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ACKNOWLEDGEMENT

It is indeed a matter of great pleasure and privilege to be able to present this project on the HYBRID VEHICLES the latest technological advancement in automobile sector

The completion of seminar work is a milestone in a student' s life and its execution is inevitable in the hands of my guides. I am highly indebted for our FACULTY. From our college for their invaluable guidance and appreciate them for being an inspiration for us to carry out the successful completion of submitted in partial fulfilment of the requirements of the degree of bachelor of engineering in mechanical engineering in the privileged college of "Marwar Engineering College & Research center".

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INTRODUCTION

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.

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. 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.

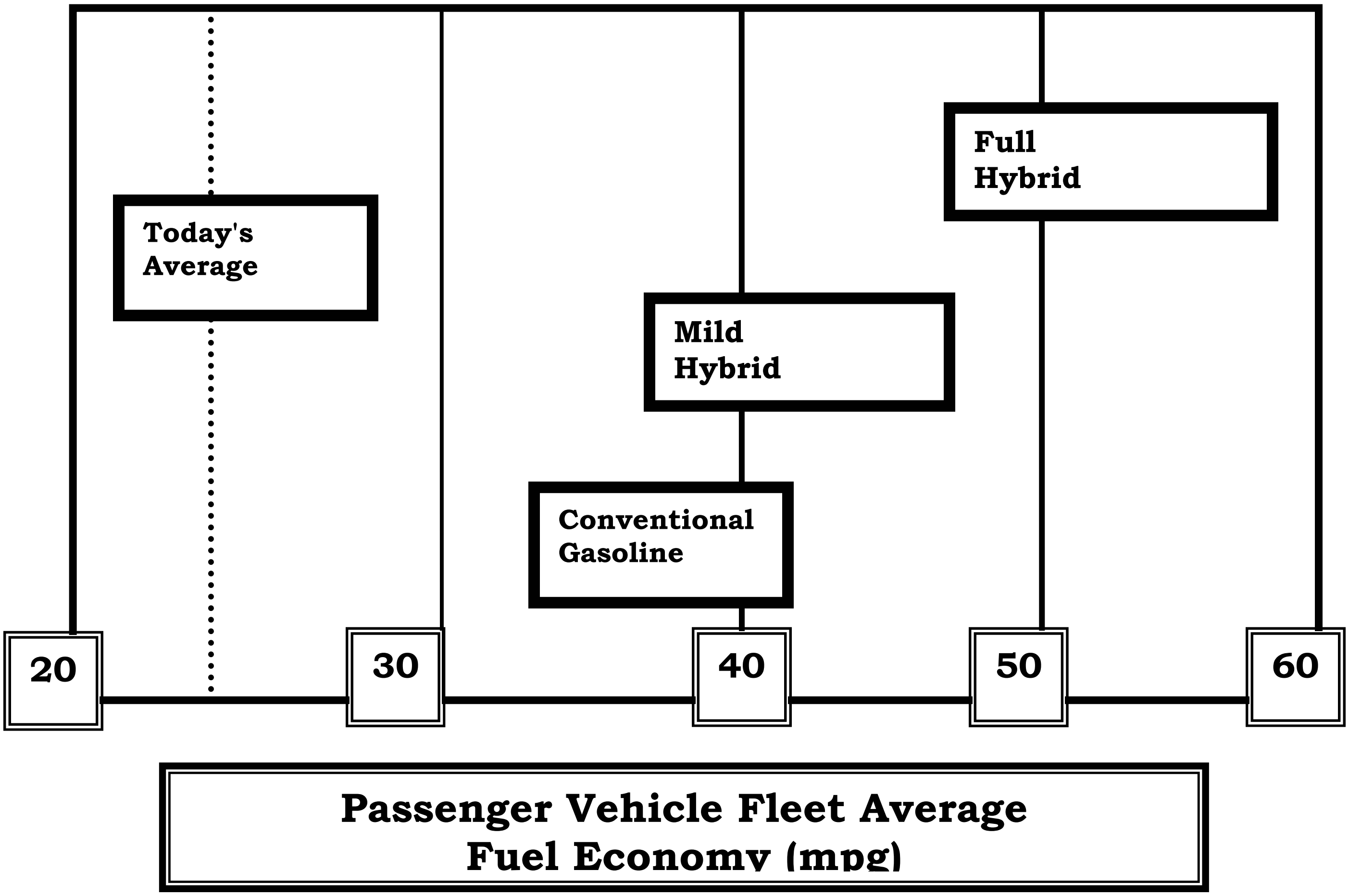
The Technology's Potential

The Honda Civic Hybrid and Toyota Prius are good examples of the current potential of hybrids but they're just 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 emissions2 (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 mis 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.

