A New Road

The Technology and Potential of Hybrid Vehicles

by DAVID FRIEDMAN

Union of Concerned Scientists
Citizens and Scientists for Environmental Solutions

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The Union of Concerned Scientists is a nonprofit partnership of scientists and citizens combining rigorous scientific analysis, innovative policy development and effective citizen advocacy to achieve practical environmental solutions.

The Union of Concerned Scientists Clean Vehicles Program develops and promotes strategies to reduce the adverse environmental impacts of the US transportation system.

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EXECUTIVE SUMMARY

The world started down a new road in 1997 when the first modern hybrid electric car, the Toyota Prius, was sold in Japan. Two years later, the United States saw its first sale of a hybrid, the Honda Insight. These two vehicles, followed by the Honda Civic Hybrid, marked a radical change in the type of car being offered to the public: vehicles that bring some of the benefits of battery electric vehicles into the conventional gasoline powered cars and trucks we have been using for more than 100 years.

In the coming years, hybrids can play a significant role in addressing several of the major problems faced by the United States and the world today: climate change, air pollution, and oil dependence. Whether this new technology delivers on its promise hinges on the choices automakers, consumers, and policymakers make over the coming years. Poor choices could result in hybrids that fall short even of what conventional technology could deliver on fuel economy, emissions, or both.

This report provides consumers and policymakers with the tools they will need to sort out the many technological, financial, and environmental differences among the hybrids that will be brought to market in the coming years. Using new research into the cost and performance of hybrid technology, this report provides a comprehensive assessment of the technology, the fuel economy, and the costs associated with a fleet of passenger cars and trucks that rely on hybrid technology to more than double the fuel economy commonly available today. If they are designed well, these hybrids can equal or better the utility, comfort, performance, and safety we've come to expect, while saving us thousands of dollars at the gas pump.

Defining Hybrids

Hybrids have been defined in a variety of ways, few of which help in determining whether a particular model realizes the technology's potential. The checklist in Table ES-1 *(see page 2)* provides a reasonable method for evaluating which cars and trucks are hybrids and for differentiating among them based on their technologies. In general, hybrids with more checkmarks do more to provide energy security and less to harm the environment than those with fewer checkmarks. However, the most effective way to gauge a hybrid's energy security and environmental performance will be to evaluate their fuel economy and emissions performance directly on the road.[1]

On this checklist, the Insight and the Civic Hybrid each receives three checkmarks and are thus considered "mild" hybrids. With four checkmarks, the Prius is a "full" hybrid. A vehicle that receives five checkmarks is a "plug-in" hybrid, none of which are yet available in the United States. If a vehicle has only one checkmark it is actually just a conventional vehicle. Two checkmarks qualifies a vehicle as a muscle-hybrid, a vehicle that uses hybrid technology to increase power and performance instead of significantly increasing fuel

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[1] The most appropriate method would combine the fuel economy and emissions level with weighting factors based on the health and economic effects of gasoline consumption and tailpipe emissions.

economy—leading to an expensive vehicle with very low cost-effectiveness. As more vehicles enter the market, this checklist can be used to evaluate the hybrids automakers offer.

The Technology's Potential

The Honda Civic Hybrid and Toyota Prius are good examples of the current potential of hybrids —but they're just a start. More technology is ready to be put to work and not only for compact cars. This study provides a broader picture of how hybrid technology could transform the whole passenger fleet both within this decade and into the next.

A fleet of cars and trucks that takes full advantage of hybrid and other advanced technologies could reach an average fuel economy of 60 mpg, as Figure ES-1 shows. Even conventional technologies could boost the passenger vehicle fleet average up to 40 mpg. And all the hybrids examined in this study can meet today's most stringent standards for tailpipe emissions[2] (excluding the zero-emissions standard). The study's key findings are outlined below.

- A fleet of passenger cars and trucks using conventional technology has the potential to reach a fleet average of 40 mpg. The average vehicle in this fleet will cost about $1,700 more in the showroom, but will save consumers $3,800 at the gas pump over the vehicle's 15-year life for a net savings of $2,100.
- A fleet of mild hybrids can reach nearly 50 mpg, with a retail price increase of about $2,900 by using advanced technologies available to automakers within this decade.[3] Lifetime gasoline savings will amount to $4,700, producing a net savings of $1,500 for the average driver when the cost of battery replacement is included.[4] Mild hybrids that use more moderate technology or smaller motor/battery systems will achieve lower fuel economy and will be less cost effective.[5]

Table ES-1 **Hybrid Checklist: Is This Vehicle a Hybrid?**

Does this vehicle...	**Conventional Vehicle**	**Muscle Hybrid**	**Mild Hybrid**	**Full Hybrid**	**Plug-in Hybrid**
Shut off the engine at stop-lights and in stop-and-go traffic	✓	✓	✓	✓	✓
Use regenerative braking and operate above 60 volts		✓	✓	✓	✓
Use a smaller engine than a conventional version with the same performance			✓	✓	✓
Drive using only electric power				✓	✓
Recharge batteries from the wall plug and have a range of at least 20 miles on electricity alone					✓

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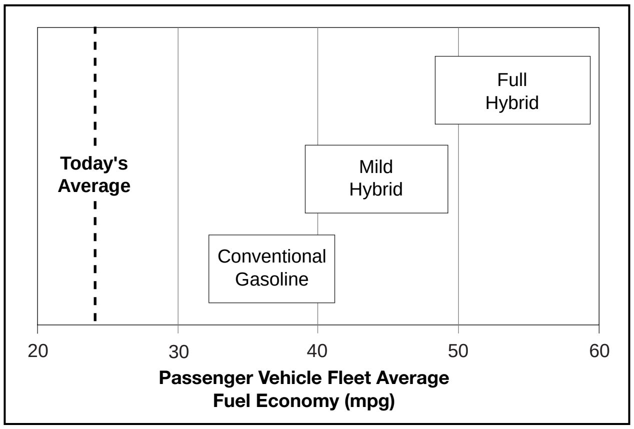
[2] The Federal Tier 2, Bin 2 standard (also California's SULEV standard).

[3] Advanced technology refers to engine, transmission, weight savings, and battery and motor technology that has already been developed by automakers, but has not found its way into the US fleet. Examples include the gasoline direct injection engine and batteries with power densities over 800 Watts per kilogram.

[4] Excludes vehicle taxes and other fees at purchase, tax credits or deductions, maintenance, and annual registration fees.

[5] Moderate technologies are available on cars and trucks today, but in limited volumes. Some examples include low-friction variable valve engines, continuously variable transmissions, and batteries with power densities of 600-700 Watts per kilogram.

Figure ES-1 **Fuel Economy Potential for Hybrid Electric and Conventional Vehicles**



NOTES:

1. The lower boundary is set by the use of moderate technology that is widely available during this decade. The upper bound is set by the use of more advanced technology that is likely to be available for wide use early in the next decade.

2. The mild hybrids are rated at 15% peak power from the motor and energy storage system, mild hybrids with lower peak power would not perform as well. Full hybrids with peak power below 25% will not perform as well as shown.

- Full hybrids using advanced technology are the key to a passenger car and truck fleet that approaches an average of 60 mpg. The average price increase for such vehicles is about $4,000 and the owners will save nearly $5,500 on gasoline over the life of the vehicle. Including battery replacement, consumers would see an average net savings of $900. Plug-in hybrids would realize even greater energy security and environmental gains, but with higher costs and lower net consumer savings.
- Using the advanced technologies available today is a key step to ensuring cost-effective hybrid options with good performance. If an automaker simply adds an electric motor and battery to the typical car or truck on the road today, the resulting vehicle will be more expensive and will not perform as well as the hybrids evaluated in this report.

In achieving higher fuel economy, future hybrids will not sacrifice safety. In fact, drivers of SUVs and pickups will be safer: battery placement in practical hybrid designs create a lower center of gravity, making SUVs and other tall vehicles less likely to tip over. And since they will be lighter, but just as strong as today, they will pose less danger to others during collisions, while keeping the SUV driver and passengers safe.

Hybrid Vehicles: Filling the Gap

This study emphasizes the role hybrids must play in our efforts to limit the contribution our cars and trucks make to US oil dependence, global warming, and local air pollution. In the short term, conventional technologies could quickly raise the average fuel economy of the passenger fleet to 40 mpg. Over the long term, we will have no choice but to adopt hydrogen fuel cells and other alternative fuel approaches. But these technologies will not be ready to replace the internal combustion engine in most new cars and trucks for over a decade.

Considering the slow turnover of the passenger vehicle fleet, this leaves a significant gap of ten to twenty years after the gains from conventional technology peak and before the promise of fuel cells will be fully realized. During that period, rising travel and increased car ownership will continue to drive us to import more and more oil from politically unstable countries and to add to global average temperature increases of 2.5 to 10.4°F by the end of the century. And the gains we will have made in air quality will begin to turn around due to rising travel and car ownership.

By filling this technological gap with well designed hybrid vehicles, passenger vehicle oil consumption and global warming emissions from cars and trucks can be reduced to below 1990 levels even before fuel cell technology makes its full impact.

As hybrids move into the marketplace, offering consumers additional choices, they also assure us that fleet average fuel economies of 50 to 60 mpg can be achieved by the end of the next decade. At the same time, growing hybrid sales will bring down the cost of future hydrogen fuel cell vehicles, since they share many technologies, such as electric motors, power electronics, and energy storage.

Realizing the Promise

The role that hybrid vehicles can play is clear, but their success at filling this role is not guaranteed. Two key things are necessary to ensure that that they live up to their promise:

1. Hybrids with the best possible conventional and electric technology need to be made available to the public.
2. Production and sales of these hybrids need to reach mass-market levels in the hundreds of thousands per year.

These keys are in the hands of automakers, governments, and consumers.

Automakers hold the first key. With most of the necessary hybrid and conventional technology in their hands, they will be responsible for building the best possible hybrid vehicles and sending them to the showrooms. Automakers that try to graft hybrid technology onto today's conventional vehicles will end up producing expensive, low-performance vehicles better left in the research lab. The resulting lemons could tarnish the image of hybrid technology and discourage consumers.

Automakers that take the practical approach of putting the best available technology to work will provide consumers with "no compromise" vehicles. And they'll garner a profit as the vehicles reach mass-market production levels. By leading the industry, these automakers will create a sound footing for future profitability and a solid image of environmental and corporate responsibility.

Automakers also hold some responsibility for helping hybrids to reach mass-market levels. They will need to support hybrid sales by aggressively educating dealers, service personnel, and consumers about their products. But unless education and advertising campaigns are backed up with the good products, they will simply be false attempts at capturing a green image.

But automakers can't do it alone.

Government at all levels must act to help hybrids sell well during this decade if automakers are to reach the economies of scale necessary for hybrids to become profitable. A variety of tools can provide this support, such as regulations, including fleet purchase requirements, tax credits and other financial or nonfinancial incentives, and education programs. All these measures must be carefully crafted to assure that they provide support to hybrids in proportion to the energy security and environmental gains they offer. And they must acknowledge the extent to which hybrids help pave the way for hydrogen fuel cell vehicles.

Consumers also have a part to play in ensuring that hybrid sales reach mass-market levels. Assuming government and industry do their parts, this should not be a challenging task. Recent market studies indicate that at least 25% to 30% of con-sumers are already interested in purchasing a hybrid instead of a conventional vehicle. When they do, they will find themselves saving money over the life of their hybrid even as they do their part to reduce oil dependence and their impact on the environment.

Chapter 1
THE ROLE OF HYBRID VEHICLES

The world started down a new road in 1997 when the first modern hybrid electric car, the Toyota Prius, was sold in Japan. Two years later, the United States saw its first sale of a hybrid, the Honda Insight. These two vehicles, followed by the Honda Civic Hybrid, marked a radical change in the type of car being offered to the public: vehicles that bring some of the benefits of battery electric vehicles into the conventional gasoline-powered cars and trucks we have been using for more than 100 years.

While hybrids are not as clean and efficient as vehicles powered by hydrogen fuel cells or solely by batteries, they offer both lower emissions than today's conventional vehicles and dramatically higher fuel economy. And they provide a steppingstone to zero emission vehicles.

Today, four years after their introduction, many of us know something about hybrids, but many of our questions remain unanswered: What exactly is a hybrid vehicle? How good will hybrids' fuel economy and environmental performance be? How fast will they go? What will they cost? Will people buy them? And where do you plug them in? The answer to the last question is simple: you don't have to! (For some this will be a disappointment, for others, a relief.)[1] The answers to the other questions are more complicated. This report provides some of those answers.

Why Hybrids?

The primary importance of hybrid technology for cars and trucks is its potential to increase fuel economy dramatically while meeting today's most stringent tailpipe emission standards (excluding the zero emission vehicle standard). At the same time, the performance of hybrid vehicles can equal or even surpass that of most conventional vehicles. Moreover, hybrids can play a critical role in helping bring the technology of motors, power electronics, and batteries to maturity and in reducing their cost. Such changes are vital to the success of future hydrogen fuel cell and other zero emission vehicles.

Thus hybrids could be a key element in US strategies to address our growing energy insecurity and environmental problems. Whether hybrids live up to their potential hinges on automakers and governments embracing them as one means of moving toward a secure energy future and a healthier environment.

Oil Dependence and the Environment. The size of our oil dependence and its rate of growth, as well as the environmental problems that are its consequence, require an immediate response. This calls for both changes in conventional technology and a longer-term investment in hybrid vehicles, hydrogen fuel cells, and alternative fuels.

In the year 2000, the United States consumed nearly 20 million barrels of oil products every day.

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[1] While the hybrids available today do not need to be plugged in, some future hybrid models may actually be able to recharge their batteries from the electricity grid, giving them superior environmental performance.

Table 1 **Economic, Oil Dependence, and Environmental Indicators of US Passenger Vehicle Travel**[a]

	2000	2020
Gasoline		
Annual Fuel Use (billion gallons)	121	189
Annual Fuel Costs (billion dollars)[b]	186	260
Oil and Other Petroleum Products[c]		
Oil Demand (million barrels per day)	19.6	27.2
Oil Imports (% of demand)	52%	64%
Passenger Vehicle Share of Oil Use (%)	40%	45%
Global Warming Pollution[d]		
Annual Greenhouse Gases (MMTCE)	358	559
Upstream Air Pollution		
Annual Smog-Forming Pollution (tons HC+NOx)	847,966	1,322,853
Annual Toxics (tons benzene-eq.)[e]	392,328	612,044

a. UCS estimates based on internal model calibrated to the Annual Energy Outlook 2001 (EIA 2000), adjusted for zero baseline growth in fuel economy.
b. Constant 2000 dollars
c. Including crude oil, natural gas plant liquids, imported refined products, imported unfinished oil, alcohols, ethers, petroleum product stock withdrawls, domestic sources of blending components, and other hydrocarbons.
d. All greenhouse gases are expressed in terms of million metric tons of carbon-equivalent emissions based on their relative radiative forcing.
e. Benzene, formaldehyde, acetaldehyde, butadiene, and diesel particulate emissions expressed as benzene-equivalent emissions based on their relative cancer unit risk factors.

Over half of that was supplied by other countries, including Iraq, Saudi Arabia, and other nations in the politically unstable Middle East.[2] Of that daily consumption, 40% (about 8 million barrels per day) went to fuel our cars and trucks, at a cost to consumers of $186 billion. By 2020, oil consumption is expected to grow by nearly 40% and our dependence on imports is projected to rise to more than 60% (Table 1).

Those same cars and trucks were responsible for over 20% of the global warming emissions produced by the United States during 2000: 1,450 million tons (358 million metric tons, carbon equivalent) of the heat-trapping gases linked to global warming.[3] Most of these gases will stay in the atmosphere for more than 100 years, contributing to an increase in the earth's average surface temperature. This is projected to rise 2.5 to 10.4°F (1.4 to 5.8°C) between 1990 and 2100, if no major efforts are undertaken to reduce emissions of global warming gases (IPCC 2001). As the earth continues to warm, we face a great risk that the climate will change in ways that threaten our health, our economy, our farms and forests, beaches and wetlands, and other natural habitats.

Cars and trucks are also major contributors to air pollution. Regulations have helped clean up passenger vehicles over the past three decades. However, rising demand for travel and increased vehicle ownership will outpace even the standards on the books through this decade. Cars and trucks will need to clean up their act even more if we are to eliminate the threat air pollution poses to public health—especially to our children and the elderly.

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[2] US oil use, imports, and expenditures from EIA 2000.

[3] This UCS estimate is based on EIA 2000. Each gallon of gasoline burned emits nearly 19 pounds of carbon dioxide, the primary pollutant responsible for global warming. The production and delivery of each gallon of gasoline are responsible for another 5 pounds of global warming pollutants (Wang 1999).

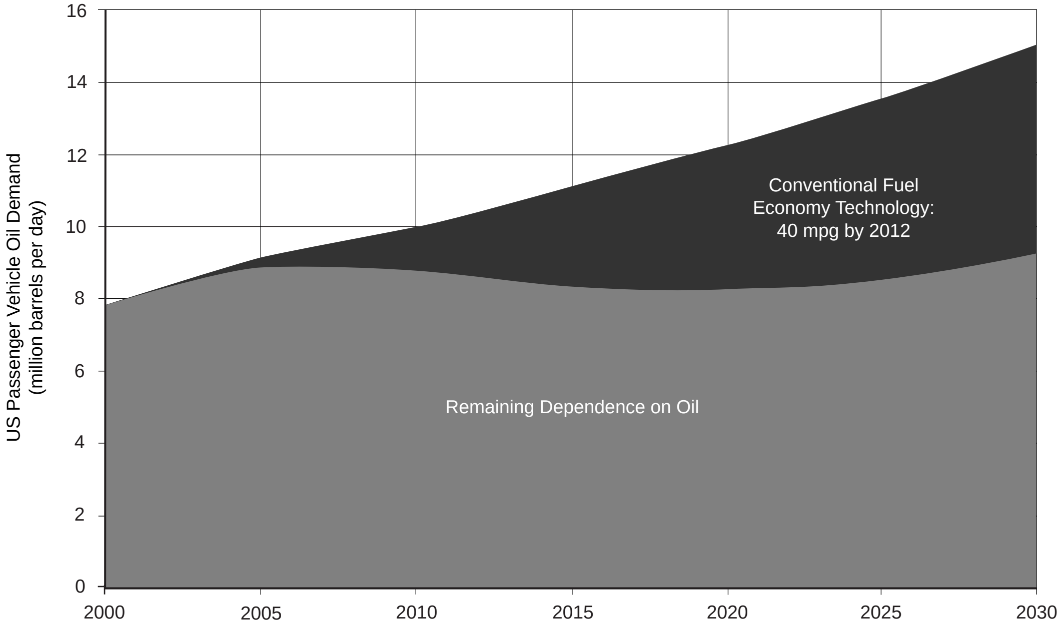
Finally, producing and distributing the gasoline that went to fuel our cars and trucks in the year 2000 resulted in the emission of 848,000 tons of smog-forming pollutants and 392,000 tons of benzene-equivalent toxic chemicals, in addition to the pollutants emitted from the tailpipes of vehicles.[4] Altogether, cars and trucks are the largest single source of air pollution in most urban areas. As with US oil use and global warming emissions, upstream air pollution is expected to continue to rise significantly over the next two decades, posing the greatest health threat to children, the elderly, and other vulnerable members of our population (Table 1).

The situation is urgent, but not hopeless. A range of technological approaches can help us break free of our oil habit and protect our health and livelihood against the environmental problems associated with vehicle use. Hybrid technology is one of the most promising.

Investing in Our Future. No single silver bullet can solve the problems posed by our use of cars and trucks. But if we choose now to invest in a variety of solutions, ranging from near to long term, together they could eliminate the use of oil for transportation. Hybrid technology can fill the midterm gap between immediate improvements to conventional vehicle fuel economy and the long-term hope offered by hydrogen fuel cells and alternative fuels.

Conventional Fuel Economy Technology.

Figure 1 **The Potential for Conventional Technology to Address Oil Dependence.**



NOTES: Based on analysis presented in Friedman 2001.

