency of 94 percent), in kWh/km Weight in kg; Range is nominal range in city driving; Price is incremental price over the same size conventional vehicle for that year. In each case, performance was controlled to “average” levels of 65 brake horsepower per ton, basal on electric motor output, with weight based on curb weight plus nominal payload. Payload was set at 150, 180, 200, and 360 kg for the subcompact, intermediate car, compact van, and standard pickup, respectively. Lead acid batteries are discharged only to 80 percent depth of discharge, others to 100 percent for fill range.

SOURCE: Energy and Environmental Analysis, Inc., “Automotive Technologies To Improve Fuel Economy to2015,” prepared for the Office of Technology Assessment, June 1995, p. 10-48.

TABLE 4-10: Sensitivity of Mid-size 2005 EV Attributes to Input Assumptions

	Battery weight	Total weight	Energy efficiency	Incremental price
<u>EV with lead acid battery</u>				
Base specifications	830	2,030	**0.250**	10,900
Reduced range (50 miles)	330	1,266	**0.156**	3,170
+ reduced performance (-20%)	319	1,230	**0.152**	2,130
+ reduced battery cost ($100/kWh)	319	1,230	**0.152**	960
+ increased motor efficiency (+10%)	270	1155	**0.127**	410
All except reduced range	603	1,683	**0.186**	4,125

SOURCE: Energy and Environmental Analysis, Inc., “Automotive Technologies To Improve Fuel Economy to 2015,” prepared for the Office of Technology Assessment, June 1995, p. 10-50.

TABLE 4-11: Energy Use for a Current (1995) Mid-size Car Converted to a Hybrid Electric Vehicle (kWh)

	Urban	Highway
Tractive energy	0.201	0.184
Motor output	0.214	0.192
Regenerative braking recovery	0.045	0.008
Tractive energy input	0.216	0.205
Engine output[a]	0.315	0.263
Fuel economy, mpg	32.7	41.2
Percent improvement over 1995 base	44.1	8.4

[a]Assumes batteries recharged to initial state at end of cycle.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-64.

TABLE 4-12: Series Hybrid Vehicle Efficiency

	1995	1995	2005(m)	2005(0)	2005(0)	2015(m)	2015(m)	2015(m)
Energy storage	Lead acid	Bipolar lead acid	Bipolar lead acid	UltraCapacitor	Flywheel	Bipolar lead acid	Ultracapacitor	Flywheel
Storage, specific power (W/kg)	125	300	,500	2,000	1,500	500	2,000	1,500
Storage, specific energy (Wh/kg)	30	42	45	5	30	50	15	35
Storage, efficiency	0.8	0.8	0.8	0.93	0.93	0.85	0.93	0.95
Vehicle weight (kg)	2469.4	1385.1	1100.7	994.3	979.5	906.3	864.8	851.6
Engine peak power (kW)	75,3	44.7	36.7	33.7	33.3	31.2	30.0	29.7
Engine size, litres	1.7	1.0	0.8	0.8	0.8	0.7	0.7	0.7
Storage, weight	795.7	1%.9	%.9	66.8	58.6	82.4	59.5	52.2
Storage, peak power (kW)	99.5	59.1	48.5	133.5	87.9	41.2	119.0	78.4
Storage energy (kWh)	23.9	8.3	4.4	0.3	1.8	4.1	0.9	1.8
Motor power (kW)	133.5	79.3	65.0	59.7	59.0	55.3	53.2	52.6
Drag coefficient	0.33	0.33	0.28	0.26	0.26	0.25	0.25	0.25
Rolling resistance coefficient	0.0110	0.0110	0.0085	0.0080	0.0080	0.0070	0.0070	0.0070
Urban fuel economy (mpg)	21.5	32.7	43.7	55.9	56.4	59.2	65.9	67.7
Highway fuel economy (mpg)	29.5	41.2	56.1	67.5	67.9	74.6	78.9	80.1
Composite fuel economy (mpg)	24.5	36.1	48.5	60.6	61.1	65.3	71.2	72.8
Range as electric vehicle (miles)	83.9	40.4	28.2	2.4	12.8	32.7	5.4	11.2
Time at maximum power (minutes)	11.6	7.2	4.8	0.4	2.2	5.5	1.2	2.6

NOTE: Motor efficiency, urban = 82 percent; motor efficiency, highway = 90 percent.

SOURCE: Office of Technology Assessment, adapted from Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-66.

TABLE 4-13: Comparison Between OTA and SIMPLEV Model Calculations of Hybrid Fuel Economy

	2005 (0)		2015 (m)	
	City	Highway	City	Highway
OTA	55.9	67.5	65.9	78.9
SIMPLEV	68.6	66.4	75.0	75.1
Difference	+22.7	-1.6	+13.8	-4.8

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

TABLE 4-14: Potential Parallel Hybrid Configurations for 1995 Mid-size Vehicle

	Base	Case 1: Parallel hybrid	Case 2: Parallel hybrid
Curb weight (lbs)	3,130	-3,400	3,250
Engine			
Size (L)	3.0	2.0	1.0
Power (HP)	140	120	49
Torque (newton-meters)	165	125	58
Motor			
HP	0	26.8	60
Torque	0	40	90
Electric Storage	N/A	Flywheel	Bipolar lead acid
Weight (lbs)	0	64	400
Power (HP)	0	60	60
Energy (kWh)	0	1	7.5

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-76.

TABLE 4-15: Incremental Prices for Series Hybrids

	Storage Device		
	Battery	**Ultracapacitor**	**Flywheel**
2005 (m)	$4,420	**$9,730**	**$7,260**
2015 (m)	**$3,170**	**$8,300**	**$6,100**

KEY: m = mean assumptions about new technology.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-78.

TABLE 4-16: Characteristics of a PEM Fuel Cell Intermediate-Size Vehicle in 2015

	Bipolar Lead Acid Battery	Ultracapacitor
"Zero engine" body weight	540.0	540.0
Fuel cell rating (kW)	37.1	30.8
Cell weight (kg)	148.3	131.2
Power storage: power (kW)	39.0	116.4
Energy (kWh)	3.5	0.9
Weight (kg)	78	58.2
Total hybrid weight	914.5	893.4
EV range (for cold start)	22.1	5.2
Time at peak power (minutes)	4.6	1.2
Energy efficiency (mpg, gasoline equivalent)	83.1	85.5
Price increment		
($650/kWh)	$38,750	$36,500
($65 /kWh)	$4,510	$4,920

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-82.

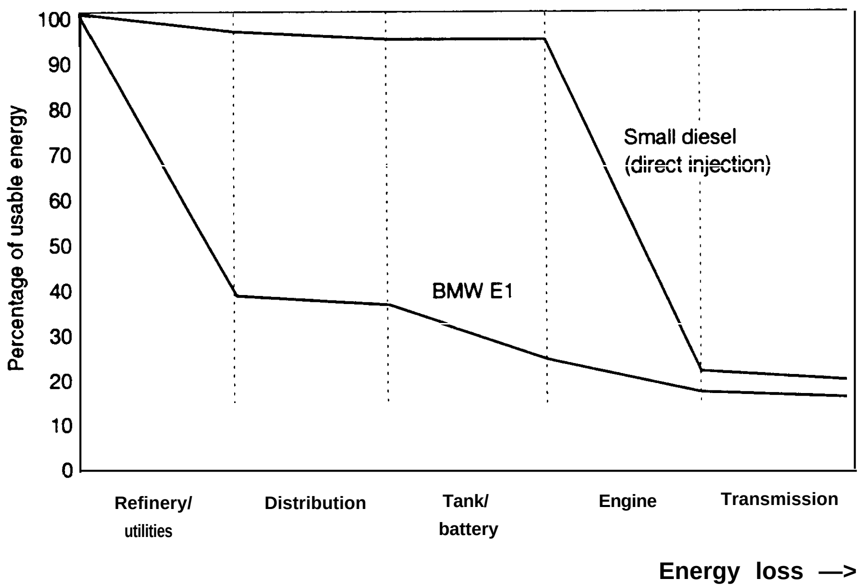
TABLE 4-17: Fuel Consumption and Annual Fuel Costs of Advanced Mid-size Vehicles

Type of vehicle	Fuel consumption	Fuel cost per year[a]
Baseline (Taurus)	33 mpg	$535[b]
Advanced conventional	53 mpg	$333
EV (lead acid)	0.27 kWh/mile	$223
EV (Ni-MH)	0.17 kWh/mile	$137
Series hybrid (lead acid)	65 mpg	$272
PEM fuel cell (methanol)	83 mpg (gasoline equiv)	$182

[a]Based on $1.50/gallon gasoline, 75 C/gallon methanol, 7¢/kWh offpeak electricity, 10,000 miles/year.
[b]The fuel economy values shown are EPA unadjusted values. Fuel costs are based on the assumption that on-road efficiencies are about 15 percent less. Clearly, each vehicle type will have a different adjustment factor, but it is not clear what those factors should be. For example, EVs will lose less energy from congestion effects (because they have regenerative braking and no idling losses), but will use substantially more energy to heat the vehicle--which is not accounted for in the EPA tests, where accessories are not used.
[c]Optimized aluminum body, DISC engine.

SOURCE: Office of Technology Assessment, 1995.

Figure 4-1: Losses Within the Overall Energy Chain (comparison of diesel and electric car)



SOURCE: BMW Traffic and Environment.

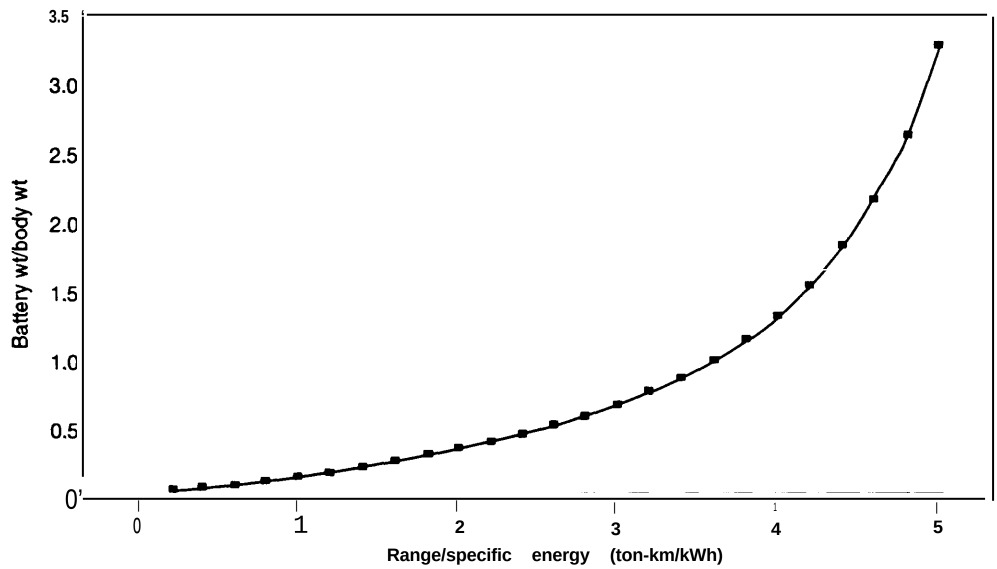
Efficiency	Diesel car	Electric car
Refinery or power station[a]	96%	36%
Distribution	98%	95%
Tank/battery	100%	68% (charge cycle and heating loss during standstill)
Engine (depending on drive cycle)	23%	66%
Transmission	90%	95%
Final result	19%	15%

[a]Without energy losses from the drilling hole to the refinery or power station.

NOTE: Figures for the electric car are for a daily mileage of 30 km (18.6 mi).

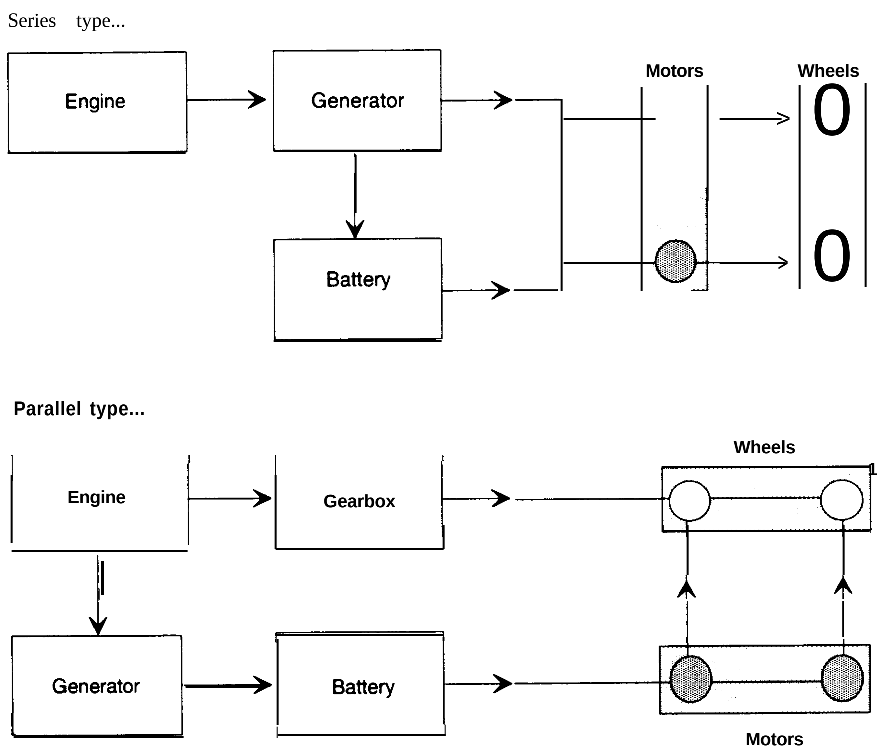
SOURCE: Electric car - BMW calculations, Diesel - MTZ 52 (1991) No. 2, p. 60-65.

Figure 4-2: Battery Weight vs EV Range



SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies to Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-41.

Figure 4-3: Hybrid Concepts



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. 10-53.

Chapter 5

Advanced Automotive R&D Programs: An International Comparison

This chapter attempts to describe and evaluate the federal role in the research and development (R&D) of advanced automotive technologies. It begins with a historical perspective on federal involvement in automotive R&D, from the early 1970s to the present. It then describes ongoing government/industry programs in the United States, Japan, and Western Europe, and draws some conclusions about the competitive position of the U.S. automotive industry in these technologies. The analysis compares the R&D needs resulting from the Office of Technology Assessment 's (OTA's) technical assessment with federal R&D budget priorities proposed for fiscal year (FY) 1996. The chapter concludes with a discussion of the federal role and the way it might evolve in the future.

At this writing, Congress is considering significant cuts in finding for federal agency programs that have supported advanced automotive R&D. If these cuts are implemented, recent initiatives such as the Clinton Administration's Partnership for a New Generation of Vehicles (PNGV, see below) will be seriously jeopardized, and will be competing with more traditional R&D programs (e.g., alternative fuels, heavy-duty engines) for a smaller pool of government resources. In any case, while this chapter provides a snapshot of current federal R&D efforts as of the summer of 1995, the reader should be aware that the landscape of federal R&D programs could change radically in the coming months and years.

AUTOMOTIVE R&D

It is important to understand that the largest source of finding for automotive R&D around the world is the industry itself. There is intense pressure on the manufacturers and their suppliers to innovate and to reduce production costs through the adoption of new technologies. The costs of innovation are very high. For example, the total cost of developing a new vehicle from concept to prototype may be hundreds of millions of dollars; moving it from prototype to production typically costs billions more. In 1992, R&D expenditures in the U.S. auto industry (vehicles and parts) totaled $12.3 billion, the second highest of all U.S. industrial sectors, and about 4 percent of total sales.[1] In 1992, General Motors (GM) and Ford had the first and third highest R&D expenditures among all U.S. companies.[2]

Some of the research conducted by the manufacturers is quite long term. For example, GM has investigated fuel cells for decades, and Ford has developed expertise in advanced composites for body structures. Yet, according to OTA's analysis, neither fuel cells nor advanced composites will likely be commercialized in light-duty vehicles for at least 10 years.

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[1] International Trade Commission, *Industry, Trade, and Technology Review,* August 1994, p.22.

[2] Ibid.

The bulk of private R&D funding, however, goes toward incremental technological improvements that could be commercialized in the next 5 to 10 years. The funding levels and directions of these private R&D programs are closely held, particularly for near-term products. For longer term technologies of the type discussed here, however, results are often published in the literature. Where information on these private R&D programs is available, it is included here.

Collaborative R&D

Compared with the billions of dollars spent by the industry on product R&D, government-supported R&D programs amounting to a few hundred million dollars per year may seem insignificant. However, there is a growing acceptance by manufacturers that commercialization of many of the advanced technologies discussed above will require a precompetitive, collaborative effort involving the major manufacturers, suppliers, universities, and government laboratories.

This has come about for several reasons. First, the manufacturers realize that it makes little sense for each separately to fund the development of technologies whose benefits are uncertain and difficult for an individual company to capture. Moreover, some of the benefits are social goods, such as increased energy security and reduced emissions, which are legitimate reasons for government interest, but not a high priority for the typical car buyer. Finally, much of the expertise in these technologies lies outside the knowledge base of the manufacturers or their traditional suppliers, residing instead with defense-oriented companies or government laboratories. It is too expensive for the major manufacturers to develop and maintain all the necessary engineering expertise for the advanced technologies in-house.

SCOPE

In this chapter, OTA focuses primarily on those collaborative programs that receive federal funding, including consortia of the major manufacturers and regional consortia involving suppliers, small entrepreneurial companies, and public utilities. OTA believes that an examination of these collaborative programs is most relevant to congressional committees making decisions about advanced automotive technology program funding and direction. It also provides a basis for evaluating the relative emphases of comparable efforts in Europe and Japan, particularly for "leapfrog" technologies that are still at the precompetitive stage. Nevertheless, the sketchy information available on the in-house R&D activities of individual manufacturers is an important caveat to recall in evaluating the conclusions reached here.

OTA makes no attempt here to catalog all federal research that might be in some way relevant to advanced vehicles. Instead, the emphasis is on describing the R&D programs that are explicitly targeted on the advanced light-duty vehicle fleet. Several R&D areas are considered beyond the scope of this report: R&D aimed at incremental improvements to conventional vehicles, whether in the areas of safety, reduced friction, or emissions control are excluded, as is R&D on alternative fuels for internal combustion engines. The area of intelligent vehicle highway systems

(IVHS) is also excluded, although there is a case to be made for integrating advanced vehicle technologies more closely with the broader systemwide concerns of IVHS.

THE FEDERAL ROLE IN ADVANCED VEHICLE R&D: A HISTORICAL PERSPECTIVE-1970-1995

The federal government has played an active role in R&D of advanced automotive technologies for more than 20 years. Fuel efficient, low-emission vehicles have long been seen by both federal and state governments as crucial to achieving the twin goals of reduced U.S. dependence on imported oil and improved urban air quality. Key pieces of federal legislation that have promoted advanced vehicle R&D are shown in table 5-1.

Reduced Oil Use

Beginning with the first oil shock in 1973, reducing U.S. dependence on imported oil became a major focus of U.S. transportation policy. In an effort to stimulate the development and commercialization of more fuel-efficient vehicles, Congress passed a series of laws beginning with the Energy Policy and Conservation Act of 1975, which mandated a doubling of the fuel economy of the new car fleet from 14 to 28 mpg. The Electric and Hybrid Vehicle Research, Development, and Demonstration Act was passed in 1976, which launched the Department of Energy's (DOE's) Electric and Hybrid Vehicle Program.[3] Congress continued to promote the reduction of transportation oil use through the Automotive Propulsion Research and Development Act of 1978, the Alternative Motor Fuels Act of 1988, and the Energy Policy Act of 1992.

Air Quality

The desire for cleaner air, particularly in urban centers whose air quality falls below federal standards, has also been a major motivator for government involvement in advanced vehicle technologies. In fact, the Public Health Service (and later, the Environmental Protection Agency--EPA) began finding research on cleaner-burning hybrid vehicles in the period 1969 to 1974.[4] But perhaps no regulation has had a greater impact on R&D than California's Low Emission Vehicle Program--LEV (adopted in September, 1990), which was devised to ensure compliance with the federal Clean Air Act Amendments of 1990.

In particular, California's requirement that 2 percent of vehicles sold in the state in 1998 (about 40,000 vehicles) must have zero emissions, rising to 10 percent--or 200,000 vehicles--by 2003, has greatly stimulated research on battery electric and fuel cell electric vehicles, the only

[3] The EHV Program had three parts, including R&D funding, vehicle procurement for market demonstrations, and loan guarantees to promote the involvement of small and medium-sized companies.

[4] Victor Wouk, "Hybrids: Then and Now," IEEE Spectrum, July 1995, p. 16.

technologies currently known that have zero tailpipe emissions of criteria pollutants.[5] The California LEV program (and its proposed adoption in several northeastern states) has not only stimulated joint research by the Big Three on advanced batteries and electric vehicles (EVs), it also spawned a myriad of small companies aiming to produce EVs (either converted from gasoline vehicles or purpose-built) to meet the 1998 requirements. Japanese manufacturers interviewed by OTA indicated that they had largely abandoned EV research until the California mandate forced them to renew it in earnest.

Perspectives on the Federal Role

The fact that the federal government has been involved with development of advanced automotive technologies for more than **20 years** might suggest that these technologies are now mature and ready for the market, but this is far from true. The principal reason is that there has been no market pull on these advanced technologies to provide a coherent market vision. Manufacturers have been able to meet government mandates for higher fuel economy and lower emissions through relatively inexpensive improvements to conventional vehicles, and, with falling real prices for gasoline, consumers place a very small premium on the high fuel economy offered by advanced technologies. These factors, combined with the high risk of investing in advanced technologies, have meant that industry cost sharing of government R&D contracts has been rather low--typically less than 20 percent.

There are additional reasons, however, that 20 years of government programs have failed to further develop the vehicle state of the art: government support has been inconsistent, poorly coordinated, and lacking in well-defined goals. As one example, figure 5-1 reveals the budget history of the DOE Electric and Hybrid Vehicle Program (for more detail, see box 5-l). This figure clearly shows the "rollercoaster" nature of federal R&D finding during the period 1976 to 1995. These budget fluctuations have made it impossible to sustain a coherent development program. For instance, after an initial flurry of activity on hybrid vehicles at DOE from 1978 to 1980, the hybrid effort was shelved until 1992.

The federal R&D effort has also suffered from agency parochialism. DOE has focused on the oil import reduction problem, with some attention to reducing the emission of greenhouse gases. The DOE view, however, has been that concerns about emission of criteria pollutants regulated under the Clean Air Act Amendments of 1990 are the purview of EPA, and there has been very little coordination between DOE and EPA' on advanced vehicle R&D.[6] The Department of Defense (DOD), particularly the Advanced Research Projects Agency (ARPA), has also been conducting research on electric and hybrid vehicles, which, until recently, was not well integrated with DOE research.

