Chapter 4

Advanced Vehicles -- Technical Potential and Costs

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

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

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

OTA’s Methodology

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

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

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

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

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

Types of Vehicles Examined

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

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

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

[2] G. Sovran and M.S. Bohn, "Formulae for the Tractive Energy Requirements of Vehicles Driving the EPA Schedule," SAE paper 810184, February 1981.
[3] These returns reflect the oligopolistic nature of the auto industry, and are somewhat higher than they would be if the industry were perfectly competitive.

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

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

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

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

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

Vehicle Attributes

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

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

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

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

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

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

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

Technologies Introduced Individually or in Combination

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

Uncertainty in Technology Forecasting

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

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

- the possibility that the market rejected the technology because of its expense or perceived disadvantages (high rates of failure, adverse effect on noise or ride quality, and so forth), and/or market preferences may have changed after the forecast was made;
- other technologies that are lower cost or have lower operating expenses may do a better job;

- the technical "context" that made the technology attractive or unattractive--the prevalent fuel or the nature of the technologies affecting or affected by the technology--may change;

- new regulations (for example, emission standards not easily complied with by the technology) can either hinder or enhance technology introduction;

- manufacturing the technology in large quantities can turn out to be more difficult and expensive than was expected, or improvements in manufacturing can do the reverse;

- problems may occur in the "real world" operating environment that are difficult to overcome (some automotive technologies fail because they require levels of maintenance that are difficult to *get* U.S. car owners to comply with, or because driving patterns place more severe strains on performance than were originally forecast by test results).

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

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

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

- to gain a rough estimate of the magnitude of fuel economy improvement potential over the next 20 years;

- to identify future policy challenges associated with advanced vehicles, such as potential for higher costs, difficult market challenges, potential safety problems; and

- to provide assistance in evaluating existing and proposed vehicle research programs.

ENERGY USE AND REDUCTION IN LIGHT-DUTY VEHICLES

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

BASELINE

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

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

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

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

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

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

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

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

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

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

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

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

ADVANCED CONVENTIONAL VEHICLES

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

ELECTRIC VEHICLES

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

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

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[13] See chapter 3 discussion of diesel engines.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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[29] Private communications with AC-Delco representatives.

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

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

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

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

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

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

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

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

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

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

Emission Effects

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

HYBRID VEHICLES

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

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

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

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

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

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

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

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

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

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

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

Series Hybrids

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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[54] The peak efficiency point occurs at 40 to 45 percent of peak rpm and 70 to 80 percent of maximum torque.

[55] Assuming the engine weighs about 2 kg/kW of peak output, or 2.2 to 2.6 kg/kW including radiator, exhaust system, and catalyst.

[56] This requirement is a placeholder for a number of long-duration, high-power requirements such as trailer towing or long-duration climbs at lower grades but higher payloads.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Emissions

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

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

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

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

Other Studies

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

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

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

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

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

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

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

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

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

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

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

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

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

- Car weight (total) would be 580 to 400 kg, less than half of what is estimated by OTA even with carbon fiber construction.
- Drag co-efficients are reduced to 0.14 to 0.10, about half the best levels forecast by OTA.
- Switched reluctance motors that drive the wheels directly are assumed to have an average efficiency over the EPA test cycle of 93 percent. This is an unusally high average value for a motor.
- Accessory loads on the engine would be reduced to zero.
- Regenerative braking efficiency is assumed to have very high (>75%) recovery of inertia losses.

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

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

Parallel Hybrids

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

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[64] Merrit and Wipke, see footnote 49.

There are two possible operating strategies for a parallel hybrid:

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

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

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

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

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

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

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[65] Josefowitz and Köhle, see footnote 53.

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

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

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

Prices

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

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[66]Chrysler, presentation to OTA, September 8, 1994.
[67]E. Chattot et al., "The Continuing Development of a Charge Depletion HEV, Aftershock, at UC-Davis", SAE Paper 95000.
[68]Actually, a parallel hybrid will require greater 50 kW/ton of available peak power to match OTA's power requirement, because part of the power for peak acceleration is provided by the vehicle's electric motor, at 50 kW/ton required and part by the engine, at 60 kW/ton required.