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					√



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

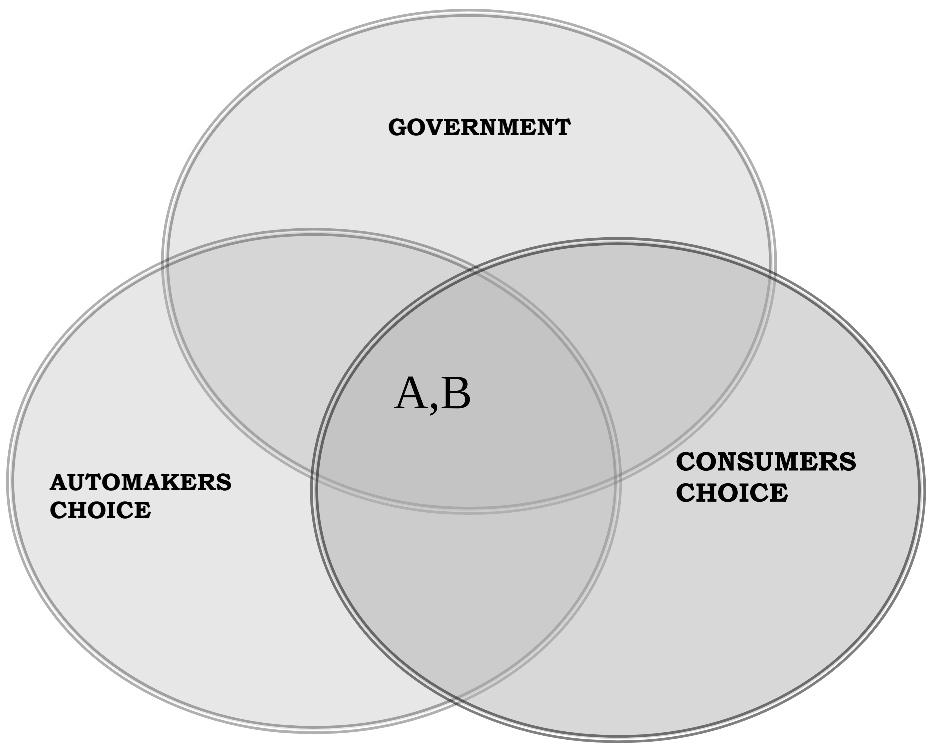
This study emphasizes the role hybrids must play in our efforts to limit the contribution our cars and trucks make to US oil dependence, global warming, and local air pollution. In the short term, conventional technologies could quickly raise the average fuel economy of the passenger fleet to 40 mpg. 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, lowperformance 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 massmarket 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.

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. 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. 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.

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

	2000	2020
Gasoline		
Annual Fuel Use (billion gallons)	121	169
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