Since the advent of PNGV in September 1993 (see below), however, interagency coordination has improved. For example, DOE has established the Interagency Coordination Task Force for

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[5] Tom Cackette, "California's Zero Emission Vehicle Requirements and Implications for Hybrid Electric Vehicles,"
[6] Ken Heitner, U.S. Department of Energy, Office of Transportation Technologies, personal communication, Apr. 24, 1995.

Electric and Hybrid Vehicle Technologies to coordinate federal R&D in these technologies, and signed a Memorandum of Understanding with ARPA in June 1994 to lay out common interests and objectives and to minimize duplication.[7]

Finally, there has been little attempt to link R&D goals for advanced automotive technologies to specific national goals for imported oil reduction and emissions reduction from the transportation sector. DOE has proposed no specific overall goals or timetables for technology development in this areas In the absence of a coherent strategic plan by the administration, programs are driven by fragmentary congressional guidance contained in various pieces of legislation over the past 20 years. As one example, the Energy Policy Act of 1992 established the goal of displacing 10 percent of petroleum-based fbels with alternative fuels (ethanol, methanol, propane, natural gas, electricity, hydrogen) by 2000 and 30 percent by 2010. These goals, however, are not well integrated with the stated goals of current R&D initiatives such as PNGV, which does not address alternative fuels.

Partnership for a New Generation of Vehicles

The centerpiece of the current federal effort in advanced automotive R&D is PNGV, (see Box 5-2). Initiated by the Clinton administration together with the Big Three automakers in September 1993, PNGV is conceived as a joint government-industry R&D program aimed at the following three goals:

1. reducing manufacturing production costs and product development times for all car and truck production;

2. pursuing advances that increase fuel efficiency and reduce emissions of conventional vehicles; and

3. developing a manufacturable prototype vehicle in 10 years that gets up to three times the fuel efficiency of today's comparable vehicle, without sacrificing safety, affordability, comfort, or convenience.

Goal 3 is deliberately chosen to require technological breakthroughs in the vehicle power source, drivetrain, and structural materials (see chapter 3 for a discussion of candidate technologies). The PNGV timetable for Goal 3 is to select component technologies by 1997, produce a concept vehicle by 2000, and have a manufacturable prototype by 2004.

PNGV is actually a "virtual" program, in the sense that it coordinates and refocuses the various existing agency programs and resources toward the PNGV goals. NO "new" federal appropriations per se are planned for PNGV although the underlying agency programs that address PNGV goals may receive increases. PNGV has helped to bring greater coherence to the federal advanced vehicle R&D effort, by bringing representatives of the various government

[7] U.S. Department of Energy, "Electric and Hybrid Vehicle Program: 18th Report to Congress for Fiscal Year 1994," April 1995.
[8] Ken Heitner, see footnote 6.

agencies and industry together around the same table. However, while the defining goal of PNGV--developing midsize vehicles with fuel efficiencies up to 80 mpg--is clearly relevant to national goals of reducing oil consumption and greenhouse gas emissions, it appears to have been chosen because of the technical challenges that must be overcome to achieve it, rather than because of any relationship to specific national goals.

PNGV does bring one new dimension to the federal role in advanced automotive R&D that departs from past programs--an explicit federal interest in promoting the international competitiveness of the U.S. auto industry. According to the president's Budget for FY 1996, for example, "The PNGV initiative is a partnership with U.S. industry to ensure the global competitiveness of the U.S. automobile industry and its suppliers and improve environmental quality." In this new economic partnership, the federal government has given the U.S. industry (and particularly the Big Three) an unprecedented degree of control over the technology development agenda. This emphasis on competitiveness in turn has lent a proprietary flavor to PNGV that was not a characteristic of past programs. For example, foreign-based auto manufacturers are excluded from participating in PNGV (although foreign-based suppliers may participate under certain conditions).

OVERVIEW OF MAJOR ADVANCED AUTOMOTIVE R&D PROGRAMS

This section provides an overview of the major R&D programs and institutions involved in advanced automotive technology development in the United States, Europe, and Japan. It is based on published information as well as visits by OTA staff and contractors to European, Japanese, and U.S. manufacturers and government laboratories.

United States

According to a survey of federal program managers conducted by the PNGV secretariat, a total of $270 million was budgeted in 1995 for technological development in 14 key areas judged critical to the goals of the Partnership for a New Generation of Vehicles (see table 5-2). For FY 1996, the Clinton Administration requested an increase to $386 million or about 43 percent.

These budget figures are controversial, however. Industry sources contacted by OTA believe these estimates are inflated--that much of the government R&D included by agency program managers is not actually relevant to PNGV.[9] Depending on the accounting criteria used, the total figure for federal spending on technologies relevant to advanced automobiles could be higher or lower (see box 5-3).

[9] According to one PNGV participant, the *total* (government plus industry) R&D effort may approach $270 million in FY 1995.

Major Automotive R&D Programs in Federal Agencies

The discussion below characterizes the major advanced automotive R&D programs underway in the federal agencies, together with their finding levels and strategies for commercializing advanced vehicles.

Department of Commerce (DOC)

DOC's National Institute of Standards and Technology (NIST) is the focal point for the agency's advanced automotive research. NIST is a world-class center for physical science and engineering research with long experience in areas such as automated manufacturing processes, advanced materials, and development of measurement standards and techniques.

Overall, NIST's ongoing research is predominantly in the area of advanced manufacturing, followed by advanced composites and design methods. In the future, NIST's capabilities in the area of standards development could become very important for advanced vehicles--for example, standards for product data exchange, standards for measuring the performance of composite materials, or for information exchange between an electric vehicle and a charging station during rapid charging.

Although NIST's advanced vehicle-related R&D is scattered among several programs, the bulk of the finding is provided through the Advanced Technology Program (ATP), a 50-50 cost-shared R&D program with industry. ATP solicits research proposals from industry in several areas related to automobiles, including advanced composites, materials processing for heavy manufacturing, and automotive manufacturing. For example, in FY 1995 ATP initiated eight new projects, all related to the use of composite materials in vehicles, with annual finding of about $8.5 million (matched by an equal industry contribution).

DOC's advanced vehicle budget request shows an apparent decrease from nearly $20 million in FY 1995 to $9 million in FY 1996. The $9 million figure, however, includes only the cost of continuing projects started in earlier fiscal years. In fact, ATP expects to initiate $30 million in new auto-related contracts in FY 1996, but negotiations on these contracts are not yet completed. Thus, instead of being cut in halt the actual NIST budget for PNGV-related technologies would nearly double to $39 million in FY 1996. [10]

Department of Defense

DOD has numerous projects under way to improve the readiness and fighting capability of military vehicles. Many of these involve the same advanced technologies that are also being considered for the civilian light-duty vehicle fleet under PNGV DOD research is sponsored by a number of institutions, including research laboratories of the Army, Navy, and Air Force, as well as ARPA. In addition to sponsoring its own research, ARPA is the coordinator of the Technology Reinvestment Project (TRP), which promotes the development of "dual use" technologies that have both civilian and military applications. DOD's participation in PNGV is coordinated by the

[10] However, ATP funding is controversial in Congress, and significant cuts are being debated.

U.S. Army Tank Automotive Research, Development, and Engineering Center, which is the world's largest producer of military ground vehicles.

DOD's PNGV-related budget request shows an apparent increase from about $24 million in FY 1995 to over $42 million in FY 1996. In fact, this increase does not measure increased R&D activity, but rather reflects different accounting methods used in the two years.[11] In FY 1996, additional projects were included in the PNGV inventory that had been excluded in FY 1995. Indeed, actual DoD finding for auto-related R&D could fall substantially in FY 1996, if ARPA finding is cut as anticipated.

The ***Advanced Research Projects Agency, views*** its role in advanced vehicle development as a supporter of research on both medium-duty and heavy-duty drivetrains for military vehicles (e.g., buses, "humvees," and Bradleys); in the future, these technologies could be scaled down to light duty vehicles. ARPA contrasts this with the DOE approach, which is aimed primarily at the light-duty vehicle fleet. ARPA funds research on electric and hybrid vehicles through two mechanisms: the Electric/Hybrid Vehicle and Infrastructure (EHV) Program, and the TRP. The EHV Program was a congressional add-onto the budget in FY 1993, which grew to $45 million in FY 1994, but dropped to $15 million in FY 1995 and is zeroed out in the FY 1996 budget request.

All of the finding of the EHV Program is channeled through seven regional consortia (see table *5-3)* that provide at least 50 percent cost-sharing of ARPA finds. The consortia involve universities, state and local governments, small businesses, defense contractors, Big Three automotive suppliers, federal laboratories, transit agencies, environmental groups, utilities, and military departments.

ARPA's EHV Program has been a major source of finding for small companies interested in conducting advanced vehicle research that is not channeled through the Big Three automakers. The consortium approach has helped to keep contract management costs low while stimulating cross-fertilization of ideas among consortium members through triannual meetings. It is unclear what impact the elimination of the EHV Program will have on these consortia.

ARPA also manages the TRP, a program launched in 1993 to conduct joint govemment/industry research both to "spin off" defense technologies to the commercial sector and to "spin-on" state-of-the-art commercial technologies for military applications. TRP finds are currently supporting seven research projects with industry contractors, some of which are relevant to advanced vehicles, such as a project on developing computer simulation tools for concurrent engineering and vehicle design. Advanced vehicle powertrains were designated as a TRP "focus area" for 1995, with anticipated funding of around $25 million; however, these finds have been rescinded by Congress, and the future of the entire TRP is in doubt.

[11] According to information provided by the PNGV Secretariat.

DOE's involvement in advanced automotive research dates back to its inception in 1976 and before that in its predecessor agency, the Energy Research and Development Agency. Many elements of DOE's mission are directly relevant to advanced vehicles, especially the goals of improving efficiency of energy use, diversifying energy sources, and improving environmental quality.

DOE's 10 national laboratories are heavily involved in advanced vehicle research and have been encouraged to form Cooperative Research and Development Agreements (CRADAS) with industry and with the U.S. Council for Automotive Research (USCAR) consortia to develop jointly automotive technologies. In these CRADAS, DOE finds the laboratory efforts, while the industry funds its share of the work. A master CRADA has been developed to be the model for all such efforts by PNGV which eliminates the need to renegotiate the terms for each new agreement. Focal areas of DOE research include advanced engine technologies such as gas turbines, hybrid vehicles, alternative fuels, fuel cells, advanced energy storage, and lightweight materials.

DOE has the lion's share of PNGV-related federal R&D with $159 million of the total of $270 million (59 percent) in FY 1995. As noted above, the Office of Transportation Technologies (OTT) programs are the centerpiece of PNGV Major OTT R&D programs are described below.

The **Electric and Hybrid Vehicle Propulsion Program is** the cornerstone of DOE's transportation fuel efficiency research. Established under the Electric and Hybrid Vehicle Research Development, and Demonstration Act of 1976 as amended, this program recently released its 18th annual report to Congress. The three components of this cost-shared program with industry consist of Advanced Battery Systems, Fuel Cell Systems, and Propulsion Systems Development, including hybrid vehicles.

Advanced Battery Systems and High Power Energy Storage Devices. In October 1991, DOE joined with the Big Three and the Electric Power Research Institute to fund the U.S. Advanced Battery Consortium (USABC), a 12-year, 50-50 cost-shared, $260 million program to develop batteries with acceptable energy and power densities for electric and hybrid vehicles. USABC has identified both mid-term and long-term goals for battery performance. As of early 1995, the program involved six industrial contractors and six CRADAs with national laboratories. Three of the development contracts are for batteries that can satisfy the mid-term criteria, and three are for longer term technologies that could make EVS competitive with conventional gasoline-powered cars. In FY 1995, DOE provided $26.9 million to the joint USABC program, as well as $1.8 million for exploratory research on new battery technologies at several national laboratories. Requested finding for FY 1996 is $20 million for USABC and $2 million for exploratory research. The decrease in USABC funds from FY 1995 to FY 1996 reflects a focus on fewer batteries and the completion of mid-term battery development.

In FY 1996, roughly $10 million is requested to let cost-shared contracts through USABC for development of high-power energy storage devices, implementing a program begun in FY 1994. Development contracts for storage devices will be competitively selected among batteries, ultracapacitors, and flywheels. These will be used in hybrid and fuel cell propulsion systems.

Fuel Cell Program. There has been widespread consensus that proton exchange membrane (PEM) fuel cells are the most suitable type for light-duty vehicles, though the best method of supplying the hydrogen needed by the fuel cell is less clear. Currently, the two principal fueling options being explored are: on-board reforming of hydrogen-containing liquids, especially methanol; and on-board storage of hydrogen that is generated externally.[12]

In 1991, DOE contracted with GM's Allison Gas Turbine Division to develop a proof-of-feasibility methanol-fueled PEM fuel cell for light-duty vehicles. The first phase ended in FY 1993 with the testing of a 10 kW fuel cell system. In 1994, DOE signed contracts with teams headed by Ford and Chrysler/Pentastar Electronics to develop fuel cell systems using on-board hydrogen storage.

In parallel, DOE has been supporting a team headed by H-Power to develop a municipal bus powered by 50 kW phosphoric acid fuel cells. DOE is also conducting feasibility studies on fuel cell-powered locomotives.

In FY 1995, DOE was finding fuel cell contracts for light-duty vehicles at $16.1 million, for buses at $2 million, and for locomotives at $1.5 million. Additional exploratory fuel cell research on advanced electrodes and membranes was funded at $3.5 million, conducted at national laboratories such as Los Alamos, Brookhaven, and Lawrence Berkeley. Requested funds for FY 1996 increase to $28 million for light-duty vehicles, and supporting research at national laboratories increases to over $9 million, with level finding for bus and locomotive research. Cost-sharing of contracts by industry is expected to be around 20 percent.

Hybrid Propulsion Systems. DOE has supported hybrid vehicle research for well over a decade. In the late 1970s and early 1980s, General Electric (GE) developed a prototype hybrid vehicle that achieved up to 50 percent improvement in fuel economy compared with a similar conventional vehicle. The vehicle, however, was complicated, heavy, and expensive, and the effort was discontinued in 1984. In addition, in 1984, DOE began a cost-shared contract with Ford and GE to develop modular electric powertrains. Ford fabricated nearly a dozen 56 kW (75 hp) electric drivetrains that were tested in 1994 and inserted in Ford Ecostar vans.

DOE's current program for hybrid vehicles began in FY 1992 and is structured as a five-year, 50 percent cost-shared cooperative program with industry to achieve two-fold fuel economy improvement with low emissions and performance comparable to conventional vehicles. Contracts have been signed with teams, headed by Ford and GM, who are working primarily on series hybrid configurations. DOE finding of $35.4 million was provided for these contracts in FY 1995. In addition, DOE supported $1.5 million in "enabling" technology for hybrids, and $1.3 million for the Hybrid Challenge, a student competition in which university teams build hybrid vehicles that are then tested against one another.

In FY 1996, a finding increase to $52 million is requested for cost-shared hybrid vehicle contracts, which includes contracting with a third development team (from Chrysler) "enabling" R&D increases to $3 million.

12= oxidation of methanol fuel, without reforming, is a long-term option being explored in exploratory research programs.

The **Heat Engine Technologies Program** encompasses both light-duty and heavy-duty engine technologies, including research on turbine engines, automotive piston engines, diesel engines, and supporting combustion and emissions research.

Light-Duty Engine Technologies. DOE's gas turbine research programs have focused on the use of ceramic components to achieve the highest possible operating temperatures (around 2,500 'F) and efficiencies. Whereas early efforts were directed at turbines as the only power source for the vehicle (100 kW), direct drive with turbines is now recognized to be impractical, owing largely to the inefficiency of gas turbines at part load. Nevertheless, the prospect of using a small gas turbine (30 to 50 kW) as the auxiliary power source (operating continuously at high load) in a hybrid vehicle has given the turbine a new lease on life in the automotive context. Current programs, which are managed for DOE by the National Aeronautics and Space Administration, are focused on these scaled-down turbines. Funding in FY 1995 was about $7 million, with a requested increase in FY 1996 to $8.5 million.

In FY 1994, DOE began an effort called the Automotive Piston Engine Technologies program to accelerate the commercialization of lean-bum engines to enable the U.S. auto industry to regain market share from foreign competitors. This program works with industry through 50 percent cost-shared CRADAs with USCAR and other companies in such areas as lean-bum engine catalysts. It was funded in FY 1995 at $3 million, with a FY 1996 request at $4.5 million. In addition, DOE requested new activities in FY 1996 on improved internal combustion engines for hybrids, including spark ignited and compression ignited, for a total of $2 million. Combustion research was requested to increase from $2 million to $3 million in FY 1996.

Heavy Duty Engine Technologies. Although this program focuses on diesels for heavy-duty applications, successful technology will probably be scaled down to light-duty diesels. The program is developing ceramic coatings to allow much higher operating temperatures and pressures, as well as for better performance and reduced fiction in cam rollers, turbochargers, valves, and fuel injectors. Thermal efficiencies of over 50 percent have been demonstrated in truck-sized engines. Funding in FY 1995 was $6 million, requested to stay level in FY 1996.

The **Transportation Materials Program** has two distinct parts: propulsion system materials (primarily ceramics for heat engines) and vehicle system materials (lightweight metals and composites for vehicle bodies):

Propulsion System Materials. The thrust of this program is to develop cost-effective methods for manufacturing ceramic components for heat engines in the near term. During the past 10 years, there have been dramatic improvements in the processing and properties of ceramic materials (especially silicon nitride) for heat engines. So impressive have been these improvements that DOE officials interviewed by OTA feel that processing and reliability problems have been solved, and that the principal remaining challenge is to reduce the cost of ceramic components. Funding for FY 1995 was about $17 million, with a 2 percent increase requested in FY 1996.

Vehicle System Materials. This program seeks to develop lightweight, cost-effective materials for autos, including low-cost carbon fiber composites, as well as advanced alloys of magnesium and aluminum. Some of the work is performed in the national laboratories, and some in cooperation with USCAR's Automotive Materials Program. Funding in FY 1995 was $12 million with a requested increase in FY 1996 to $17 million. Much of the increase would go toward development of improved composite manufacturing technologies.

Related programs that are not part of PNGV include:

Alternative Fuels Utilization Program (AFUP), The Energy Policy Act (EPACT) of 1992 is the major impetus behind DOE's efforts to accelerate the commercial deployment of alternative fuel vehicles (AFVs).[13] EPACT defines AFV acquisition mandates for four major classes of fleets--federal, fuel provider, state, and privat/local fleets. Each has a well-defined schedule for the number or percent of acquisitions that must be AFVs. By FY 1995, about 15,000 AFVs had been purchased for the federal fleet, with 12,500 more purchases planned for FY 1996.[14] AFUP supports two major R&D thrusts--basic research on combustion and emission characteristics of various alternative fuels and demonstration programs of the performance of AFVs in daily use. The fleet test program includes a cross-section of over 2,000 cars, trucks, and buses. In FY 1995, overall finding of $52.6 million was apportioned as follows: AFV procurement subsidy to federal agencies, $20 million; data acquisition $13.2 million; AFV deployment, $9.6 million; engine R&D $7.8 million; atmospheric reactions, $2.0 million.

Pursuant to EPACT Title VI, the AFV deployment budget includes the Infrastructure Development and Demonstration Program, a $2 million, 50 percent cost-shared program with electric utilities and universities to test and evaluate electric and hybrid vehicle components and associated support equipment. The program provides an early market for evaluation of new electric vehicle technology.

Biofuels Research. DOE has a separate effort to develop alternative fuels from biomass, a domestic, renewable source, led by the National Renewable Energy Laboratory. If renewable fuels can be produced at a competitive cost, this would not only reduce U.S. reliance on imported energy, it would also reduce greenhouse gas emissions from the transportation sector. The largest effort in the program is to produce ethanol from agricultural and forestry residues, waste paper, and low-value industrial waste streams. Funding for development of transportation biomass fuels in FY 1995 was $35 million, with a requested increase to $38 million in FY 1996.

Hydrogen Program. Hydrogen is the preferred source of energy for automotive fuel cells. DOE's Hydrogen Program was initiated in the mid-1970s following the OPEC oil embargo and its resultant energy supply shocks. Congress has encouraged additional DOE activity through the Matsunaga Hydrogen Research, Development, and Demonstration Act of 1990, the Clean Air Act Amendments of 1990 (Title IV), and EPACT. The Matsunaga Act required the development of a five-year management plan to develop hydrogen technologies, while the EPACT required DOE to initiate work with industry to produce hydrogen from renewable energy sources and evaluate the feasibility of modifying natural gas pipelines to transport hydrogen and natural gas mixtures. A

[13] Fuels of interest to the program include electricity, ethanol, hydrogen, methanol, natural gas, and propane.

[14] Executive Office of the President, Office of Management and Budget, *FY96 Budget Highlights* (Washington, DC: Printing mice, 1995), p. 22.

Hydrogen Technical Advisory Panel has been established to provide oversight of the federal program.

The current DOE hydrogen program is located in the Office of Utility Technologies. The program is a comprehensive effort that involves development of technology for hydrogen production, storage, transport, and utilization. This infrastructure will also be required for the use of hydrogen as a transportation fuel Funding in FY 19 95 was $9.5 million, with a decrease to $7.4 million requested for FY 1996.[15]

Department of Interior (DOI)

Current activities are quite limited (only $495,000 in FY 1995), but include research to improve titanium and aluminum matrix composite casting processes, and recycling strategies for nickel-metal hydride batteries. A budget increase to $2.5 million is proposed for FY 1996.

DOI's Bureau of Mines has developed considerable experience in tracking materials and energy flows through product life cycles. Life-cycle assessment of advanced vehicles and components can help to anticipate problems with raw materials availability, environmental impacts, and recyclability. This includes the worldwide availability of raw materials, environmental impacts of industrial processes, and strategies for recycling of materials. No other agency appears to be ***looking*** seriously at these issues.

Department of Transportation (DOT)

Since 1982, when DOT research on fuel-efficient engines was terminated by the Reagan Administration, DOT has not done significant research on light-duty vehicle propulsion systems. However, DOT's Federal Transit Administration (FTA) has been supporting fuel cell research for transit buses that is likely to be relevant to fuel cell-powered light-duty vehicles. In 1987, FTA initiated a jointly funded program with DOE to develop a fuel cell-powered bus test bed, which was demonstrated in April 1994. The 30-foot bus is powered by a 50 kW phosphoric-acid fuel cell with a nickel cadmium (NiCd) battery that supplies peak power. Two similar buses are to be tested starting in spring of 1995. FTA's participation in that project has ended (no finds were allocated in FY 1995), but a new project is beginning that is expected to involve 40-foot buses powered by an advanced phosphoric acid or PEM fuel cell.