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[4] The production, refining, and delivery of each gallon of gasoline in the United States emit an estimated 6.4 grams (0.014 pounds) of smog-forming pollutants (Wang 1999). Upstream activities also release harmful toxic pollution into the air. This poses a major health hazard near refineries, along distribution routes, and at gasoline stations. For every gallon of gasoline delivered, 2.9 grams (0.0065 pounds) of benzene-equivalent toxic emissions are produced (Winebrake, He, and Wang 2000; Wang 1999).

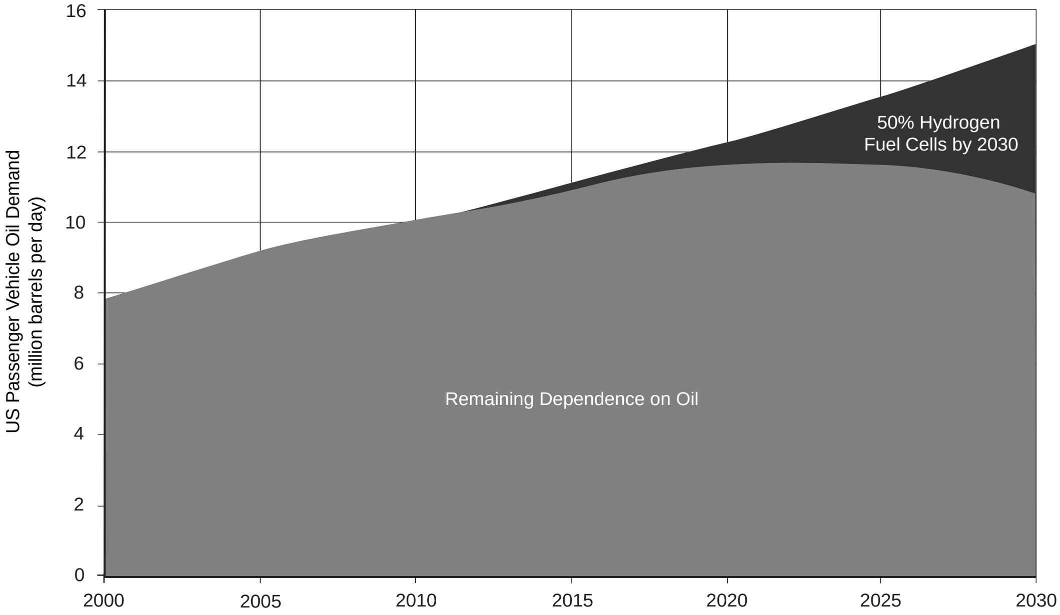
The quickest and most effective way to limit oil dependence during the next 10 to 15 years is to improve the fuel economy of gasoline-fueled cars and trucks. Analysis of existing and emerging technologies based on reports by the National Academy of Sciences, researchers at MIT, and others indicates that conventional fuel economy technology can enable conventional cars and trucks to reach an average of 40 miles per gallon before the middle of the next decade (DeCicco, An, and Ross 2001, Friedman et al. 2001, NRC 2002, Weiss et al. 2000). Moreover, this can be done cost effectively.

With more efficient engines, improved transmissions, and better aerodynamics and tires, automakers could reach a fleet average of 40 mpg over the next ten years. At that rate of implementation, passenger vehicle oil use would stop growing by 2007, stabilizing at today's level through 2020 (Figure 1). This would save consumers billions of dollars every year, effectively paying us to reduce our oil habit and our impact on the environment (Friedman et al. 2001).

Conventional fuel economy technologies are thus a good short-term investment in energy security and the environment. But if we stopped there, after 2020 increases in the number of miles traveled and the number of vehicles on the road would begin to overwhelm the fuel economy improvements and oil use would again rise. Thus a long-term investment strategy is necessary.

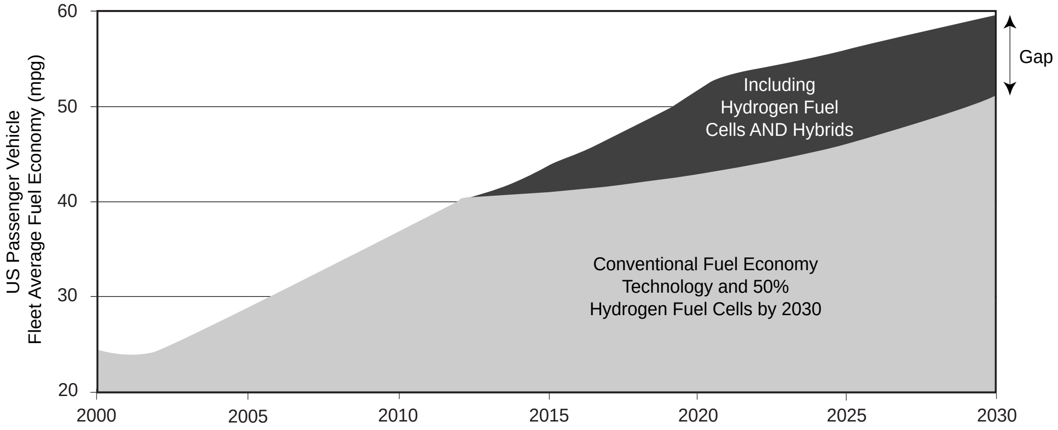
Hydrogen Fuel Cells. Hydrogen fuel cells and alternative fuels are the most promising technologies in the long run, since they could virtually eliminate oil use in cars and trucks. But they are not yet available and are unlikely to reach significant market penetration for 10 to 15 years. Moreover, while these technologies will shift us off oil, they will not make as rapid progress toward eliminating cars' and trucks' global warming emissions.

Figure 2 **The Potential for Hydrogen Fuel Cell Vehicle Technology to Address Oil Dependence**



NOTES: Developed from analysis presented in Friedman in 2001 and Doniger et al. (2002). Assumes hydrogen fuel cell vehicles reach 15% of new vehicles sales by 2020 and 50% by 2002.

Figure 3 **Oil Security and Environmental Gap Left Without Applying Hybrid Technology**



For example, during the first decades after fuel cells are introduced, the hydrogen they use is likely to be produced from natural gas. This will result in lower, but still substantial emissions of global warming gases.

Today's vehicles stay on the roads an average of 15 years, so waiting 10 to 15 years for hydrogen fuel cell or other alternative fuel technologies would mean locking ourselves into a path of increased oil dependence and environmental problems for the next 20 to 30 years, as Figure 2 shows.

Since hydrogen fuel cells are not yet right around the corner, the best solution in the very near term is to bring more advanced conventional technologies to the marketplace. At the same time, we will need to prepare for the long term by investing in developing and demonstrating hydrogen fuel cells and alternative fuels.

But that's not enough. This scenario leaves a gap of ten or more years without significant progress in reducing our oil dependence. While that's not a good prospect, the consequence for climate change is worse, since the severity of global warming is a function of cumulative global warming gases. Every ton of global warming gas that could have been avoided is another ton that will remain in the atmosphere for the next 100 years. Since hydrogen fuel cell vehicles are likely to deliver only modest global warming emission savings by 2030, another technology is needed as the gains from conventional technology level off in the next decade.

Hybrid Vehicles. With their recent entrance into the market, hybrids are poised to serve a key role in pushing down oil demand and global warming emissions from cars and trucks through the next two decades. They offer a solid midterm strategy of investment in energy security and the environment, filling the temporal gap between conventional technology and hydrogen fuel cells (Figure 3).

Hybrids can also serve as an insurance policy for regulators contemplating significant increases to fuel economy standards over the next decade. While a 40-mpg fleet could be reached with existing conventional technology, hybrid vehicles provide additional assurance of reaching that goal, since they promise fuel economy levels as high as 50 to 60 mpg. Further, they open the door to fuel economy standards of 50 mpg or higher by the end of the next decade.

In addition, hybrid vehicles can mitigate the risk of delays in hydrogen fuel cell development and market success. They'll also help ensure the success of fuel cell vehicles by bringing down the costs of the technologies—motors, batteries, and power electronics—that the two share. And they'll help pave the way by acquainting consumers with electric drive technology.

Given the necessity of continuing to reduce oil use and global warming emissions over the coming decades, hybrids are a key interim step, taking over where improved conventional technologies leave off and before fuel cells can fulfill their promise.

The "Gee-Whiz" Factor. In addition to the logic of hybrids as a key part of investing in energy security and the environment, other factors, such as consumer and automaker choice, could prove crucial to their success.

Consumer Choice. Despite automakers' claims to the contrary, consumers are showing interest in having an option to buy cars and trucks with better fuel economy. A consumer preference study by J.D. Power and Associates found that 30% of the more than 5,000 recent new-vehicle buyers they surveyed would definitely consider a hybrid for their next purchase. An additional 30% showed strong consideration. The primary reason people noted for considering a hybrid was their concern about high fuel prices (J.D. Power 2002).

A second study, by Applied Decision Analysis LLC, performed as part of larger study on hybrids by the Electric Power Research Institute, found that 25% of the 400 potential car and truck buyers surveyed would purchase a hybrid vehicle instead of a conventional vehicle when given information on the potential costs, savings, and performance of the hybrid (Graham 2001).

Clearly, consumers want automakers to provide them with hybrid vehicles as additional choices when they step into the showroom.

Automaker Choice. Only Toyota and Honda have so far offered hybrids for sale in the US market. Both are likely to offer more models very soon, as are most other automakers. Ford intends to enter the market with a hybrid SUV using a design similar to the Prius. GM and DaimlerChrysler are expected to offer hybrids in 2004 or 2005.

These new vehicles will help build the hybrid market, bringing in consumers interested in pickups or SUVs as well as those who want compact and family cars. But if some of the automakers choose to offer vehicles with hybrid nameplates just to capitalize on the "gee whiz" factor or the "green" image of hybrids, much of the potential benefits from hybrid technology will be lost. Automakers have a responsibility to society and consumers to market hybrids that provide the dramatic improvements in fuel economy the technology promises, along with substantially cleaner tailpipe emissions. And consumers must hold them to it, by putting their dollars where they will do the most good. Chapter 2 provides a checklist for determining whether a vehicle is a hybrid and what kind of hybrid it is. Chapter 3 evaluates how much environmental benefit is provided by a variety of hybrid designs.

A New Road

The next decade may see a revolution in which the automobile industry offers consumers more choices than ever before. But predicting the exact role hybrid vehicles will play in transportation's future is beyond the scope of this report. Instead, the following chapters explore the questions outlined above: What exactly is a hybrid vehicle? What kind of fuel economy, cost, and vehicle performance can we expect from hybrids? And what will it take to help ensure that hybrids live up to their promise?

Chapter 2

SOMETHING NEW UNDER THE HOOD

From the outside, the Toyota Prius or the Honda Civic hybrid don't look much different from a Toyota Echo or a conventional Honda Civic. (Hint, besides the hybrid label on the back, the antennas of both hybrids sit at the center of the roof's front edge). Looking under the hood doesn't help much either. They still have an engine and some type of transmission along with several unidentifiable metal boxes, wires, and other gadgets.

The instrument panels on the dashboard provide the clearest indication that these are hybrids. They show power going into and out of the battery pack and when it's the engine or the motor that is driving the wheels. It's this sharing of driving power between the electric motor and the engine that defines these vehicles as hybrids. Other than that, they are in many ways the same as their conventional counterparts.

hybrid vehicle

PRONUNCIATION: **`\hI-br&d vE-&-k&l`**

FUNCTION: noun

ETYMOLOGY: Latin *hybrida* and French *véhicule* (from Latin *vehiculum* carriage, conveyance, from *vehere* to carry).

DEFINITION: A means of transportation that incorporates two or more methods of providing power for movement.

SOURCE: Pronunciation and etymology from Merriam-Webster 2002. Definition by author.

Defining Hybrids

The hybrid vehicles on sale today are referred to as *hybrid electric vehicles (HEVs)* or *engine electric hybrid vehicles.* That means they obtain driving power from both an internal combustion engine and an electric motor powered by batteries.

Several other types of hybrid vehicles have reached the prototype phase. For example, in the 1990s Chrysler combined a combustion engine with a flywheel that stored mechanical energy and provided power to the wheels (Lowell 1994). Currently, Ford and the US Environmental Protection Agency are developing a hydraulic hybrid that uses an internal combustion engine along with a hydraulic/nitrogen gas system that recovers braking energy and can help launch a heavy-duty vehicle from a stop (McElroy 2002).

Many other hybrid variations could undoubtedly be envisioned, but the key to success lies in creating a hybrid vehicle that provides consumers, at a reasonable cost, the performance they seek along with improved fuel economy and decreased emissions. So far, only hybrid electric vehicles meet these criteria for success and have made it to market. The remainder of this report is about hybrid electric vehicles and hereafter the term *hybrid* should be understood to refer to hybrid electric vehicles.

Hybrid Electric Drivetrains. Just as combustion engines can be combined with a variety of technologies to create hybrid vehicles, so too can hybrid *electric* vehicles result from mixing and matching technologies. One major variation depends on whether the hybrid electric uses a series drivetrain, or parallel drivetrain, or a bit of both.

Series Drivetrains. In a series hybrid electric vehicle, an electric motor is the only means of driving the wheels (Figure 4). The motor obtains electricity either from a battery pack or from a generator powered by an engine in much the same way as a portable generator. A controller determines how power is shared between the battery and the engine/generator set.

The batteries in a series hybrid are recharged both by the engine/generator set and by storing some of the energy that is normally lost during braking (typically referred to as regenerative braking).

Series drivetrains are the simplest hybrid electric configuration. Because the electric motor alone drives the wheels, no clutch or complicated multispeed transmission is required. At the same time, the engine, since it is not connected to the wheels, can operate at or near optimum efficiency. This also opens the door to using unconventional engine types such as gas turbine, Atkinson, or Stirling engines, rather than more conventional gasoline engines.

To gain the most advantage in efficiency from using a small engine, series drivetrains typically use relatively large battery packs. But batteries and motors cost more than engines for the same amount of power, so series hybrids are generally more expensive than the parallel hybrids described below. The generator needed to produce electricity from the engine also adds to the cost.

Series hybrids show to their greatest advantage under slower operating conditions characterized by stop-and-go driving. During high-speed and highway driving, the inefficiency of always converting the mechanical power from the engine into electricity, storing some of it, and then converting it back to mechanical power through the motor takes its toll. For this reason, most of the

Figure 4 **Series Hybrid Electric Vehicle Drivetrain**

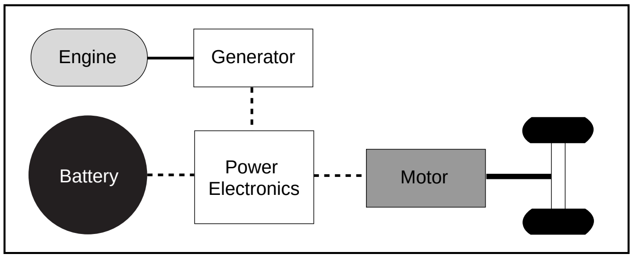


Figure 5 **Parallel Hybrid Electric Vehicle Drivetrain**

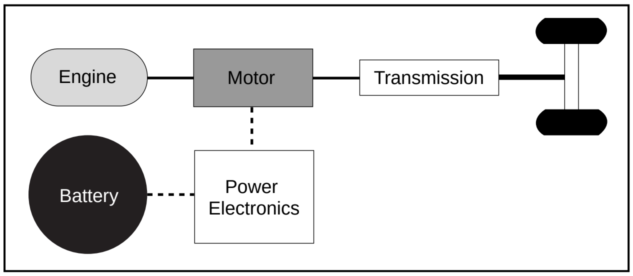


Figure 6 **Split-Parallel Hybrid Electric Vehicle Drivetrain**

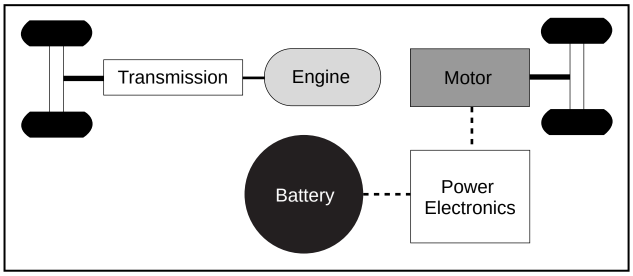
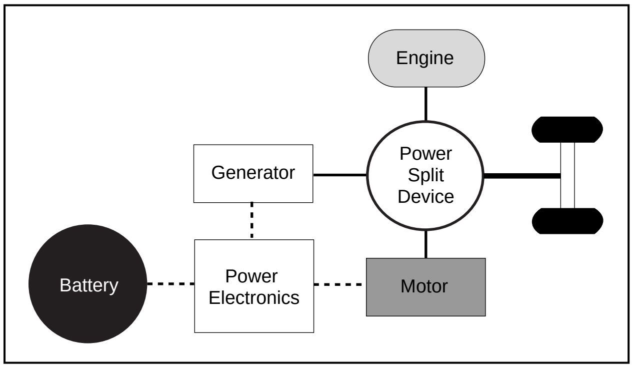


Figure 7 **Toyota Series-Parallel Hybrid Electric Vehicle Drivetrain**



series hybrids currently under development are for buses or other heavy-duty urban vehicles.

Parallel Drivetrains. In a parallel hybrid electric vehicle, both the engine and the motor can drive the wheels (Figure 5). Both the Honda Insight and the Honda Civic Hybrid are parallel hybrids.

Parallel drivetrains are mechanically more complicated than series drivetrains. For one thing, a transmission is required to allow the engine to drive the wheels. Then there must be a means of coupling the engine, motor, and transmission. Finally, the controller necessary to make all these components work together is more complex than in the series drivetrain.

Parallel drivetrains use a smaller engine than a conventional vehicle, though it is typically larger and somewhat more expensive than the engine in a series drivetrain. As in series hybrids, the batteries in parallel hybrids can be recharged through regenerative braking. Since parallel drivetrains typically use smaller battery packs, much of the recharging can be done this way. In addition, the drive motor can be turned into a generator during driving to recharge the batteries, in much the same way alternators do in conventional cars.

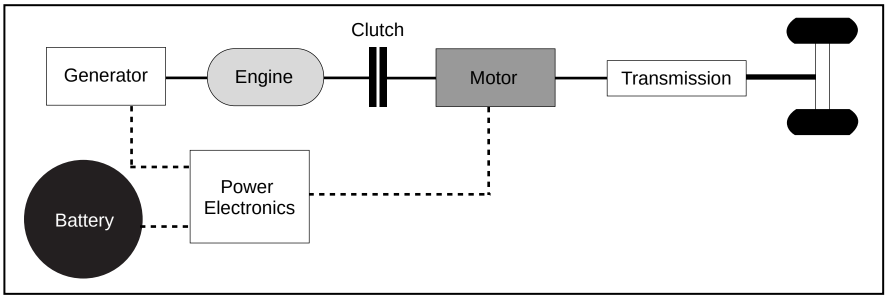
The smaller motors and battery packs used in parallel drivetrains help keep down the costs of parallel hybrids relative to series hybrids. But the necessity of transmissions and the need to couple everything together means their cost advantage will diminish as battery and motor costs come down over time.

Because the engine is connected directly to the wheels in parallel drivetrains, these hybrids do not suffer the efficiency penalty series hybrids experience on the highway. In the city, this same structure will reduce, not eliminate, some of the efficiency benefits of a parallel drivetrain. As a result, parallel drivetrains provide some advantages in both city and highway driving.

One special type of parallel hybrid uses a “split” drivetrain, in which the engine drives one set of wheels, while an electric motor drives another (Figure 6). This can provide 4-wheel drive, although recharging the batteries by the engine is then more complicated since it involves operating the front wheels in regenerative braking mode while the engine is driving the rear wheels. At one time, DaimlerChrysler planned to produce a Dodge Durango SUV with such a system.

Series/Parallel Drivetrains. The Toyota Prius made popular a new concept that combines many of the advantages of the parallel drivetrain with the series drivetrain’s ability to maintain engine operation near its most efficient operating point (Figure 7) (Inoue et al. 2000). Variations on this design (Figure 8) have shown up in the Nissan Tino Hybrid, which was sold for a short period in Japan, and is being incorporated into a hybrid vehicle developed by Paice Corporation (Matsuo et al. 2000, Severinsky et al. 2002).