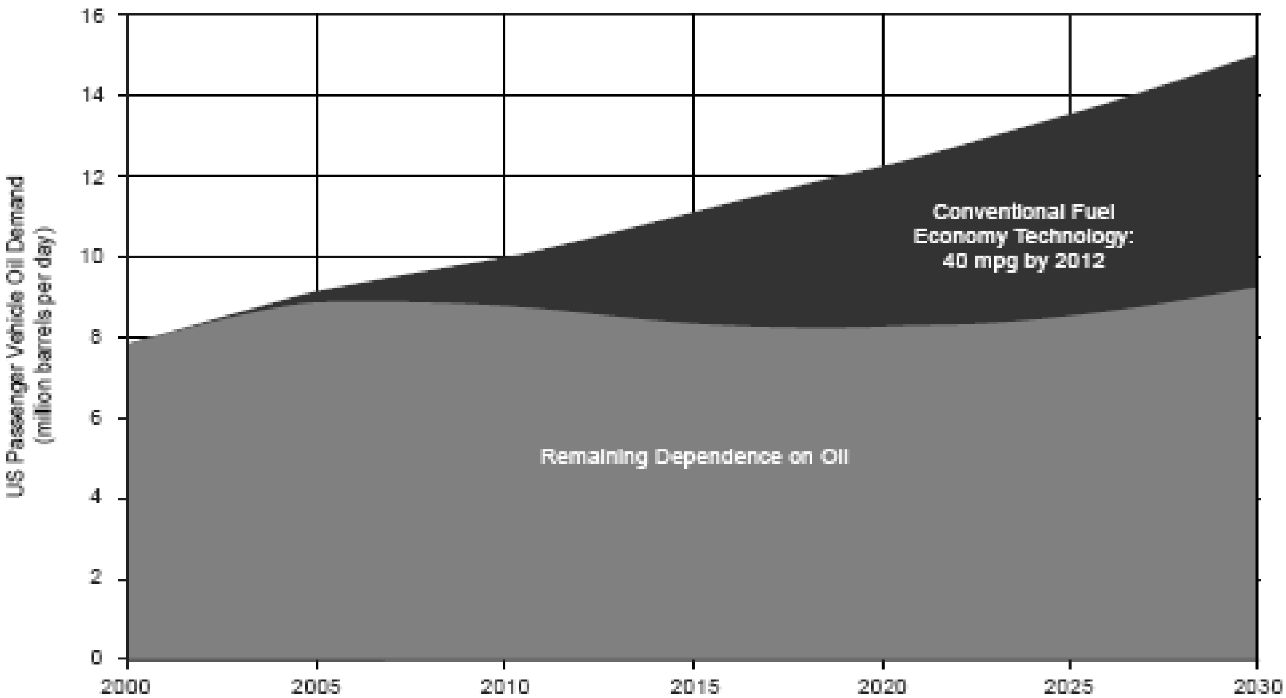
As with US oil use and global warming emissions, upstream air pollution is expected to continue to rise significantly over the next two decades, posing the greatest health threat to children, the elderly, and other vulnerable members of our population (Table). The situation is urgent, but not hopeless.
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.

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

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



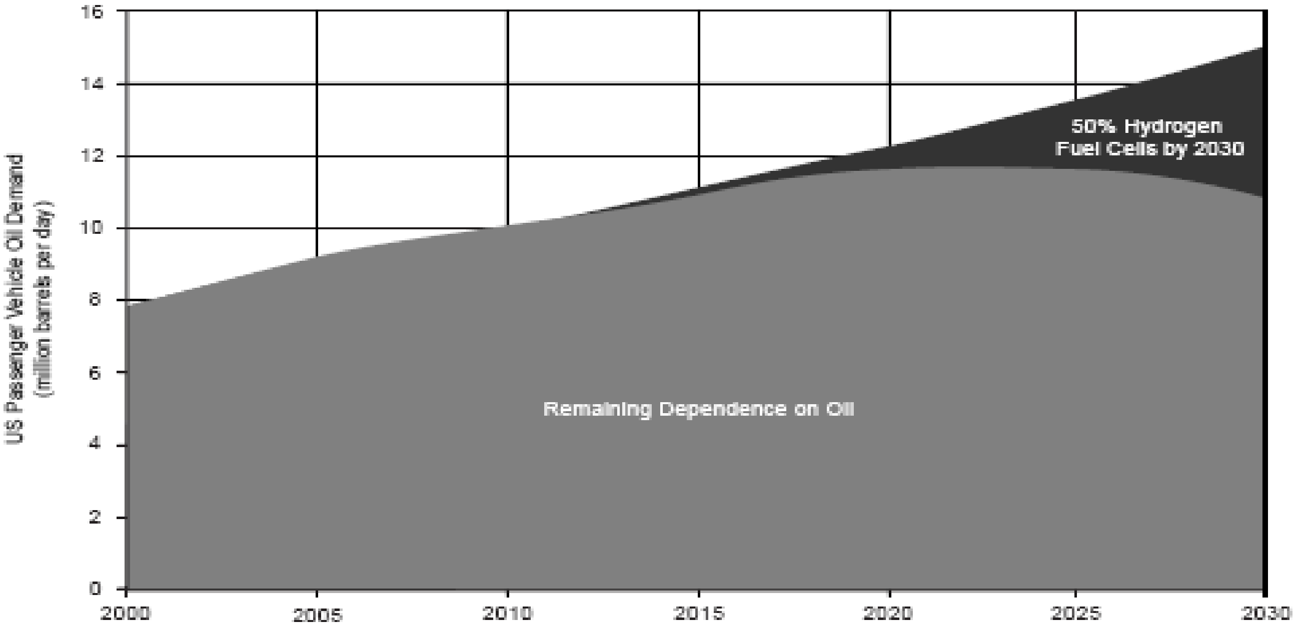
NOTES: Based on analysis presented in Friedman 2001.