DOT has designated the National Highway Traffic Safety Administration (NHTSA) as the coordinator for all DOT activities relating to PNGV NHTSA is responsible for conducting safety research and promulgating federal standards for motor vehicles. As such, much of the ongoing research on crashworthy structures, improved restraint systems, rollover protection, biomechanics, crash modeling, and crash avoidance for conventional vehicles is also highly relevant to advanced vehicles. NHTSA's FY 1995 budget request for crashworthiness research

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[15] On February 1, 1995, the House Committee on Science held hearings on H.R. 655, "The Hydrogen Future Act of 1995," which would authorize increases in the Hydrogen Program to $25 million in FY 1996, $35 million in FY 1997, and $40 million in FY 1998.

(including safety systems and biomechanics) contracts was about $10 million, with an equal amount requested for crash avoidance research.

In FY 1996, NHTSA has requested $5 million in PNGV-relevant R&D Of this, $3.5 million will be used to develop computer models to evaluate the crashworthiness of lightweight automotive structures; 1.5 million is requested to study the impact of advanced vehicles on consumers, the U.S. economy, and the U.S. transportation system. NHTSA will administer a congressionally earmarked program involving joint efforts between West Virginia University and its industrial partners to demonstrate the use of advanced materials (e.g., metal foams, composites, and sandwich structures) to improve crashworthiness.

Environmental Protection Agency (EPA)

EPA's main interest in advanced vehicles relates to their emissions, both criteria pollutants such as nitrogen oxides (NO_x) and hydrocarbons, and greenhouse gases. EPA had one Of the earliest R&D programs on advanced propulsion systems, dating back to a program under the Public Health Service in 1971. After the formation of DOE in 1976, the program moved to that agency and evolved into what is now DOE's Office of Transportation Technologies.

There are two current thrusts at EPA relevant to advanced vehicles: one involves cleaner alternative fuels the other seeks to reduce criteria pollutants from highly efficient, hybrid vehicles (those having small ICES engines). The requested increase in EPA's PNGV budget from $7.6 million in FY 1995 to $12.5 million in FY 1996 will go to support the latter thrust. Industry has identified four-stroke, direct injection engine technology as a "gap area" that needs additional federal finding. Reducing the emissions from these engines is a major challenge, especially if the vehicle-operating strategy calls for the engine to be turned on and off repeatedly over the driving cycle (see hybrid discussion in chapter 3).

EPA also has a small program to develop testing and certification standards for electric and hybrid vehicles. This effort in FY 1995 involved less than one full-time equivalent employee, but will probably have to be expanded to provide a solid basis for evaluating these vehicles as they are developed.

National Aeronautics and Space Administration (NASA)

NASA has experience installing many advanced technologies in aircraft and spacecraft that are now being considered for light-duty vehicles. These include components such as gas turbines, fuel cells, lightweight metals and composites, as well as broader system experience with efficient electric power management and optimization of complex systems. A focal point of these technologies is the Lewis Research Center, which has managed the advanced gas turbine program for DOE and fuel cell programs for DOE and DOD.

Recent workshops with U.S. automakers identified several NASA technologies that can be introduced into vehicles in the near term: sensors to measure cylinder pressure and hot exhaust characteristics; insulating and high-temperature ceramics for improved catalytic converters; thermoelectric materials to generate electricity from exhaust heat; and optical inspection technology for cylinder liners. NASA's indicated PNGV-related budget ($5 million in FY 1995 increasing to $7 million in FY 1996) probably understates the amount of R&D that would be of interest to the auto industry.

In the future, NASA plans to launch a significant thrust directed at improved electric drivetrains. The overall concept will include management of the primary power source, energy storage, and power management systems, as well as the development of a high-speed 80-120 kW dynamometer for system development. This is expected to reduce significantly powertrain losses during acceleration and braking transients. The basis for this activity is the NASA technology for space power systems, high-capacity actuators for launch vehicle thrust control, and power-by-wire systems for advanced aircraft. NASA will also lead an industry/government team to conduct tradeoff studies to evaluate candidate concepts and technology that could meet the PNGV 80 mpg goal.

National Science Foundation (NSF)

NSF conducts research on the enabling technologies that may provide the basis for major breakthroughs and advances. NSF identified around $54 million in FY 1995 projects that are related to advanced vehicles, with a requested increase to nearly $57 million in FY 1996. Invariably, however, this research is basic or generic research in areas such as materials synthesis and behavior, engineering, manufacturing, sensors, and computer organization and operation. Although this basic research could be critical in solving such challenges as lubrication of high-temperature ceramic engines, virtually none is targeted on advanced vehicles per se.

Collaborative Private-Sector R&D Activities

United States Council for Automotive Research (USCAR)

Collaborative research among the Big Three has been under way since 1988. USCAR was formed in 1992 to help coordinate administrative and information services for existing and future research consortia aimed at addressing common technological and environmental concerns. USCAR is an umbrella research organization of the Big Three that currently covers 14 research consortia. It is also the administrative coordinator for the industry's participation in PNGV The USCAR consortia support a broad range of research, much which is funded privately. A portion of the research is jointly funded by the federal government, however, and eight CRADAs are in force between USCAR and various national-laboratories. Highlights of the activities of several of the key consortia are described below.

The mission of the ***U.S. Advanced Battery Consortium*** (USABC) is to develop EV batteries that will significantly improve range and performance. Although several battery types are available today (e.g., lead acid and nickel-cadmium), USABC does not believe that they offer sufficient long-range performance potential. As of early 1995, USABC had awarded six major research contracts to develop mid-term (nickel-metal hydride and sodium sulfur) and long-term (lithium iron disulfide and lithium polymer) batteries. USABC is currently funded under a 12-year, $260 million budget that is shared equally between DOE, USCAR and the electric utility industry. DOE finding in FY 1995 was $26.9 million.

The ***Automotive Materials Partnership*** (USAMP), which now includes the former Automotive Composites Consortium, conducts joint research to develop lightweight materials for improved fuel economy. Materials included are: polymer composites; light metals (aluminum, magnesium, titaniu, and metal composites); engineered plastics, cast iron, steel, and ceramics. At this writing, all research on polymer composites had been on the less expensive, but lower performing glass-fiber reinforced materials, rather than the more expensive carbon-fiber materials. Life cycle assessment of materials use is also being investigated under USAMP.

The ***Low Emission Technologies R&D Partnership*** (LEP), in addition to research funded exclusively by the Big Three aimed at such areas as 100,000-mile in-use emission compliance and evaporative emissions control systems, has a number of ongoing projects with the national laboratories on emission control technologies, the largest of which is on the development of a lean NO_x catalyst. LEP is also working with NASA in the areas of advanced sensor technology and thermoelectric materials for generating electricity from exhaust heat.

The activities of the ***Supercomputer Automotive Applications Partnership*** include development of technology to reduce drastically design time through computer visualization, and to analyze crashworthiness, especially for modeling the behavior of composite materials.

The ***Vehicle Recycling Partnership is*** working on recycling technologies for numerous automotive components and materials, and also on strategies for material sorting and identification, as well as material selection and design criteria for improving the recyclability of cars.

Utilities

Suppliers of alternative fuels for alternative vehicles (e.g., natural gas and electricity) have an inherent interest in supporting research, development, and demonstration programs that would expand transportation markets for those fuels. A further incentive is that energy utilities come under the procurement mandates of the Energy Policy Act of 1992, which require that they increase purchases of alternative fuel vehicles for their own fleets. Thus, utilities are assuming a leadership role in fleet demonstration programs and in developing the necessary refueling infrastructure to support wider use of their own fuels.

DOE coordinates 13 institutions participating in the *Site Operator Program,* they are located in various regions of the country, and test electric vehicles under many different conditions of weather, climate, and terrain. In FY 1994, these institutions, which include universities, electric utilities, and military installations, were testing approximately 190 electric vehicles, and more than 40 additional vehicles were on order. Cost sharing of DOE contracts among the site operators is generally more than 90 percent.

The Electric Power Research Institute, which is the principal research arm of the electric utility industry, established the ***Infrastructure Working Committee*** (IWC) in 1991. IWC brings together representatives of the auto industry, utilities, universities, regulators, and others to work in five key areas: establishing standards for safe, efficient electrical connectors and charging stations; addressing health and safety codes (e.g., for ventilation, and electro magnetic field exposure); examining the impact of EVS on load management, power quality, transmission, and distribution systems; educating customers about the EV infrastructure; and developing protocols for communication between the EV and the electric utility during recharging. The Department of Energy works closely with IWC.

In addition, the Electric Vehicle Association of the Americas, the Edison Electric Institute, the Electric Transportation Coalition and the Electric Power Research Institute have jointly initiated the "EV America" program, which seeks to place incrementally as many as 5,000 roadworthy EVS in a controlled market demonstration.

European Union

Several countries in Europe have major programs underway to develop electric and hybrid vehicles as well as their supporting technologies and infrastructure. These include France, Germany, and Sweden. There is considerable cooperation in development activities across national borders among auto manufacturers and suppliers.

The European Union (EU) supports these efforts through precompetitive research programs. Funding is provided primarily through the Framework Program. The nature of precompetitive research is such that the specific programs are of interest to several different industries, which makes it difficult to determine a specific finding level for the auto industry. It is estimated that EU support of technologies of interest to the auto industry was about ECU 100 million ($125 million) in 1994. [16] About 80 percent of the awards support R&D activities; the remaining 20 percent support demonstration projects to create the necessary standards and prove the technologies ready for commercialization.

Auto manufacturers in the European Union have stepped up their collaborative R&D efforts in advanced technology, at least in part as a competitive response to U.S. consortia under USCAR and programs such as the PNGV In May 1994, the European car industry formed the European Council for Automotive Research and Development (EUCAR), a consortium of nine European automakers including Ford of Europe and Adam Opel AG, the German subsidiary of General Motors. EUCAR will facilitate collaborative-research projects (especially on traction batteries)[17] and give the manufacturers a unified voice on matters relating to R&D In June, EUCAR released a proposed "Automotive Research and Technological Development Master Plan" for consideration under the Fourth Framework Program (1994 to 1998). The Master Plan proposes to focus on three areas:

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16 According to the European Union, a significant portion of these monies are spent on such areas as intelligent vehicle technologies and intelligent highway systems.

17 EUCAR Working Group, "Traction Batteries," Second Progress Report, July 1994.

- product-related research on advanced powertrains, materials, and so forth,
- manufacturing technologies to match the new vehicle concepts, and
- the total transport picture, including the integration of the vehicle into a multimodal transport system.

Total finding for the proposed EUCAR program is estimated at ECU 2,430 million over five years, of which about ECU 570 million (about $715 million) is estimated to involve projects of a specifically automotive nature. Although the goals of the Master Plan bear some resemblance to the PNGV goals, the plan describes research that is not so close to the market (with no mention of a timetable for prototype vehicle development, for instance) and broader in scope (encompassing such issues as worker training and broader "sustainable transportation" concerns).

EU officials indicated to OTA that only a fraction of these projects would be funded, and that the primary source of finding would be the five-year Framework IV program, which is currently soliciting proposals. [18]

To stimulate R&D on advanced vehicles using traction batteries, the EU has announced, beginning in 1995, a Task Force called "Car of Tomorrow" that will pursue the following objectives:

- identify research priorities in consultation with industry, including small companies and users,
- ensure coordination among R&D programs of the EU and with other national and international initiatives, and
- encourage the use of additional financial resources (e.g., venture capital) for advanced automotive R&D

France

France is considered by many observers to be a promising market for advanced vehicles, particularly EVs. One official cited three reasons that France, as opposed to the United States in general (and California in particular), offers greater market opportunities for EVs: more compact urban areas result in shorter commute distances; 90 percent of electricity generation in France is nuclear or hydro, so that power plant emissions associated with EV use are low; and gasoline is expensive. [19]

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[18] Awards are expected to be made during the period April through June 1995.

[19] Jean-Yves Helmer, Executive Vice President, Peugot Citroen, memorandum distributed at a press conference in Anaheim, CA, Dec. 2, 1994.

Government-Funded Programs

Active interest of French automakers in electric and hybrid vehicles dates back to the late 1960s. It is estimated that support of battery and fuel cell research by the French government has exceeded $35 million to date.[20] As in Germany (see below), much of French government finding for advanced vehicles supports EV demonstration programs and infrastructure development.

In July of 1992, an agreement was signed by government officials, Electricite de France (EDF), and two major automobile groups (Renault and PSA Peugeot) to develop supporting infrastructure for EVs and equip at least 10 battery charging sites by 1995.[21] In 1993, La Rochelle, a city of 120,000 on the Atlantic coast, became the first often cities to participate in a two-year EV demonstration program. Fifty vehicles are involved in the Phase 1 La Rochelle trial. The project envisions providing 20 to 50 EVs and supporting infrastructure to each participating city, along with vehicle financing and driver training. PSA Peugeot Citroen is manufacturing the vehicles for the La Rochelle site. EDF is actively involved in the program.[22]

The city of Paris and EDF formed a partnership in 1993 to promote the use of EVs in Paris.[23] Paris, with approximately 1,000 EVs in use, has installed 50 municipal recharge stations throughout the city, and plans to have 200 by the end of 1995. The city of Paris and EDF have committed to acquiring EVs for their vehicle fleets and hope to have as many as 260 in operation during 1995. The combined cost of the project to the two partners is estimated at around FFR $48 million ($1O million).

Industry R&D

The PSA Group (Peugeot and Citroen) have developed an EV city car they claim could be in production (with a subsidy from the French government) by the end of the decade. The price difference between the electric and gasoline versions of the Peugeot 106 (assuming production volumes of 10,000 units) is estimated to be $4,000 to 5,000, not including the batteries. Peugeot also announced plans to convert 10,000 gasoline-powered vans to electric power.

Renault is also active in the development of EVs It has delivered EVs to Sweden for participation in its three-city demonstration project and hopes to launch an electric version of the Clio in 1996 with annual production of 1,000 units. It is cooperating with Matra in the development of a purpose-built EV.[24] EDF operates approximately 500 EVs primarily small vans.

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20 U.S. General Accounting Office, *Electric Vehicles: Likely Consequences of U.S. and Other Nations' Programs and Policies,* GAO/PEMD-95-7 (Washington, DC: December 1994), p. 69.

21 Ibid, p. 65.

22 Noel Bureau, "Electric Peugeot 106 and Citroen AX Vehicles in Customers' Hands in La Rochelle," *The 12th International Electric Vehicle Symposium (EVS-12),* vol. 1, (San Francisco, CA: Electric Vehicle Association of the Americas, 1994), pp. 11-17; P. Beguin and C. Peyiere, 'Gearing Up for Industrial Production of Peugeot 106 and Citroen AX Electric Models," *The 12th International Electric Vehicle Symposium (EVS-12),* vol. 1, (San Francisco, CA: Electric Vehicle Association of the Americas, 1994), pp. 111-115; and C.A. Bleijs et al., "Analysis of the Results Obtained with EDFs Electric Fleet and the La Rochelle Program," *The 12th International Electric Vehicle Symposium (EVS-12),* vol. 1, (San Francisco, CA: Electric Vehicle Association of the Americas, 1994), pp. 171-180.

23 Patrick LeFebvre and Jean-Paul Camous, 'A Partnership in Paris for the Development of the Electric Vehicle," *The 12th International Electric Vehicle Symposium (EVS-12), vol. 2,* (San Francisco, CA: Electric Vehicle Association of the Americas, 1994), pp. 247-256.

24 That is, a vehicle designed "fire the ground up" to be an EV, not just a converted gasoline-fueled vehicle.

Germany

Government-Funded Programs

Contemporary research in Germany on EVs began in 1971.[25] By 1978, a fleet of 140 electric vans were in operation, supported by thirteen battery transfer stations. At present, there are about 4,000 to 5,000 EVs on the road in Germany.[26] Government financial support of advanced battery research since 1974 has exceeded DM 97.5 million ($66 million), and support of fuel cell research to date has exceeded DM 35 million ($24 million) .27

Recently the German government has concentrated on supporting projects that seek to demonstrate and evaluate EVs.[28] Three major programs are currently underway. The most important is a four-year EV demonstration and evaluation program on the island of Rugen. The project began in October 1992, and aims to test EV performance under a full range of driving conditions. It is ultimately expected to involve 60 vehicles. The German government is providing half of the estimated budget of DM 40 to 50 million ($23 to $30 million). A second program, dubbed Project Telecom, is expected to last three years and involve forty electric and hybrid vehicles.[29] Finally, the German Postal Service began a two year test of 20 to 25 zinc-air battery vehicles and their supporting infrastructure. In December 1994, it was announced that an additional 50 vehicles would be purchased and that the test program would be extended through 1996. The budget for the Postal Service Test is about DM 25 million ($18 million) .30

In Germany, EVs are free from taxes for five years, but otherwise receive little direct support at the national level.[31] However, some local regions are actively supporting them. For example, Bavaria and Baden subsidize as much as 30 percent of the purchase price of EVs.

Industry R&D

German automakers have been investigating advanced vehicle concepts for more than 20 years. Volkswagen alone has built and tested over 400 electric and hybrid vehicles. German automakers can take credit for some remarkable achievements. For example, in 1994, Daimler Benz announced the development of a prototype van powered by a PEM fuel cell, the result of an R&D investment reportedly over $lbillion. Also in 1994, VW's Audi division marketed the A8, a luxury car featuring a novel aluminum space frame design, the result of a 10-year development effort with Alcoa.

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25 U.S. Department of Energy, *Electric and Hybrid Vehicle Program: The Second Annual Report to Congress for Fiscal Year 1978, DOEICS-0068* (Washington DC: January 1979), p. 60.

26 Dietrich Naunin, "Survey on the Drive Systems, Battery Technology, Charging and Infrastructure Systems for German Electric Vehicles," *The 12th international Electric Vehicle Symposium*, (EVS-12), *vol. 2, (San* Francisco, CA: Electric Vehicle Association of the Americas, 1994), pp. 768-776.

27 Ibid.

28 U.S. General Accounting Office, see footnote 20, p. 72.

29 Ibid, pp. 63-65.

30 Yehuda Harats et al., "Electric Fuel and the Deutche Bundespont Postdienst: A Joint EV Demonstration Program," *The 12th International Electric Vehicle Symposium (EVS-12)*, vol. 2, (San Francisco, CA: Electric Vehicle Association of the Americas, 1994), pp. 226-235.

31 U.S. General Accounting Office, see footnote 20, p. 47.

In May 1994, OTA staff visited four German automakers: Volkswagen, BMW, Porsche, and Mercedes Benz, and one supplier, Robert Bosch, to discuss advanced vehicle R&D Some of the results are illuminating. There was uniform optimism about the future of direct-injection diesel engines, which can achieve a 40 percent increase in fuel efficiency compared to current gasoline engines. Considerable skepticism was expressed, however, about the ability of pure electric and hybrid vehicles to meet the performance and cost expectations of consumers. Although some German automakers have designed advanced vehicles from the ground up (e.g., BMW's E-1 electric car), most prototypes involve conversions from production gasoline or diesel vehicles with batteries and electric motors added. This approach reduces financial risk, while enabling companies to test alternative concepts.

Sweden

Government-Funded R&D

Swedish government support for contemporary research on electric and hybrid vehicles began in the mid 1970s. Owing to concerns about the performance and range of pure EVs the Swedish research program has primarily focused on hybrids. The Swedish National Board for Industrial and Technical Development (NUTEK) and the Swedish Transport and Communications Research Board (KFB) have begun three complementary electric and hybrid vehicle programs.[32] These are:

1. Beginning in 1993, a six year electric and hybrid vehicle research program funded by NUTEK with an annual budget for the first three years of $1 million.

2. A four-year KFB-led electric and hybrid vehicle demonstration program with government finding of $16 million and matching finds from participants.

3. A technology procurement program was established in 1992 by NUTEK to create demand pull for electric and hybrid vehicles. In 1994, two purchasing groups formulated specifications for vehicle performance and price. Eight to 10 prototypes are to be delivered in 1995 for evaluation. Members have committed to purchase 220 vehicles, if their specifications are met.

The three largest cities in Sweden (Stockholm, Gothenburg, and Mamlo) have EV and hybrid demonstration projects under way. Major participants include Renault, Volvo, the national government, and regional electric power producers. The city of Gothenburg has taken the lead with its "Start" Project, involving 10 vehicles and at least one electric charging station, funded at $1.25 million per year. Recently, KBF has signed four-year agreements with Gothenburg and Mamlo that will enable them to deploy a wider variety of vehicles and to increase each of their electric and hybrid vehicle fleets to more than 50 vehicles.[33]

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[32] B. Essle and A. Lewald, "Swedish National Programs for Electric and Hybrid Electric Vehicles," *The 12th International Electric Vehicle Sympo.m @J&12)*, vol. 1, (San Francisco, CA: Electric Vehicle Association of the America% 1994), pp. 698-706.

[33] Ibid.

Industry R&D

In 1992, Volvo unveiled its Environmental Concept Car, which used a gas turbine with an electric drivetrain. More recently, it has announced plans to market a hybrid electric vehicle in the United States in 1997 or 1998. The hybrid will be based on its 850 sedan using a four-cylinder gasoline engine, and will meet California ULEV requirements. The vehicle is expected to cost 30 percent more than a gasoline vehicle of comparable performance, have 25 percent better fuel efficiency, and have a range of more than 160 miles.[34]

Japan

Government-Funded Programs

The major ongoing Japanese government/industry collaborative programs relevant to advanced vehicle R&D are shown in table 5-4. Japan was the first country to pursue the development of electric vehicles through a collaborative research program. MITI's Agency for Industrial Science and Technology launched a modest program with Japanese manufacturers to advance the state of the art of EVs that ran from 1971 to 1977, with total finding of $19 million. The program did not develop any successful vehicles, but did lead to improved EV components. A follow-on 10-year program to promote EVs intended to have 250,000 on-road and off-road EVs in the fleet by 1986, but actually only 1,200 on-road and 10,000 off-road vehicles (mostly golf carts) were produced in that year.

Under the recently launched New Sunshine Program, an umbrella for MITI's ongoing energy programs, are several R&D programs relevant to advanced vehicles. The "Eco-Station 2000" program intends to convert 2,000 Japanese service stations (of a total 60,000 stations) into "Eco-Stations" by the year 2000. Eco-Stations will provide motorists with access to a range of alternative fuels including methanol and natural gas, as well as electric charging facilities. The program is funded at a total of 3.66 billion yen FY 1993 to 1995), and there are currently several Eco-Stations established in the Kanto, Chubu, and Kinki areas.

Another collaborative MITI program, the Dispersed-Type Battery Energy Storage Technology program which runs from 1992 to 2001 with total finding of 14 billion yen, aims to develop long-life lithium batteries for small-scale load-leveling systems for home use and high-energy density lithium batteries for EVs

MITI's New Energy and Industrial Technology Development Organization has supported research on PEM fuel cells from 1992 to 1995, aimed at development of 1 kW modules. Funding is reported at an annual average of 200 million yen. The program involved eight companies, including Sanyo, Fuji, Mitsubishi, Toshiba, and Asahi Glass.[35] A follow-up program is now being planned, with the goal of developing PEM stacks in the tens of kW range. Industry sources interviewed by OTA stressed that, although the Japanese PEM program got a slow start, it is

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[34] Jack Keebler, "Volvo Hybrid EV Slated for U.S. Sale," *Automotive News*, Dec. 19, 1994, p. 43.
[35] Kenneth Dircks, Ballard Power Systems, personal communication, Apr. 19, 1995.

rapidly catching up to North American programs and PEM fuel cells are being actively developed and tested by some of the most powerful companies in Japan.