Figure 8 **Basic Series-Parallel Hybrid Electric Vehicle Drivetrain**



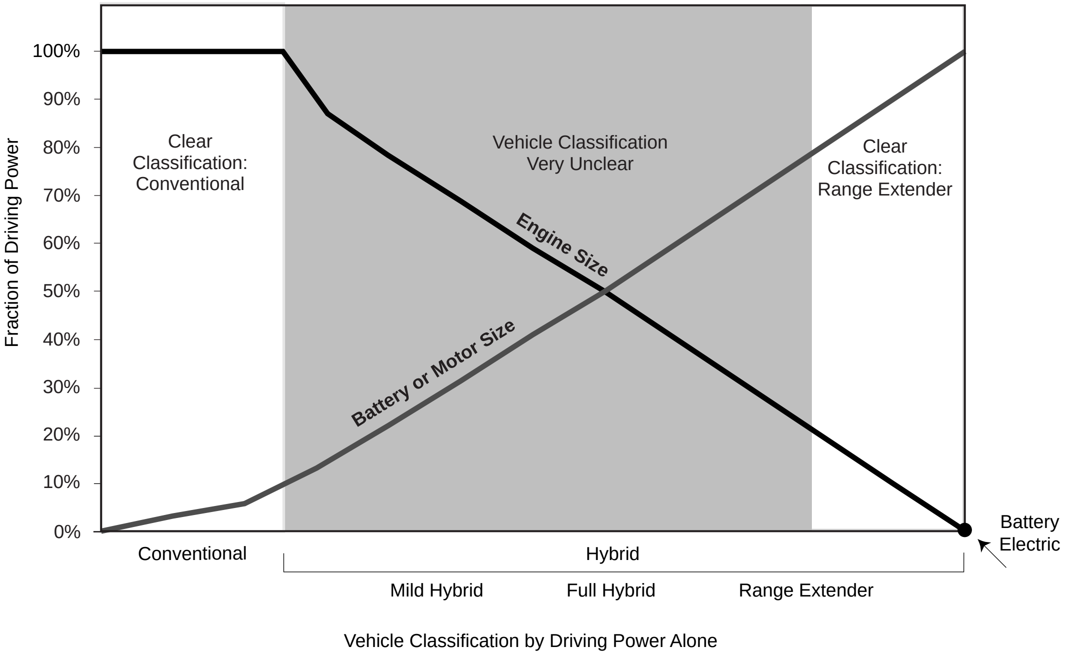
This series/parallel design is similar to the basic parallel drivetrain in that the engine can drive the wheels directly. What makes the design unique is that the engine can be effectively disconnected from the transmission and operated in the same way as a series drivetrains' engine/generator set.

As a result, the engine can operate near optimum efficiency more often. During lower-speed driving, the engine is disconnected from the demands of the wheels and the vehicle operates with many of the efficiency benefits of a series drivetrain. During higher-speed driving, when the engine can power the wheels efficiently, the inefficient energy-conversion steps of the series drivetrain can be avoided or minimized.

The series/parallel drivetrain has the potential to perform better than either the series or the parallel drivetrain. However, it inherits some of the higher costs of the series hybrid because it needs a generator and a larger battery pack. The series/parallel drivetrain also inherits the mechanical complexity of the parallel drivetrain, and be-cause it combines the two drivetrains, it requires more computing power to control the system.

Degrees of Hybridization. Hybrids have been traditionally classified by the amount of driving power supplied by the electrical system and the amount supplied by the engine (Figure 9). For battery electric vehicles and hybrid electrics with large electrical systems and very small engines, this definition works pretty well. It also works relatively well for vehicles that do not have a downsized engine and have simply added on a technology referred to as an integrated starter generator: these are just conventional vehicles that can turn the engine off when the vehicle is stopped.

Figure 9 **An Attempt to Classify Hybrid Vehicles by the Amount of Onboard Electrical Power**



Once regenerative braking is included or the engine is downsized, how to classify the hybrid becomes less clear. What, for example, is the dividing line between a mild hybrid, as most people call the Civic Hybrid, and a full hybrid, as many call the Prius? More importantly, classification by the amount of electrical system power does not necessarily indicate the level of environmental performance of the hybrid, since improvements in fuel economy correlate only weakly with the amount of electrical power onboard.[1]

A more informative way to classify hybrids is according to the discrete technological steps that move them away from conventional vehicles and toward battery electric vehicles. This classification provides a better indication both of how a particular model of hybrid will operate on the road and of how well it measures up to the technology of a full function electric vehicle. The amount of power supplied by the electrical system can then become an important secondary factor for evaluation within hybrid classes.

This method divides the space between conventional and battery electric vehicles into five technology steps, each of which provides a step-increase in similarity to a fuel cell or battery electric vehicles and helps indicate potential for improved environmental performance:

1. Idle-off capability
2. Regenerative braking capacity
3. Engine downsizing
4. Electric-only drive
5. Extended battery-electric range

Idle-Off. All hybrids can turn the engine off when the vehicle is at a stop; however, not all vehicles that are equipped with idle-off technology are hybrids. Conventional vehicles can achieve idle-off using an integrated starter-generator, a beefed up starter motor combined with an alternator, while a hybrid would use a larger, full function electric motor. Therefore, the inclusion of idle-off is not sufficient to distinguish a hybrid from a conventional vehicle. In fact, a vehicle must also incorporate the next two steps, regenerative braking and engine downsizing, to make the transition from conventional vehicle to “mild” hybrid.

Regenerative Braking. “Regen,” or regenerative braking, requires an electric drive motor large enough to take over some of the braking duties and a battery pack big enough to capture the braking energy that is typically wasted.[2] This is a key technology for battery electric vehicles and marks an important step beyond conventional technology. Some automakers have proposed adding regenerative braking to conventional vehicles that incorporate the integrated starter-generators used for idle-off, but these systems typically operate at power levels and voltages that are too low to recover any significant braking energy to influence fuel economy. A system that obtains about 10% of its peak power from the electric motor will be necessary to ensure that regen technology is included in more than just name only.

Engine Downsizing. In downsizing, a smaller engine is complemented by an electric motor that boosts vehicle power to meet the same performance as a larger engine. For example, reducing the engine size allows a vehicle that would typically use a 6-cylinder engine to gain the fuel economy of a 4-cylinder engine while retaining the 6-cylinder performance using the boost available from the

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[1] Some initial research indicates that the difference may be related in part to vehicle acceleration or other performance factors, but these do not fully explain the discrepancies (Santini, Vyas, and Anderson 2002).

[2] Motors and generators are effectively the same things, just operated in different directions. A motor uses electricity to generate mechanical power; a generator uses a source of mechanical power to generate electricity.

electric motor. This is clearly a hybridization step, since it combines two technologies to achieve the performance of one, while improving fuel economy at the same time.

If an electric motor is added, but the engine is not downsized, such a vehicle may technically be a hybrid. But in that case, the technology is serving primarily to boost performance, not to improve fuel economy. This wastes a significant benefit of hybridization, failing to fulfill the promise of hybrid technology and instead creating a muscle hybrid.

If a vehicle's technology includes both regen and engine downsizing, it can be classified as a "mild" hybrid.

Electric-Only Drive. Using the electric motor and battery pack for driving is the technology step that separates "mild" from "full" hybrids. This takes full advantage of the technology by turning the engine off not just when the vehicle is stopped, but also while driving.

This takes a step beyond engine downsizing, moving toward electric vehicle technology. It also has the advantage of improving engine efficiency, since it eliminates engine operation in its most inefficient low-power regions. Full hybrids thus use the battery and motor to launch the vehicle and drive until it reaches the speed at which the engine can be operated more efficiently. Engine efficiency can be improved significantly by driving with the electric motor alone up to 10 to 15 miles per hour. Above these speeds, efficiency benefits begin to diminish, although similarity with electric vehicles continues to increase.

Extended Battery-Electric Range. The final level of hybridization extends the battery-electric range by allowing the vehicle's battery to be recharged from a clean electricity grid. These "plug-in" or "range extender" hybrids can operate as battery-electric vehicles for 20 to 60 miles each day, satisfying much of a consumer's daily driving needs (Graham 2001). The remainder of a consumer's driving needs can then be met by operating the vehicle as a typical full hybrid.[3]

By getting much of their driving energy from the electricity grid, plug-in hybrids can achieve superior environmental performance relative to other hybrids, approaching the efficiency and cleanliness of purely electric vehicles. However, since plug-ins can still operate without recharging from the electricity grid, these benefits are highly dependent on how often consumers plug them in.

Energy and Environmental Performance

The clearest and most direct way to evaluate the environmental performance of a hybrid electric vehicle is to measure its fuel economy and emissions directly. Since only a few hybrids are available today, this is not practical for investigating the potential for a full fleet made up of hybrid compact cars, family cars, SUVs, pickups and minivans. Chapter 3 provides findings based on computer modeling of the fuel economy and economics of several hybrid designs in order to provide such a measure for the variety of cars and trucks in today's passenger vehicle fleet. However, the utility of the technology-based classification laid out above is that it provides an indication of how similar a vehicle is to a fuel cell or battery electric vehicle. It also provides a rough indication of a vehicle's energy and environmental potential.

Fuel Economy. Figure 10 lays out the links between the technologies, the hybrid classifications, and their potential to improve fuel economy for a typical mid-size family car. The gains shown for

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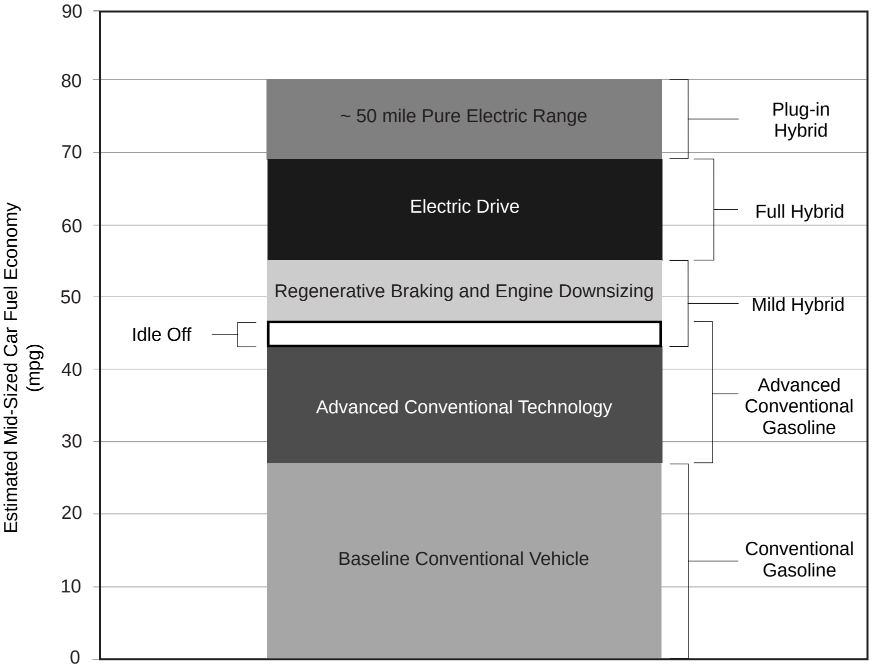
[3] For a plug-in hybrid, this is typically called the charge-sustaining mode, as the charge in the battery is kept up by the engine/generator set.

Figure 10 **Estimated Fuel Economy Potential for Various Hybrid Classifications**



NOTES: Hybrid fuel economy levels assume specific engine and battery/motor sizing in a mid-sized vehicle parallel hybrid driveline configuration, altering that sizing, the driveline configuration, or the vehicle type will affect the fuel economy to some degree. This should only be used as a general guide.

hybrids' fuel economy are over and above those that can be achieved with advanced conventional vehicles because, as chapter 3 will show, it is not cost effective to hybridize a vehicle without first applying many of the best conventional technologies available.

In ranking the potential environmental performance of the various hybrid configurations, the clear trend is that the closer a vehicle is to a full function battery electric vehicle, the better its fuel economy. Note, however, that a vehicle which incorporates the five technology steps laid out above will not necessarily have superior environmental performance. Figure 10 indicates only the *potential* for higher fuel economy: how an automaker actually applies the technology will determine how well it performs. The only way to evaluate a vehicle's environmental performance is to actually test its fuel economy and emissions under realistic driving conditions.

Tailpipe Emissions. Unlike their fuel economy performance, hybrids do not have substantial advantages over conventional vehicles when it comes to decreasing tailpipe pollution. While hybrids can meet the world's most stringent non-zero tailpipe emissions standard, the federal Tier 2-Bin 2 or California's SULEV standard, several conventional cars can do the same today.[4] For example, the Toyota Prius and one version of the

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[4] The federal Tier 2-Bin 2 standard and California's Super Ultra Low Emission Vehicle (SULEV) standard require tailpipe emissions to be no greater, over the useful life of the vehicle, than the following: nonmethane organic gases: 0.01 grams per mile; oxides of nitrogen: 0.02 grams per mile; particulates: 0.01 grams per mile.

Honda Insight have garnered a SULEV rating in several states. However, SULEV-rated models of the conventional Nissan Sentra, Honda Accord, and BMW 325i are also available in several states today. In general, hybrids will have some emission advantages over conventional vehicles and some added emission challenges.

Advantages. The primary emissions advantage of most hybrids is that they can use smaller, lighter engines, which heat up quickly. Faster heating reduces start-up emissions, which are the primary challenge in achieving lower exhaust levels.

Just as hybrids, especially series and series/parallel hybrids, will achieve higher fuel economy by ensuring their engines operate most often near their most fuel-efficient points, they can also run the engine in ways that minimize emissions. This will reduce average running emissions, but the effect is not likely to be dramatic.

Finally, plug-in hybrids could dramatically decrease on-the-road emissions. Since they can recharge from a clean electricity grid instead of relying on the engine, a substantial amount of their operation could be in true zero-tailpipe-emission mode. However, realizing this potential hinges on the owner consistently recharging the batteries from the grid.

Challenges. Hybrids face two key challenges in meeting SULEV tailpipe emission levels: frequent engine restarting and the associated problem of evaporative canister purging.

Until the engine is running on its own, the fuel does not burn well, producing a lot of pollution. Thus the more often an engine is started and the longer it takes for a successful start, the more pollution it produces. And while the engine and emissions control system are warming up, partially burned fuel escapes out the tailpipe. Automakers have made headway in controlling these emissions, but they remain challenging to control. In hybrids, the engines stop and start more often than in conventional vehicles because of their idle-off feature. Full hybrids may see even more frequent stop/start cycles because of their electric-only drive capability.

This issue, however, appears manageable. As noted above, the engines can heat up quickly because they are light and small. In addition, effective control of the engine cooling system can keep the engine warm for quite some time. For example, many modern engines stay warm between the time we pull in to do our grocery shopping and when we drive away. Moreover, hybrids can restart their engines quickly because they have much more electrical power onboard than a conventional vehicle. Electric power can also be used to heat the emission-control system quickly.

The problem of evaporative canister purging is also a function of the frequent engine starts and stops. When an engine turns off, unburned fuel vapor remains in the fuel system. Rather than let those smog-forming hydrocarbons escape into the environment, today's cars capture them in a special canister. When the engine next turns on, the canister is purged, allowing the captured fuel to be burned and then treated in the exhaust system.

Hybrids have less opportunity to purge the canister, because the engine operates less frequently and for shorter periods of time than in conventional vehicles. If the canister is not fully purged by the time the engine shuts off again, the evaporative canister may not be able to hold all of the unburned fuel vapor and some may escape into the air. A larger evaporative control canister might be one method of dealing with this problem. Another alternative might be a completely sealed fuel system.

Toyota's and Honda's achievement of SULEV emission levels indicates that hybrids can overcome these emissions challenges. However, while hybrids can clearly meet and probably exceed today's toughest emission standards, we cannot assume that a vehicle is inherently clean just because it is a hybrid. The proof will have to come in real-world driving tests.

Added Consumer Benefits

In addition to promising higher fuel economy and improved tailpipe emissions, hybrids will have many benefits that may raise additional consumer interest. While these might cost extra if implemented in a conventional vehicle, they come free as part of the hybrid package. Here's a short list:

- *Good low-end torque:* That is car-talk for improved acceleration in lower speed ranges, such as from 0 to 30 mph. This property is inherent in electric-drive vehicles because electric motors produce their best acceleration at low speeds (0–2,000 rpm). (Conventional engines produce their best acceleration between 4,500 and 6,000 rpm.)
- *Reduced noise and vibration at stops:* Because the engine turns off when the vehicle stops, there's no vibration or engine noise.
- *Smooth acceleration and reduced noise and vibration at low speeds:* On full hybrids, the electric drive keeps the engine off until around 10 to 15 mph.
- *Reduced engine vibration:* Unlike electric motors, combustion engines do not produce power continuously. In fact, each cylinder produces power about one quarter of the time (in a 4-cylinder engine). This produces a pulse, which shows up as vibration. The more cylinders the vehicle has, the less vibration there is. A hybrid can dramatically reduce vibration by filling the spaces between engine pulses with the electric motor. This requires modern control technology, but is well within the capability of a hybrid.
- *Better shifting performance:* An automatic transmission produces a short drop in power each time it shifts. In a hybrid, the motor can make up for much of this lost power. This makes less difference for continuously variable transmissions.
- *Added electrical capacity:* Hybrids can be designed to provide 110 or even 220 volt power. This means a microwave could heat up breakfast on the way to work. Or, instead of a dirty diesel generator, a series/parallel hybrid truck could provide the power source for construction equipment. This could, however, undermine efficiency by increasing the amount of energy used while driving.
- *Reduced engine and brake maintenance:* A hybrid recovers much of the energy required to stop through regenerative braking. Thus its mechanical brakes will see less wear than those of a conventional vehicle and will need to be serviced or replaced less often.
- *Fewer stops at the gas station:* The hybrid's good fuel economy means that it may need to fill up only every 500 to 600 miles.

Engineering Challenges

Overall, hybrids can provide the same performance as most of the vehicles consumers own today. In a few circumstances, however, differences may become noticeable. And in some extreme cases, such as towing multiton loads, a hybrid may not be an appropriate choice. Several of the performance challenges engineers face are sketched below:

- *Reduced high-end torque:* While the hybrid's electric motor more than makes up for its downsized engine in accelerating at low speeds, it provides somewhat less torque at high speed. This means that high-performance highway passing may take as much as 1 second longer. Few drivers are likely to notice this.

- *Sustained high-speed grade ability:* A typical performance goal for a vehicle ascending a grade is to be able to sustain 60 miles per hour on a steep 6% grade indefinitely. Using both the engine and the motor, hybrids will be able to sustain a 6% grade at 60 mph for a time. But if the grade lasts too long, the battery pack could be drained and the vehicle may have to downshift to allow the engine to take over more of the load. Most drivers will never encounter such a situation.
- *Reduced high-speed towing capacity:* As with ascending a grade, towing a boat or trailer puts a significantly heavier load on a vehicle than normal. Hybrid trucks can be designed to tow a three-quarter or one-ton boat or camper trailer, but may not be the right choice for towing a two-ton load.

Safety

In achieving higher fuel economy, future hybrids will not sacrifice safety. In fact, drivers of SUVs and pickups will be safer: battery placement in practical hybrid designs creates a lower center of gravity, making SUVs and other tall vehicles less likely to tip over.

Overall, the key to a hybrid vehicle's safety is the same as for conventional vehicles: good engineering design. Recent analysis of safety data for modern cars and trucks highlights this fact, showing that well designed cars can be safer for their drivers than many of the trucks on the road today are for theirs. For example, the model year 1995–1999 Toyota Camry, Honda Civic, and Volkswagen Jetta are all safer for the driver and passengers than the larger Chevrolet Blazer SUV, Dodge Ram pickup, and Toyota 4Runner SUV from the same years (Ross and Wenzel 2002).

Automakers that incorporate good safety design will be able to produce safe hybrids that also get higher fuel economy. And hybrid SUVs and pickups that include high-strength steel and aluminum components will get better fuel economy and pose less danger to others during collisions, while keeping their drivers and passengers safe.

Paving the Way for Fuel Cell Vehicles

As this chapter shows, hybrids incorporate many of the technologies of electric vehicles. As a result, they will pave the way for hydrogen fuel cell vehicles.

