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 A11.

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

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

[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

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[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:

[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

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

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[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.

[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	39	+400	
	1st generation aluminum	42	+1,600	
Electric vehicle (EV)	Optimized steel	31[c]	+11,400	Lead acid battery
	Optimized steel	48	+18,400 (9,300)	NiMH battery (lower price assumes battery cost $200/kWh, based on developer claims)
Hybrid-electric	Optimized steel	49	+4,900	Bipolar lead acid battery energy storage
	1st generation aluminum	61	+7,800/10,200	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).