Japan has also had a massive fuel cell development program aimed at energy production since 1981, with cumulative finding of 61.4 billion yen (1981 to 1995). These fuel cells, including molten carbonate, solid oxide, and phosphoric acid electrolytes, are intended for electric power generation plants and are not directly applicable to vehicles, but industry sources interviewed by OTA suggested that the experience gained from these investments should be applicable to development of automotive PEM fuel cells.

MITI has also been supporting ceramic gas turbine development in a program from 1988 to 1996, funded at 16 billion yen. The turbines, however, are 300 kW units intended for electric power generators, not automobiles. Numerous past ceramic technology programs, together with private industry investments, have given Japanese companies the most advanced ceramic capability in the world. For example, the best ceramic turbocharger rotors, widely considered to be the closest analog of automotive ceramic gas turbine rotors, are made by Japanese companies such as Kyocera, NGK Insulators, and NGK Sparkplug.

Industry Programs

Japanese auto manufacturers have been involved in research on electric vehicles for more than 20 years. Nevertheless, OTA's interviews with the automakers suggested that much of this work had been put on the back burner owing to continuing problems with traction battery performance and doubts about the broad consumer appeal of EVs This attitude changed, however, with the adoption of California's zero emission vehicle (ZEV) regulations. Currently, all of the major Japanese manufacturers (often in collaboration with electric utilities) have developed electric cars in anticipation of the California ZEV regulations that go into effect beginning in 1998. Nevertheless, these efforts may fairly be described as defensive. The automakers appear to believe that many of the environmental and energy efficiency concerns with current ICE cars can be solved by improvements to ICES and intelligent vehicle-highway systems, rather than by resorting to exotic technologies such as EVs hybrids, and fuel cells. Thus far, the Japanese industry has not been inclined to develop collaborative R&D programs that rival USCAR and PNGV

OTA staff visited with engineers from Honda, Nissan, Toyota, and Mitsubishi in Japan to discuss advanced automotive R&D Despite the fact that the Japanese government has sponsored research in the past, and Japanese companies have in-house research programs on advanced technologies, it appeared clear that much of this work had been allowed to lapse until the California ZEV regulations revived their EV programs.

Japanese companies agreed with OTA staff conclusions that substantial improvements in fuel economy are possible through lightweighting and more aerodynamic design, but thought some of the gains projected in OTA's scenarios were too optimistic (for example, one company suggested that maximum weight reduction with aluminum would be 24 percent of curb weight, while OTA projects that a **30** percent reduction is possible), Like the German automakers, the Japanese were skeptical about the future cost and performance characteristics of traction batteries for EVs and about the fuel efficiency potential of hybrids. In contrast to the Europeans, the Japanese companies appeared relatively uninterested in compression-ignited (diesel) engines for passenger cars. They have, moreover, aggressive programs to introduce cleaner and more efficient spark-ignited engine technologies such as lightweight aluminum lean-bum engines and lean NO_x catalysts. Actually, recent model Toyotas and Hondas using conventional engines are poised to meet California's ultralow emission vehicles (ULEV) standards in 1998, which is an achievement that could undermine the desirability of more expensive vehicles that bum "cleaner" alternative fuels such as alcohols and natural gas.

ANALYSIS OF ADVANCED AUTOMOTIVE R&D PROGRAMS

U.S. Competitive Status in Advanced Automotive Technologies

"Leapfrog" Technologies

All of the world's major auto manufacturers began investigating electric and hybrid vehicle technologies during the late 1960s and early 1970s. Over the years, each manufacturer has developed and tested prototype EVs and hybrids with varying design configurations, and there have been some notable achievements. Mercedes Benz has deployed a prototype fuel cell-powered van. General Motors has developed the Impact, a prototype EV sports car that goes from zero to 60 mph in eight seconds. If current plans hold, Volvo will be the first manufacturer to offer a gasoline engine/electric drive hybrid car in the United States in 1997 or 1998.

Despite significant improvements in the cost and performance of advanced vehicle technologies, though, automakers interviewed by OTA remain skeptical about the ability of leapfrog vehicles to compete with steadily improving conventional vehicles in the near term, at least without government subsidies. For example, Volvo's hybrid is expected to cost 30 percent more than a comparable conventional vehicle, and have a range of only 160 miles.[36] Japanese manufacturers credit the California ZEV mandates with forcing the revival of R&D on EVs that had been allowed to lapse.

Despite the problems with the federal R&D programs discussed above, the U.S. R&D effort on leapfrog automotive technologies appears to be more comprehensive in both scope and content than similar efforts in other industrialized countries. No other country has collaborative R&D organizations comparable to USCAR the DOE national laboratories, and PNGV nor the regulatory aggressiveness of California's (and potentially several northeastern states') ZEV regulations. Using the PNGV secretariat's budget estimate of $270 million in FY 1996--no other government comes within a factor of two of these levels. While other countries have specific areas of relative strength (e.g., the Japanese industry's expertise in advanced ceramics and a growing

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[36] Keebler, see footnote 34.

fuel cell effort), a continuation of the more comprehensive U.S. approach is likely to put U.S. companies in a strong position technologically. Whether this technological lead will be translated into early commercialization in the United States will depend on government policies as well as the way in which the vehicles perform and how much they cost relative to steadily improving conventional vehicles of the same generation.

"Advanced Conventional" Technologies

The U.S. car industry's competitive position in "advanced conventional" automotive technologies--those that promise significant but evolutionary improvements in fuel efficiency and reduced emissions--does not appear to be as strong. For example, German automakers have developed advanced, direct injection diesel engines that offer a 40 percent increase in fuel efficiency, while reducing the noise, vibration and particulate emissions that formerly have been associated with diesels. A significant fraction of new passenger car sales in Germany are diesel-powered, whereas diesel passenger cars have disappeared from the U.S. market. In OTA's view, if NO_x emissions from these engines can be reduced through the use of improved catalysts, diesel-powered cars could make a comeback in the U.S. market. Based on their experience with building small, efficient diesels for passenger cars, European automakers may also be in an excellent position to exploit the use of compact diesel powerplamts in hybrid electric vehicles. This is a promising option currently being evaluated by the PNGV partners.

Japanese manufacturers apparently believe they can achieve many of the benefits of leapfrog technologies through evolutionary improvement in conventional technologies, at much lower cost. One example is the lean-bum gasoline engine (see previous chapters), which offers fuel efficiency improvements of 10 percent at relatively low cost. This has been a technology targeted by Japanese manufacturers, especially Honda. If NO_x emissions from lean-bum engines can be reduced through catalysts or other means, these vehicles will be able to meet California's ULEV standards. To date, no U.S. automaker has announced its intention to market a lean-bum engine vehicle.

Another "advanced conventional" technology that can improve fuel economy is the use of lightweight aluminum instead of steel in the vehicle structure. This is another case where some foreign manufacturers have been more aggressive than U.S. automakers, at least in introducing actual production vehicles. In 1991, Honda introduced its aluminum-intensive sports car, the NSX. In 1994, Audi (working with Alcoa) unveiled the A8 luxury coupe, which has an innovative aluminum space frame structure. Although neither of these vehicles is particularly lightweight (or cheap), they demonstrate a near-term technology that could be used for fuel efficiency gains.

These examples are not offered to suggest that U.S. automakers are ignoring these technological opportunities. Rather, they reflect differences in automakers' assessments of the cost-effectiveness of these technologies, given current fuel prices and consumer preferences in the United States. In fact, the Big Three have extensive in-house research programs on lean NO_x catalysts, and will build direct injection diesels for the European market through their subsidiaries in Europe. Furthermore, Federal finding for compact diesels, lean NO_x catalysts, and aluminum manufacturing technologies is requested to increase substantially in the FY 1996 budget (see below). The principal lesson from this experience for leapfrog technologies is that even when the feasibility of these technologies is proven, commercialization will depend on the manufacturers' judgments of cost effectiveness and market acceptance.

U.S. R&D Program

The U.S. R&D program for leapfrog automotive technologies is technologically diversified and includes a mix of near term and long-range options. For example, batteries, ultracapacitors, and flywheels are being researched in parallel as energy storage devices, as are gas turbines, diesels, and advanced gasoline engines for hybrid powerplants. Near term prospects, such as advanced lead acid traction batteries and aluminum body structures, are being investigated, along with longer term technologies such as fuel cells and advanced composites. At this writing, it is very uncertain which powertrains, drive systems, body designs, and materials will combine to give the best package of cost and performance in advanced light duty vehicles of the future. Indeed, depending on the desired vehicle function, location, and driving conditions (e.g., fleet or private, cold or warm climate, urban or rural), different combinations of technologies may be most appropriate. The federal R&D program is conscious of these uncertainties, and is structured to pursue several options in parallel, so as not to pick a timer prematurely.

The current research program involves a large number of participants, including eight government agencies, the national laboratories, and the Big Three and their suppliers and contractors. Government officials interviewed by OTA noted that mechanisms such as the Interagency Hybrid and Electric Vehicle Task Force, PNGV technical meetings, and ARPA-sponsored meetings of regional consortia were stimulating an unprecedented level of information sharing. Industry officials also expressed satisfaction with the new climate for collaborative research and noted enthusiastic cooperation from the agencies and laboratories with which they were associated. Industry cost-sharing of government contracts is growing, ranging from 50 percent or more for nearer term technologies (e.g., piston engines for hybrids) to around 15 to 20 percent for longer term technologies (e.g., fuel cells).

Key Budgetary Changes in FY 1996

FY 1996 is significant because it is the first real opportunity for the PNGV program to influence the budget priorities of the participating federal agencies. Table 5-5 gives a summary of some of the larger budget changes requested in FY 1996 for the agency programs discussed above. In the analysis section below, the impact of these proposed changes is assessed.

As might be anticipated, the largest increases in FY 1996 are in DOE's Electric and Hybrid Vehicle Program, the cornerstone of the PNGV effort; specifically, in high-power energy-storage devices, fuel cells, and hybrid systems. Small piston engines and turbines for hybrids are requested for a significant increase at DOE, as are materials for lightweight vehicles; however, hybrid vehicle and composite materials programs in NIST and ARPA may confront large cuts.

The priorities reflected in the federal budget request for FY 1996 appear generally consistent with the results of OTA's technical analysis, presented in previous chapters. Research needs identified by OTA including the need for more cost-effective ceramic and composite manufacturing processes, improved high-power energy-storage systems, and cost reduction of fuel cell systems, are all targeted for increases by DOE.[37] The opportunity noted by OTA for using a small, efficient direct injection diesel in a hybrid vehicle is also part of additional finding requested by DOE in FY 1996, and the challenge of reducing the emissions from these vehicles is being addressed by EPA.

The finding priorities also tend to support recent statements by observers of PNGV that the most likely configuration of the PNGV prototype vehicle is a hybrid, powered in the near term by a piston engine, and in the longer term perhaps by a fuel cell. Funding for advanced battery research is steady or declining, while there are significant increases for contracts on power storage devices, hybrid systems (including a new hybrid development team at Chrysler), and fuel cells. Interestingly, while two out of three of DOE's fuel-cell contracts (with Ford and Chrysler) call for on-board storage of hydrogen fuel the budget request for DOE's Hydrogen Research and Technology Program is down by 22 percent from FY 1995.

R&D Areas Likely to Require Increased Support

By its own acknowledgment, PNGV is a technology development program focused primarily on component and vehicle hardware to achieve its 80 mpg goal. At this stage, less attention is being given to several issues--including safety, infrastructure, standards development, and life-cycle materials management--that must be addressed before successful commercialization of an advanced vehicle. In each of these areas, the private-sector role is dominant, but government also has an important role to play. The result is that, as the initial hardware problems with advanced vehicles are solved, substantial additional federal resources will have to be allocated to address these issues.

safety. Advanced vehicles raise numerous new safety concerns stemming from both their lightweight structures and exotic propulsion systems. These include the lack of experience with crash behavior of complex new vehicle designs and composite materials, as well as the question of how safety regulations may have to be modified to account for a fleet that contains a mixture of heavier conventional steel vehicles and lighter aluminum or composite vehicles.

In addition advanced propulsion systems will also introduce new safety concerns. Advanced batteries may pose new safety risks, not only from their large mass, but also owing to corrosive electrolytes, toxic materials, high operating- temperatures, and potential for electric shock of passengers.[38] Flywheel power-storage devices that must spin at many tens of thousands of revolutions per minute pose obvious risks in crash situations. The manufacture, transport, servicing, and disposal of these materials and components raise additional safety issues.

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[37] Note, however, that the contemplated cuts in NIST's Advanced Technology Program and ARPA's Electric and Hybrid Vehicle program hit some research areas, such as composites manufacturingg, particularly hard. If these programs are eliminated, they will more than offset proposed increases by DOE in composites processing finding.

[38] An overview of in-vehicle safety issues for electric vehicles can be found in J. Mark, National Renewable Energy Laboratory, "Environmental, Health, and Safety Issues of Sodium-Sulfur Batteries for Electric and Hybrid Vehicles, Volume IV: In-Vehicle Safety," NREL/TP-463-4952, November 1992.

Of course, the primary responsibility--and liability--for vehicle safety lies with the automakers. Government, however, has the responsibility to understand the issues and set appropriate safety peformance standards. NHTSA, under the Department of Commerce, is responsible for safety regulations for motor vehicles. NHTSA has received comments on new and amended Federal Motor Vehicle Safety Standards collected under an Advanced Notice of Proposed Rulemaking, but has not drafted any final rules. NHTSA has determined that EVs should comply with the intent or purpose of all existing standards," although it recognizes the need to modify existing regulations that apply to ICE vehicles as appropriate.

DOE's National Renewable Energy Laboratory (NREL) has conducted a number of studies on EV safety issues,[39] and since 1990 has chaired the Ad Hoc EV Battery Readiness Working Group, a government/industry advisory body.[40] While NREL and the Working Group have made a good start, much remains to be done. Examples include: the need for better data from a more extensive testing and demonstration program; developing "systems" approaches to EV safety (as opposed to battery or component-oriented approaches); comprehensive risk assessment to place particular risks in perspective; and the need to broaden the focus to include additional technologies, such as flywheels and ultracapacitors.

As discussed in the section on crashworthiness of vehicle materials and structures, preliminary tests have demonstrated that vehicles made of aluminum and polymer composites can meet safety standards. Designers and regulators, however, do not currently have the tools to predict accurately the behavior of these advanced vehicle structures in crash situations, especially for composites. In FY 1996, NHTSA has requested $3.5 million to model the crashworthiness of advanced, lightweight vehicles. Much more experience with the crash behavior of these materials is likely to be required before designers and regulators develop the confidence they currently have in steel.

Infrastructure. Advanced vehicles cannot operate in a vacuum; they require a supporting infrastructure comparable to the existing conventional vehicle infrastructure. As used here, infrastructure refers not only to fuel production, distribution, storage, and transfer to the vehicle, but also to manufacturing issues such as materials availability, manufacturing expertise, and capabilities for servicing, repair, and recycling vehicles.

Depending on the specific vehicle design, fuel and structural materials, this infrastructure could look very different from those of today, although a major transformation of the infrastructure will not occur rapidly. It is more likely that advanced vehicles for the mass market will be designed to function within the existing infrastructure--at least initially--than that the massive petroleum-based fuel infrastructure will be changed to accommodate new vehicle technologies.[41] Eventually, vehicle technologies and supporting infrastructure may evolve together incrementally into new forms.

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39 Studies have included safety issues associated with shipping, in-vehicle safety, and recycling/disposal of a number of EV battery types, including sodium sulfur, nickel-metal hydride, lithium polymer, and lithium ion.

40 C.J. Hammel, Engineering Society of Detroit, "Electric Vehicle Environmental, Health, and Safety Program and Battery Readiness Working Group," January 1994.

41 Examples would be hybrids that can run On dual fuels such as gasoline and methanol, or fuel cells that run on reformed gasoline or diesel fuel

The current federal R&D program focuses almost exclusively on developing advanced vehicles; at most, a few million dollars--perhaps 1 percent of the hardware budget--has been set aside for infrastructure considerations. DOE has a $2 million program to work with the electric utility industry to develop infrastructure for EVs and finding for studies to determine infrrastructure needs for fuel cell vehicles has been requested in FY 1996.

There are undoubtedly many reasons for the lack of federal attention to infrastructure issues. One is the chicken-or-egg problem: it is risky to invest in infrastructure development for vehicles whose numbers and requirements are not yet clearly defined. Another has been the belief that the private sector has the responsibility for infrastructure development. A third reason has been a lack of follow-through on the part of government. For example, although $40 million was authorized by Congress in the Energy Policy Act of 1992 for electric vehicle infrastructure development and demonstration programs, no money was ever appropriated.

U.S. experience with programs aimed at promoting the use of alternatively fueled vehicles has shown that the lack of a convenient refueling infrastructure is a critical constraint. The infrastructure issue is certain to constrain advanced vehicle development as well. Ultimately, the cost of developing a national infrastructure for advanced vehicles is the responsibility of fuel providers and the automakers. Experience with AFV programs, however, has shown that the government has an important role to play in such areas as national standards development, federal fleet procurement, coordinating with states and localities to ensure an adequate concentration of vehicles in a given area, demonstration programs, and so forth. As the technological uncertainties of advanced vehicles are resolved, the federal government will have to pay increased attention to this area to ensure the national availability and reliability of infrastructure to support these vehicles.

Standards. Today's light-duty vehicle fleet is largely uniform in terms of the structural materials and propulsion system technologies. Although there are slight variations among models--such as in their use of plastics or size of engine, for the most part the fleet is composed of steel vehicles using gasoline internal combustion engines. The standards and specifications for these materials and engines are well established.

With the prospect of a fleet of vehicles made of exotic structural materials, mix-and-match powertrains, operation algorithms, and alternative fuels and fueling systems, manufacturers, consumers and regulators must each be assured of the safety, reliability, and performance of these vehicles and subsystems. This is certain to -become a critical area of government involvement (along with standards organizations and private companies) for complex new vehicle technologies. Standards associated with crashworthiness and infrastructure have already been mentioned above. In addition, however, much more work will be needed in the areas of vehicle testing, component testing, and material testing. With an increasingly global automobile industry, harmonization of U.S. standards with international standards is also essential.

Again, the primary responsibility for development of these standards will be private-sector organizations such as the Society of Automotive Engineers. The government, however, must also be able to set such standards as are necessary to fulfill its regulatory functions (examples include emissions testing standards, fuel economy standards, and standard procedures for handling emergency situations).

As one example, emissions testing of hybrid vehicles presents a complex problem. Depending on the relative sizes of the engine and battery (or other energy storage device), the control algorithm that determines when the power sources turn on and off, and the fuel type, the emissions from the hybrid over the test cycle may range from zero to a significant level. How the test procedures are established and how emissions limits are set could have a major impact on what kinds of hybrids are produced as well as their cost. Yet, EPA currently has less than one full time equivalent employee working on this problem. In the future, important roles can be seen for NIST (for materials and manufacturing standards), EPA (for environmental performance standards), DOE (for component testing and certification standards, and refueling standards), and NHTSA (for safety standards).

Life Cycle Materials Flows. Light-weight vehicles with advanced powertrains will utilize a very different set of materials than do current autos. Because the auto industry is such a prodigious user of materials, any significant change would have wide-ranging ramifications for the entire life cycle of materials use, from extraction of raw materials to final disposal. As one example, if 10 percent of all new vehicles sold in California in 2003 are electric vehicles, and most of these use advanced lead acid batteries, the auto industry's demand for lead will increase significantly. While the lead mining industry may be able to handle the increased demand, a significant impact is expected on the battery-recycling industry. In fact, significant increases can be expected in releases of lead residues to the environment from battery-recycling processes.[42] To the extent that battery recycling facilities are not located in California, the net effect of the California ZEV regulations would be to "export" lead pollution to other states where recycling is performed. Similar life-cycle impacts on the economy and environment may result from use of other advanced materials in other propulsion systems or structural components.

DOE conducted some studies of materials flows associated with battery EV's in the early 1980s.[43] These appeared to concentrate primarily on questions of materials availability, rather than environmental impacts on the entire materials cycle. These studies must be updated to reflect modem technologies and regulations. The Department of the Interior Bureau of Mines has developed considerable expertise in recent years in the areas of life-cycle materials flows, and might be an effective agency for preliminary studies.

Future Role of Federal R&D Programs

At this writing, Congress is debating the appropriate federal and private-sector roles in supporting scientific research and technology development across a broad range of areas. Advanced vehicle R&D and especially the joint public/private partnership concept of PNGV is part of that debate. Below, OTA discusses several issues that Congress should consider in its deliberations.

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42 Lester Lave et d., "Environmental Implication of Electric Cars," *Science, vol. 268,* May 19, 1995, p. 993.
43 See, for example, U.S. Department of Energy, "Electric and Hybrid Vehicle Program: First Annual Report to Congress," December 1977, p. 29.

Issue 1: Should Congress continue to support advanced vehicle K&WY

During the past 20 years, government policies at the federal and state levels have been the principal drivers for leapfrog vehicle development. Auto manufacturers and their suppliers are anxious not to be blindsided by new technologies, but have had little market incentive to invest in developing leapfrog technologies on their own.[44] The rationale for this government involvement has been that the benefits offered by these vehicles--improved air quality, enhanced U.S. energy security--are social benefits that do not command higher prices in the marketplace.

Government policies to stimulate advanced vehicle R&D have been of two types: "carrots" such as R&D contracts or procurement subsidies for advanced vehicles; and "sticks" such as higher regulatory standards for emissions control and fuel economy. Regardless of one's view of California's ZEV regulations, for instance, it is undeniable that they have stimulated extensive research on batteries and fuel cells that would not have occurred in their absence. In addition numerous small, entrepreneurial companies producing small numbers of electric vehicles and fuel cell prototypes are dependent on the ZEV regulations for their continued existence. The automakers, however, have fought bitterly against these regulatory mandates, claiming that they are forcing technologies into the marketplace before they are ready.

This lack of market demand for advanced vehicles seems unlikely to change in the foreseeable future, absent a major oil price shock or other unforeseen developments. With real gasoline prices at historic lows and urban air quality improving, car buyers care more about such attributes as good acceleration performance and carrying capacity than about increased fuel economy and reduced emissions. This is especially true if these attributes carry a higher price, as OTA's analysis suggests. Thus, if government wishes to continue to pursue the goal of superefficient vehicles, it will likely need to continue its involvement, whether through R&D finding, mandates, or other incentives.

Issue 2: Is the federal advanced vehicle R&D effort coherent and consistent with national needs?