For each hybrid that is sold, another motor and another battery pack will be produced, driving down the cost of future electric motors and batteries that will be used in fuel cell vehicles. Thus hybrid sales will help electric drive components achieve economies of scale sooner than if they had to wait for fuel cell vehicles to reach the market in large numbers. Hybrids with larger motors and advanced battery technologies such as nickel metal-hydride and lithium-ion, or even ultracapacitors, will do more for fuel cell vehicles than those with smaller motors and lead-acid batteries.

A minimum requirement for hybrids to support fuel cell development is that they must operate above 60 volts. Fuel cell vehicles will likely operate at 300 to 400 volts, requiring automakers to follow different codes and standards in selecting electric components and in designing their vehicles. A typical dividing line in automotive design procedure is 60 volts.[5]

How many hybrids automakers put on the road will affect how soon and at what cost hydrogen fuel cell vehicles arrive at market.

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[5] For example, Society of Automotive Engineers standards J1654, J1673, J1678 and J2183.

Chapter 3

TOMORROW'S HYBRID

Today's hybrids are already finding success in the marketplace. Toyota has sold over 120,000 hybrids since 1997, with more than 40,000 Prius sales in the United States and 50,000-plus in Japan as of December 31, 2002 (Kim 2002). Honda's Insight has sold over 12,000 units and their mainstream Civic Hybrid appears close to meeting Honda's sales goal of 2,000 cars per month since its introduction in April 2002 (Visnic 2002).

Each of the six major automakers selling cars and trucks in the United States today[1] plans to introduce at least one hybrid car or truck by 2006. But many of these will be first-generation vehicles. How will they perform on key fuel economy and environmental measures? To help evaluate and compare the energy security and environmental performance of these vehicles, this study examines the promise of hybrid electric passenger vehicles in the five major vehicle classes: compact cars, mid-size "family" cars, minivans, full-size pickups, and mid-size SUVs. This chapter provides a summary of the findings to show the potential of technologies that could be implemented over the next 10 to 15 years to transform the fuel economy and environmental performance of conventional vehicles, mild hybrids, and full hybrids. It also determines the cost of achieving that performance. In addition, a set of case studies explores the challenges in hybridizing compact cars. A second set demonstrates how effectively hybridization can address the problem of gas-guzzling SUVs. The broader set of detailed results for each of the five car and truck types considered is provided in Appendix B.[2]

Vehicles and Technologies

Many technologies that could significantly alter fuel economy are currently available, but have not been widely implemented. This study evaluates the effect of designing conventional vehicles, mild hybrids, and full hybrids to take advantage of two different technology packages. Each of the hybrids considered uses a parallel hybrid drivetrain.[3]

The "moderate" technologies, outlined in Table 2, are conventional and electric technologies already in limited use in cars and trucks today.[4] They could be widely implemented across the passenger fleet by 2010. "Advanced" technologies, also listed in Table 2, have yet to enter the marketplace, but have already passed out of the research and devel-opment stage and could enter production in the near term. They could be applied throughout the passenger fleet by 2015. These are the technologies that will provide the bulk of the energy security and environmental improvements from passenger vehicles through 2015.

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[1] Sales from DaimlerChrysler, Ford, General Motors, Honda, Nissan, and Toyota made up about 90% of the US light-duty passenger vehicle market in model year 2001 (Mark 2002).

[2] All manufacturers' retail price values in this analysis come from the recent hybrid vehicle cost study by Lipman and Delucchi (2003). All fuel economy and vehicle performance results come from the recent hybrid vehicle performance study by Friedman and An (2003). All costs and savings are shown in year 2000 US dollars.

[3] Recent work indicates that series hybrids are likely to be more expensive than parallel hybrids and will achieve lower fuel economy (Plotkin et al. 2001). For these reasons, this study does not analyze pure series hybrids.

[4] The conventional moderate and advanced technology packages are drawn in part from earlier reports (DeCicco, An, and Ross 2001; An, Friedman, and Ross 2002) that investigated the potential for improving conventional vehicle technology.

Table 2 **Moderate and Advanced Technology Available for Fuel Economy Improvement**

	Moderate	Advanced
Vehicle Load Reduction	• Improved Aerodynamics • Low Rolling Resistance Tires • Advanced High Strength Steel • Electric Power Steering • Electric Power Brakes	High Strength Aluminum
Improved Transmissions	• Optimized Shift Schedules • 6-Speed Automatic Transmissions • Five-Speed Motorized Gear Shift Transmissions • Continuously Variable Transmissions	High-Torque Continuously Variable Transmissions
Efficient Engines	• Low Friction Lubricants • Low Friction Engine Components • Variable Valve Control Gasoline Engines	Stoichiometric Burn Gasoline Direct-Injection Engines
Electrical Components	• Integrated Starter Generators • Permanent Magnet Electric Motors • High-Power Nickel Metal Hydride Batteries	Advanced High-Power Nickel Metal Hybride Batteries Lithium-Ion Batteries

The analysis assumes that each of the vehicles evaluated is in mass production, with each of the Big 6 automakers producing at least 200,000 units per year of each model.

Conventional Vehicles. The evaluation starts with conventional vehicles, since they provide the natural comparison for hybrids. But the comparison is not to the average vehicle on the road today. Many of the technologies that improve fuel economy and tailpipe emissions in hybrids can also be implemented on gasoline-powered cars and trucks. This study thus evaluates conventional vehicles that incorporate the same moderate and advanced technologies shown in Table 2, with the exception of the electrical components. That is, they use the efficient engines, improved transmissions, and vehicle load-reduction technologies just as the hybrids do.[5] Detailed results for all of these vehicles can be found in Appendix B.

Mild Hybrid. The first set of hybrids considered in the evaluation are mild hybrids rated at 15% peak power, with parallel hybrid drivetrains similar in design to the Honda Civic or Honda Insight. The mild hybrid, by definition, does not have the ability to drive using electric power alone. The 15% peak power rating indicates that the vehicle's electric drive contributes roughly15% of its propulsion.[6] At this size, the motor is able to provide significant regenerative braking capability. The engine is downsized from that of the base conventional vehicle so that the 0-60 mph acceleration achieved using both the engine and the motor meets or beats the acceleration of its baseline counterpart.

In this configuration, the motor is attached directly to the gasoline engine and provides idle-off capability (Figure 5). The mild hybrid is evaluated under two design scenarios, one using moderate technology for the electric drive components, engine, transmission, and base vehicle (e.g., aerodynamics), the other using advanced technology for these systems.

Full Hybrid. The evaluation's final set of vehicles are full hybrids, rated at 25%, similar to the Toyota

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[5] The advanced technology conventional vehicle case is drawn directly from work by DeCicco, An, and Ross (2001). The moderate technology conventional vehicle case, while based on the same work, has been modified to be less aggressive in its use of technology.

[6] Percent peak power for a hybrid is the maximum power of the electric motor when powered by the battery, divided by the sum of the maximum power of the gasoline engine and the electric motor when powered by the battery. In practice, both devices cannot produce their maximum power level at the same time, so this measure usually overestimates the motor and battery contribution when the drivetrain is at its maximum power output level.

Prius,[7] and 40% peak power. Unlike the mild hybrids, these are able to drive at low speed on electric power alone.

The full hybrid uses a parallel drivetrain (as do all hybrid vehicles evaluated in this study). The engine is downsized to meet or exceed the same acceleration as its baseline conventional vehicle, while still providing sufficient power for hill climbing. In this configuration, the motor can be disconnected from the engine and provides idle-off capability, regenerative braking exceeding that of the mild hybrid, and electric drive capability. The electric motor propels the vehicle until it reaches 7 to 10 mph for the 25% peak power version or about 15 mph for the 40% version. Then the engine starts and takes over as the primary means of moving the vehicle down the road.

The process of starting the engine while the vehicle is already moving can be handled in two ways. One method uses an integrated heavy-duty version of the starter motor used in cars today. The other method is to bump-start the engine by reconnecting it to the drivetrain, using the drive motor and the momentum of the vehicle to start the engine. The former method was assumed for the vehicle with 25% peak power, and the latter, which is the less expensive method, for the 40% version. Note that bump-starting is difficult to implement smoothly, so basing analysis on this option may underestimate vehicle costs.

Evaluation of the full hybrid rated at 40% peak power examined vehicles using both moderate and advanced technologies. Only advanced technologies were evaluated for the 25% version.

A Fleet of Clean, Green Machines

The whole fleet of cars and trucks used to haul people, coffee, and occasionally a camper, can benefit from hybridization. This analysis shows that, compared with today's fleet of conventional vehicles, a fleet made up of well-engineered mild and full hybrids can realize significant fuel economy and environmental gains.

The bar set by the average conventional vehicle in today's passenger car and truck fleets is quite low: about 24 miles per gallon of gas. This means that the average new vehicle owner spends over $9,000 on gasoline, which produces nearly 80 tons of global warming emissions during the life of today's average cars and trucks (Table 3). In comparison, the savings from a fleet of hybrids, or even conventional vehicles designed to improve fuel econ-omy, are quite impressive (Table 4). Full hybrids using advanced technologies and rated at 40% peak power improve 150% on the fuel economy of today's conventional vehicles, saving

Table 3 **Average Fuel Economy, Economic and Lifetime Environmental Impacts of Model Year 2000 Conventional Vehicles**

	Passenger Fleet Average Vehicle
CAFE Rated Fuel Economy (mpg)	23.8
Real World Fuel Economy[a] (mpg)	19.5
MSRP[b]	$20,772
Lifetime Fuel Cost[c]	$9,248
Lifetime Gasoline Use[d] (gallons)	6,606
Lifetime Global Warming Emissions (tons CO2-equivalent)	79
Lifetime Upstream Smog-Forming Emissions (lb)	93
Lifetime Upstream Toxic Emissions (lb)	43

NOTES:

a. CAFE test fuel economy adjusted by 18% per fuel economy shortfall found in EIA (2001).

b. Manufacturer's Suggested Retail Price, excludes tax, title and destination charges.

c. Based on an average gasoline cost of $1.40 per gallon (EIA 2002).

d. Assumes a 15-year, 170,000-mile vehicle lifetime. Average life based on scrappage rates from Davis and Diegel (2002). Vehicle mileage based on 1995 National Personal Transportation Survey (NPTS) data.

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[7] The Toyota Prius currently sold in the United States is rated at about 28% peak power, using our definition.

nearly $5,500 in gasoline and keeping 47 tons of global warming gases out of the atmosphere. Mild hybrids with advanced technologies show more than a 100% improvement on the fuel economy of today's vehicles, saving $4,700 in gasoline and reducing global warming emissions by 41 tons.

Just building conventional vehicles with moderate technologies makes a noticeable difference: 37% better fuel economy, $2,500 less for gas, and 21 tons less contributed to global warming. In fact, in all cases but the full hybrid using moderate technology, society would see a net benefit from investing in improving fuel economy.

Table 4 **Average Fuel Economy and Lifetime Savings from Applying Conventional and Hybrid Technology**

Fleet Average Passenger Vehicle	Moderate Technology Conventional Gasoline	Advanced Technology Conventional Gasoline (with Idle-stop)	Moderate Technology Mild Hybrid Electric (15% Peak Power)	Moderate Technology Full Hybrid Electric (40% Peak Power)	Advanced Technology Mild Hybrid Electric (15% Peak Power)	Advanced Technology Full Hybrid Electric (25% Peak Power)	Advanced Technology Full Hybrid Electric (40% Peak Power)
CAFE Rated Fuel Economy (mpg)	32.7	40.8	39.3	48.0	49.0	58.2	59.6
Real World Fuel Economy[a] (mpg)	26.8	33.5	32.2	39.3	40.2	47.7	48.9
Fuel Economy Improvement vs. Baseline	37%	71%	65%	101%	106%	144%	150%
Retail Cost of Fuel Economy Improvement[b]	$611	$1,729	$3,004	$4,897	$2,858	$3,969	$4,383
Lifetime Fuel Cost Savings[c]	$2,504	$3,847	$3,637	$4,651	$4,752	$5,458	$5,551
Lifetime Net Savings[d]	$1,893	$2,118	$154	-$1,501	$1,546	$907	$236
Lifetime Gasoline Savings[e] (gallons)	1,789	2,748	2,598	3,322	3,394	3,898	3,965
Lifetime Savings in Global Warming Gases (tons CO2-equivalent)	21	33	31	40	41	47	47
Avoided Upstream Smog-Forming Emissions (lb)	25	39	36	47	48	55	56
Avoided Upstream Toxic Emissions (lb)	12	18	17	22	22	25	26

NOTES:

a. CAFE test fuel economy adjusted by 18% per fuel economy shortfall found in EIA (2001).

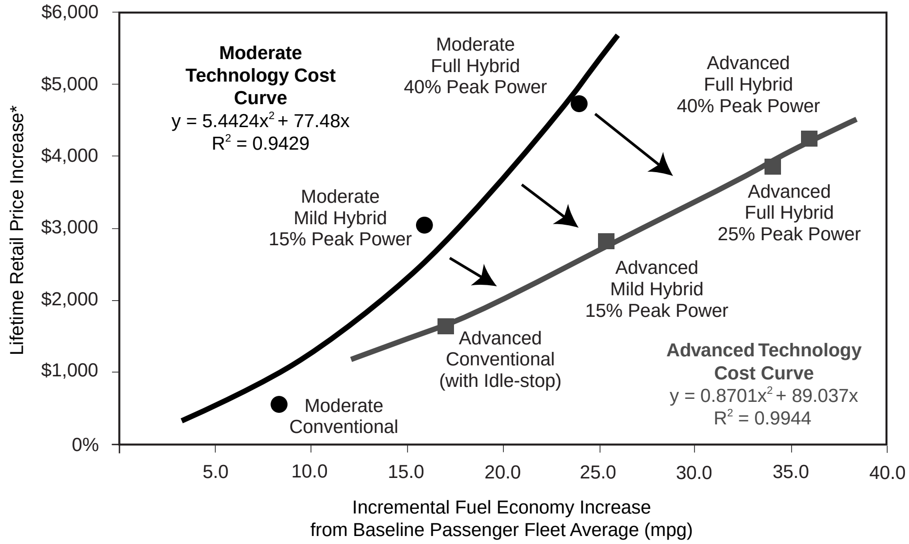
b. Difference between MSRP of hybrid and today's baseline conventional vehicle.

c. Based on an average gasoline cost of $1.40 per gallon (EIA 2002).

d. Includes the cost of two battery pack refurbishments, one after year 8 and one after year 12.

e. Assumes a 15-year, 170,000-mile vehicle lifetime. Average life based on scrappage rates from Davis and Diegel (2002). Vehicle mileage based on 1995 National Personal Transportation Survey (NPTS) data.

Figure 11 **Fuel Economy Cost Curves for Conventional and Hybrid Vehicles Incorporating Technological Progress**



NOTES: *Including present value of battery replacement cost for hybrids.

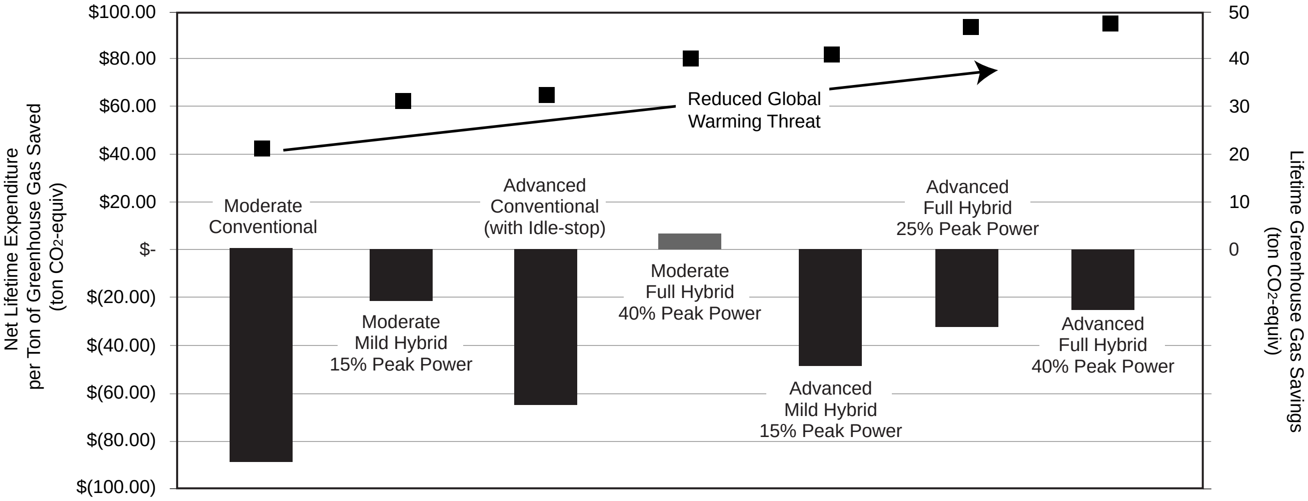
Moving along the Technology Frontier. Two main lessons emerge from the fleetwide analysis. First, hybrids will rely on technological progress—moving from moderate to advanced technologies—to achieve dramatic improvements in fuel economy. The resulting vehicles will be far better for the environment and can play a significant role in decreasing US dependence on foreign oil. Second, the technological progress that enables hybrids to provide these benefits will, at the same time, save consumers money that can then be fed back into the economy.

The curve on the left represents the application of moderate technology to both conventional vehicles and mild and full hybrids. Figure 11 summarizes this lesson. A fleet of conventional passenger vehicles using moderate technology improves fuel economy about 9 mpg over that of a conventional fleet using today's technology to achieve a fleet average of 32.7 mpg, for about $600 per vehicle. The additional cost increases significantly, to $3,000 each, for a 39-mpg fleet of moderate technology mild hybrids, and to almost $5,000 each for a 49-mpg fleet of moderate full hybrids.

However, as the curve on the right indicates, the cost of reaching similar and even higher fuel economy levels drops as more advanced technologies are applied to conventional and hybrid vehicles. A 40-mpg fleet becomes possible when conventional vehicles are outfitted with advanced technology. This can be achieved at a cost increment of only $1,700 per vehicle, rather than the $3,000 or so to reach the same 40-mpg fleet with moderate mild hybrids. Advanced mild hybrids produce a 49-mpg fleet for $3,000 each, $2,000 less than meeting that goal with moderate full hybrids. Finally, a nearly 150% improvement in fleet fuel economy can be achieved with advanced full hybrids for an average incremental price of about $4,000 each.

These cost curves assume the same fleet mix as existed in model year 2000. Recent trends toward increased SUV and pickup sales would reduce these averages; however, a fleet made up of only

Figure 12 **Environmental Cost Effectiveness for Conventional and Hybrid Vehicles**



pickups, minivans, and SUVs could still rely on full hybrids with advanced technology to reach over 50 mpg.

Measuring Cost Effectiveness and the Break-Even Test. The second lesson revolves around the balance between costs and benefits. A basic measure often used to evaluate a technology is its cost effectiveness: how expensive it is for a particular approach to save a gallon of gasoline or one ton of global warming gases.

This cost-effectiveness approach is, however, only useful in comparing two technologies that meet the same goal. If the technologies cannot meet the same goal, then one of them is clearly doing a better job at addressing the root problem, even if it costs more to do so. In this case, a cost-effectiveness comparison between the two is misleading.

For example, both advanced technology conventional vehicles and moderate technology mild hybrids achieve about the same improvement in fuel economy and therefore provide the same benefits in addressing energy insecurity and the threat of global warming. Applying a cost effectiveness measure for energy security shows that, of the two, advanced conventional technology has the lowest net cost per ton of global warming gases saved (Figure 12). Thus, advanced conventional technology vehicles are just as effective as moderate mild hybrids, but they are a significantly more cost-effective approach to creating a 40-mpg fleet.

Figure 12 indicates that another pair that can be properly evaluated by a cost-effectiveness measure are the moderate full hybrid and the advanced mild hybrid. The advanced mild hybrid is more cost effective than the moderate full hybrid in meeting the goal of a 50-mpg fleet. (It may, however, take longer to get there since moderate technologies are likely to be brought into vehicles sooner). Since the fuel economies of the two advanced full hybrids are quite close, cost effectiveness is also appropriate for comparison: the 25% peak power advanced full hybrid appears more cost effective at approaching a goal of a 60-mpg fleet than the 40% peak power advanced full hybrid. Figure 13 provides similar information, but for the effectiveness and cost effectiveness of addressing rising oil dependence through technologies that improve fuel economy.