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

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

FUEL CELL VEHICLES

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

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

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

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

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

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

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

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

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

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

CONCLUSIONS ABOUT PERFORMANCE AND PURCHASE PRICE

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

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

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

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

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

LIFECYCLE COSTS

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

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

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

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

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

Battery Replacement Costs

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

Differences in Maintenance Costs and Longevity Between EV and ICE Drivetrains

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

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

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

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

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

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

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

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

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

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

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

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

Trade-In Value

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

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

- Many early vehicles will serve niche markets; the buyer pool for used vehicles would then be limited, depressing prices;

- For a number of years following commercialization, innovation of drivetrain technologies should be rapid, making older vehicles less attractive in comparison.

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[75] Ibid.

Energy Costs

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

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

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

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

Conclusions

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

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

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

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

SAFETY OF LIGHTWEIGHT VEHICLES

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

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

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

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

[79] Delucchi, see footnote 73.

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

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

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

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

The Role of Weight in Accident Prevention and Crashworthiness

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

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

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

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

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

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

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

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

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

83 L. Evans and M.C. Frick, General Motors, "Car Size or Car Mass: Which Has Greater Influence on Fatality Risk," 1992.

84 Crush distance is the amount of length that the vehicle can give up to compression and energy absorption through controlled collapse.

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

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

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

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

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

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

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

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

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

What Accident Statistics Tell Us

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

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

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

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

Design Solutions

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

[87] Evans and Frick, see footnote 83.

[88] Ibid

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

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

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

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

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

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

Additional Issues

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

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

[92] Ibid.

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

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

[95] Ibid.

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

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

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

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

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

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

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

[98] Ibid.

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

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

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

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

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

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

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

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

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

SOURCE: Office of Technology Assessment, 1995.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

KEY: FE= fuel economy; HP = horsepower.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

TABLE 4-6: Specifications of Some Advanced Electric Vehicles

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

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

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

TABLE 4-7: 2005 Electric Vehicle Characteristics

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

[a]Unrealistic Scenario.

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

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

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

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

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

KEY: RPE = retail price effect.

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

TABLE 4-9: 2015 Electric Vehicle Characteristics

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

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

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

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

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

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

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

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

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

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

TABLE 4-12: Series Hybrid Vehicle Efficiency

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

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

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

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

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

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

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

	Base	Case 1: Parallel hybrid	Case 2: Parallel hybrid
Curb weight (lbs)	3,130	-3,400	3,250
Engine			
Size (L)	3.0	2.0	1.0
Power (HP)	140	120	49
Torque (newton-meters)	165	125	58
Motor			
HP	0	26.8	60
Torque	0	40	90
Electric Storage	N/A	Flywheel	Bipolar lead acid
Weight (lbs)	0	64	400
Power (HP)	0	60	60
Energy (kWh)	0	1	7.5

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-76.

TABLE 4-15: Incremental Prices for Series Hybrids

	Storage Device		
	Battery	**Ultracapacitor**	**Flywheel**
2005 (m)	*$4,420*	**$9,730**	**$7,260**
2015 (m)	**$3,170**	**$8,300**	**$6,100**

KEY: m = mean assumptions about new technology.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-78.

TABLE 4-16: Characteristics of a PEM Fuel Cell Intermediate-Size Vehicle in 2015

	Bipolar Lead Acid Battery	Ultracapacitor
"Zero engine" body weight	540.0	540.0
Fuel cell rating (kW)	37.1	30.8
Cell weight (kg)	148.3	131.2
Power storage: power (kW)	39.0	116.4
Energy (kWh)	3.5	0.9
Weight (kg)	78	58.2
Total hybrid weight	914.5	893.4
EV range (for cold start)	22.1	5.2
Time at peak power (minutes)	4.6	1.2
Energy efficiency (mpg, gasoline equivalent)	83.1	85.5
Price increment		
($650/kWh)	$38,750	$36,500
($65 /kWh)	$4,510	$4,920

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-82.