Government policies toward advanced vehicles have been driven by a diverse set of concerns, including the desire to improve urban air quality, reduce oil imports and, more recently, to avoid global climate change. This diverse set of concerns has led to a patchwork of legislation and programs that attempt to address the concerns through different technical and economic approaches. The result has been a federal effort that has been poorly coordinated and that lacks clearly defined relationships to national needs.

Traditionally, for example, R&D on controlling vehicle emissions to address air quality issues such as those addressed in the Clean Air Act have been the province of EPA, while R&D on improving fuel economy to address energy security issues has been the province of DOE.

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[44] Historically, industry cost-sharing on government R&D contracts to develop risky, long-term technologies (e.g., gas turbines, fuel cells) has generally been less than 20 percent. In some recent programs, such as the DOE R&D contracts with the automakers on advanced batteries and hybrid vehicles, industry cost-sharing is around 50 percent.

Although fuel economy and emissions characteristics are closely related in actual vehicle operation, R&D programs at EPA and DOE have not been well coordinated.

Many other examples might be cited. During the past 20 years, finding for R&D programs such as DOE's Electric and Hybrid Vehicle Program has fluctuated wildly, making it impossible to sustain a coherent effort to develop hybrid vehicles. And, although Congress outlined clear goals for bringing alternatively fueled vehicles into the fleet in the Energy Policy Act of 1992, federal tax policies favor some fuels at the expense of others, without regard for the fuels' relative energy content or desirability from an environmental point of view.

PNGV is clearly an attempt to address some of these issues, by coordinating government and industry R&D efforts toward achieving commonly accepted goals; principally, the development of an **80** mpg prototype vehicle by 2004. Nevertheless, the 80 mpg target appears to have been chosen more for the technological innovations that will be required than for any direct relationship to national goals for reduced oil imports or reduced greenhouse gas emissions. Although a superefficient vehicle would clearly contribute greatly to these goals, little thought has apparently been given about whether the 80 mpg target is the most cost-effective approach. For example, the same amount of imported oil might be displaced more cheaply through a combination of a 50 mpg target with a more aggressive alternative fuels program.

The point here is not that a high fuel economy target is wrong, but that appropriate planning and analysis are lacking that would enable an evaluation of the entire federal R&D program in the context of broader national goals for air quality, energy security, and reduced potential for global climate change. This analysis becomes especially important in a tight budget environment in which PNGV-inspired R&D programs may be competing with other continuing programs (e.g., alternative fuels heavy-duty vehicle research) for the same resources.

Issue 3: ***Is the federal R&D relationship with industry structured to encourage maximum innovation?***

There is an ongoing debate about how federal R&D funding can best catalyze the emergence of advanced vehicle technologies. On the one hand, there are advantages to supporting work by the major automakers and their suppliers, since the automakers are in a position to commercialize rapidly a successful innovation in mass-market vehicles. On the other hand, many observers are concerned that federal efforts to develop leapfrog vehicle technologies rely too heavily on the existing industry, which they argue has a considerable stake in maintaining the status quo. In their view, more agile small and medium sized companies are best able to commercialize novel technologies, particularly in niche markets that initially maybe too small to attract the attention of the major automakers.

OTA's investigations for this study suggest that many small and medium-size U.S. companies have developed innovative advanced vehicle technologies not currently being displayed by the automakers.[45] Most of these companies recognize that successful commercialization of these innovations will require working in concert with a large company in the industry. The automakers

[45] Examples include superior regenerative braking systems and thermal management systems to enhance EV battery capacity in cold climates.

for their part recognize that small entrepreneurial companies have important contributions to make in solving the many challenging problems. These considerations suggest that the federal advanced vehicle R&D program should maintain a balance between small and large company participation to ensure the most successful outcome.

Traditionally, DOE advanced vehicle technology programs have worked primarily with large companies--defense contractors, automotive suppliers, or the Big Three themselves. To the extent that small or medium-size companies have participated, it has generally been as part of a subcontractor team. CRADA agreements with federal labs are also difficult for small companies to participate in, owing to the 50 percent cost sharing requirements. PNGV which is structured to work as a partnership under the leadership of the Big Three, seems likely to reinforce the large company orientation of the federal effort.[46]

Recently, other government programs, such as NIST's Advanced Technology Program, and ARPA's Electric and Hybrid Vehicle Program and Technology Reinvestment Project have begun to provide significant finding to contractors outside the traditional auto industry, especially to small and medium-sized companies. The Administration, however, has requested no finding for EHV in FY 1996, and substantial cuts in TRP and ATP are being debated in Congress. If these cuts are made as threatened, the federal program would become even more dependent than it currently is on the traditional industry.

Conclusions

The 20-year plus federal involvement with advanced vehicle R&D provides an important perspective on current efforts to commercialize advanced automotive technologies. First, from the earliest days of these programs, the amount of time that would be required to commercialize advanced vehicle technologies was severely underestimated. For example, according to a projection made in the first annual report to Congress of DOE's Electric and Hybrid Vehicle Program, dated December 1977: "The technology of electric and hybrid vehicles is such that . . . advanced vehicles with advanced energy storage systems are not likely to appear before the early to mid-1980 s." In fact, many of the technical challenges cited in those early reports, such as battery energy storage capacity, power density, and lifetime continue to be major challenges today.

Although most of the technologies involved in advanced vehicles (batteries, flywheels, motors and controllers) have received government finding for decades, this funding has been highly variable,[47] and only in the last five years has there been a concerted attempt by both the auto industry and government to develop viable commercial vehicles. Thus, although the technologies are by no means "new," we still have little experience with the way they perform as an integrated system in on-the-road vehicles, or with rapid, cost-effective manufacturing processes. At this

[46] The PNGV steering committee has recognized the need to find ways to bring innovative ideas from entrepreneur and small companies into the program, and has published a document titled "Inventions Needed for PNGV."

[47] For example funding for DOE's Electric and Hybrid Vehicle program roae to a peak of $37.5 million in 1979, but dropped to $8.4 million in 1985. By 1995, it had risen again to about $90 million.

writing, government finding for advanced vehicle R&D appears once again poised for a downturn owing to budget cuts. PNGV has begun to define the R&D priorities for some of these technologies, particularly for hybrid vehicles; however, it will be difficult, if not impossible, to address these priorities and solve the many remaining problems without sustained, and even increased, finding.

BOX 5-1: DOE's Electric and Hybrid Vehicle Program

DOE funding rose rapidly from startup in 1976 to a peak of $37.5 million in 1980. During this period, several prototype vehicles were constructed that established the "state of the art." General Electric developed a hybrid prototype vehicle with Volkswagen and the Jet Propulsion Laboratory. GE also developed a battery EV prototype with Chrysler. In the early 1980s, however, government and industry interest in the program began to wane, owing to three factors-the Reagan Administration's negative attitude toward what it viewed as government intervention in private-sector activities; a rapid decline in energy costs; and economic recession.[1] By FY 1995, program funding reached a low of $8.4 million. After cuts forced the elimination of government loan guarantees, small companies dropped out of the program, and after testing the GE vehicle, the hybrid development activity was shelved.

Most of the activity during the mid-1980s involved battery and electric drivetrain development (e.g., transistorized motor controllers, induction motors) with Ford, GE, and Eaton. Cost-sharing in the contracts by industry was generally from 10 to 20 percent, reflecting the high risk of these technologies as perceived by industry. Following the passage of the California Low Emission Vehicle program regulations in 1991, however, and the establishment of the U.S. Advanced Battery Consortium in the same year, government and industry funding turned a corner. The Big Three, which had made only a modest investment in advanced technologies during the 1980s, were forced to become more actively involved. A new five-year hybrid development program began in 1992, and fuel cell vehicle development contracts were negotiated with each of the Big Three. DOE funding for the Electric and Hybrid Vehicle program rose to about $90 million in FY 1995, with industry cost-sharing as much as 50 percent.

[1] Ken Barber, Department of Energy Office of Transportation Technologies, personal communication, May 15, 1995.

BOX *5-2:* The Partnership for a New Generation of Vehicles PNGV

PNGV was conceived as a model government/industry research program that would provide a template for government/industry cooperation in other industries in the future. The program combines a "stretch" goal (up to a threefold increase in fuel economy) with a clear timetable for achieving it (10 years).

Considerable care was taken to define clearly both government and industry roles in the partnership. The federal role in PNGV is to provide resources for technology development from relevant defense work and from the national laboratories, particularly for the longer term goal 3. PNGV research is to be jointly funded by industry and the federal government, with industry funding proportionally greater for near-term, low-risk projects (goals 1 and 2), and federal funding greater in long-term, high-risk areas (goal 3). Industry will shoulder increasing responsibility for goal 3 as the program nears the concept vehicle and production prototype stages. In the first two years of the program, cumulative federal funding is estimated at around $500 million, with $200 million contributed by private industry. ' Over the 10 years, it is expected that government and industry spending on the program will be about equal.

The Big Three manufacturers were given a leadership role in resource allocation decisions, particularly in regard to the commercial viability of various technologies. This was consciously done to correct the government-led model that characterized federally funded automotive R&D previously, in hopes that the prototype vehicles that emerge from the program will be commercially attractive.

PNGV is directed jointly by a government and an industry steering group. The government group consists of representatives of the eight participating agencies (Departments of Commerce, Defense, Interior, Transportation, Environmental Protection Agency, National Aeronautics and Space Administration, National Science Foundation) and other executive branch organizations, chaired by the under secretary of commerce for technology. The industry group is led by the vice presidents for research of the Big Three auto manufacturers, together with a representative of the U.S. Council for Automotive Research (USCAR)--the umbrella organization under which joint research is conducted by the Big Three (see below). Separate technical task forces have also been organized on both the government and industry side.

PNGV released its first Program Plan in July 1994, outlining its organizational structure and plans. At the invitation of DOC, the National Research Council formed a review committee to evaluate PNGV and its first report was released in November 1994.[2] The report found that PNGV had made a good start, but that many issues (especially in project management) would have to be resolved if the program were to succeed.

The existence and structure of the PNGV program raise some important issues for policymakers. For some, PNGV represents a classic "technology push" approach that attempts to develop technology and then find a market for it. According to this view, the government involvement will waste both public and private funds in an attempt to skew the production of cars toward characteristics that are not demanded by consumers. A second type of criticism, heard from some small companies and environmental groups, is that PNGV is skewed too heavily toward the existing industry--that the technologies are promising, but that the Big Three cannot be expected to wholeheartedly pursue new technologies that undermine their extensive investments in internal combustion engines and installed plant and equipment. In this view, the central role of the Big Three crowds out smaller, more innovative companies that are not constrained by the baggage of existing investments.

PNGV's 10-year time frame for goal 3 is also a source of potential concern. This timetable has advantages in providing a concrete target and structure for the program. The 1997 date for beginning technology selection for the prototype will, however, exclude promising longer term technologies that could contribute to goal 3 (such as composites and fuel cells) but which, according to OTA's analysis, will not be available in this time frame. If these technologies are excluded from subsequent PNGV funding on that basis, long term efforts to improve fuel economy may be harmed. Finally, what will happen after 2004 is unclear. Participation in PNGV involves no commitment on the part of the Big Three to produce commercially any vehicles that result from the research.

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1 "Clinton Budget Boosts Clean-Car Funding 23%," *Automotive News*, Feb. 13, 1995, p. 8.

2 National Research Council, Research *Program of the Partnership for a New Generation of Vehicles*, (National Academy Press, Washington, *DC: 1994).*

BOX 5-3: Federal Spending on Advanced Auto R&D

The federal government conducts a wide range of R&D that is relevant to advanced vehicles, from basic science to vehicle deployment programs. This makes it difficult to define precisely a total budget for automotive R&D The federal R&D effort can be described by analogy to an onion. At the core of the onion are projects that are clearly related to advanced vehicles; an example would be DOE's Electric and Hybrid Vehicle Program (see below). As one moves away from the core, successive layers include projects that are less and less closely identified with vehicles per se.

One of the first initiatives of PNGV **was** to conduct an inventory of **all** federal R&D that might be relevant to PNGV goals.[1] All eight federal agencies involved were asked to nominate projects that relate to 14 technology areas judged by PNGV to be critical to achieving its goals. Although the general technology areas were specified, however, no common criteria were given for the agencies to determine which program to include or exclude. As a result, different agencies used different criteria, and sometimes the criteria changed in subsequent rounds of the inventory. For example, DOD projected an increase in funding for PNGV-relevant projects from FY 1995 to FY 1996 (from $24 million to $42 million); however, this "increase" did ***not*** involve increased R&D activity, but instead the inclusion of a number of ongoing projects in FY 1996 that had been excluded in the FY 1995 inventory.[2]

In early agency responses to the inventory effort, the agencies listed both "directly relevant" research, as well as "indirectly relevant, or "supporting" research. An example of supporting research might be the National Institute of Standards and Technology's project on ceramic machining, which is intended to develop cost-effective techniques for machining ceramics within specified tolerances. These techniques eventually might be used to machine ceramic gas turbine rotors to their final dimensions, or they might be used for very precise ceramic spray painting nozzles or ball bearings. Funding for such basic research cannot be accurately allocated 100 percent to advanced vehicles, as it serves much broader purposes.

Typically, the agencies reported spending four or five times as much on "supporting" research as on "direct" research. Yet, this supporting research is not currently included in the budget totals for PNGV In addition, many vehicle-related federal programs are also excluded from the PNGV budget because they are not considered part of PNGV's scope. PNGV defines itself as being concerned only with the rolling stock-that is, not with infrastructure, policy, marketing, or other "systems" considerations. Thus, DOE's battery electric vehicle program, its alternative fuels fleet demonstration program, its biofuels research program, and its hydrogen technology development program are not generally included *in* PNGV even though the results of these efforts could have a direct impact on the commercialization of a PNGV prototype vehicle. Depending on one's point of view, total federal spending on R&D relevant to advanced vehicles could fall anywhere in the range of about $170 million to $500 million.

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1 The inventory process is being repeated and improved.

2 According to information supplied by the PNGV Secretariat in the Department of Commerce.

TABLE 5-1: Key Legislation Affecting Automotive Research and Development

Title	Public law number	Major provisions	Comments
Clean Air Act Amendments of 1966	PL 89-675	Provides Department of Housing, Education, and Welfare (HEW) funding to support the development of technologies to assist in improving air quality.	Legislative history emphasizes that a balanced research program is to be followed regarding automobile-related air pollution, including supporting research to develop cleaner internal combustion engine-powered vehicles and the development of electric vehicles.
Clean Air Act Amendments of 1970	PL 91-604	Provides the secretary of HEW with the authority to set and enforce national air quality standards, including for automotive emission control, motor vehicle testing and certifications, and for automotive and other fuels	Directs the secretary to test, as he deems appropriate, any new motor vehicle or engine as it comes off the assembly line to determine whether it conforms to applicable standards, and to conduct R&D activities with respect to low-cost instrumentation techniques to facilitate the measuring of automotive emissions.
Energy Reorganization Act of 1974	PL 93-48	Gives Energy Research and Development Agency (ERDA) responsibility for accelerating the commercialization of electric and hybrid vehicles.	Responsibility for this was transferred to DOE under the Department of Energy Reorganization Act of 1977, PL 95-91.
Non-Nuclear Energy R&D Act of 1974	PL 93-577	instructs ERDA in Sec. 6.(3)(A)(iii) to advance energy conservation technologies in the near term through "improvements in automobile design for increased efficiency and lowered emissions, including investigation of the full range of alternatives to the internal combustion engine . . ."	ERDA initiated a near-term Electric Vehicle Program.
Electric and Hybrid Vehicles Research, Development and Demonstration Act of 1976	PL 94-413	Authorizes Department of Energy (DOE) to, *inter alia*, "encourage and support accelerated research into, and development of, electric and hybrid vehicle technologies. "	Launched DOE's Electric and Hybrid Vehicle Program. Subsequently amended by PL 95-238.
Department of Energy Act of 1978 --Civil Applications.	PL 95-238	Directs the Department of Energy to undertake research and development of new automotive propulsion systems to achieve improved fuel economy, which can be adapted to various alternative fuels.	Amended PL 94A13. Launched DOE's Automotive Technology Development Program, which currently consists of two major engine-related projects: (1) the Advanced Turbine Technology Applications Project and (2) the Heavy-Duty Transport Project. [n addition, basic ceramic materials and alternative fuels technologies for all engine projects are being developed under the Advanced Materials Development Project and the Alternative Fuels Utilization Program.

Alternative Motor Fuels Act of 1988	PL 100-494	Directs DOE to prepare studies on alternative motor fuels such as methanol, ethanol, and natural gas, and established Interagency Commission on Alternative Motor Fuels to coordinate federal activities and report to Congress.	Relies mainly on plarming, information exchange, and coordination, rather than mandates, to encourage production of alternative fuels.
Clean Air Act Amendments of 1990	PL 101-549	Provides increased standards for vehicle emissions. Phase 1 standards were to be implemented in 1993. Phase 2 standards, which reduce acceptable emissions to half of their 1993 levels, are to be implemented in 2003.	Phase 1 standards were achievable with 1990 technology for most vehicles. It was recognized at the time that further R&D would be required to meet Phase 2 standards.
Energy Policy Act of 1992	PL 102-486	Directs secretary of DOE to determine feasibility of replacing 10 percent of petroleum fuels with alternative fuels by 2000 and at least 30 percent by 2010. Mandates a schedule for purchase of AFVs by public and private fleets. Section 1913 provides a 10 percent tax credit (up to $4,000) for electric vehicles. Title VI authorizes up to $50 million for electric and electric hybrid vehicle demonstrations between 1993 and 2002, as well as $40 million for electric vehicle infrastructure development between 1993 and 1997.	Target schedule for acquisition of AFVS considered very difficult to meet, and costs and benefits are uncertain.

SOURCE: Office of Technology Assessment, 1995.

TABLE 5-2: PNGV-Related FY 1995 Appropriations by Technical Area and Agency ($ millions)

Technical area	DOC[a]	DOD[b]	DOE	DOI	DOT	EPA[c]	NASA	NSF	TOTAL
Lightweight materials	6.83	7.03	47.42	0.50				19.24	81.02
Energy conversion			70.47			2.75		0.85	74.07
Energy storage	0.04		0.47			2.00		2.69	5.20
Efficient energy management		1.20					1.00	15.41	17.61
Exhaust energy recovery			1.04				0.20		1.24
Analysis and design methods	1.50	1.00	2.71				2.20	1.85	11.24
Reduction of mechanical losses	0.25							25	50
Aero and rolling improvements			0.78						0 8
Advanced manufacturing	10.46	2.75	23.64					4 6	4 46
Improved internal combustion	0.58	11.02	7.04			2 90	0 25	3 02	24 8
Emissions control			3.78				35	2 0	20
Fuel prep, delivery, storage								0.15	0.15
Efficient heating, cooling, etc.			0.50					2.81	3.31
Crashworthiness								0.14	0.14
TOTAL	10.66	23.08	158.85	0.50	0.00	7.65	5.00	54.09	269.73

[a]In addition to the base of $19.7 million, DOC through the National Institute of Standards and Technology's Advanced Technology Program has selected relevant projects with requested funding of $30.1 million. Contracts are not yet in place for these selected proposals.
[b]DOD numbers are based on program personnel contact and are still tentative.
[c]EPA numbers still in discussion.

NOTE: Numbers indicated in the table are specific to PNGV and identified as such. DOT program personnel indicate that an additional $20 million each year is spent on R&D related to PNGV with dual purpose; in FY96, $1 million of the $20 million will be targeted specifically for PNGV.

KEY: DOC = Department of Commerce; DOD = Department of Defense; DOE = Department of Energy; DOI = Department of the Interior; DOT = Department of Transportation; EPA = Environmental Protection Agency; NASA = National Aeronautics and Space Administration; NSF = National Science Foundation; PNGV = Partnership for a New Generation of Vehicles; R&D = research and development.

SOURCE: PNGV Secretariat.

TABLE 5-3: Regional R&D Consortia Supported by the Advanced Research Projects Agency (ARPA)

Consortium	Members	Activities	Comments
Hawaii Electric Vehicle Demonstration Project	24 members including companies, university% utilities, and local government.	Developing technology and infrastructure for electric cars and buses.	Began in 1993 with $5 million from ARPA, matched by local sources.
Calstart	Over 100 members including GM, defense and electronic companies, small companies, utilities, universities, and local government.	Technology development for electric, hybrid, and natural gas vehicles and infrastructure.	Has operated more than 15 technology programs, with a budget of over $60 million--mostly private funding sources.
Sacramento Electric transportation Consortium	Over 30 members led by the Sacramento Municipal Utility District and local Air Force installations.	Development of “dual use” advanced vehicle technologies, including flywheels and fuel cells.	Joint finding from ARPA and local sources.
Electricore, the Mid-America Electric Vehicle Consortium	Over 36 groups from 17 states, including GM subsidiaries.	Electric vehicle (EV) development and deployment, including a strong emphasis on public awareness.	Joint projects over $18 million, cost-shared by ARPA and local sources.
Southern Coalition for Advanced Transportation	Over 45 utilities, universities, and manufacturers.	Development of advanced EV technologies for civilian and military vehicles, including rapid charging,	Joint projects over $24 million, including EV fleet for 1996 Olympics in Atlanta.
Northeast Alternative Vehicle Consortium	Over 60 organizations, led by defense-oriented companies.	Technology development, cost studies.	Begun in 1993, now has more than $25 million in joint projects.
Mid-Atlantic Regional Consortium for Advanced Vehicles	Organizations in 7 states.	Development of high efficiency EV components.	Newest consortium.

SOURCE: Advanced Research Projects Agency, “Progress Report,” vol. 1, No. 1, Winter 1994.

Table 5-4: Government-Funded Advanced Automotive R&D in Japan

Agency	Project	Comment
MITI/New Sunshine Program	Fuel cell power-generation Technology	R&D on many fuel cell types including some 700 million yen for 1 kW proton exchange membrane modules (1992-1995).
	Ceramic gas turbine	1988-1996 at about 1.8 billion yen per year; focus is on 300 kW turbines for power generation, though past public and private R&D have given Japan the lead in automotive ceramics.
	Dispersed-type battery energy storage technology	1992-2001, with total funding of 14 billion yen, focus is on high-energy-density, long-life batteries for stationary or vehicle applications.
	Lean NO_x catalysts	1993-2000, to develop better catalyst compositions to remove NO_x from the exhaust of lean-bum engines. Japan is a world leader in this technology.
	Hydrogen energy system	1993-2020, currently in planning stages, includes R&D on use of hydrogen for all stationary and mobile needs.
MITI/JEVA	Electric vehicle (EV) popularization	5-year program begun in 1992, total funding is 1.1 billion yen. The goal is to demonstrate optimum load-leveling measures and charging systems for the mass introduction of EVs
MITI/Agency of Natural Resources and Energy	Eco-Station *2000*	1993-2000, goal is to have a nationwide network of 2,000 refueling stations with multiple alternate fuels by the year ***2000.***

SOURCE: Office of Technology Assessment, 1995.