The moderate full hybrid shows up as a unique case in both figures. It is the only vehicle that fails a break-even test. To break even, a vehicle designed to improve fuel economy must save at least as much on fuel costs as is spent on achieving the improvement. If the vehicle fails to break even, society bears a net cost for achieving improved energy security and a reduced global warming threat. Of the seven vehicle designs graphed here, only one does not break even.

The irony of the break-even test is that it simply tests whether or not the improvements are free when spread over the vehicle's lifetime. How often in our daily lives are we presented with several options that address problems we are trying to solve *and* give us money back? This is an impressive finding of this study: over the life of these vehicles, the energy security and environmental benefits come free to society, as long as we make the up-front investment (plus we get fun cars or trucks to drive around in).

The cost effectiveness and break-even information in these two figures indicates that three hybrid configurations are more expensive and could be excluded in choosing a technology pathway to address our energy insecurity and global warming problems. The moderate technology hybrid configurations should be considered stepping stones in developing the more advanced full and mild hybrids, rather than ends in themselves. The advanced full hybrid rated at 40% peak power appears to use too much electric power without a significant return on the investment. This vehicle would probably benefit significantly from adding in the ability to recharge the batteries from the electricity grid, transforming it into a plug-in hybrid, with all the associated fuel economy and emissions benefits (Graham 2001).

When these three cases are excluded, a clear technology implementation pathway emerges from this evaluation of the effectiveness of each option. A near-term goal of achieving an average fuel economy of about 33 mpg within this decade is achievable with moderate technology conventional gasoline vehicles. A 40-mpg average fuel economy is possible with advanced technology conventional gasoline vehicles within the next ten years. Building on developments and early market

Figure 13 **Oil Security Cost Effectiveness for Conventional and Hybrid Vehicles**

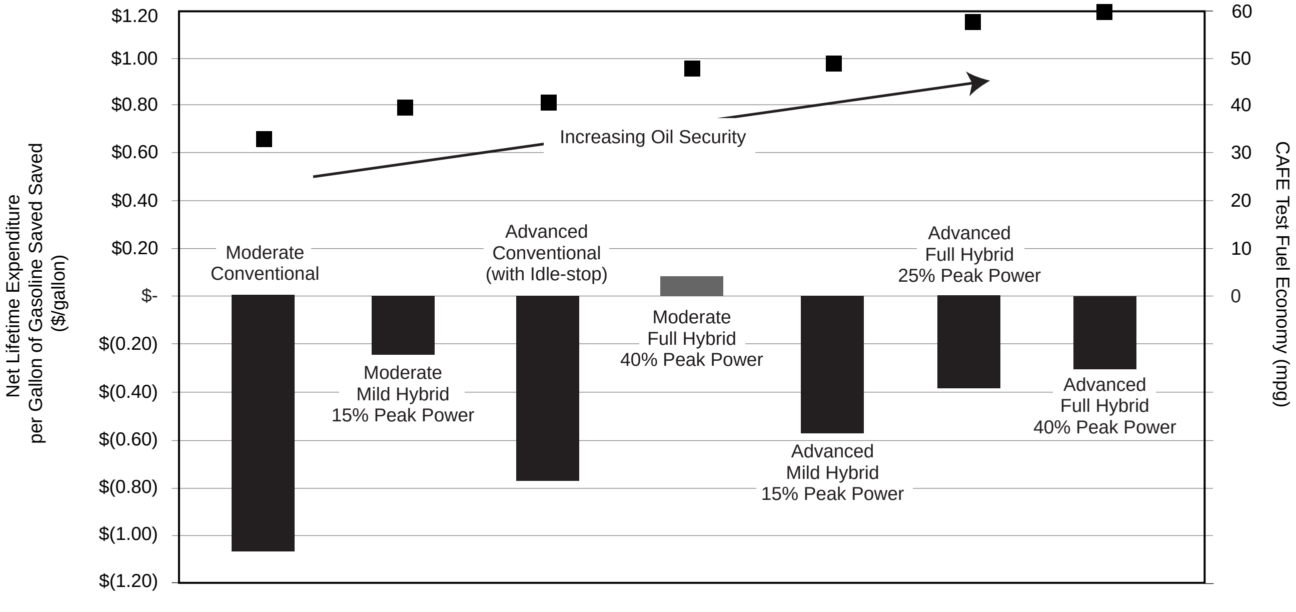


Figure 14 **Window Sticker for a Typical Model Year 2000 Compact Car (e.g. Chevrolet Cavalier)**

Engine:	2.2 liter L4, 115 hp	**MSRP**[a]	$14,295
Motor:	NA	**Performance**	
Battery Pack:	NA	• 0–60 mph Acceleration:	11 seconds
Transmission:	4-speed automatic		
Body:	standard aerodynamics, Cd: 0.36, A 2.0	**Certification Values**	
		• CAFE Test Fuel Economy:	30.8 mpg
Tires: :	standard tires, Crr: 0.010	• Federal and California Emission Ratings:	LEV
Test Weight:	3,125 pounds		

Economic, Environmental and Energy Security Performance

Real World Fuel Economy[b]**:**	25.3 mpg	**Lifetime Fuel Cost**[c]**:**	$7,151
Lifetime Gasoline Savings[d]**:**	None	**Lifetime Net Savings**[e]**:**	None
Lifetime Greenhouse Gas Savings:	None		

NOTES:
a. Manufacturer's Suggested Retail Price, excludes tax, title and destination charges.
b. CAFE test fuel economy adjusted by 18%.
c. Based on an average gasoline cost of $1.40 per gallon (EIA 2001).
d. Based on the "real world" fuel economy value. Assumes a 15-year, 170,000-mile vehicle lifetime. Average life based on scrappage from Davis and Diegel (2002). Vehicle mileage based on 1995 National Personal Transportation Survey (NPTS) data.
e. Includes the cost of two battery packs refurbishments, one after year 8 and one after year 12.

entry of moderate technology hybrids, the advanced technology mild and full hybrids can achieve the goal of a 50-mpg to 60-mpg fleet by 2020. Then, adding plug-in capability to a 40% peak power full hybrid or relying on hydrogen fuel cell vehicles could take us even further.

Case Studies: Hybrid Compacts and SUVs

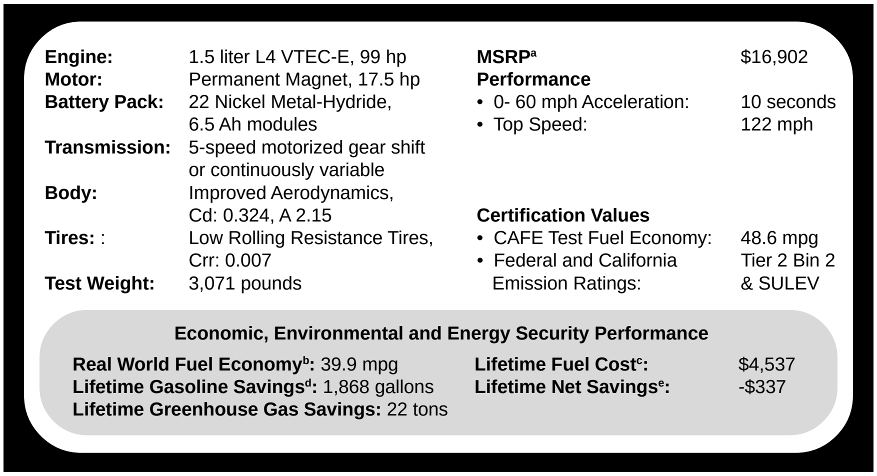
Conventional compact cars are already fairly fuel efficient. Thus it's a challenge to improve their fuel economy through hybridization without increasing costs too much. A set of case studies explores this challenge. A second set of case studies demonstrates how much can be gained by hybridizing gas-guzzling SUVs.

The Hybrid Compact Car. Achieving large fuel economy gains by hybridizing a compact car is a greater challenge than for larger vehicles, because there are fewer areas open to improvement. For example, just eliminating unnecessary weight goes a long way toward improving the fuel economy of SUVs or passenger trucks, but compacts have little weight to lose. This challenge makes them an interesting class for exploring how much value hybridization can add. In addition, since the two principal hybrid vehicles currently on sale in the United States are compacts, it seemed worth a closer look at how this class of cars might evolve over the next 15 years.

The case studies laid out below examine a range of possibilities for hybridizing compact cars, from mild hybrids with moderate technology to full hybrids with advanced technology. Each is accompanied by a mock-up of a dealer window sticker, listing specifications and performance measures.

2000 Conventional Compact Car. A typical compact car weighs around 3,000 pounds and can go from 0 to 60 mph in about 11 seconds (Figure 14). The model year 2000 Chevrolet Cavalier, for example, gets around 30 miles to the gallon, according to government tests. Over a 15-year lifetime, it will use over 5,000 gallons of gasoline and will be responsible for 61 tons of global warming emissions. The vehicle costs $14,000 to $15,000 at the dealer and uses an estimated $7,151 worth of gasoline over 15 years.[8]

Figure 15 **Window Sticker for a Moderate Technology Mild Hybrid Electric Compact Car (15% Peak Power)**



Engine:	1.5 liter L4 VTEC-E, 99 hp
Motor:	Permanent Magnet, 17.5 hp
Battery Pack:	22 Nickel Metal-Hydride, 6.5 Ah modules
Transmission:	5-speed motorized gear shift or continuously variable
Body:	Improved Aerodynamics, Cd: 0.324, A 2.15
Tires: :	Low Rolling Resistance Tires, Crr: 0.007
Test Weight:	3,071 pounds

MSRP[a]	$16,902
Performance	
• 0- 60 mph Acceleration:	10 seconds
• Top Speed:	122 mph
Certification Values	
• CAFE Test Fuel Economy:	48.6 mpg
• Federal and California Emission Ratings:	Tier 2 Bin 2 & SULEV

Economic, Environmental and Energy Security Performance

Real World Fuel Economy[b]: 39.9 mpg		**Lifetime Fuel Cost**[c]:	$4,537
Lifetime Gasoline Savings[d]: 1,868 gallons		**Lifetime Net Savings**[e]:	-$337
Lifetime Greenhouse Gas Savings: 22 tons			

This 2000 model year conventional compact is the baseline vehicle against which the hybrid compacts are compared.

2010 Moderate Mild Hybrid Compact Car (15% Peak Power). The mass-market mild hybrid compact that could be made using moderate technology looks a lot like the Honda Civic Hybrid available today. Both have a peak power rating close to 15%. Neither can drive using electricity alone. And their weights are nearly the same. The manufacturer's suggested retail price (MSRP) is likely to be about $2,600 above the price of the baseline compact car, including standard built-in dealer and manufacturer profits (Figure 15).[9]

While the lifetime fuel cost savings ($4,537) are higher than the price increase, the cost of battery replacement[10] means that, on net, this vehicle is about $340 more expensive to own than the baseline compact car.[11] At the assumed production level of 200,000 units per year, the profit margin built into the mild hybrid compact car analyzed here is larger than the $340 expense to the consumer. An automaker could still make a profit with this vehicle even if it were priced a bit lower to ensure that it reached a break-even point for the consumer. However, especially in the first several years of production, before these mass-manufacturing levels are reached, federal tax credits would be a good investment, helping to assure that a vehicle with good environmental performance achieves success in the marketplace.

Analysis of the moderate mild hybrid shows that its incremental MSRP in mass production ($2,600) is about $900 lower compared to the

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[8] Fuel costs are based on an average gasoline price of $1.40 per gallon in constant 2000 dollars (EIA 2001) and are discounted at an annual rate of 5%. Real world fuel economy is used to calculate these costs and represents the federal CAFE test fuel economy, discounted by 18% in accordance with findings in EIA (2001).

[9] All manufacturer's retail price values in this analysis come from the recent hybrid vehicle cost study by Lipman and Delucchi (2003). All fuel economy and vehicle performance results come from the recent hybrid vehicle performance study by Friedman and An (2003).

[10] Battery replacement costs include two pack replacements, at 8 years and 12 years, with refurbished packs costing about a quarter of the initial retail price of the battery system (including all cooling, monitoring, and support components). Appendix A provides details on battery performance and retail costs.

[11] The lifetime cost comparison includes the initial MSRP of the vehicle and the lifetime fuel cost savings over a 170,000-mile, 15-year average vehicle life. It does not include taxes, registration, and destination charges at vehicle purchase or any differences in operating costs other than fuel and battery replacement.

Figure 16 **Window Sticker for a Moderate Technology Full Hybrid Electric Compact Car (40% Peak Power)**

Engine:	1.1 liter L4 VTEC-E, 72.5 hp
Motor:	Permanent Magnet, 48 hp
Battery Pack:	44 Nickel Metal-Hydride, 9.0 Ah modules
Transmission:	5-speed motorized gear shift or continuously variable
Body:	Improved Aerodynamics, Cd: 0.324, A 2.15
Tires: :	Low Rolling Resistance Tires, Crr: 0.007
Test Weight:	3,218 pounds

MSRP[a]	$18,402
Performance	
• 0- 60 mph Acceleration:	9.6 seconds
• Top Speed:	121 mph
Certification Values	
• CAFE Test Fuel Economy:	57.6 mpg
• Federal and California Emission Ratings:	Tier 2 Bin 2 & SULEV

Economic, Environmental and Energy Security Performance

Real World Fuel Economy[b]: 47.2 mpg	**Lifetime Fuel Cost**[c]:	$3,828
Lifetime Gasoline Savings[d]: 2,374 gallons	**Lifetime Net Savings**[e]:	-$1,694
Lifetime Greenhouse Gas Savings: 28 tons		

NOTES:
a. Manufacturer's Suggested Retail Price, excludes tax, title and destination charges.
b. CAFE test fuel economy adjusted by 18%.
c. Based on an average gasoline cost of $1.40 per gallon (EIA 2001).
d. Based on the "real world" fuel economy value. Assumes a 15-year, 170,000-mile vehicle lifetime. Average life based on scrappage from Davis and Diegel (2002). Vehicle mileage based on 1995 National Personal Transportation Survey (NPTS) data.
e. Includes the cost of two battery packs refurbishments, one after year 8 and one after year 12.

Honda Civic Hybrid, which is priced at about $3,500 more than a similarly equipped conventional Civic.[12] The Civic Hybrid however is in low-volume production of 20,000 to 30,000 units per year, which probably explains a significant part of its higher price.

The moderate mild hybrid here achieves a CAFE fuel economy rating of 48.6 mpg, which is about equal to the Civic Hybrid's on-road performance, but 9 mpg lower than the Civic's fuel economy test rating.[13]

This 15% drop in fuel economy is probably due to two performance factors. First, the moderate mild hybrid analyzed here can accelerate from 0 to 60 mph in 10 seconds, 1 to 2 seconds faster that the Civic Hybrid.[14] In addition, the moderate mild hybrid attains California's stringent SULEV emissions rating, while today's Civic Hybrid has achieved only the less stringent ULEV rating, likely because it uses a more efficient, but dirtier "lean-burn" gasoline engine.[15] A similar drop in the fuel economy of the Honda's other hybrid, the Insight, occurs between the version that includes a lean-burn gasoline engine and meets only ULEV and the version that achieves a SULEV emissions rating without the lean-burn engine.[16]

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[12] A Civic Hybrid with continuously variable transmission has an MSRP of $20,550. Its closest counterpart is the Civic LX, with an MSRP of $16,500, but the LX does not include an anti-lock brake system (ABS), which we assume would cost about $500 installed, for a total MSRP of $17,000. MSRP values from www.hondacars.com.

[13] Estimated difference calculated based on the Civic Hybrid's EPA fuel economy rating of 46 mpg city and 51 mpg highway, which correspond to a CAFE (Corporate Average Fuel Economy) fuel economy rating of 58 mpg.

[14] All hybrid acceleration times in this study are measured with the battery at 50% of its capacity. At 20% of its capacity, the hybrid will accelerate similarly to the baseline vehicle; however, the hybrid control strategy will seek to keep the battery charged at 50% or higher as often as possible.

[15] Lean-burn engines typically cannot meet California's Super Ultra Low Emission Vehicle (SULEV) tailpipe standard because of higher smog-forming emissions, particularly the nitrogen oxides (NOx), which are inherently higher for lean-burn technology. SULEV NOx emission levels are required to be one-tenth that of California's Ultra Low Emission Vehicle (ULEV) tailpipe standard.

This emissions performance issue demonstrates the current tradeoff between air quality and global warming gases created by using lean-burn technologies. Lean-burn technologies such as diesels and Honda's lean-burn gasoline engine deliver good fuel economy, thereby cutting global warming emissions, but are inherently dirty, emitting substantial smog-forming pollutants—and in the diesels' case, toxics—at a cost to public health. Emission-control technologies are being developed in an attempt to address these problems. These technologies will increase the vehicle price and may, in the case of diesel particulates, still not adequately protect public health.

2010 Moderate Full Hybrid Compact Car (40% Peak Power). The moderate technology full hybrid compact car demonstrates the benefit of adding electric drive capability to a hybrid. This vehicle reaches a CAFE fuel economy rating of nearly 58 mpg, 9 mpg higher than the moderate technology mild hybrid. The manufacturer's suggested retail price (MSRP) is projected to be about $4,100 above that for the baseline conventional compact, including standard built-in dealer and manufacturer profits (Figure 16).

In this case, the lifetime fuel cost savings are less than the price increase and, with the addition of the cost of battery replacement, this vehicle is about $1,700 more expensive to own than the baseline compact car. In effect, this $1,700 is the price of reduced oil dependence, a diminished warming threat, and clean air. However, this is just the first step in the development of full hybrids.

There is no clear counterpart to the 40% peak power full hybrid analyzed here, but the Prius is the closest vehicle available today. This moderate full hybrid achieves a fuel economy similar to that of the Toyota Prius. The incremental MSRP is also similar to the Prius, which is priced about $4,300 more than a similarly equipped Echo.[17] However, these two vehicles, while both full hybrids, are different in several ways. The Prius uses a series/parallel drivetrain, a more efficient engine, and a smaller battery pack (28% peak power)—and this is only a second generation design. The similarity in fuel economy may disappear once the next generation Prius reaches the United States: recent news reports indicate that the next version of the Prius may have as much as a 7% increase in both fuel economy and acceleration performance (Ward's Auto World 2002).

Because of the high costs of the Prius and the moderate technology full hybrid analyzed here, it does not appear that automakers will be able to make significant profits from these designs, although they will be able to cover their costs. However, as discussed below, an advanced technology version of a full hybrid will more than break even, enabling the automaker to make a profit on the vehicle. Because of their superior environmental performance, this issue highlights the need for federal tax credits to make sure that a solid market can be developed for near-term full hybrids. Further, federal tax credits that support the market success of these vehicles will help make sure the superior-performing full hybrid compact car of the next decade will succeed.

2015 Advanced Mild Hybrid Compact Car (15% Peak Power). The advanced mild hybrid compact car takes a significant step up in environmental performance from the moderate mild

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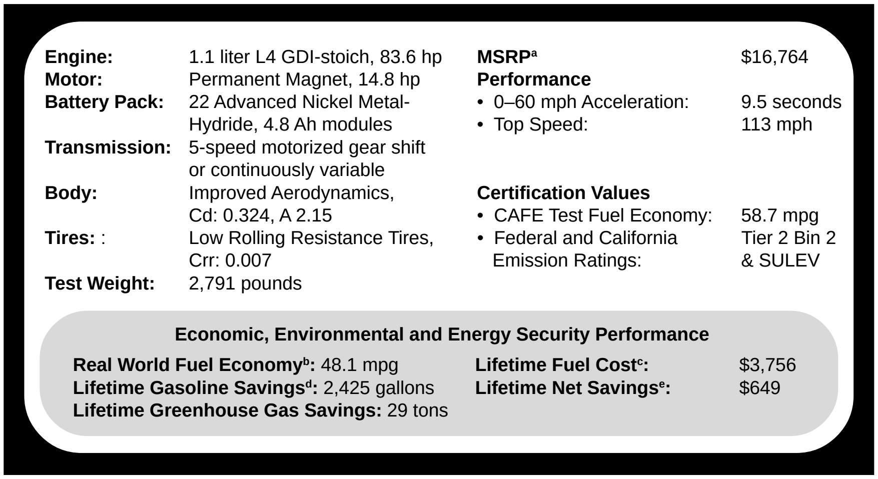
[16] The CAFE rating of the Insight is about 77 mpg with the lean-burn engine and about 68 mpg without, a 12% difference. The two versions achieved about the same 0-60 mph performance.