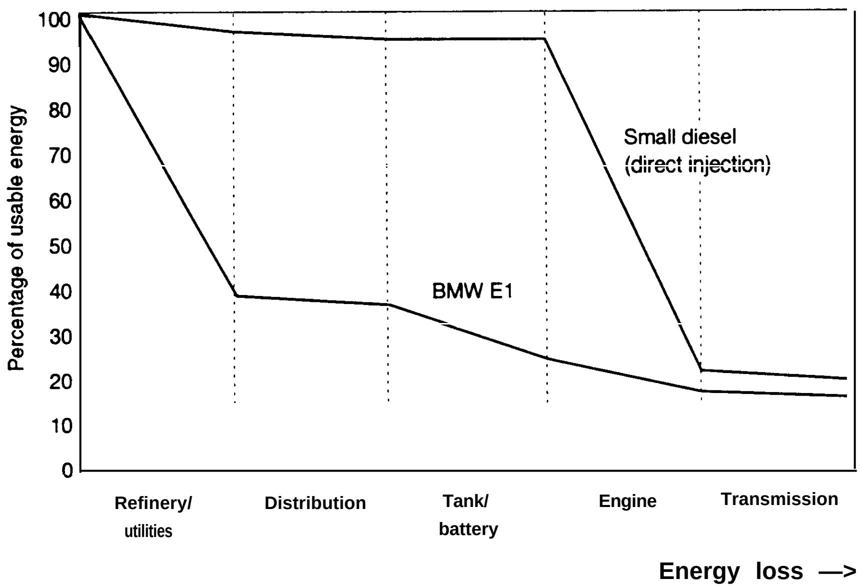
TABLE 4-17: Fuel Consumption and Annual Fuel Costs of Advanced Mid-size Vehicles

Type of vehicle	Fuel consumption	Fuel cost per year[a]
Baseline (Taurus)	33 mpg	$535[b]
Advanced conventional	53 mpg	$333
EV (lead acid)	0.27 kWh/mile	$223
EV (Ni-MH)	0.17 kWh/mile	$137
Series hybrid (lead acid)	65 mpg	$272
PEM fuel cell (methanol)	83 mpg (gasoline equiv)	$182

[a]Based on $1.50/gallon gasoline, 75 C/gallon methanol, 7¢/kWh offpeak electricity, 10,000 miles/year.
[b]The fuel economy values shown are EPA unadjusted values. Fuel costs are based on the assumption that on-road efficiencies are about 15 percent less. Clearly, each vehicle type will have a different adjustment factor, but it is not clear what those factors should be. For example, EVs will lose less energy from congestion effects (because they have regenerative braking and no idling losses), but will use substantially more energy to heat the vehicle--which is not accounted for in the EPA tests, where accessories are not used.
[c]Optimized aluminum body, DISC engine.

SOURCE: Office of Technology Assessment, 1995.

Figure 4-1: Losses Within the Overall Energy Chain (comparison of diesel and electric car)



SOURCE: BMW Traffic and Environment.