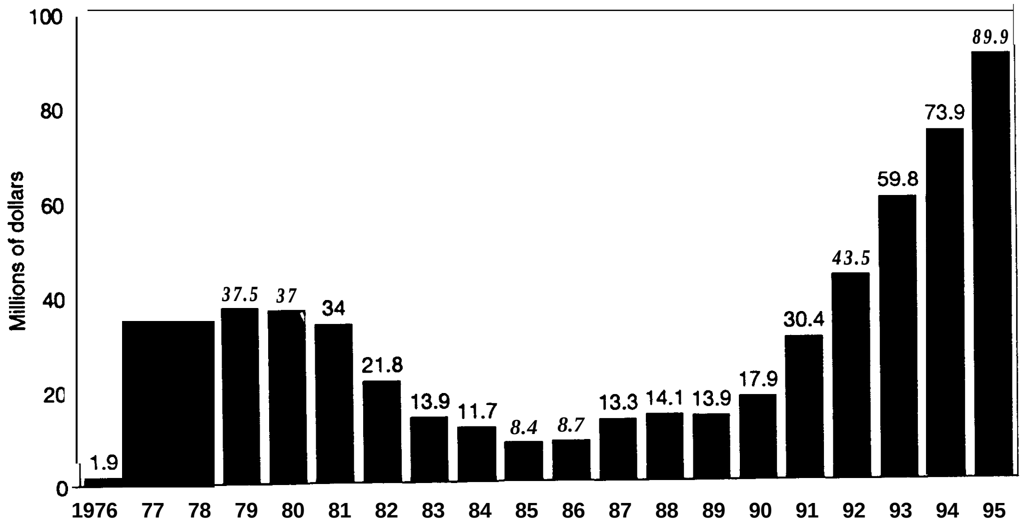
TABLE 5-5: PNGV Budgetary Changes in FY 1996

Agency/program	R&D area	FY 1996 dollars in millions, requested change (in percent)	Comments
DOC/NIST/ATP	8 new projects on composite manufacturing initiated in FY 1995.	-lo *(50%)*	Requested budget does not include an expected $30 million in new auto-related contracts to be negotiated in FY 1996. However, funding for ATP is controversial in Congress, and substantial cuts have been proposed.
DOD/ARPA/EHV	Hybrid and electric vehicle development	-15 (loo%)	Congressional add-on to ARPA budget in FY 1993, provides funds to seven regional consortia including small businesses. Funding zeroed out in President's FY 19% budget request.
DOD/ARPA/TRP	Advanced vehicle drivetrains	?	Supports development of "dual use" technologies; focus area on vehicle drivetrains designated in FY 1995. Funding for TRP is controversial in Congress, and large cuts have been proposed.
DOE/OTT/material technology	Composite and light metal manufacturing processes, recycling, and crashworthiness	+5 (42%)	Joint work with USAMP and national laboratories.
DOE/OTT/heat engine technologies	Develop gas turbine, spark-ignited piston, and diesel engines as hybrid vehicle APUs	+6 (48%)	Cost-shared work with industry, national labs.
DOE/OTT/electric and hybrid propulsion	Battery and other energy storage device development	+3 (lo%)	A $9 million increase for power storage devices for hybrids is offset by a $6 million decrease for advanced batteries.
DOE/OTT/electric and hybrid propulsion	Automotive fuel cell development	+19 (84%)	Increase equally divided between 15 percent cost-shared contracts with Big Three, and enabling research at national labs.
DOE/OTT/electric and hybrid propulsion	Hybrid vehicle development	+17 (45%)	Adds a third contractor team to existing teams at Ford and General Motors (presumably at Chrysler).
DOE/UT/hydrogen research and development	Production, storage, distribution, and conversion of hydrogen as fuel	-2 (22%)	Reduction comes from stretch-out of joint industry/lab efforts on near-term natural gas reforming and storage system.
EPA	Reducing emissions from four-stroke, direct-injection engines	+5 (65%)	Addresses a key problem with hybrids.

KEY: APUs = auxiliary power unit; ARPA = Advanced Research Projects Agency; ATP = Advanced Technology Program; DOC = Department of Commerce; DOD = Department of Defense; DOE = Department of Energy; EHV = Electric and Hybrid Vehicle program; EPA = Environmental Protection Agency; NIST = National Institute of Standards and Technology; OTT = DOE's Office of Transportation Technologies; TRP = Technology Reinvestment Project; USAMP = U.S. Advanced Materials Partnership; UT = DOE's Office of Utility Technologies.

SOURCE: Office of Technology Assessment, 1995; and U.S. Department of Energy, FY1996 ***Congressional*** Budget ***Request,*** vol. 4, DOE/CR-0030 (Washington, DC: February 1995).

Figure 5-1: DOE Electric and Hybrid Vehicle Program Budget History, FY 1976-95



SOURCE: Ken Barber, Department of Energy, personal communication, May 1995.

APPENDIX A: Method for Evaluating Vehicle Performance

The Office of Technology Assessment's (OTA's) analysis of vehicular performance and fuel economy hinges on examining the vehicle on the Environmental Protection Agency (EPA) driving cycle, using average ("lumped parameter") estimates of key variables such as motor efficiency and battery efficiency over the urban or highway portions of the cycle. Ideally, a performance analysis of complex vehicles such as hybrids should be based on detailed engine and motor maps coupled with models that are capable of capturing the second-by-second interactions of all of the components. Such models have been developed by the auto manufacturers and others. Nevertheless, OTA believes that the approximate performance calculations described here give results that are adequate for our purposes. Also, the detailed models require a level of data on technology performance that is unavailable for all but the very near-term technologies.

ENERGY CONSUMPTION IN CONVENTIONAL AUTOMOBILES

It is relatively easy to derive a simple model of energy consumption in conventional automobiles that provides insight into the sources and nature of energy losses. In brief, the engine converts fuel energy to shaft work. This shaft work is used to overcome the tractive energy required by the vehicle to move forward, as well as to overcome driveline losses and supply accessory drive energy requirements. The tractive energy can be separated into the energy required to overcome aerodynamic drag force, rolling resistance, and inertia force. It is useful to consider energy consumption on the EPA urban and highway test cycles, which provide a reference for comparing fuel economy.

The engineering model used in this study follows the work by GM Research Laboratory scientists Sovran and Bohn.[1] Defining the average engine brake specific fuel consumption over the test cycle as bsfc, fuel consumption FC[2] is given by:

[1] G. Sovran and M. Bohn, "Formulae for the Tractive Energy Requirements of Vehicles Driving the EPA Schedules," SAE paper 810184, 1981.

[2] In other words, bsfc is an expression of the average efficiency of the engine as one element of the total vehicle system; and FC expresses the fuel consumption of that complete vehicle system.

$$FC = \frac{bsfc}{\eta_d} \cdot [E_R + E_A + E_K] + bsfc\, E_{AC} + G_i\,(t_i + t_b)$$

where

η_d	is the drive train efficiency
E_R	is the energy to overcome rolling resistance
E_A	is the energy to overcome aerodynamic drag
E_K	is the energy to overcome inertia force
E_{AC}	is the accessory energy consumption
G_i	is idle fuel consumption per unit time
t_i, t_b	are the time spent at idle and braking

The first term in the above equation represents the fuel consumed to overcome tractive forces. Because the Federal Test Procedure (FTP) specifies the urban and highway test cycle, ER, EA, and Ek can be readily calculated as functions of the vehicle weight, the rolling resistance, body drag coefficient, and frontal area. Note that weight reduction reduces both inertia force and rolling resistance. It should also be noted that not all of the inertia force is lost to the brakes, as a vehicle will slow down at zero input power owing to aerodynamic drag and rolling resistance, without the use of brakes. The fuel energy is used not only to supply tractive energy requirements but also to overcome transmission losses, which accounts for the transmission efficiency that is in the first term.

The second term in the equation is for the fuel consumed to run the accessories. Accessory power is needed to run the radiator cooling fan, alternator, water pump, oil pump, and power-steering pump (but the water pump and oil pump are sometimes excluded from the accessory drive loads). The air conditioner is not included because it is not turned on during the FTP. Idle and braking fuel consumption are largely a function of engine size and idle rpm, while transmission losses are a function of transmission type (manual or automatic) and design. The engine produces no power during idle and braking but consumes fuel so that factor is accounted for by the third term.

Tables A-l(a) and (b) show the energy consumed by all of these factors in a typical midsize car with a three litre overhead valve (OHV) engine, four-speed automatic transmission with lockup, power steering, and typical alternator size. Table A-l(a) shows the distribution of the vehicle's tractive energy and total fuel consumption for the two cycles as well as the EPA 55/45 composite cycle. Table A-l(b) indicates the absolute energy consumption and estimates the car's engine efficiency.

The values in table A-l(a) can be easily utilized to derive sensitivity coefficients for the reduction of various loads. For example, reducing the weight by 10 percent will reduce both rolling resistance and inertia weight forces, so that tractive energy is reduced by (30.5 + 39.6) x O. I or 7.01 percent on the composite cycle. Fuel consumption will be reduced by 7.01 percent x 0.708 which is the fraction of fuel used by tractive energy, or 4.96 percent. This matches the common wisdom that reducing weight by 10 percent reduces fuel consumption by 5 percent.

However, if the engine is also downsized by 10 percent to account for the weight loss, fuel consumption will be reduced by 6.02 percent as idle and braking fuel consumption will be reduced in proportion to engine size. **Table A-1 provides a framework by which total fuel consumption for any automobile can be analyzed for the FTP cycle.**

On a total energy basis, energy can be allocated to the various losses using different conventions on the treatment of idle and accessory power loss. One example of this allocation is provided in a chart from the Partnership for a New Generation of Vehicles (PNGV)[3] shown in figure A-1. The figure implies that the engine usefully converts 20.4 percent of fuel energy into useful power in the city cycle, and 10.8 percent of this useful power (or 2.2 percent of fuel energy) is used for accessory drives. The other 18.2 percent is used by the drivetrain. The PNGV chart specifies a drivetrain efficiency of 69.2 percent in the city cycle, which appears unusually low. Most modern transmissions with lockup converters operate at efficiencies of over 85 percent in the city cycle, and 92 to 94 percent on the highway cycle. The PNGV allocations to kinetic energy, rolling resistance, and drag force are also different born the values shown in table A-1, especially in the allocation between the rolling resistance and inertia forces, but these differences may be owing to the conventions followed in allocating energy to the different loads. The source of these numbers is not documented.

A separate analysis,[4] shown in figure A-2, also differs somewhat from the tractive energy values calculated from Sovran and Bohn's formula, probably because of differences in the accounting conventions. Their estimate of overall energy efficiency appears low, as engine thermal efficiency (excluding idle loss) is shown at 20.1 percent for the composite cycle, rather than the more common 23 to 24 percent. Although these differences may seem academic, they may play a significant part in explaining the widely different results estimated in the literature for the fuel economy of hybrid vehicles. For example, if the PNGV value for transmission efficiency is connect, a 30 to 35 percent fuel economy increase (or a 23 to 26 percent fuel consumption decrease) would be possible simply by eliminating the transmission, as is likely with electric motor drives. The resolution of these figures is one key to reconciling the widely varied findings regarding hybrid vehicle efficiency.

The analysis of conventional vehicles in this report is based on the formulae and sensitivity indices computed using a methodology similar to the one described for weight. The weighting factors for E_K, E_A and E_R utilize the relationships developed by Sovran and Bohn. All of the other coefficients are computed as ratios so that the actual equation used is in the form of FC_{new}/FC_{old}. This is particularly convenient as most of the variables such as bsfc have been analyzed in terms of potential changes from current values. For example, engine average bsfc over the composite cycle was forecast to be reduced by 18 percent from current values. All of the analysis is in fuel consumption space. The same tractive energy equations also hold for electric and hybrid vehicles, although the bsfc and weight calculations for hybrid vehicles are far more complex.

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[3] P.G. Patil, "Partnership for a New Generation of Vehicles", Automotive Technology Development Contractors Coordination Meeting, U.S. Department of Energy, October 1994.

[4] M Ross and W Wu, "Fuel Economy of a Hybrid Car Based on a Buffered Fuel-Engine Operating at It's Optimal Point," SAE paper 95000, 1995.

PERFORMANCE, EMISSIONS, AND FUEL ECONOMY

The previous section described energy use over a prescribed driving cycle, and treated the variable of average engine brake specific fuel consumption, bsfc, as constant. The value of bsfc is dependent on the size of the engine, the gear ratios and final drive ratio, as well as the engine's emission calibration. The size of the engine and the transmission/axle ratios have an impact upon vehicle performance capability and affect bsfc, although the driving cycle over which fuel economy is measured remains constant. These issues and the resultant tradeoffs with fuel economy are discussed below.

Different levels of performance can be attained most simply be varying axle ratio, which determines the engine rpm to vehicle speed ratio in any particular gear. Increased numerical values of axle ratio imply higher rpm at a given speed and increased performance. The tradeoff of fuel economy with axle ratio is nonlinear, however; fuel economy increases with decreasing axle ratio up to a point, but decreases beyond this maximum level at even lower axle ratios. The reason is that, at very low axle ratios, gear shifts must be delayed owing to insufficient torque at low speed to follow the driving cycle. Figure A-3 provides an illustration of the tradeoff between fuel economy and performance with changing axle ratio, holding all else constants As can be seem axle ratios below 3:1 (in this example) make both performance and fuel economy worse, and would make no sense for a manufacturer to employ. The tradeoff between axle ratio, performance, and fuel economy is defined to the right of the fuel economy maximum point in the figure. Statistical analysis of data from EPA tests indicates that a linear approximation of the effect of a 10 percent increase in axle ratio is a 2.0 percent decrease in fuel economy, and a 5 percent decrease in O to 60 mph time.[6]

The next option is to increase engine size, and figure A-4 shows the family of tradeoff curves of fuel economy and performance with axle ratio for different engine sizes.[7] Larger engines obtain worse fuel economy than smaller engines for two reasons:

- increased fuel consumption during braking and idling, when the fuel consumption rate is largely a fiction of engine size, and
- lower average load relative to the maximum which requires more throttling and higher pumping loss.

Of course, a larger engine could be utilized with a lower axle ratio that changes the performance and fuel economy tradeoffs. As can be seen in the figure, for some combinations of axle ratios and engine size, different engine sizes have nearly identical fuel economy and only slightly different performance. Statistical analysis has shown that increasing engine size by 10 percent, while keeping all other factors constant (including weight and axle ratio), leads to approximately a 3.6 percent increase in fuel consumption.

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[5] Ford Motor Co., presentation to the Department of Energy on five-speed automatic transmissions, September 1992.
[6] H.T. McAdams, "Statistical Projection of Fuel Economy to the Year 2000," presentation at the SAE Government Industry Meeting, 1992.
[7] Ford Motor Co., see footnote 5.

With larger engines and more performance potential, however, many other vehicle factors change. Larger engines require stronger drivetrain components and better suspension and brakes, all of which increase weight. In addition heavier “performance” tires with higher rolling resistance may be used. Increased engine displacement could also require that the number of cylinders be increased, leading to an even larger weight increase and increased internal engine fiction. Hence, the tradeoff leads to even larger differences in fuel economy for each increment of performance.

Manufacturers have a wide set of options to improve performance to a given level, and the actual fuel economy impact depends on the particular set of options chosen. A statistical analysis of data from the EPA test car list at constant engine technology showed a tradeoff of the form:

$$\text{Percent change in F/E} = -0.20 * (\Delta \text{ HP}) - 0.560 * (\Delta \text{ HP})^2$$

which represents an average of all strategies represented in the data, where A HP is percent change in horsepowers

The impact of emission standards *on* fuel economy and performance is less clear, but this is principally because the impacts are relatively small. Most modem cars calibrated to current Tier I standards produce very little emissions once the engine is warmed up, and the cold start phase (which lasts about two minutes after cold start) is responsible for 75 percent of all emissions on the test.[9] In this context, the ability to meet future low emission vehicle/ultralow emission vehicle (LEV/ULEV) standards is based on reducing emissions in the first two minutes of operation, and the methods developed include the use of small “start” catalysts that light-off very quickly, electrically heated catalysts, intake air heaters, improved fuel atomization and heated fuel spray targets. An evaluation of different methods conducted for NESCAUM[10] concluded that the direct effects were small but the indirect effects, such as the increased back pressure owing to start catalysts and increased weight associated with more components, would cause fuel economy penalties in the 2 percent range. Electrically heated catalysts could have larger penalties, but recent data suggests that they may not be necessary in most vehicles, even at ULEV emission levels. For example, the 1995 Toyota Camry (California version) comes very close to meeting ULEV standards with virtually no advanced aftertreatment methods, while Honda plans[11] to certify an Accord to ULEV standards for 1998, and has publicly stated that fuel economy penalties are very small.[12] The impact on performance owing to increased back pressure is also likely to be in the same range as the impact on fuel economy--that is, about 2 percent, and Honda hopes that costs will be below $300 (as an incremental retail price effect (RPE)).

“Off-cycle” emissions are also of concern as the EPA and Air Resources Board have found that emissions increase dramatically during hard accelerations and high speeds, which currently are not represented in the FTP but occur often in actual driving. These increases are associated with the engine going into enrichment mode (i.e. increased fuel-air ratio) at high loads, which increases

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[8] Energy and Environmental Analysis, Inc., “The Fuel Economy Model - Documentation report to EL%” October 1993.

[9] Honda R&D Co. "Honda ULEV Technology," brochure, January 1995.

[10] E.H. Pechan and Energy and Environmental Analysis, Inc., “Adopting the California LEV Program in the North Eastern States," report prepared for NESCAUM, September 1991.

[11] U.S. Environmental Protection Agency, ‘EPA Certification List," 1995.

[12] The issue of fuel composition ia important but not discussed here.

hydrocarbon and carbon monoxide emissions dramatically. EPA is now planning a separate "high-speed driving cycle" (that is, unfortunately, independent of vehicle characteristics) with new emission standards for these cycles.[13] Such an approach would favor the high-performance vehicle as the engine may not reach the high load levels to require enrichment on such a vehicle during the new EPA cycle. Low performance vehicles however will be hurt more, because the enrichment levels must be cut back, which will improve fuel economy but hamper performance. In sum, the effect of this potential new regulation will not be to hurt fuel economy directly, but will indirectly affect it by making the trend toward higher performance more attractive.

ELECTRIC VEHICLES

The energy use of an electric vehicle (EV) is governed by the same equation shown on page A-2, except that there is no "idle" energy consumption so that:

$$FC = E_{TR}/(\eta_m \ \eta_d) + E_{AC}$$

where η_m is motor efficiency,

E_{TR} is the traction energy $E_R + E_A + E_K$, and
FC is fuel consumption in kWh.

The relative energy efficiency of electric vehicles can be discussed with reference to this equation. First, the electric vehicle gains back the fuel consumption associated with braking and idling--a 10.8 percent savings. Second, most of the accessories used in the internal combustion engine-powered car, such as the water pump, oil pump, cooling fan, and alternator, can be eliminated if battery heat losses are not high, as motor and electronics cooling requirements do not require much power. In addition the conventional power steering must be replaced by electric power steering, which consumes only a fraction of the power of conventional systems, and consumes no power on an EPA dynamometer test where the steering is not used. This saves as much as 9.5 percent of fuel consumption on the test cycle. The EV may need power for the brakes, however, but this requirement is probably small owing to the use of regenerative braking, as described below.

Third, some of the energy lost during braking can be recovered by electric vehicles, because the motor can act as a generator when it absorbs power from the wheels. The energy can be stored in battery and later released to drive the motor. As noted earlier, the energy lost to the brakes in a conventional car in the FTP city cycle is about 35 percent of total tractive energy. For the motor to convert this to electricity, however, transmission loss and motor loss in generator mode must be considered. Typically, transmissions for electric motors are simple drive gears, and can be 95 to 96 percent efficient. Motors operated in reverse generator mode typically have cycle average efficiency in the 80 to 84 percent range. Hence, only 78 percent of the braking energy can be

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[13] Honda R&D (h., see footnote 9.

converted to electricity, which is about 27.0 percent of traction energy. The storage and retrieval of electricity in a battery causes further loss, but this is very dependent on both the battery type and its efficiency in terms of absorbing power pulses. This efficiency is only 80 percent or lower for lead acid and nickel-cadmium batteries, so that regenerative braking recaptures only 0.82 x 0.95 x 0.80x 0.35, or 21.8 percent of tractive energy using such batteries. This assumes that all of the braking can be done regeneratively, but this is not true in practice, because the motor generally is connected to only two wheels, leaving the other two wheels to be braked conventionally .14 As a result, actual systems in the Toyota EV[15] and the Cocconi CRX[16] have been reported to provide range increases of about 17 to 18 percent maximum since other system losses prevent reaching the 21.8 percent figure. These figures quoted for the Toyota EV and Cocconi CRX are the best achieved, as regenerative braking more typically extends range by only 8 to 10 percent in many vehicles, such as the BMW El.

Fourth, the motor is quite efficient in converting electrical energy to shaft energy, with typical cycle average efficiencies in the 75 to 80 percent range in the city cycle, as opposed to gasoline engines, which have an efficiency of only 20 to 23 percent on the fuel economy test cycle. Of course, the production of electricity from fossil fuels has an efficiency of only 35 to 40 percent, and there are other transmission losses, so that direct efficiency comparisons are more complex. Nevertheless, electricity stored on a car can be converted to useful power almost 300 percent more efficiently than gasoline.

Substituting these efficiency values into the fuel consumption equation, and assuming that EV accessory power consumption is only 25 percent of the power consumed by accessories in conventional vehicles, it can easily be shown that an EV uses only 14 percent of the energy used by a similar current conventional vehicle, *if the weight of both* ***vehicles are identical and if battery losses are not considered.*** When electricity generation efficiency, transmission loss, charger efficiency, battery storage efficiency, and battery internal self discharge are considered, however, the picture is quite different, and the EV of the same weight consumes 60 percent or more of the energy consumed by a current conventional gasoline vehicle of equal weight. In order to obtain sufficient range and performance, however, EV’s can be much heavier than conventional vehicles, so that the EV can be less efficient on a primary energy basis than even a conventional vehicle of equal size and acceleration performance.

The analysis of overall vehicle weight, and the range/performance tradeoffs are especially important for an electric vehicle. A simple analytical framework allows the calculation of these tradeoffs. The battery energy storage capacity and the peak-power capacity affect the range and performance capability, and the more batteries used, the greater the capacity. As battery weight increases, however, structural weights must also increase to carry the loads, and a larger motor is required to maintain performance. The weight spiral effects lead to a situation where there are rapidly declining benefits to each additional battery weight increment.

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14 Proper handling during braking requires that all four wheels be braked for stability.

15 K. Kanamaru, “Toyota EV-50: An Effort to Realize Practical EVs paper presented at the 12th International Electric Vehicle Symposium, December 1994.