[17] The MSRP for the Toyota Prius is $19,995. The 4-door Echo, its nearest counterpart, has an MRSP of $14,700, but does not include ABS and keyless entry/security, each of which is assumed to cost about $500 installed, for a total MSRP of $15,700.

Figure 17 **Window Sticker for an Advanced Technology Mild Hybrid Electric Compact Car (15% Peak Power)**



Engine:	1.1 liter L4 GDI-stoich, 83.6 hp	**MSRP**[a]	$16,764
Motor:	Permanent Magnet, 14.8 hp	**Performance**	
Battery Pack:	22 Advanced Nickel Metal-Hydride, 4.8 Ah modules	• 0–60 mph Acceleration: • Top Speed:	9.5 seconds 113 mph
Transmission:	5-speed motorized gear shift or continuously variable		
Body:	Improved Aerodynamics, Cd: 0.324, A 2.15	**Certification Values** • CAFE Test Fuel Economy:	58.7 mpg
Tires: :	Low Rolling Resistance Tires, Crr: 0.007	• Federal and California Emission Ratings:	Tier 2 Bin 2 & SULEV
Test Weight:	2,791 pounds		

Economic, Environmental and Energy Security Performance

Real World Fuel Economy[b]: 48.1 mpg		**Lifetime Fuel Cost**[c]:	$3,756
Lifetime Gasoline Savings[d]: 2,425 gallons		**Lifetime Net Savings**[e]:	$649
Lifetime Greenhouse Gas Savings: 29 tons			

NOTES:
a. Manufacturer's Suggested Retail Price, excludes tax, title and destination charges.
b. CAFE test fuel economy adjusted by 18%.
c. Based on an average gasoline cost of $1.40 per gallon (EIA 2001).
d. Based on the "real world" fuel economy value. Assumes a 15-year, 170,000-mile vehicle lifetime. Average life based on scrappage from Davis and Diegel (2002). Vehicle mileage based on 1995 National Personal Transportation Survey (NPTS) data.
e. Includes the cost of two battery packs refurbishments, one after year 8 and one after year 12.

hybrid, with a CAFE-rated fuel economy of 58.7 mpg (Figure 17). And the cost has dropped slightly as well. The MSRP will be about $2,500 above that for the conventional compact, including standard built-in dealer and manufacturer profits. With battery replacement, this vehicle is, on net, about $650 less expensive to own than the baseline compact car. Thus it is a better buy both financially and for its energy security and environmental performance.

The improved fuel economy is a straightforward result of using better technology, but the drop in cost may appear surprising. Certainly the improved engine and weight reduction can add cost to the advanced vehicle, but by 2015 the retail price of the batteries used for this vehicle is projected to drop from about $80 to $75 per kilowatt due to technology advances. Of all the technologies considered in this study, batteries are the least mature, and most predictions indicate a potential for even greater cost reductions than shown here.

In addition, the weight of this vehicle, excluding the drivetrain, has been reduced by 9% using advanced high strength steel technology.[18] This drop in weight allows for the same vehicle performance as the moderate mild hybrid, but with less power. The reduction in power translates directly into lower component costs. This synergy highlights the importance of not bringing hybrids to the market saddled with out-of-date body design and materials.

2015 Advanced Full Hybrid (40% Peak Power). The transition from moderate to advanced technologies tells much the same story for the full hybrid at 40% peak power as for the mild hybrid. Advanced technology lowers the price and improves the performance: the compact reaches nearly 70 mpg, rather than 57.6, and the increase in MSRP

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[18] Developments in the steel industry's UltraLight Steel AutoBody program indicate that significant improvements, like a 25% reduction in body weight while still attaining a 5-star crash safety rating, can be achieved at no additional cost (ULSAB 2002a,b).

Figure 18 **Window Sticker for an Advanced Technology Full Hybrid Electric Compact Car (40% Peak Power)**

Engine:	0.8 liter L4 GDI-stoich, 60.3 hp
Motor:	Permanent Magnet, 40.2 hp
Battery Pack:	44 Advanced Nickel Metal-Hydride, 6.2 Ah modules
Transmission:	5-speed motorized gear shift or continuously variable
Body:	Improved Aerodynamics, Cd: 0.324, A 2.15
Tires: :	Low Rolling Resistance Tires, Crr: 0.007
Test Weight:	2,854 pounds

MSRP[a]	$17,908
Performance	
• 0–60 mph Acceleration:	9.3 seconds
• Top Speed:	116 mph
Certification Values	
• CAFE Test Fuel Economy:	69.6 mpg
• Federal and California Emission Ratings:	Tier 2 Bin 2 & SULEV

Economic, Environmental and Energy Security Performance

Real World Fuel Economy[b]**:** 57.1 mpg		**Lifetime Fuel Cost**[c]**:**	$3,168
Lifetime Gasoline Savings[d]**:** 2,845 gallons		**Lifetime Net Savings**[e]**:**	-$343
Lifetime Greenhouse Gas Savings: 34 tons			

above baseline is $3,600, rather than $4,100 (Figure 18). Its 0-60 mph acceleration equals that of the moderate full hybrid and betters that of the baseline compact by over 1.5 seconds.

The lifetime fuel cost savings are greater than the price increase, but battery replacement makes this car $340 more expensive to own than the baseline compact. If the price of gasoline increases by just $0.15, to $1.55 per gallon, this vehicle will break even, according to our economic measure. Moreover, factoring in even conservative estimates of the costs of oil dependence and global warming would tip this vehicle even further to the positive side on cost/benefit accounting, indicating that it will provide a great deal of benefit to society at no net cost.

2015 Advanced Full Hybrid (25% Peak Power). The 40% peak power advanced full hybrid is just at the edge of breaking even. How would that change if it used fewer batteries, and what would happen to the performance? The full hybrid, rated at 25% peak power has the same advanced technologies as the 40% peak car, except that it uses a starter/generator system to start the engine instead of bump starting it.

Reducing the battery and motor size has only a small impact on fuel economy, dropping it from 70 to 67.3 mpg (Figure 19). But the effect on the cost is significant: the MSRP increases only $3,300 above the baseline vehicle, rather than $3,600 for the 40% peak power full hybrid. And acceleration remains the same as that of the 40% peak car.

As was noted in chapter 2, the key to the improvement in a full hybrid's fuel economy is its electric drive capability. The increase from raising the peak power is slight, as shown here. The decrease in fuel economy is less than 4%, while the incremental change in MSRP drops by 8%. This initial drop in cost, plus the reduced cost of replacing a smaller battery pack, means that this vehicle is $131 less expensive to own than the baseline compact car. That brings this lower-power full hybrid across the break-even line, according to our economic measure. The Prius should, in the future, be able to meet these performance and cost levels, bringing Toyota significant profit.

The Hybrid SUV. At the other end of the spectrum from compact cars, gas-guzzling mid-size SUVs bring to the fore both the magnitude of our dependence on oil and the potential to apply technol-

Figure 19 **Window Sticker for an Advanced Technology Full Hybrid Electric Compact Car (25% Peak Power)**

Engine:	1.0 liter L4 GDI-stoich, 76.4 hp	**MSRP**[a]	$17,577
Motor:	Permanent Magnet, 25.5 hp	**Performance**	
Batttery Pack:	33 Advanced Nickel Metal-Hydride, 5.3 Ah modules	• 0–60 mph Acceleration:	9.3 seconds
		• Top Speed:	115 mph
Transmission:	5-speed motorized gear shift or continuously variable		
Body:	Improved Aerodynamics, Cd: 0.324, A 2.15	**Certification Values**	
		• CAFE Test Fuel Economy:	67.3 mpg
Tires: :	Low Rolling Resistance Tires, Crr: 0.007	• Federal and California Emission Ratings:	Tier 2 Bin 2 & SULEV
Test Weight:	2,818 pounds		

Economic, Environmental and Energy Security Performance

Real World Fuel Economy[b]**:** 55.2 mpg	**Lifetime Fuel Cost**[c]**:**	$3,276
Lifetime Gasoline Savings[d]**:** 2,768 gallons	**Lifetime Net Savings**[e]**:**	$131
Lifetime Greenhouse Gas Savings: 33 tons		

Figure 20 **Window Sticker for a Typical Model Year 2000 Mid-Sized SUV (e.g. Ford Explorer)**

Engine:	4 liter V6, 210 hp	**MSRP**[a]	$26,778
Motor:	NA	**Performance**	
Battery Pack:	NA	• 0–60 mph Acceleration:	8.9 seconds
Transmission:	5-speed automatic		
Body:	standard aerodynamics, Cd: 0.45, A: 2.4	**Certification Values**	
		• CAFE Test Fuel Economy:	19.9 mpg
Tires: :	standard tires, Crr: 0.011	• California Emission Ratings:	LEV
Test Weight:	4,500 pounds		

Economic, Environmental and Energy Security Performance

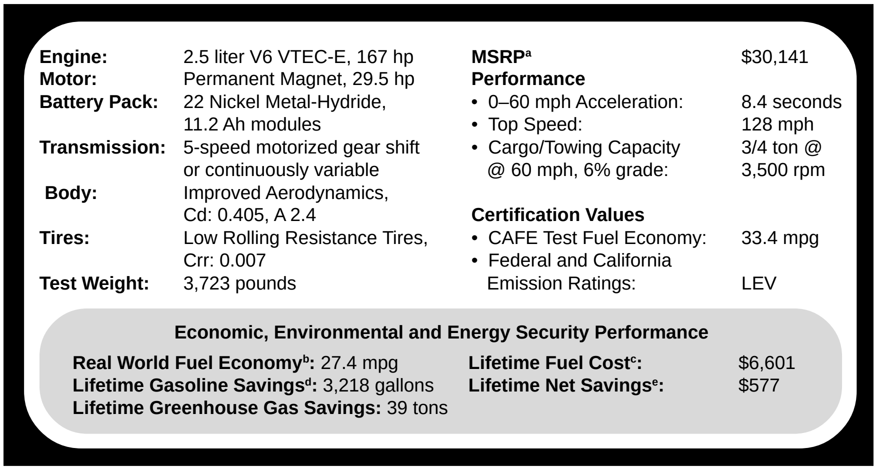
Real World Fuel Economy[b]**:** 16.3 mpg	**Lifetime Fuel Cost**[c]**:**	$11,107
Lifetime Gasoline Savings[d]**:** None	**Lifetime Net Savings**[e]**:**	None
Lifetime Greenhouse Gas Savings: None		

NOTES:
a. Manufacturer's Suggested Retail Price, excludes tax, title and destination charges.
b. CAFE test fuel economy adjusted by 18%.
c. Based on an average gasoline cost of $1.40 per gallon (EIA 2001).
d. Based on the "real world" fuel economy value. Assumes a 15-year, 170,000-mile vehicle lifetime. Average life based on scrappage from Davis and Diegel (2002). Vehicle mileage based on 1995 National Personal Transportation Survey (NPTS) data.
e. Includes the cost of two battery packs refurbishments, one after year 8 and one after year 12.

ogy to curb that thirst. They offer an opportunity for aggressive weight reduction to cut out the fat that drives up their fuel consumption and makes them a significant danger to other vehicles in side impact collisions (Stoffer 2002). But the need to maintain towing capacity puts constraints on the changes that can be made to the engine.

2000 Mid-Size Conventional SUV. A typical mid-size SUV weighs around 4,500 pounds and can go from 0 to 60 mph in a sports-car-like 9 seconds or less. The Ford Explorer is the most popular SUV in this class and the 210-horsepower model year 2000 Explorer provides a good baseline for comparison (Figure 20). This vehicle gets

Figure 21 **Window Sticker for a Moderate Technology Mid-Sized SUV (15% Peak Power)**



Engine:	2.5 liter V6 VTEC-E, 167 hp
Motor:	Permanent Magnet, 29.5 hp
Battery Pack:	22 Nickel Metal-Hydride, 11.2 Ah modules
Transmission:	5-speed motorized gear shift or continuously variable
Body:	Improved Aerodynamics, Cd: 0.405, A 2.4
Tires:	Low Rolling Resistance Tires, Crr: 0.007
Test Weight:	3,723 pounds

MSRP[a]	$30,141
Performance	
• 0–60 mph Acceleration:	8.4 seconds
• Top Speed:	128 mph
• Cargo/Towing Capacity @ 60 mph, 6% grade:	3/4 ton @ 3,500 rpm
Certification Values	
• CAFE Test Fuel Economy:	33.4 mpg
• Federal and California Emission Ratings:	LEV

Economic, Environmental and Energy Security Performance

Real World Fuel Economy[b]**:**	27.4 mpg	**Lifetime Fuel Cost**[c]**:**	$6,601
Lifetime Gasoline Savings[d]**:**	3,218 gallons	**Lifetime Net Savings**[e]**:**	$577
Lifetime Greenhouse Gas Savings:	39 tons		

around 20 miles to the gallon, according to government tests. Over a 15-year lifetime, it will use nearly 8,000 gallons of gasoline and emit 61 tons of global warming gases. The 4-door version of the Explorer costs anywhere from $22,000 to $35,000 at the dealer and then an additional $11,107 for gasoline over 15 years.

Hybridizing an SUV is somewhat different from hybridizing a car or minivan since it is important to maintain towing capacity. For this analysis, the components were sized to ensure that the SUV could haul a three-quarter-ton trailer up a steep 6% grade at 60 miles per hour using the engine alone.

2010 Moderate Mild Hybrid SUV (15% Peak Power). Much like the moderate technology mild hybrid compact car, the moderate mild hybrid SUV shows significant improvement in fuel economy and acceleration performance. This vehicle reaches a CAFE fuel economy rating of 33.4 mpg, a 68% improvement over the baseline vehicle, while shaving about one half second off the 0 to 60 mph acceleration time. This vehicle will be able to tow a three-quarter-ton trailer up a 6% grade at 60 mph indefinitely, using only the gasoline engine.

Unlike the compact car, which did not break even when hybridized with moderate technology, the moderate mild hybrid SUV is projected to be less expensive, including fuel, purchase price and battery replacement costs, than its baseline counterpart on the streets today. The increase in the MSRP is about $3,360, including standard built-in dealer and manufacturer profits (Figure 21).

The $4,500 saved on fuel over this 33.4 mpg SUV's lifetime covers both the added initial price and the cost of battery replacement. That makes this vehicle $575 less expensive than the baseline conventional SUV over its life. No comparable mild hybrid mid-size SUVs are expected to reach market during the 2003 model year. Rumors exist, however, that Honda may produce mid-size SUV hybrids of some type, though it is unclear whether they will be mild or full hybrids.

This vehicle would benefit significantly from tax credits to help boost sales. These incentives are especially useful during the first few years when automakers are unlikely to make a profit due to low sales volumes and early development costs.

2010 Moderate Full Hybrid Mid-Size SUV (40% Peak Power). The moderate full hybrid

Figure 22 **Window Sticker for a Moderate Technology Full Hybrid Electric Mid-Sized SUV (40% Peak Power)**

Engine:	1.8 liter L4 VTEC-E, 121 hp
Motor:	Permanent Magnet, 80.5 hp
Battery Pack:	44 Nickel Metal-Hydride, 15.5 Ah modules
Transmission:	5-speed motorized gear shift or continuously variable
Body:	Improved Aerodynamics, Cd: 0.405, A 2.4
Tires:	Low Rolling Resistance Tires, Crr: 0.007
Test Weight:	3,958 pounds

MSRP[a]	$32,326
Performance	
• 0–60 mph Acceleration:	8.3 seconds
• Top Speed:	126 mph
• Cargo/Towing Capacity @ 60 mph, 6% grade:	3/4 ton @ 4,500 rpm
Certification Values	
• CAFE Test Fuel Economy:	39.9 mpg
• Federal and California Emission Ratings:	Tier 2 Bin 2 & SULEV

Economic, Environmental and Energy Security Performance

Real World Fuel Economy[b]**:**	32.7 mpg	**Lifetime Fuel Cost**[c]**:**	$5,526
Lifetime Gasoline Savings[d]**:**	3,986 gallons	**Lifetime Net Savings**[e]**:**	-$1,458
Lifetime Greenhouse Gas Savings:	48 tons		

NOTES:
a. Manufacturer's Suggested Retail Price, excludes tax, title and destination charges.
b. CAFE test fuel economy adjusted by 18%.
c. Based on an average gasoline cost of $1.40 per gallon (EIA 2001).
d. Based on the "real world" fuel economy value. Assumes a 15-year, 170,000-mile vehicle lifetime. Average life based on scrappage from Davis and Diegel (2002). Vehicle mileage based on 1995 National Personal Transportation Survey (NPTS) data.
e. Includes the cost of two battery packs refurbishments, one after year 8 and one after year 12.

SUV achieves a CAFE fuel economy rating of nearly 40 mpg, cutting its lifetime fuel use by nearly 4,000 gallons and its lifetime global warming emissions by 48 tons (Figure 22). As with the mild hybrid, acceleration is improved compared with the baseline vehicle. This vehicle will still be able to tow a three-quarter-ton load up a steep grade at 60 mph with the engine alone, but the engine will be operating at an elevated speed of about 4,500 rpm.

The MSRP increases by about $5,550, including standard built-in dealer and manufacturer profits. The lifetime cost savings for fuel ($5,526) for this 40-mpg hybrid SUV are about the same as the price increase, but battery replacement means this vehicle is about $1,460 more expensive to own than the baseline SUV.

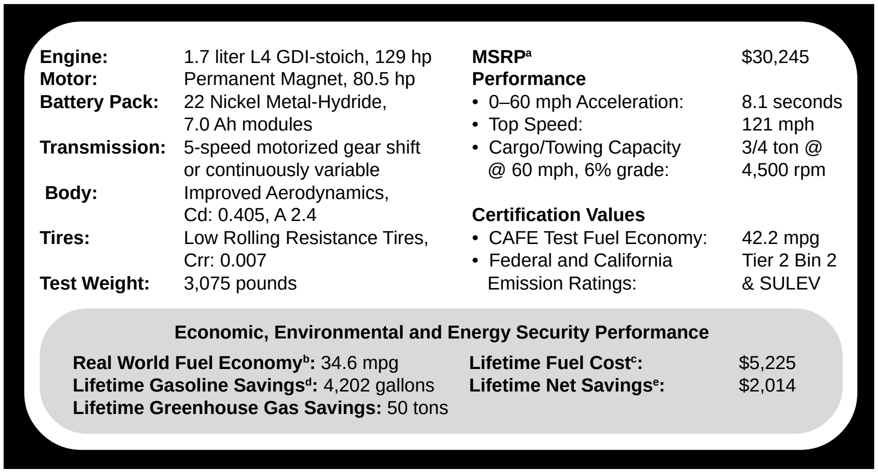
As with the moderate full hybrid compact, automakers are unlikely to make a profit on these vehicles in the early years. It will take the switch to advanced technologies to ensure that the significant environmental and energy security gains are achieved at a net benefit to the consumer, allowing the automaker to pass along the full cost of the vehicle along with standard profits. Again federal tax credits are key to developing a solid market for hybrid SUVs in the near-term, thereby paving the way for the cost-effective advanced full hybrid SUVs.

As with the mild hybrid SUV, no existing hybrids are available for comparison. Ford is expected to introduce a full hybrid version of their Escape by 2003 or 2004, and Toyota will likely introduce one in a similar timeframe.

2015 Advanced Mild Hybrid Mid-Size SUV (15% Peak Power). The results for this SUV show how cost-effective advanced hybrid technology can significantly improve vehicles in the gas-guzzling SUV market. This vehicle reaches an impressive 42.2 mpg CAFE-rated fuel economy and shaves nearly 1 second off the baseline 0-60 mph acceleration time (Figure 23).