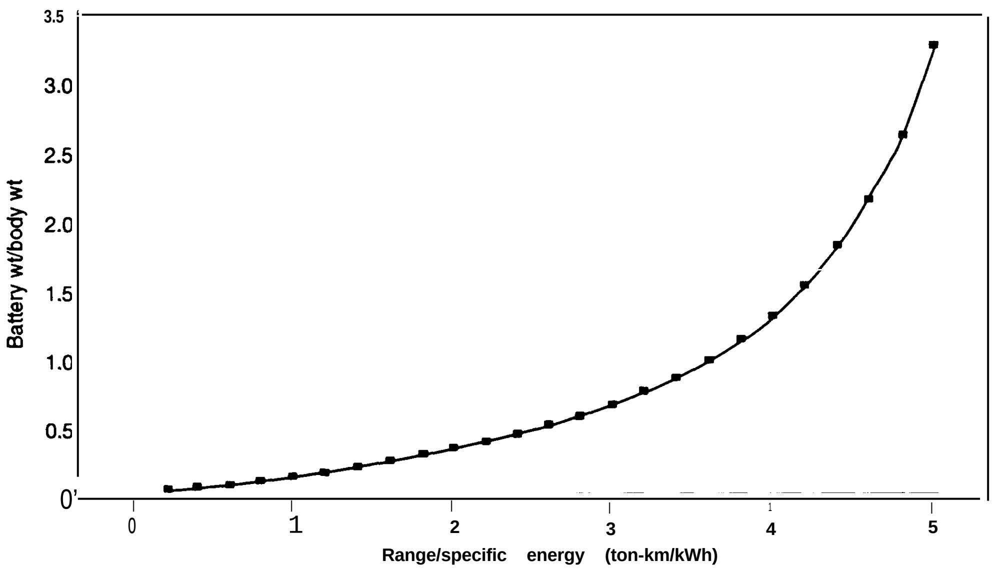
Efficiency	Diesel car	Electric car
Refinery or power station[a]	96%	36%
Distribution	98%	95%
Tank/battery	100%	68% (charge cycle and heating loss during standstill)
Engine (depending on drive cycle)	23%	66%
Transmission	90%	95%
Final result	19%	15%

[2]Without energy losses from the drilling hole to the refinery or power station.

NOTE: Figures for the electric car are for a daily mileage of 30 km (18.6 mi).

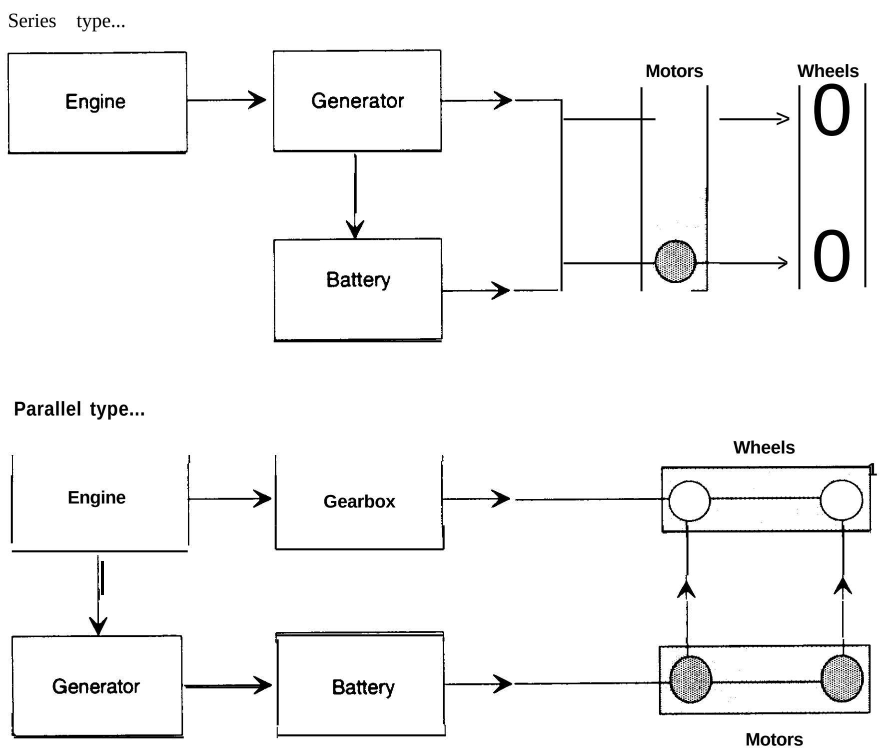
SOURCE: Electric car - BMW calculations, Diesel - MTZ 52 (1991) No. 2, p. 60-65.

Figure 4-2: Battery Weight vs EV Range



SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies to Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-41.

Figure 4-3: Hybrid Concepts



SOURCE: Energy and Environmental Analysis, Inc., Automotive Technologies To Improve Fuel Economy to 201 5," prepared for the Office of Technology Assessment, June 1995, p. 10-53.