16 A Burke Institute of Transportation SW&~ University of California at Davis, "Dynamometer and Road Testing of Advanced Electric Vehicle,” 1995.

For a vehicle of a given size, there is a specific "zero weight engine" body weight that is essentially a theoretical body weight if engine weight were zero, assuming a flow through of secondary weight reduction. This was calculated to be 50 to 54 percent for several cars whose detailed weight breakdowns were available, assuming a secondary weight reduction of 0.5 for each unit of primary weight reduction. Denoting this "zero weight engine" body weight as M_{B_Z} we have total EV weight given by:

$$M_{EV} = M_{Bz} + 1.5\,M_{BATT} + 1.5\,M_{MOTOR}$$

where: M_{BATT} is the battery (including tray and thermal management system) weight

M_{MOTOR} is the weight of the motor and controller.

The traction energy needed to move a vehicle forward normalized by total vehicle weight is the specific traction energy, and one analysis[17] has shown that this number is relatively constant in city driving, being a weak function of rolling resistance coefficient and the ratio of drag force to mass. Denoting specific traction energy as E, we have the range, R, given by:

$$R = (M_{BATT} \cdot S_E) / (E \cdot M_{EV})$$

where S_E is the battery specific energy. This equation simply balances the energy stored in the battery to the energy demanded by the car. Of course, this range represents the maximum range, if the battery were discharged down to zero charge, which is not recommended for some battery types. This leads to a simple relationship to derive the ratio of battery to vehicle weight, as follows:

$$M_{BATT}/M_{EV} = R\,E/S_E$$

The above equation effectively links the battery weight to vehicle range and battery specific energy.

The size of the motor is simply determined by the output requirement as set by performance requirements. Setting the performance requirement in the form of horsepower to vehicle weight ratio, we have:

$$P' \frac{HP}{M_{EV}} = K \cdot M_{MOTOR}/M_{EV}$$

where k is the power to weight ratio of the motor. As discussed in chapter 4, a typical vehicle with average performance requires 80 HP per ton (1000 kg) of weight (curb + payload), but an electrical motor of 20 percent lower output can provide equal performance at low to mid speeds.

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17 Sovran and Bohn, see footnote 1.

Hence, an electrical motor power output of 50 kW (or 67 HP) per ton of vehicle weight provides comparable or average performance. Typically, electrical motors (and their controllers) weigh about 1.0 to 1.2 kg for each kW of output so that a M_{MOTOR}/M_{EV} ratio of 0.05 provides a reasonable approximation of motor weight to vehicle weight.

The weight-compounding effect is best illustrated by the ratio of battery weight to "zero weight engine" body weight, which is a constant for a car of a given design and size. Using the above relationship, it can be shown that:

$$M_{BATT}/M_{BZ} = \frac{RE/S_E}{1 - 1.5\ RE/S_E - 1.5\ P/K}$$

$$= \frac{RE/S_E}{0.9025 - 1.5RE/S_E}$$

for an acceptable performance car. This relationship is very useful in illustrating the effects of different specific energy storage capability and the choice of vehicle range on battery weight.

Table A-2 lists the actual and specific energy consumption of several recent EV models, based on the city cycle test procedure. The energy consumption values for these EVs indicate that the specific traction energy E is similar across most cars ranging between 0.084 to 0.151 kWh/ton-km or 0.12 to 0.22 kWh/ton-mile. Vehicles at the high end of the spectrum were models with low regenerative braking efficiency or with less efficient motor/electronics, but the body characteristics or total weight did not have a significant impact on the specific energy efficiency. (For example, the GM Impact is slightly less efficient than the Cocconi CRX-4 using this measure). The Cocconi CRX stands out with an energy consumption of 0.084 kWh/mi but it has no accessories, not even power steering. These energy consumption figures are based on federal city cycle driving, and are often not the ones quoted in the press.

Many publications also provide inconsistent and in many instances, significantly lower estimates of energy used for each ton-mile, based on the same cars shown in table A-2. For example, ARB tests of the Cocconi CRX were used to derive energy from the battery used as 96.5 Wh/km, but this is based on subtracting all of the regenerative energy going into the battery from the battery output[18]; this is incorrect because not all of the regenerative power going in can be recovered owing to charge/discharge loss in the battery. The GM Impact is another car where city cycle energy consumption has been reported as low as 0.065 kWh/km.[19] However, GM claims a range of 70 miles in the city based on the discharge of a 16.3 kWh battery to 80 percent DoD.[20] If 13 kWh (0.8x 16.3) is required to travel 70 miles (112.6 km), it is easy to see that the quoted 0.065 kWh/km cannot be correct. Finally, it should be noted that E is calculated in Wh/km per kg of

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[18] Air Resources Board Tests of Cocconi CRX, private communication with ARB.
[19] A. Burke, personal communication, April 19, 1995.
[20] General Motors, preview brochure on Impact specifications, 1994.

empty weight in this calculation, as opposed to Wh/km per kg of inertia weight (empty weight + 300 lbs), which yields lower results.

Using a representative value of E of 0.1 kWh/ton-km for a vehicle with power steering and developed from a glider body, figure A-5 shows the relationship between battery weight and "zero engine" body weight, and its nonlinear increase with range is obvious. At an R/SE of 6, battery weight is infinite, as the added weight of the battery does not provide enough energy to increase range while maintaining performance. When battery weight equals zero engine body weight, the value Of R/S_E is 3.6. To place this in perspective, an advanced lead acid battery, which has an S_E of 42 Wh/kg, provides a range of 150 km (42 x 3.6) or 90 miles, when battery weight equals zero engine body weight. For a current (1995) mid-size car such as the Taurus, the "zero engine" body weight is about 730 kg or 1,600 lbs. Hence, to obtain a 90-mile range even with an advanced semi-bipolar lead acid battery, 1,600 lbs of battery are required, and the total weight of the car increases from the current 3,100 lbs to 5,240 lbs. (In reality, usefud range is only about 70 miles since lead acid batteries should be discharged only to 20 percent of capacity). In contrast, a nickel-metal hydride battery, with an S_E of 72 Wh/kg, of the same weight will provide a range of more than 150 miles. The weight of nickel-metal hydride battery to provide a 100-mile range is 957 pounds, while the car weight falls to 3,305 lbs, illustrating the importance of weight compounding effects in an EV.

The second constraint on the battery size is that it must be large enough to provide the peak-power requirement of the motor, or else some peak-power device such as an ultracapacitor or flywheel may be necessary. To meet this requirement, we have the following:

$$M_{BATT} \cdot S_P > K \cdot M_{MOTOR}$$

where S_p is the specific power capability of the battery. Algebraic manipulation and substitution can be employed to show that:

$$S_P/S_E \geq P/R \cdot E$$

For a value of P of 50 kW/ton, a range of 160 km, and a value of E = 0.1 kWh/ton-km (or 0.1 Wh/kg-km), we have:

$$S_P/S_E > 3.125 \text{ hr}^{-1}$$

At a range of 100 miles or 160 km, the specific power to specific energy ratio must be at least 3.125 hr^{-1}; otherwise, the power requirement becomes the limiting factor on battery size. If the range requirement is doubled to 200 miles, then the minimum ratio declines to 1.56 hr^{-1}. For a 100-mile range, the advanced semi bipolar lead acid battery meets this requirement, with an S_p/S_E ratios of almost 5, while the Ni-MH battery has a ratio of about 3.1, close to the minimum. The existing "hot-battery" designs provide ratios of only 1.25, while more recent advanced designs provide ratios closer to 2. The important point of this discussion is that doubling the specific energy does not automatically lead to half the battery size, if the battery's power capability is inadequate to provide "average performance." Relaxing the performance requirement reduces the required ratio, illustrating that hot batteries with good specific energy but low specific power have best application in commercial vehicles, where range is more important than performance. One alternative is to include peak-power devices such as ultracapacitors with such batteries to provide adequate peak power.

HYBRID VEHICLES

Series Hybrids

The equations governing hybrid fuel consumption, performance, and weight are similar to these for EV's, with the motor generator added. The total weight of the vehicle, using the notation employed for EVs is given by:

$$M_{HEV} = M_{Bz} + 1.4M_{BATT} + 1.4M_{MOTOR} + 1.4M_{EG}$$

where M_{EG} is the weight of the engine + generator. The performance, P, as defined by the peak power (kW) to vehicle weight ratio, is given by:

$P = K \cdot \text{Motor}/M_{HEV}$ (using the same notation employed for EVs

and $K \cdot M_{Motor} = S_p M_{BATT} + C \cdot M_{EG}$

where C is the specific power output of the engine and generator in kw/kg. The main defining idea of the series hybrid is that the engine can be run at nearly constant output, and the output level be matched to the engine peak efficiency point. Hence, the engine is either run at this optimal point or shut off, and the energy stored in the battery for use over any arbitrary driving cycle (in practice, running at exactly one point is quite a restrictive operating strategy, as explained below).

Typically, a modem internal combustion engine (ICE) produces its peak output at 5,000 to 6,000 rpm and the weight of an engine (dressed) is about 2 kg/kW of peak output. Other items such as the radiator, exhaust system, and catalyst, however, which are required to operate the engine, make the total weight closer to 2.2 to 2.6 kg/kW as shown in table A-3. The peak efficiency point usually occurs at 40 to 45 percent of peak rpm and 70 percent to 80 percent of maximum torque. Hence, a typical engine operating at its best efficiency point produces about 40 percent of its peak output, and such an engine and generator would weigh 7.5 to 8.5 kg/kW, and its specific power is about 117 to 130 W/kg. (i.e., the value of C in the equation is 117 to 130). Advanced lead acid batteries of the semi-bipolar or bipolar type provide specific power of over 300 W/kg for a 30-second rating, while ultracapacitors and flywheels can provide 2 kW/kg or more. These specific power values make it clear that the engine should provide energy while the battery, ultracapacitor, or flywheel can provide peak power. Hence, the engine should be small and provide the total energy for driving, while the battery or other storage device should be sized to provide the peak power output, so that the total weight is kept low. This also implies that batteries with high specific peak power are better suited for use in Hybrid Electric Vehicles (HEVs).

Because the battery is capable of providing peak power in short bursts only, the critical engine size is limited by the maximum continuous demand under the most severe design condition. Consistent with the analysis for EVs we impose the requirement that an HEV must have a continuous power capability of 30 kW/ton of vehicle and payload weight. This sets a lower limit on engine size. Peak-power requirement is 50 kW/ton of vehicle and payload, which permits a zero to 60 mph time of about 12 seconds, so that the batteries must supply the (50-30) kW/ton for peak accelerations. Calculations are performed to show that operating the engine at its single "best efficiency" point at all times is not an optimal solution.

Given these specifications, it is easy to solve for the weight of the vehicle given M_{Bz}, the zero engine body weight. Using the mid-size vehicle as the example, with an M_{Bz} of 750kg and a payload weight of 200 kg, we have the following HEV characteristics, derived from the equations shown in table A-4:

Vehicle curb weight	1843 kg
Engine output (nominal)	61.3 kW
Battery peak output	40.9 kW
Battery weight	136.2 kg
Battery type	Semi-bipolar lead acid, 300 w/kg

The engine must be a 3.3L four-valve valve engine that can be rated 155 kw at its normal peak. The amazing result is that the engine must actually be more powerful than that of the current Taurus. The reason of course, is that the engine of the current Taurus already operates near the maximum efficiency point at an output of 30 kW/ton. Hence, if the engine of the HEV is sized in the same proportion it must be larger to provide the increased power to overcome the weight associated with the motor, battery, electrical system, and generator, which adds 360 kg to the weight.

This is only one of the unattractive aspects of limiting engine operation to only one output level. Another factor is that on the FTP city cycle, the engine operates for a very brief duration. The 23-minute cycle requires about 2.3 kwh of energy at the motor to cover the cycle, which means that the engine needs to run 2.3/(61.3 x 0.8) percent of the cycle time (where 61.3 x 0.8 is the electrical output of the engine ***in*** kW stored and retrieved from the battery), or about 1.1 minutes, and be shut off the rest of the time. Hence, cold-start fuel consumption will add a significant penalty to total fuel consumption. The battery is capable of storing 5.7 kWh, and the vehicle can be run as a reduced performance EV over the entire FTP cycle, if it starts with the battery fully charged.

A less restrictive scenario could allow the engine to operate at much higher peak ratings, if the control logic determines that the load is not a transient one. For example, if high peak-loads persist for more than 20 or 30 seconds, the control logic can allow the ICE to provide more power rapidly (albeit with much lower efficiency), so that the batteries are not taxed too heavily. In addition the engine can provide a range of horsepower, if efficiency is allowed to decline to within 10 percent of the maximum. Such an operating strategy does not require as much power to be available from the battery with attendant charge/discharge losses, so that the 10 percent efficiency loss in the ICE is compensated by a 20 percent gain (for example) in avoiding the charge/discharge loss.

These requirements could be achieved by a smaller engine that is capable of providing the peak-power requirement at its normal maximum RPM. Such an engine would weigh 2.3 kg/kW, and assuming the generator weighs 1.0 kg/kW, we find the value of C_2 increases to 285 W/kg (i.e. 1/(2.3+1)). However, the batteries must now be able to provide more power for short duration accelerations when the engine is still providing only 140 W/kg. Again, solving for vehicle weight for the same Taurus example, we have the following HEV specification:

Vehicle curb weight		1385 kg
Engine peak output		44.7 kW
Continuous output		19.0 kW
Engine + generator weight		167 kg
Battery:	Peak output	59.1 kW
	Energy stored	8.3 kWh
	Weight	197 kg
	Type	Semi-bipolar lead acid
Motor:	output	79.3 kW
	Weight	80 kg

Here, the solution is far more reasonable, as an engine of 44.7 kW peak rating, with a displacement of 1.0 litre would be all that is required. The total weight of this type of system is very similar to the current intermediate size car. On the urban cycle, the engine would be on 28 percent of the time, and shut off for the rest of the cycle. On the highway cycle, the engine is on for 62 percent of the time, and the engine would be operating continuously at speeds above 70 mph cruise on level ground. This is favorable for fuel efficiency as the engine would be operating at or near its optimal bsfc point, and energy can flow directly from generator to motor without going through the battery.

Efficiency calculations shown are not as detailed as those that would be obtained from a simulation model, but a reasonably accurate picture can be established using the equations presented earlier in this section. The major assumption here is that the engine can be operated at close to optimal bsfc (but run occasionally at higher output when it is needed for high accelerations or prolonged periods of hill climbing or other high vehicle loads), or else be turned off. Using the details provided in table A-1, one can compute the following fuel consumption reduction. First, as there is no idling, the 16 percent of fuel consumed on the city cycle and 2.0 percent on the highway cycle is saved. Second, accessory power demand is not likely to be reduced in a hybrid, because an engine running at or near its optimal bsfc point rejects much more heat to the coolant, and, hence, cooling fan and water-pump requirements will increase, but the engine itself is much smaller. Accessory fuel consumption will be reduced by the improvement in bsfc or efficiency. Third, the use of regenerative braking will reduce tractive energy requirements by an amount similar to that for an EV, but the smaller battery (relative to an EV) may not be able to absorb the power spikes as efficiently. Fourth the use of an electric motor drive eliminates the transmission and improves drivetrain efficiency. Finally, by operating at or near its optimal efficiency point, the engine bsfc is greatly reduced.

On the negative side, a small engine (with smaller cylinders) is inherently less efficient owing to the higher surface/volume ratios of its combustion chamber. In the Taurus example, the engine would be a 1.0 litre four-valve four-cylinder engine, rather than the 3. O-litre two-valve V-6 currently used. Although some have discussed using one-or two cylinder engines, the noise and vibration characteristics of such engines are so poor that only a four-cylinder engine is thought to be acceptable in a midsize car (Even the three-cylinder Geo Metro engine is considered quite rough in automotive circles). Hence, peak efficiency is sacrificed by 2 percent to 3 percent relative to a 2.0 litre four-cylinder or 3.0 litre six-cylinder engine. The generator also must be sized for peak continuous output of 45 kW, while operating at a nominal output of 19 kW, which makes it heavier and less efficient under the standard operating mode.

Detailed analysis of the efficiency without a comprehensive simulation model requires some assumptions regarding average generator and motor efficiency. For a “2005 best” calculation, the assumptions are as follows:

• Generator efficiency:	at 19.0 kw	91 percent
	at 45 kw	94 percent
. Motor Efficiency:	Urban cycle	82 percent
	Highway cycle	90 percent
. Drivetrain gear efficiency:	Urban	94 percent
	Highway	96 percent

The motor and generator efficiency values are 3 to 4 percent higher than those of the “best” current motor/generators.

Engine efficiency was assumed at a slightly off-peak value of 33 percent (in reality, this is higher than the peak efficiency of small engines today). A cold-start related fuel economy loss of 5 percent was also used on the urban cycle. A sample calculation is shown in table A-5; the calculations assumes the 1995 mid-size car body and a 1995 “prototype” battery and motor/generator with the 2005 production component efficiencies detailed above. Urban fuel economy for the HEV “Taurus” is computed to be 32.74 mpg, and highway fuel economy is 41.2 mpg, yielding a composite fuel economy of 36.07 mpg, about 30 percent better than the current Taurus. Most of the improvement is in the urban cycle, with only a small (8.4 percent) improvement on the highway cycle.

The 30 percent value is an optimistic number for current technology, since every ***one*** of the components have been selected to be at the 2005 expected values, which are higher than the actual observed range. It also assumes the availability of a semi-bipolar battery that can produce high peak power for acceleration. It is easy to see that in the absence of such high peak-power capability, fuel economy drops precipitously. If a normal lead acid battery with a peak-power capability of 125 W/kg is used, composite fuel economy is only 24.5 mpg, which is almost 12 percent lower than the conventional Taurus! These findings are in good agreement with the observed fuel efficiency of some HEVS with conventional lead acid batteries. As noted, both Nissan and BMW reported lower fuel economy for their series hybrid vehicles, even though they used nickel cadmium batteries with specific peak power of 125 to 150 W/kg.

TABLE A-1 (a): Energy Consumption as a Percent of Total Energy Requirements for a Mid-size Car

	Percentage of total tractive energy		
	City	**Highway**	**Composite**[a]
Rolling resistance	**27.7**	**35.2**	30.5
Aerodynamic drag	18.0	50.4	29.9
Inertia (weight) force	54.3	14.4	39.6
Total	100	100	100

	Percentage of total fuel consumed		
Tractive energy	**58.5**	**81.5**	**66.6**
Accessory energy	11.0	7.0	9.6
Idle + braking consumption	16.0	2.0	10.7
Transmission + driveline loss	14.5	9.5	12.9

[a]Assumes that highway fuel economy = 1.5 X city fuel economy.

NOTE: Mid-size car of inertia weight= 1588 kg, CD= 0.33, A = 2.1 m^2,CR=0.011, 3L OHV V-6, power steering, four-speed automatic transmission with lockup, air conditioning.

SOURCE: Derived from G. Sovran and M. Bohn, “Formulae for the Tractive Energy Requirements of Vehicles Driving the EPA Schedules,” SAE paper 810184, 1981.

TABLE A-1 (b): Energy Consumption for a Mid-size Car
Consumption in kWh/mile

	City	Highway	Composite
Tractive energy requirement	0.2064	0.1974	0.2024
Transmission loss	0.0336	0.0160	0.0257
Accessory energy	0.0314	0.0164	0.0247
Total energy required	0.2714	0.2298	0.2528
Total fuel energy used	1.2146	0.8469	1.0490
Idle and braking loss	0.2314	0.0173	0.1348
Total fuel used	1.4460 (22.7 mpg*)	0.8642 (38.0 mpg*)	1.1838 (27.72mpg*)
Engine efficiency (w/idle)	22.34% 18.77%	27.13% 26.59%	24.10% 21.35%

*Fuel lower heating value of 32.8 kWh/gallon.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," report prepared for the Office of Technology Assessment, June 1995, p. 10-6.

TABLE A-2: Specifications of Some Advanced Electric Vehicles

Vehicle type	Total weight (kg)	Motor output peak (hp)	Fuel consumption (kWh/km)	P (hplkg)	E (Wh/kg-km)
GM Impact	1,348	137	0.115	0.091	0.086
Cocconi Honda CRX	1,225	120	0,103	0.087	0.084
BMW E-1	880	45	0.133	0.044	0.151
Chrysler Van	2,340	70	0.300	0.028	0.128
Ford Ecostar	1,405	75	0.188	0.040	0.134
Honda CUV4	1,680	66	0.155	0.036	0.093

KEY: P = performance rating of vehicle + payload; E = specific efficiency of vehicle.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economyto 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-39. Compiled from manufacturer brochures; Cocconi data from California Air Resource Board tests.

TABLE A-3: Engine and Accessory Weights (lbs)

	Ford Taurus 3.OL	Toyota Corolla 1.5L
Base engine	444	264
Accessories[a]	34	26
Electrical system[b]	38	27
Emission controls	30	incl.
Exhaust system	33	33
Catalyst	30	24
Total	609 lbs (276 kg)	374 lbs (170 kg)
output	105 kW	78 kW
Specific output	0.3 kWlkg	0.460 kW/kg
Specific weight	2.63 kg/kW	2.17 kg/kW

[a]Includes radiator, water pump, hoses, coolant.
[b]Includes starter, alternator and ignition system

SOURCE: American Automobile Manufacturers Association, 1994.

TABLE A-4: Equations for Deriving HEV Weight

1) Engine operates at optimal bsfc only.

$$M_{HEV} + \text{Payload} = M_{Bz} + \text{Payload} + 1.4\,M_{BATT} + 1.4M_{MOTOR} + 1.4M_{EG}$$

$$\text{Peak Performance} = (S_p \cdot M_{BATT} + C \cdot M_{EG})/(M_{HEV} + \text{Payload})$$

$$\text{Maximum Continuous Performance} = C \cdot M_{EG}/(M_{HEV} + \text{Payload})$$

If peak-power requirements are *50* kW/ton and the continuous requirement is 30 kW/ton, we have:

$$\frac{M_{Bz} + \text{Payload}}{M_{HEV} + \text{Payload}} = 1 - \frac{1.4 * 30}{C_1} - \frac{1.4 * (50-30)}{S_P} - \frac{1.4 * 50}{K}$$

2) If the engine normally operates at or near optimal bsfc but can produce higher power output for a continuous requirement, such as hill climb, we have:

$$\text{Maximum Continuous Performance} = C_2\,M_{EG}/(M_{HEV} + \text{Payload})$$

$$\frac{M_{Bz} + \text{Payload}}{M_{HEV} + \text{Payload}} = 1 - \frac{1.4 * 30}{C_2} - \frac{1.4 * (50 - 30 * C_1/C_2)}{S_P} - \frac{1.4 * 50}{K}$$

where

M_{HEV}	=	weight of hybrid electric vehicle
M_{Bz}	=	"zero engine" body weight
M_{BATT}	=	weight of battery
M_{MOTOR}	=	weight of motor
M_{EG}	=	weight of ICE + generator
C or C_1	=	continuous specific output of engine + generator, kW/ton
K	=	specific output of motor, low/ton
C_2	=	peak specific output engine + generator, kW/ton
S_P	=	peak specific power of battery, kW/ton

Note: Typical values used are S_P = 300 kW/ton, K = 1000 kW/ton, C_1 = 125 kW/ton, C2 = 285 kW/ton

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," report prepared for the Office of Technology Assessment, June 1995, p. 10-60.