The MSRP increases about $3,500 from that for the conventional mid-size SUV, including

Figure 23 **Window Sticker for an Advanced Technology Mild Hybrid Electric Mid-Sized SUV (15% Peak Power)**



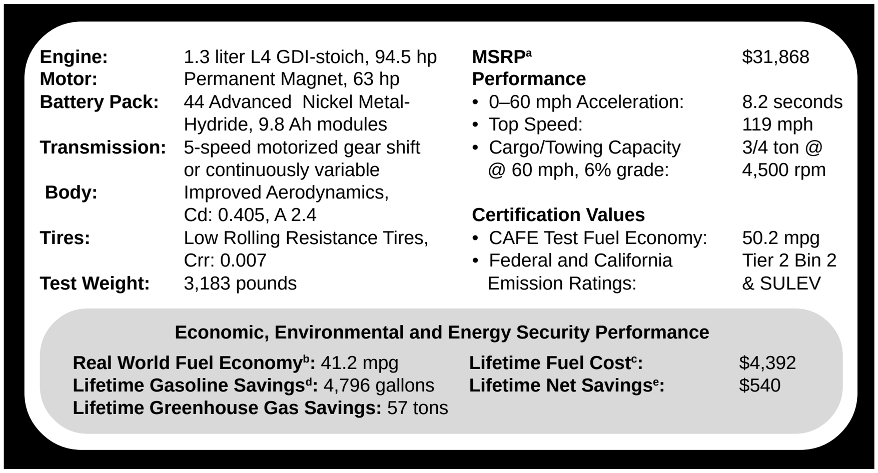
Engine:	1.7 liter L4 GDI-stoich, 129 hp
Motor:	Permanent Magnet, 80.5 hp
Battery Pack:	22 Nickel Metal-Hydride, 7.0 Ah modules
Transmission:	5-speed motorized gear shift or continuously variable
Body:	Improved Aerodynamics, Cd: 0.405, A 2.4
Tires:	Low Rolling Resistance Tires, Crr: 0.007
Test Weight:	3,075 pounds

MSRP[a]	$30,245
Performance	
• 0–60 mph Acceleration:	8.1 seconds
• Top Speed:	121 mph
• Cargo/Towing Capacity @ 60 mph, 6% grade:	3/4 ton @ 4,500 rpm
Certification Values	
• CAFE Test Fuel Economy:	42.2 mpg
• Federal and California Emission Ratings:	Tier 2 Bin 2 & SULEV

Economic, Environmental and Energy Security Performance

Real World Fuel Economy[b]**:** 34.6 mpg
Lifetime Gasoline Savings[d]**:** 4,202 gallons
Lifetime Greenhouse Gas Savings: 50 tons
Lifetime Fuel Cost[c]**:** $5,225
Lifetime Net Savings[e]**:** $2,014

Figure 24 **Window Sticker for an Advanced Technology Full Hybrid Electric Mid-Sized SUV (40% Peak Power)**



Engine:	1.3 liter L4 GDI-stoich, 94.5 hp
Motor:	Permanent Magnet, 63 hp
Battery Pack:	44 Advanced Nickel Metal-Hydride, 9.8 Ah modules
Transmission:	5-speed motorized gear shift or continuously variable
Body:	Improved Aerodynamics, Cd: 0.405, A 2.4
Tires:	Low Rolling Resistance Tires, Crr: 0.007
Test Weight:	3,183 pounds

MSRP[a]	$31,868
Performance	
• 0–60 mph Acceleration:	8.2 seconds
• Top Speed:	119 mph
• Cargo/Towing Capacity @ 60 mph, 6% grade:	3/4 ton @ 4,500 rpm
Certification Values	
• CAFE Test Fuel Economy:	50.2 mpg
• Federal and California Emission Ratings:	Tier 2 Bin 2 & SULEV

Economic, Environmental and Energy Security Performance

Real World Fuel Economy[b]**:** 41.2 mpg
Lifetime Gasoline Savings[d]**:** 4,796 gallons
Lifetime Greenhouse Gas Savings: 57 tons
Lifetime Fuel Cost[c]**:** $4,392
Lifetime Net Savings[e]**:** $540

standard built-in dealer and manufacturer profits. Adding in battery replacement means that, on net, this vehicle is about $2,000 less expensive to own than the baseline SUV. That money is free cash that can be put back into the economy.

The superior economic and fuel economy performance of the advanced mild hybrid SUV are linked to improved battery technology and to a 30% weight reduction, excluding the drivetrain. Advanced high-strength steel and some high-strength aluminum are required to meet the weight savings target. These technologies add to the cost, but the investment pays off.

2015 Advanced Full Hybrid (40% Peak Power). The case for an advanced full hybrid SUV at 40% peak power is much improved over the moderate technology hybrid SUV. Advanced technology brings the full hybrid SUV to 50.2 mpg with an increase in MSRP of $5,000 (Figure 24). This is actually $500 less expensive than the moderate technology full hybrid SUV. This vehicle also has better 0–60 mph acceleration

Figure 25 **Window Sticker for an Advanced Technology Full Hybrid Electric Mid-Sized SUV (25% Peak Power)**

Engine:	1.6 liter L4 GDI-stoich, 117 hp	**MSRP**[a]	$31,400
Motor:	Permanent Magnet, 40 hp	**Performance**	
Battery Pack:	33 Advanced Nickel Metal-Hydride, 8.1 Ah modules	• 0–60 mph Acceleration:	8.1 seconds
		• Top Speed:	121 mph
Transmission:	5-speed motorized gear shift or continuously variable	• Cargo/Towing Capacity @ 60 mph, 6% grade:	3/4 ton @ 4,000 rpm
Body:	Improved Aerodynamics, Cd: 0.405, A 2.4	**Certification Values**	
Tires:	Low Rolling Resistance Tires, Crr: 0.007	• CAFE Test Fuel Economy:	49.3 mpg
		• Federal and California Emission Ratings:	Tier 2 Bin 2 & SULEV
Test Weight:	3,133 pounds		

Economic, Environmental and Energy Security Performance

Real World Fuel Economy[b]**:** 40.4 mpg	**Lifetime Fuel Cost**[c]**:**	$4,472
Lifetime Gasoline Savings[d]**:** 4,739 gallons	**Lifetime Net Savings**[e]**:**	$1,338
Lifetime Greenhouse Gas Savings: 57 tons		

NOTES:
a. Manufacturer's Suggested Retail Price, excludes tax, title and destination charges.
b. CAFE test fuel economy adjusted by 18%.
c. Based on an average gasoline cost of $1.40 per gallon (EIA 2001).
d. Based on the "real world" fuel economy value. Assumes a 15-year, 170,000-mile vehicle lifetime. Average life based on scrappage from Davis and Diegel (2002). Vehicle mileage based on 1995 National Personal Transportation Survey (NPTS) data.
e. Includes the cost of two battery packs refurbishments, one after year 8 and one after year 12.

than the baseline vehicle, by nearly 1 second.

The economic case for this vehicle can be made with net lifetime savings of about $540. And the 57-ton global warming gas and 4,800-gallon gasoline savings over its lifetime more than justify investment in this vehicle. This vehicle can be both a profitable product for the automaker and a means of protecting our country and the environment.

2015 Advanced Full Hybrid (25% Peak Power). The economics for the 25% peak power full hybrid look even better than that for the 40% version. While achieving a fuel economy of 49.3 mpg, this advanced hybrid can produce a net lifetime savings of about $1,300. The increase in retail price is about $4,600, driven close to its higher electric power cousin by the cost of the starter/generator system (Figure 25).

Case Study Lessons. Two clear lessons emerge from the compact car and the mid-size SUV case studies. The first simply reinforces the lesson learned in the fleetwide analysis: the route to cost-effective hybrid designs relies on automakers choosing to put the best available technology to work. More moderate technology hybrid compact cars and SUVs should be viewed as steppingstones to reaching cost-effective advanced technology hybrid designs, not as final ends. In other words, there is a lot more to come in the world of hybrids than today's Prius and Civic Hybrid and the hybrid SUVs entering the market soon.

The second lesson is that even the most challenging vehicle to hybridize, the compact car, can pass the break-even point and become a cost-effective part of reaching a 50 to 60 mpg fleet-wide average. For SUVs, it is even easier to reach a cost-effective performance level while still providing some towing capability, although even a hybrid SUV will still use more gasoline than a hybrid compact car. As the data in Appendix B shows, the results for the additional vehicle classes (family sedans, pickups and minivans) all fall into similar patterns of cost-effectiveness and overall performance improvements.

Chapter 4
REALIZING THE PROMISE

This report highlights the significant potential hybrid vehicles offer in addressing climate change, air quality, and oil dependence. For this promise to be realized, government at all levels must provide both vision and support. Automakers will have to step up to the plate and set their talented design, engineering, production, marketing, and sales force to the task of putting the cleanest and most efficient vehicles into the hands of con-sumers. Consumers have the easy part of the job, purchasing passenger cars and trucks that will, as Ford Motors said of their upcoming Escape Hybrid SUV, "offer the same functionality and performance" as the conventional version available in the showroom today (Ford 2002).

A Vision for the Future

By the end of the next decade, most new passenger cars and trucks in the United States could be full hybrid electric vehicles. This fleet of new passenger cars and trucks could get close to 60 mpg, saving consumers more than $5,000 on gasoline over the lifetime of their vehicles and cutting their contribution to global warming and oil dependence by nearly 60%.

Making this vision a reality means taking a new road as automakers tap into technologies they are developing today. The route would start with the use of cost-effective conventional technology over the next ten years, while hybrids enter the market in larger and larger numbers. By the middle of the next decade, hybrids can take over the market at the point where the energy and environmental gains from improved conventional vehicles start to lag and before hydrogen fuel cells are ready to take us into a gasoline-free future.

Government and the Vision

There are many ways to build a hybrid, as previous chapters outline, but not all the hybrids offered by automakers will provide the benefits vital for reducing oil dependence, providing cleaner air, and slowing global warming. This means that as the government considers how passenger vehicles might be transformed to limit their contribution to these problems, its vision cannot be as simple as "putting hybrids on the road." The vision must capture the urgency of dealing with these problems and provide realistic goals and timelines. It must also incorporate a means for differentiating among hybrids according to how much they contribute to the solution of these problems. Finally, the vision must be backed by the support necessary to build a successful hybrid market within this decade.

This vision and leadership will help consumers understand which choices will enable them to do their part in addressing these problems. And government leadership can provide automakers both direction for their technology development efforts and regulatory certainty.

Providing the Support

Without the necessary financial, regulatory, and other policy support, a vision of the hybrid future is nothing more than window-dressing. Some state governments, such as California, have taken a lead in developing measures that recognize the benefits of hybrids. However a broader and more comprehensive set of state, national, and local tools is needed to support a strong market introduction for hybrids. Those tools will need to include regulations, incentives, and education programs. But the first task is to develop performance metrics, since without them policies that support hybrid technology run the risk of throwing good money and resources after bad technology.

Performance Metrics. The most important sets of performance metrics are those that gauge how effectively the hybrid vehicle addresses energy security and environmental problems and the degree to which it supports the future market success of hydrogen fuel cell vehicles.

A Pair of Energy Security and Environmental Metrics. Metrics to identify a hybrid's contribution to energy security and the environment can be based on the vehicle's fuel economy and emissions performance.

Since conventional technology can already meet today's strictest non-zero emission regulations, the federal Tier 2-Bin 2 standard or California's SULEV standard,[1] the levels set by those standards should be a minimum tailpipe emissions performance requirement for all hybrids that receive support starting in 2004. This will ensure that hybrids with emissions performance worse than the average new gasoline car or truck do not benefit from government incentives. If vehicles emerge that could be certified to tighter emissions standards, additional levels of support might be appropriate.

A hybrid's contribution to energy security, reduced global warming, and improved air quality can be determined directly by measuring its fuel economy. This absolute scale could be based on improvement over the fuel economy of today's average vehicle. If financial incentives were based on fuel economy improvement, the metric would act as a market feedback mechanism, providing consumers with larger incentives when they buy vehicles of greater overall benefit to society.

Measuring Market Support for Hydrogen Fuel Cell Vehicles. Hybrids will support the future market success of hydrogen fuel cell vehicles by driving down the costs of the components they share, as well as by familiarizing consumers and local officials with electric drive technology.

The familiarization function is fulfilled principally by hybrids that have some capacity to drive on electric power alone. The cost-reduction function depends on both the specific electric technologies used and the size of the components. Thus a metric that gauges hybrids' contribution to future fuel cell vehicle markets could include both minimum technology criteria and credit for the size of the electric components. The minimum technology criteria could be as follows:

- The vehicle incorporates sufficient technology to qualify as a hybrid. This means it has idle-off capability, sufficient regenerative braking capability, and a downsized engine. It must also operate at greater than 60 volts, with at least 10% peak power furnished by the electric motor/battery system.
- The vehicle incorporates motor, controller, and battery technology similar to that used in current and future hydrogen fuel cell vehicle drive systems.
- Motor, controller, and battery components carry a significant warranty to ensure that the image of electric drive is not compromised by putting lemons on the road.

A vehicle that meets these minimum criteria could receive additional credit based on the power of the electric motor and battery system.

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[1] The "Bin 2" standard appears under the upcoming federal Tier 2 tailpipe emission regulations.

Types of Government Support. Once performance metrics have been created, they can be used to establish comprehensive government policies to support hybrids. Typically, such policies take four forms:

- Regulations
- Financial and other incentives
- Research, development, and demonstration (RD&D)
- Education

Regulations could take the form of higher fuel economy standards. In the near term, that would encourage automakers to put conventional technology that enhances fuel economy on the road. Such technologies are vital for hybrid design, as discussed in chapters 2 and 3. It will also encourage automakers to plan to make hybrids a significant part of their vehicle sales mix further down the road.

Other regulations might emulate the California zero emissions vehicle program, which supports technology advancement on clean air grounds. And hybrids might be added to federal, state, and local fleet purchase requirements.

Incentives could include tax deductions similar to the federal clean fuel deductions that currently apply to hybrids,[2] or more effective measures such as tax credits based on the performance metrics outlined above. Other incentives, such as preferential parking or access to high-occupancy vehicle (HOV) lanes may be proposed, but these will need to be closely evaluated to address their environmental impacts.[3]

Most hybrid technologies have passed the point where government can play a significant role in research, development, or demonstration: the technologies are already in the hands of automakers. The key now is building up sales volumes to bring down costs and take advantage of economies of scale. Still, government support might be of value for break-through battery and other energy storage technologies, but these will not be make-or-break technologies for either hybrid or hydrogen fuel cell vehicles.

The development of codes and standards has mostly been taken care of through past efforts with battery electric vehicles, though understanding and incorporating these codes and standards at the local level will still be vital.

Finally, government has been playing a role in educating the public about hybrids. These efforts could be ramped up to help consumers differentiate among hybrids and make informed purchases, as well as to highlight their availability.

Putting Technology to Work

Automakers have the most important role in ensuring the success of hybrids in the marketplace. As the vehicle manufacturers, they can put the best possible technology in the showrooms, providing "no compromises" vehicles that build on existing hybrids to give consumers more choice. This means pulling fuel economy technology off the shelf to ensure superior performance, not just adding a motor and battery system to garner a hybrid label.

Automakers are also the primary consumer interface, which gives them the opportunity and the responsibility to educate the public about the hybrid technology in their showrooms and the environmental performance these vehicles offer.

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[2] The IRS has determined that hybrid vehicles qualify for a "clean-fuel" vehicle tax deduction. This tax deduction is retroactive and will be $2,000 through 2003, then $500 less each year thereafter until it is eliminated in 2007.

[3] For example, as hybrids succeed in the marketplace, HOV lane access would have to phase out, otherwise HOV lanes would become clogged with hybrids, discouraging people from ride-sharing (which cuts fuel use by even more than hybrids).

This requires developing a sales and maintenance staff who are well informed and trained on hybrid technology.

A Cooler, Cleaner and More Secure Future

The technology exists to build a future with a significantly lower dependence on oil and a cleaner, cooler atmosphere. With sufficient political will and automaker participation, this future can arrive in time to address these significant and growing problems.

Hybrids can play an important role in realizing this future, filling the gap between immediate improvements through conventional technology and the long-term promise of hydrogen fuel cells and alternative fuels. Building on a 40-mpg fleet that relies on existing conventional technology, hybrids can help drive passenger vehicle oil consumption and global warming emissions from cars and trucks below 1990 levels.

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Appendix A

MODELING METHODOLOGY AND ASSUMPTIONS

Two sets of analysis were performed for this report: a stock analysis for the scenarios in chapter 1 and a vehicle-based economic and savings analysis for the results in chapter 3.

Stock Model

To evaluate the oil savings for the conventional vehicle and fuel cell vehicle scenarios in chapter 1, we developed and calibrated a stock model covering the period 2000 to 2030. This model uses the annual sales and fuel economy of new vehicles, along with other key input data, to predict annual fleet gasoline and oil use.

Our baseline model is calibrated against the *Annual Energy Outlook 2001* report by the Energy Information Administration (EIA 2000). Annual fleet energy use is kept to within ± 2.5% of the AEO results, using their new vehicle fuel economy values as inputs. However, we assume no increase in fleet fuel economy based on the past 15 years of declining average fuel economy, whereas EIA assumes future fuel economy increases resulting from economic forces. Additional details on this stock model are available in the appendices of Friedman (2001).

Vehicle Economic, Fuel Use and Emission Model

The vehicle economic model used the MSRP values from Lipman and Delucchi (2003) and fuel economy values from Friedman and An (2003) as the fundamental inputs for the cost and performance of the five vehicle classes considered in this report: compact cars, family sedans, full size pickups, minivans, and mid-size SUVs. The reader is referred to those reports for the detailed assumptions and modeling methodologies that result in the fuel economy and MSRP values used in this report. The economic, fuel use, and emission modeling in this report was performed using the following data and assumptions:

Vehicle-miles traveled as a function of vehicle age. The 1995 National Personal Transportation Survey provides the most recent breakdown of vehicle mileage versus age. The vehicle mileage used in our model is a simplified version of that data, using 15,600 miles as the distance driven in the first year, declining at a rate of 4.5% per year as used in the recent National Research Council CAFE report (NRC 2002).

Car and light-truck lifetime. Data in Davis and Diegel (2002) suggests that the median life of a 1990 model-year car is 16.9 years, while the median life of a 1990 model-year light truck is reported to be 15.5 years. Combined data suggest a median lifetime of over 16 years for 1990 model cars and light trucks. For simplicity we have assumed a 15-year vehicle life.

Real-world vs. CAFE-certified fuel economy. Values for the relative difference between real world and CAFE fuel economy for conventional vehicles in EIA 2000 vary between 17% and 19.6%, depending on the year. We assume that all CAFE fuel economy results are discounted by 18% to account for the difference between test and real world driving conditions. This may underestimate the fuel economy of hybrids on the road, as they appear to be less sensitive to driving conditions compared with conventional vehicles (Plotkin et al. 2001).

Annual average gasoline cost. Average gasoline costs are based on EIA 2001 and have been converted to 2000 dollars. The average value during the period from 2000 to 2020 in EIA 2001 is $1.40, which is used here. Given recent trends, these costs are probably low and can therefore be considered conservative.

Vehicle sales mix. Fleetwide calculations are based on the sales mix from 2000, based on Ward's 2000. The sales mix was as follows:

Compact Cars:	25%
Large and Mid-Size Cars:	29%
Pickup Trucks:	17%
Minivans:	9%
SUVs:	20%

Recent trends have shown increased light truck sales now surpassing car sales. If this trend continues, the fleetwide results in this report will represent overestimates of the potential fleet average fuel economy performance.

Battery module and pack performance. Each battery pack in this study includes several battery modules. The moderate technology battery modules included in this study have power densities, at 50% state of charge, ranging from 700 to 730 W/kg, depending on the case. The advanced technology battery modules included in this study have power densities, at 50% state of charge, ranging from 800 to 820 kW/kg. Battery manufacturers already claim to have achieved performance superior to the advanced battery technology case used here (Menjak et al. 2000).

The battery packs include an additional 25% weight to account for the battery box, cables, monitoring and cooling systems. Including this extra mass, the full battery packs for the moderate cases have a specific energy of 37 Wh/kg, while those in the advanced cases are 33 Wh/kg.

Battery pack replacement. Existing battery technology may not last the life of the hybrid vehicle. To account for the potential costs of battery replacement we include two battery refurbishments over a vehicle's life. The first takes place after year 8 and the second after year 12.