TABLE A-5: Energy Use for a Current (1995) Mid-size Car Converted to an HEV (kWh)

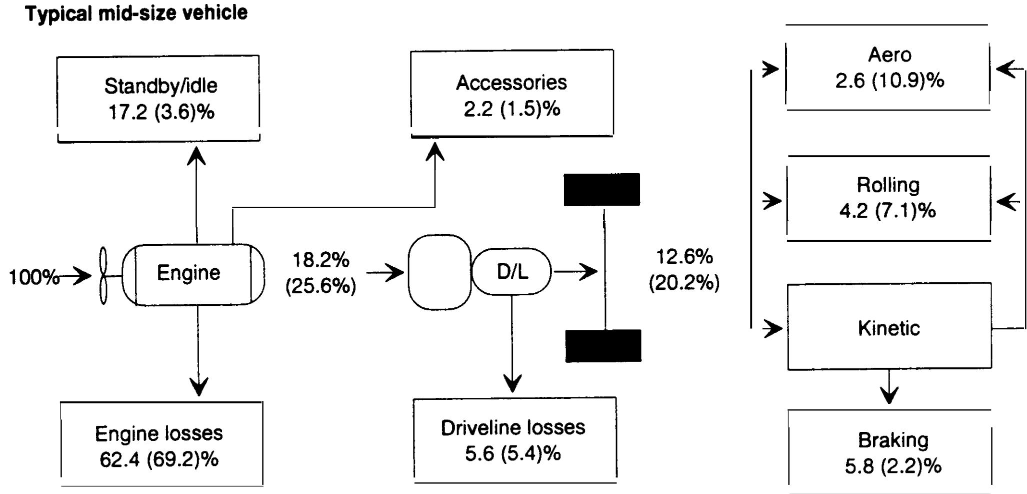
	Urban	Highway
Tractive energy	0.201	0.184
Motor output	0.214	0.192
Regenerative braking recovery	0.045	0.008
Tractive energy input	0.216	0.205
Engine output[a]	0.315	0.263
Fuel economy, mpg	32.7	41.2
Percent improvement over 1995 base	44.1	8.4

[a] Assumes batteries recharged to initial state at end Of Cycle. Analysis assumes highly optimized electrical drivetrain components.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," report prepared for the Office of Technology Assessment, June 1995, p. 1O-64.

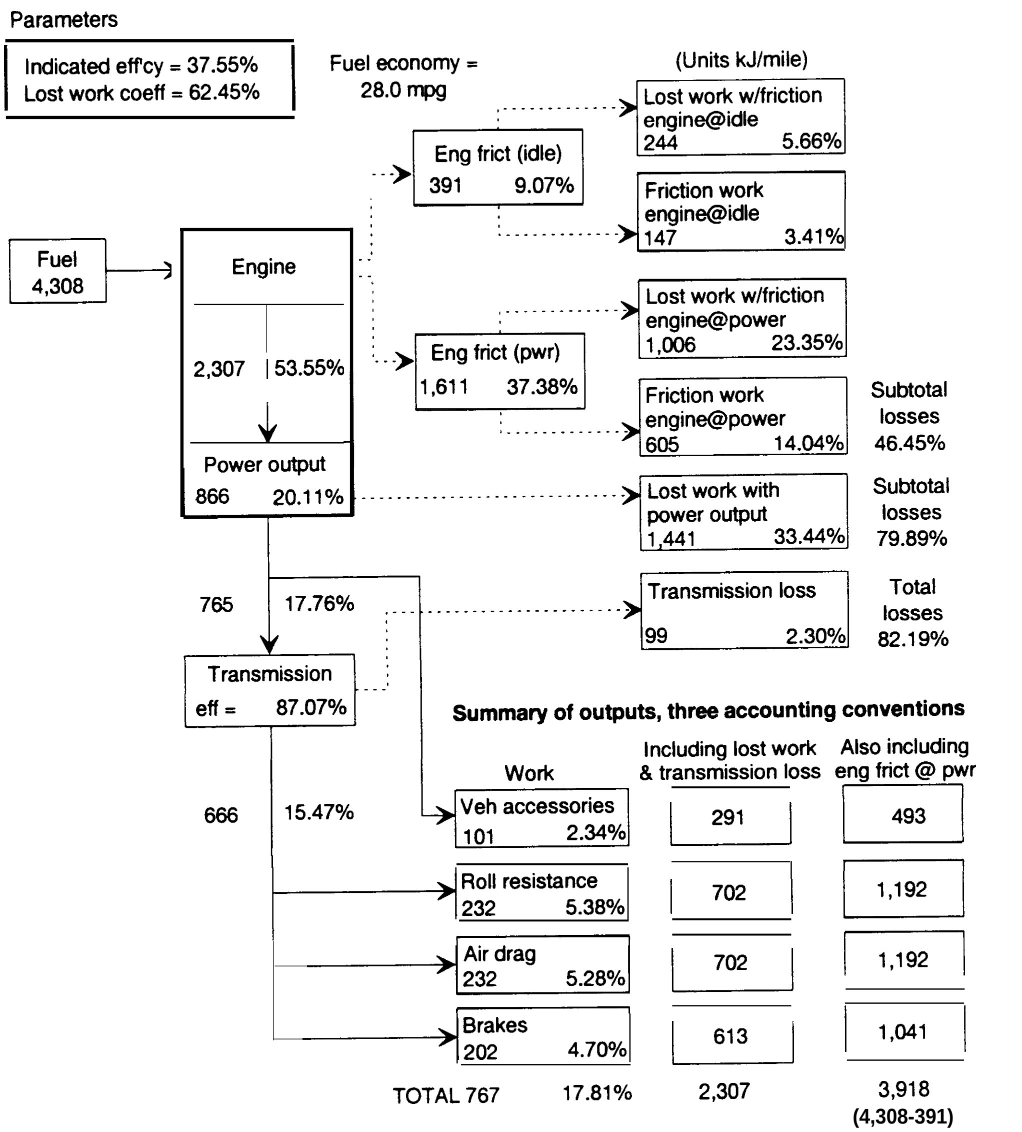
Figure A-1: Energy Distribution

Typical mid-size vehicle



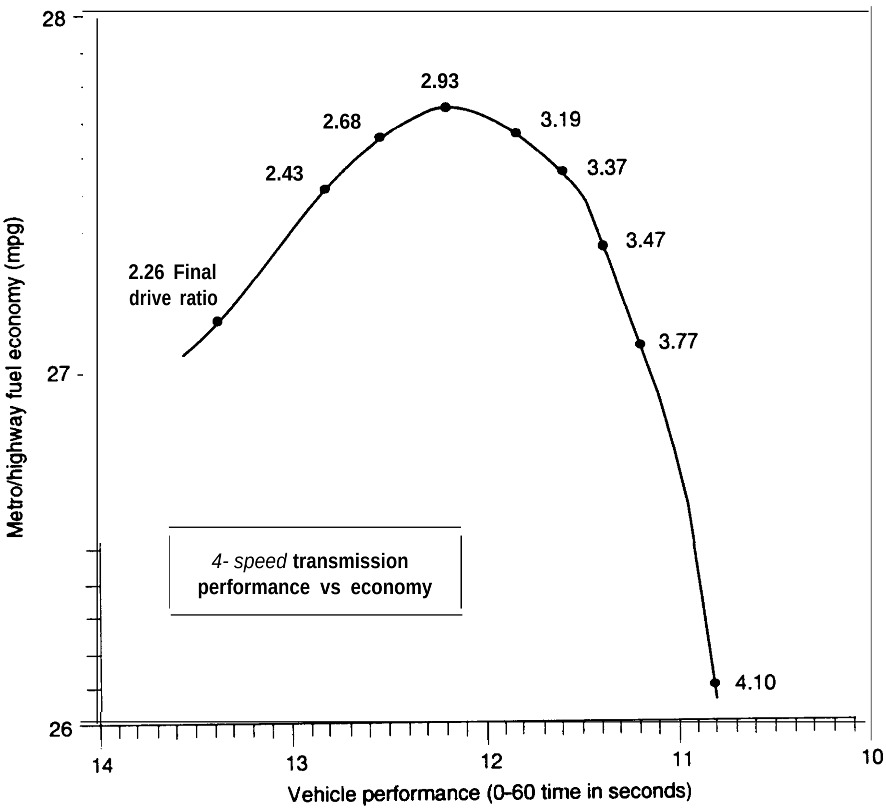
NOTE: Numbers indicate urban energy distribution. Numbers in parentheses indicate highway energy distribution.
SOURCE: Partnership for a New Generation of Vehicles.

Figure A-2: Energy Flows, AVCAR '93, EPA Composite Cycle



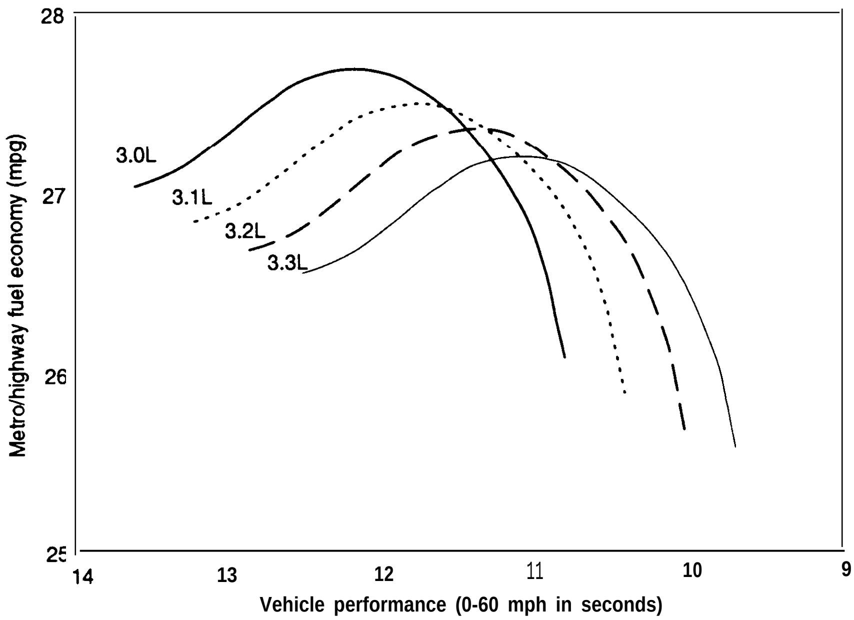
SOURCE: M. Ross and W. Wu, "Fuel Economy of a Hybrid Car Based on a Buffered Fuel-Engine Operating at its Optimal Point," SAE paper 95000,1995.

Figure A-3: Vehicle Performance vs. Fuel Economy



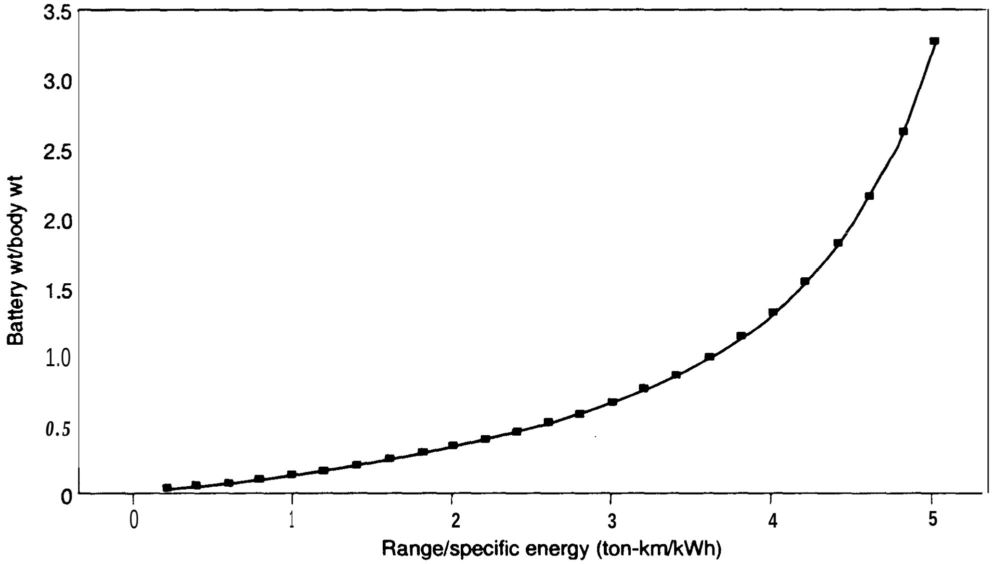
SOURCE: Ford Motor Co.

Figure A-4: Fuel Economy vs Performance (effect of displacement on best fuel economy)



SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies to Improve Fuel Economy to 201 5," prepared for the Office of Technology Assessment, June 1995, pp 10-13.

Figure A-5: Battery Weight vs EV Range



SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies to Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-41.

APPENDIX B:

Methodology: Technology Price Estimates

In this report, the Office of Technology Assessment (OTA) has estimated the approximate retail price of technologies that range from those already present in the current light-duty vehicle fleet to those whose final design, choice of materials, and manufacturing process are not known. Some warning about these estimates and their sources is warranted:

1. ***For technologies far from commercialization, price estimates should be treated with skepticism.*** The only available manufacturing experience with these technologies is likely to be one-of-a-kind hand building. Redesigning to solve remaining problems may increase costs; mass production will certainly lower costs; the technologies will be redesigned to cut manufacturing costs; and learning over time will cut costs both through product redesign and through continual cost-cutting in manufacture. The magnitude of changes over time is not particularly predictable.

2. Although technology developers know the most about their technology's costs and remaining problems, their estimates of costs are particularly suspect. Technology developers are at the mercy of their finding sources--their company's directors, venture capitalists, and government agencies--and these sources generally will not proceed without assurances that costs will be competitive. The sole exception occurs when regulatory demands require proceeding with a technology regardless of market factors.

3. Alternative estimates of technology prices are exceedingly difficult to compare, because they rarely focus on precisely the same technological specifications and often differ in their inclusion of key cost components. For example, vehicle price estimates must include a range of expenses, including amortization of design costs, transportation, dealer markups, and so forth, but key cost components are frequently ignored in cost analyses.

OTA's analysis focuses on the incremental effect introduction of the technology will have on a vehicle's retail price, averaged across new vehicles. The price effect on an individual car or light truck model may be higher or lower than the estimated "retail price equivalent" (RPE), but these price variations represent cross subsidies between consumers. For example, marketing strategies may require certain models to be priced lower than other technologically similar models to compete efficiently in the marketplace, but average price increment is the focus of this analysis.

The analysis assumes that the industry is sufficiently competitive, and the technology and production methods are widely enough understood by competing companies, that manufacturers earn only their usually expected returns on capital--that is, they get no benefit by being able to charge a premium because no one else has the technology. In fact, most of the technologies considered in this report, except for battery and fuel cell technology, cannot be considered proprietary. This is also true of production methods, although different companies can be more or less efficient in production. In a competitive marketplace, all manufacturers must price their product so that the average producer earns a normal rate of return on capital; more efficient producers can gain market share by pricing lower than average at the expense of less efficient producers, or they can increase unit profits by charging the same as their less-efficient competitors.

In reality, the auto manufacturers are not a fully competitive industry but an oligopoly, in that three manufacturers control more than 70 percent of the U.S. market, and there are difficult barriers to entering the market. The picture is further complicated by a segmented car market that has some highly competitive market segments while others, such as large-car segments, are less competitive. The methodology used here is based on a manufacturer's "expected" rate of return on capital, which may be higher than the "normal" rate of return (if sales volume goals are attained) because the market is not perfectly competitive. Using this method, the calculated price impact may overstate the actual price impact in very market competitive segments, but may understate the impact in more oligopolistic segments.

Some technologies, such as diesel engines, are all already widely available, and their price effect is reported from direct observation of market prices. For most technologies, the method of estimating RPE is based on first estimating the cost of manufacturing a technology, then translating this to a retail price equivalent, assuming an expected rate of return. For those technologies that affect horsepower and performance, RPE is adjusted to account for the market value of performance. For example, the RPE of a four-valve engine would be determined as an increment to a two-valve engine of ***equal performance,*** which translates into a comparison with a larger displacement two-valve engine.

METHODOLOGY TO DERIVE RPE FROM COSTS

The RPE evaluation uses an approach followed by industry that includes the variable cost for each unit of the component or technology, and the allocation of the fixed costs associated with facilities, tooling, engineering, and launch expenses. The methodology has been used widely by regulatory agencies and is described in a report to the Environmental Protection Agency.[1] It has been adopted here with modifications suggested by recent manufacturer submissions to the U.S. Department of Transportation.

The methodology estimates both the amortization (based on the expected rate of return) of the investment cost of R&D engineering, tooling, production, and launch, and the labor, material, and plant operating costs, based on expected sales. If actual sales volume exceeds expected volumes, the manufacturer records a higher profit margin, but a lower volume can result in a loss. These excess profits and losses are balanced over a range of models which exceed, or are below, sales targets for a given manufacturer. The expected rate of return is set at 15 percent (real), which is higher than the normal rate of about 10 percent, and represents the risk-adjusted oligopoly rate of return.

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[1] U.S. Environmental Protection Agency, "Cost Estimation for Emission Control Related Components/Systems and Cost Methodology," Report No. 460/3-78402, 1978.

The methodology uses a three-tier structure of cost allocation. A specific component, such as a new piston or a turbocharger, is first manufactured by a supplier company, or by a division of the manufacturer that is an in-house supplier (e.g., Delco supplies GM with electrical components). The supplier part "cost" to the manufacturer has both variable and fixed components--the variable cost is associated with materials, direct labor, and manufacturing overhead, and the pretax profit is calculated as a percentage of variable costs.[2] Fixed costs--tooling and facilities expenses--are based on amortizing investments undertaken before production and include the return on capital. In-house and external suppliers are treated identically, so that RPEs are not affected by outsourcing decisions, which is consistent with the idea of a competitive marketplace for subassemblies.

The second cost tier is associated with vehicle assembly, where all of the components are brought together (for example, the stamping plant producing body sheet metal parts can be treated as a "supplier" for costing). Manufacturer overhead and pretax profit are applied to the components supplied to an assembly plant plus the assembly labor and overhead.[3] Fixed costs include the amortization of tooling, facilities, and engineering costs, and include return on capital. The final tier leads to the retail price equivalent, and includes the markups associated with transportation, dealer inventory and marketing costs, and dealer profits.[4]

Table B-1 summarizes the cost methodology, and all of the overheads and profits are specified as standard percentage rates applied to variable costs.

Amortizing fixed costs and applying them to individual vehicles requires estimates of:

- fixed-cost spending distribution over time,
- return on capital,
- annual production capacity, and
- amortization periods

The fixed-cost spending occurs over five years before technology introduction in the marketplace, with most spending taking place in the two-year-period before launch. The rate of return on capital is assumed to be 15 percent real (inflation adjusted), consistent with the normal project rate used by the automotive industry (using this rate, every dollar of total investment in a project has a net present value of $1.358 at launch).

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[2]Supplier overhead and profit are both assumed to be 0.20, based on ibid., and auto industry submissions to the U.S. Department of Transportation.

[3]Manufacturer overhead assumed to be 0.25, manufacturer profit to be 0.20, W on ibid., and auto industry submissions to the U.S. Department of Transportation.

[4]Dealer margin assumed to be 0.25, based on auto industry submissions to the U.S. Department of Transportation.

[5]Energy and Environmental Analysis, Inc., "Documentation of the Fuel Economy, Performance and Price Impact of Automotive Technology," report prepared for the Oak Ridge National laboratory, Martin Marietta EnergSystems, July 1994.

Plant capacity is 350,000 units a year, a "representative average" for automotive body-related technologies. Atypical model lifecycle is eight years, with a "facelift" at the midpoint in a model's product cycle; the appropriate period for amortization of engineering expenses related to the exterior design is four years. Engine and drivetrain components usually have a longer lifecycle than vehicle platforms, ranging from 8 to 10 years. In general, there are no major changes during this period, so that cost recovery over an 8-year-period is appropriate. Typical production capacity is 500,000 units a year for engines and transmission plants and designs. Calculations to derive unit costs assume operation at 85 percent capacity. Table B-2 shows the conversion method for deriving unit prices from variable and fixed costs for engine and drivetrain components.

It should be noted that the purpose of this analysis is not to derive the total cost, but the incremental cost, of a technology relative to the existing baseline technology. The analysis, therefore, estimates the ***difference*** in variable costs and investment between a technology and the one it supersedes. In this context, the choice is not between continuing production of an existing technology whose investment costs may have been fully amortized versus a new technology, but between a new model with baseline technology versus a new model with new technology. This is a ***crucial*** difference that potentially accounts for the great differences between some very high estimates of technology RPE and estimates presented here. The high estimates basically treat the fixed costs of the conventional vehicles as "sunk," making the conventional vehicles a much greater bargain than vehicles with new technology. This may be reasonable for the short term, but eventually manufacturers will have to redesign the conventional vehicles, including their powerplants, and the decision between conventional and new technology should then be based on the framework presented here.

TABLE B-1: Costing Methodolo~

Tier I **Supplier/Division Cost**	=	[Materials + Direct Labor+ Manufacturing Overhead] x [1 + Supplier Overhead+ Supplier Profit] + Tooling Expense+ Facilities Expense+ Engineering Expense
Tier II **Automanufacturer Cost**	=	[Supplier Cost + Assembly Labor+ Assembly Overhead] x [1 + Manufacturing Overhead+ Manufacturing Profit] + Engineering Expense+ Tooling Expense + Facilities Expense
Tier III Retail Price Equivalent	=	Manufacturer Cost x Dealer Margin
Notes		
Supplier Overhead	=	0.20
Supplier Profit	=	0.20
Manufacturer Overhead	=	0.25
Manufacturer Profit	=	0.20
Dealer Margin	=	0.25

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," report prepared for the Office of Technology Assessment, June 1995, p. 9-5.

TABLE B-2: Methodology to Convert Variable and Fixed Cost to RPE

. Supplier cost to manufacturers	= A
. Total manufacturer investment in tooling, facilities, engineering, launch	= B
. Unit cost of investment for drivetrain technology	= B X 1.358 +(500,000X 0.85X 4.487) ‘ c
. Automanufacturer cost	= (A x 1.4) + C = D
• **RPE**	= D X 1.25

[a]Unit cost for body technology = (B * 1.358)+(350,000x 0.85x 2.855)

SOURCE: Energy and Environmental Analysis, Inc., “Automotive Technologies To Improve Fuel Economy to 2015,” report prepared for the Office of Technology Assessment, June 1995, p. 9-8.