The initial replacement at 8 years was chosen because existing hybrid battery warranties cover the first 8 years of vehicle life. Each battery refurbishment is assumed to cost one-quarter of the initial retail price of the battery pack at the year of replacement. Typically, battery pack failure is not packwide, but instead will require the replacement of a few modules. The second refurbishment is assumed to be required four years later to account for the failure of original modules that were not replaced at year 8. Table A-1 provides

Table A-1 **Battery Pack Initial Retail Price**

	Compact Car: Cavalier	Family Sedan: Taurus	Pickup: Silverado 1500	Minivan: Caravan	Mid-size SUV: Explorer
Moderate Technology Mild Hybrid (15% Peak Power)	$1,148	$1,356	$2,384	$1,468	$1,879
Moderate Technology Full Hybrid (40% Peak Power)	$3,027	$3,515	$6,278	$3,767	$4,953
AdvancedTechnology Mild Hybrid (15% Peak Power)	$922	$1,001	$1,651	$1,016	$1,332
Advanced Technology Full Hybrid (25% Peak Power)	$1,536	$1,666	$2,722	$1,707	$2,243
Advanced Technology Full Hybrid (40% Peak Power)	$2,373	$2,747	$4,360	$2,740	$3,604

the retail price of each of the battery packs used in this study.

Discount rate. All future costs and savings are discounted at a real rate of 5%. This corresponds to a new car loan of 8% and 3% inflation. All costs are presented in year 2000 US dollars.

Emission rates. The emission rates used for global warming gases, toxic emissions, and smog precursor emissions associated with gasoline production and delivery, so-called upstream emissions, are based on the latest available version of a model developed by Argonne National Laboratory, GREET 1.5a (Wang 1999). The model uses average national emission rates and efficiencies to estimate emissions of key pollutants throughout the fuel cycle for various types of gasoline and alternative fuels. This report assumes that federal reformulated gasoline is used nationally, since environmental rules are forcing more conventional gasoline blends out of the market.

GREET accounts for several global warming gases—including methane, nitrous oxide, and carbon dioxide—expressing the results as CO_2-equivalent emissions, based on their relative radiative forcing. The model also accounts for key criteria emissions associated with air pollution, including the volatile organic compounds and nitrogen oxides (smog precursors), carbon monoxide, sulfur oxides, and particulate matter.

In a separate analytical effort, Argonne National Laboratory developed preliminary estimates of toxic pollutant emissions associated with gasoline production (Winebrake, He and Wang 2000). The study covers four major toxics associated with motor vehicles: benzene, formaldehyde, acetaldehyde, and butadiene. All toxics are expressed as benzene-equivalent emissions based on their relative cancer unit risk factors (EPA 2000; EPA 1993). The relative risks are: formaldehyde, 1.6; acetaldehyde, 0.3; and butadiene, 34.

Winebrake, He and Wang (2000) do not estimate emissions of all potential air toxics. In particular, there is growing public health evidence linking emissions of diesel particulate matter (PM) to cancer. Moreover, diesel PM appears to be a more potent and prevalent toxic than the other four toxics traditionally associated with motor vehicle use. In the Los Angeles region, for example, diesel PM accounts for an estimated 71% of the cancer risk from outdoor air (SCAQMD 1999).

To include emissions of diesel PM, we ran GREET 1.5a to isolate diesel-powered equipment. We then assigned the cancer unit risk factor for diesel particulate matter from its recent listing as a toxic air contaminant (CARB 1998). The cancer unit risk factor for diesel PM is 36 times higher than that for benzene.

Based on the aforementioned calculations and modeling, we developed average per-gallon emissions associated with upstream activities shown in Table A-2.

Table A-2 **Emission Rates**
(grams per gallon of fuel delivered)[a]

Greenhouse Gases[b]	
Upstream GHG	2,365
Tailpipe CO_2	8,500
Total (CO_2-equivalent)	10,865
Upstream Criteria	
VOC	1.93
CO	3.4
NOx	4.43
PM_{10}	0.39
SOx	2.38
VOC+NO_x	6.36
Upstream Toxic	
Formaldehyde	0.023
Acetaldehyde	0.005
Butadiene	0.002
Benzene	0.029
Diesel PM	0.078
Total (Benzene-equivalent)[c]	2.942

NOTES:

a. UCS estimate based on full fuel cycle model, GREET 1.5a, for federal reformulated gasoline (Wang 1999; Winebrake, He, and Wang 2000).

b. All greenhouse gases are expressed as CO_2-equivalent emissions based on their relative radiative forcing.

c. All toxics are expressed as benzene-equivalent emissions based on their relative cancer unit risk factors (EPA 2000; EPA 1993; CARB 1998).

Appendix B

DETAILED RESULTS FOR FIVE CAR AND TRUCK CLASSES

Chapter 3 presents the summary fleetwide results based on five car and truck classes. The individual results for each of these classes, using each combination of technology level, and conventional and hybrid drivetrain, are presented below.

Table B-1 **Fuel Economy and Lifetime Environmental Impacts of Model Year 2000 Conventional Vehicles**

	Compact Car: Cavailier	Family Sedan: Taurus	Pickup: Silverado 1500	Minivan: Caravan	Mid-Size SUV: Explorer	Passenger Fleet Average Vehicle
CAFE Rated Fuel Economy (mpg)	30.8	26.2	19.6	22.3	19.9	23.8
Real World Fuel Economy[a] (mpg)	25.3	21.5	16.1	18.3	16.3	19.5
MSRP[b]	$14,295	$19,344	$24,350	$23,264	$26,778	$20,772
Lifetime Fuel Cost[c]	$7,151	$8,411	$11,240	$9,873	$11,107	$9,248
Lifetime Gasoline Use[d] (gallons)	5,108	6,008	8,029	7,052	7,933	6,606
Lifetime Global Warming Gas Emissions (tons CO_2-equivalent)	61	72	96	84	95	79
Lifetime Upstream Smog-Forming Emissions (lb)	72	84	113	99	111	93
Lifetime Upstream Toxic Emissions (lb)	33	39	52	46	51	43

NOTES:

a. CAFE test fuel economy adjusted by 18%.

b. Manufacturer's Suggested Retail Price, excludes tax, title and destination charges.

c. Based on an average gasoline cost of $1.40 per gallon (EIA 2001).

d. Assumes a 15-year, 170,000-mile vehicle lifetime. Average life based on scrappage rates from Davis and Diegel (2002).
Vehicle mileage based on 1995 National Personal Transportation Survey (NPTS) data.

Table B-2 **Fuel Economy and Lifetime Savings from Moderate Technology Conventional Gasoline Vehicles**

	Compact Car: Cavailier	Family Sedan: Taurus	Pickup: Silverado 1500	Minivan: Caravan	Mid-Size SUV: Explorer	Passenger Fleet Average Vehicle
CAFE Rated Fuel Economy (mpg)	39.2	36.2	26.5	31.7	28.8	32.7
Real World Fuel Economy[a] (mpg)	32.1	29.7	21.7	26.0	23.6	26.8
Fuel Economy Improvements vs. Basline	27%	38%	35%	42%	45%	37%
Retail Cost of Fuel Economy Improvement[b]	$444	$536	$765	$750	$735	$611
Lifetime Fuel Cost[c] Savings	$1,527	$2,321	$2,920	$2,918	$3,451	$2,504
Lifetime Net Savings[d]	$1,083	$1,785	$2,156	$2,168	$2,716	$1,893
Lifetime Gasoline Savings[e] (gallons)	1,091	1,658	2,086	2,084	2,465	1,789
Lifetime Savings in Global Warming Gases (tons CO_2-equivalent)	13	20	25	25	30	21
Avoided Upstream Smog-Forming Emissions (lb)	15	23	29	29	35	25
Avoided Upstream Toxic Emissions (lb)	7	11	14	14	16	12

NOTES:

a. CAFE test fuel economy adjusted by 18% per fuel economy shortfall found in EIA 2001.

b. Difference between MSRP of hybrid and today's baseline conventional vehicle.

c. Based on an average gasoline cost of $1.40 per gallon (EIA 2001).

d. Includes the cost of two battery pack refurbishments, one after year 8 and one after year 12.

e. Assumes a 15-year, 170,000-mile vehicle lifetime. Average life based on scrappage rates from Davis and Diegel (2002).
Vehicle mileage based on 1995 National Personal Transportation Survey (NPTS) data.

Table B-3 **Fuel Economy and Lifetime Savings from Advanced Technology Conventional Gasoline Vehicles (with Idle-stop)**

	Compact Car: Cavailier	**Family Sedan: Taurus**	**Pickup: Silverado 1500**	**Minivan: Caravan**	**Mid-Size SUV: Explorer**	**Passenger Fleet Average Vehicle**
CAFE Rated Fuel Economy (mpg)	48.4	45.8	33.7	41.3	34.6	40.8
Real World Fuel Economy[a] (mpg)	39.7	37.5	27.7	33.9	28.4	33.5
Fuel Economy Improvements vs. Basline	57%	75%	72%	85%	74%	71%
Retail Cost of Fuel Economy Improvement[b]	$1,125	$1,292	$2,291	$2,134	$2,458	$1,729
Lifetime Fuel Cost[c] Savings	$2,597	$3,593	$4,706	$4,538	$4,735	$3,847
Lifetime Net Savings[d]	$1,472	$2,301	$2,415	$2,404	$2,277	$2,118
Lifetime Gasoline Savings[e] (gallons)	1,855	2,567	3,361	3,241	3,382	2,748
Lifetime Savings in Global Warming Gases (tons CO_2-equivalent)	22	31	40	39	41	33
Avoided Upstream Smog-Forming Emissions (lb)	26	36	47	45	47	39
Avoided Upstream Toxic Emissions (lb)	12	17	22	21	22	18

NOTES:

a. CAFE test fuel economy adjusted by 18% per fuel economy shortfall found in EIA 2001.

b. Difference between MSRP of hybrid and today's baseline conventional vehicle.

c. Based on an average gasoline cost of $1.40 per gallon (EIA 2001).

d. Includes the cost of two battery pack refurbishments, one after year 8 and one after year 12.

e. Assumes a 15-year, 170,000-mile vehicle lifetime. Average life based on scrappage rates from Davis and Diegel (2002). Vehicle mileage based on 1995 National Personal Transportation Survey (NPTS) data.

Table B-4 **Fuel Economy and Lifetime Savings from Moderate Technology Mild Hybrid Electric Vehicles (15% Peak Power)**

	Compact Car: Cavailier	Family Sedan: Taurus	Pickup: Silverado 1500	Minivan: Caravan	Mid-Size SUV: Explorer	Passenger Fleet Average Vehicle
CAFE Rated Fuel Economy (mpg)	48.6	44.7	31.0	38.4	33.4	39.3
Real World Fuel Economy[a] (mpg)	39.9	36.7	25.4	31.5	27.4	32.2
Fuel Economy Improvements vs. Basline	58%	71%	58%	72%	68%	65%
Retail Cost of Fuel Economy Improvement[b]	$2,607	$2,682	$3,677	$3,071	$3,363	$3,004
Lifetime Fuel Cost[c] Savings	$2,615	$3,479	$4,128	$4,131	$4,506	$3,637
Lifetime Net Savings[d]	-$337	$389	-$267	$619	$577	$154
Lifetime Gasoline Savings[e] (gallons)	1,868	2,485	2,948	2,951	3,218	2,598
Lifetime Savings in Global Warming Gases (tons CO_2-equivalent)	22	30	35	35	39	31
Avoided Upstream Smog-Forming Emissions (lb)	26	35	41	41	45	36
Avoided Upstream Toxic Emissions (lb)	12	16	19	19	21	17

NOTES:

a. CAFE test fuel economy adjusted by 18% per fuel economy shortfall found in EIA 2001.

b. Difference between MSRP of hybrid and today's baseline conventional vehicle.

c. Based on an average gasoline cost of $1.40 per gallon (EIA 2001).

d. Includes the cost of two battery pack refurbishments, one after year 8 and one after year 12.

e. Assumes a 15-year, 170,000-mile vehicle lifetime. Average life based on scrappage rates from Davis and Diegel (2002). Vehicle mileage based on 1995 National Personal Transportation Survey (NPTS) data.

Table B-5 **Fuel Economy and Lifetime Savings from Moderate Technology Full Hybrid Electric Vehicles (40% Peak Power)**

	Compact Car: Cavailier	**Family Sedan: Taurus**	**Pickup: Silverado 1500**	**Minivan: Caravan**	**Mid-Size SUV: Explorer**	**Passenger Fleet Average Vehicle**
CAFE Rated Fuel Economy (mpg)	57.6	55.9	38.7	47.0	39.9	48.0
Real World Fuel Economy[a] (mpg)	47.2	45.8	31.7	38.5	32.7	39.3
Fuel Economy Improvements vs. Basline	87%	113%	97%	110%	101%	101%
Retail Cost of Fuel Economy Improvement[b]	$4,107	$4,258	$6,492	$4,686	$5,548	$4,897
Lifetime Fuel Cost[c] Savings	$3,324	$4,467	$5,543	$5,182	$5,581	$4,651
Lifetime Net Savings[d]	-$1,694	-$849	-$2,838	-$638	-$1,458	-$1,501
Lifetime Gasoline Savings[e] (gallons)	2,374	3,191	3,959	3,701	3,986	3,322
Lifetime Savings in Global Warming Gases (tons CO_2-equivalent)	28	38	47	44	48	40
Avoided Upstream Smog-Forming Emissions (lb)	33	45	56	52	56	47
Avoided Upstream Toxic Emissions (lb)	15	21	26	24	26	22

NOTES:

a. CAFE test fuel economy adjusted by 18% per fuel economy shortfall found in EIA 2001.

b. Difference between MSRP of hybrid and today's baseline conventional vehicle.

c. Based on an average gasoline cost of $1.40 per gallon (EIA 2001).

d. Includes the cost of two battery pack refurbishments, one after year 8 and one after year 12.

e. Assumes a 15-year, 170,000-mile vehicle lifetime. Average life based on scrappage rates from Davis and Diegel (2002). Vehicle mileage based on 1995 National Personal Transportation Survey (NPTS) data.

Table B-6 **Fuel Economy and Lifetime Savings from Advanced Technology Mild Hybrid Electric Vehicles (15% Peak Power)**

	Compact Car: Cavailier	Family Sedan: Taurus	Pickup: Silverado 1500	Minivan: Caravan	Mid-Size SUV: Explorer	Passenger Fleet Average Vehicle
CAFE Rated Fuel Economy (mpg)	58.7	54.4	40.2	49.1	42.2	49.0
Real World Fuel Economy[a] (mpg)	48.1	44.6	33.0	40.3	34.6	40.2
Fuel Economy Improvements vs. Basline	90%	108%	105%	120%	113%	106%
Retail Cost of Fuel Economy Improvement[b]	$2,469	$2,532	$3,342	$2,719	$3,467	$2,858
Lifetime Fuel Cost[c] Savings	$3,395	$4,359	$5,755	$5,383	$5,882	$4,752
Lifetime Net Savings[d]	$649	$1,525	$1,917	$2,358	$2,014	$1,546
Lifetime Gasoline Savings[e] (gallons)	2,425	3,113	4,111	3,845	4,202	3,394
Lifetime Savings in Global Warming Gases (tons CO_2-equivalent)	29	37	49	46	50	41
Avoided Upstream Smog-Forming Emissions (lb)	34	44	58	54	59	48
Avoided Upstream Toxic Emissions (lb)	16	20	27	25	27	22

NOTES:

a. CAFE test fuel economy adjusted by 18% per fuel economy shortfall found in EIA 2001.

b. Difference between MSRP of hybrid and today's baseline conventional vehicle.

c. Based on an average gasoline cost of $1.40 per gallon (EIA 2001).

d. Includes the cost of two battery pack refurbishments, one after year 8 and one after year 12.

e. Assumes a 15-year, 170,000-mile vehicle lifetime. Average life based on scrappage rates from Davis and Diegel (2002).
Vehicle mileage based on 1995 National Personal Transportation Survey (NPTS) data.

Table B-7 **Fuel Economy and Lifetime Savings from Advanced Technology Full Hybrid Electric Vehicles (25% Peak Power)**

	Compact Car: Cavailier	Family Sedan: Taurus	Pickup: Silverado 1500	Minivan: Caravan	Mid-Size SUV: Explorer	Passenger Fleet Average Vehicle
CAFE Rated Fuel Economy (mpg)	67.3	66.3	48.8	57.6	49.3	58.2
Real World Fuel Economy[a] (mpg)	55.2	54.4	40.0	47.2	40.4	47.7
Fuel Economy Improvements vs. Basline	118%	153%	149%	158%	148%	144%
Retail Cost of Fuel Economy Improvement[b]	$3,282	$3,705	$4,729	$3,846	$4,622	$3,969
Lifetime Fuel Cost[c] Savings	$3,875	$5,086	$6,722	$6,045	$6,635	$5,458
Lifetime Net Savings[d]	$131	$879	$1,174	$1,685	$1,338	$907
Lifetime Gasoline Savings[e] (gallons)	2,768	3,633	4,801	4,318	4,739	3,898
Lifetime Savings in Global Warming Gases (tons CO_2-equivalent)	33	44	58	52	57	47
Avoided Upstream Smog-Forming Emissions (lb)	39	51	67	61	66	55
Avoided Upstream Toxic Emissions (lb)	18	24	31	28	31	25

NOTES:

a. CAFE test fuel economy adjusted by 18% per fuel economy shortfall found in EIA 2001.

b. Difference between MSRP of hybrid and today's baseline conventional vehicle.

c. Based on an average gasoline cost of $1.40 per gallon (EIA 2001).

d. Includes the cost of two battery pack refurbishments, one after year 8 and one after year 12.

e. Assumes a 15-year, 170,000-mile vehicle lifetime. Average life based on scrappage rates from Davis and Diegel (2002). Vehicle mileage based on 1995 National Personal Transportation Survey (NPTS) data.

Table B-8 **Fuel Economy and Lifetime Savings from Advanced Technology Full Hybrid Electric Vehicles (40% Peak Power)**

	Compact Car: Cavailier	Family Sedan: Taurus	Pickup: Silverado 1500	Minivan: Caravan	Mid-Size SUV: Explorer	Passenger Fleet Average Vehicle
CAFE Rated Fuel Economy (mpg)	69.6	68.1	49.9	59.0	50.2	59.6
Real World Fuel Economy[a] (mpg)	57.1	55.8	40.9	48.4	41.2	48.9
Fuel Economy Improvements vs. Basline	126%	160%	154%	164%	153%	150%
Retail Cost of Fuel Economy Improvement[b]	$3,613	$4,123	$5,177	$4,290	$5,090	$4,383
Lifetime Fuel Cost[c] Savings	$3,984	$5,174	$6,822	$6,136	$6,715	$5,551
Lifetime Net Savings[d]	-$343	$224	$332	$1,021	$540	$236
Lifetime Gasoline Savings[e] (gallons)	2,845	3,696	4,873	4,383	4,796	3,965
Lifetime Savings in Global Warming Gases (tons CO_2-equivalent)	34	44	58	53	57	47
Avoided Upstream Smog-Forming Emissions (lb)	40	52	68	61	67	56
Avoided Upstream Toxic Emissions (lb)	18	24	32	28	31	26

NOTES:

a. CAFE test fuel economy adjusted by 18% per fuel economy shortfall found in EIA 2001.

b. Difference between MSRP of hybrid and today's baseline conventional vehicle.

c. Based on an average gasoline cost of $1.40 per gallon (EIA 2001).

d. Includes the cost of two battery pack refurbishments, one after year 8 and one after year 12.

e. Assumes a 15-year, 170,000-mile vehicle lifetime. Average life based on scrappage rates from Davis and Diegel (2002). Vehicle mileage based on 1995 National Personal Transportation Survey (NPTS) data.

A New Road

The Technology and Potential of Hybrid Vehicles

The world started down a new road in 1997 with the sale of the first modern hybrid electric car. In the coming years, well-designed cars and trucks that rely on hybrid technology can play a significant role in US strategies to address climate change, air pollution, and oil dependence.

This report provides a comprehensive assessment of the technology, fuel economy, and costs associated with a fleet of hybrid passenger cars and trucks. Integrating hybrid and advanced conventional technology, these vehicles can more than double current fuel economy, while meeting or beating today's most stringent non-zero tailpipe emission standards. The tools provided in this report will help consumers and policymakers sort out the differences among the hybrid cars and trucks offered in the coming years.

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