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. 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.

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



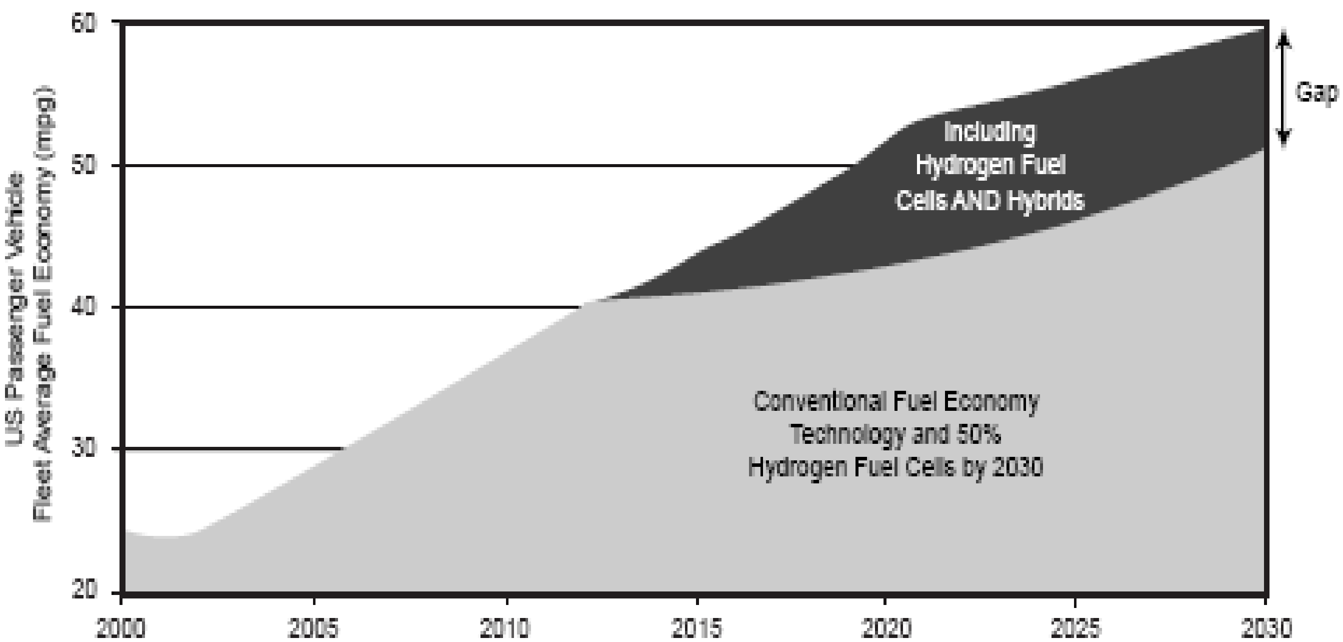
NOTES: Developed from analysis presented in Friedman in 2001 and Doniger et al. (2002). Assumes hydrogen fuel cell vehicles reach 15% of new vehicles sales by 2020 and 50% by 2002.

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

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



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

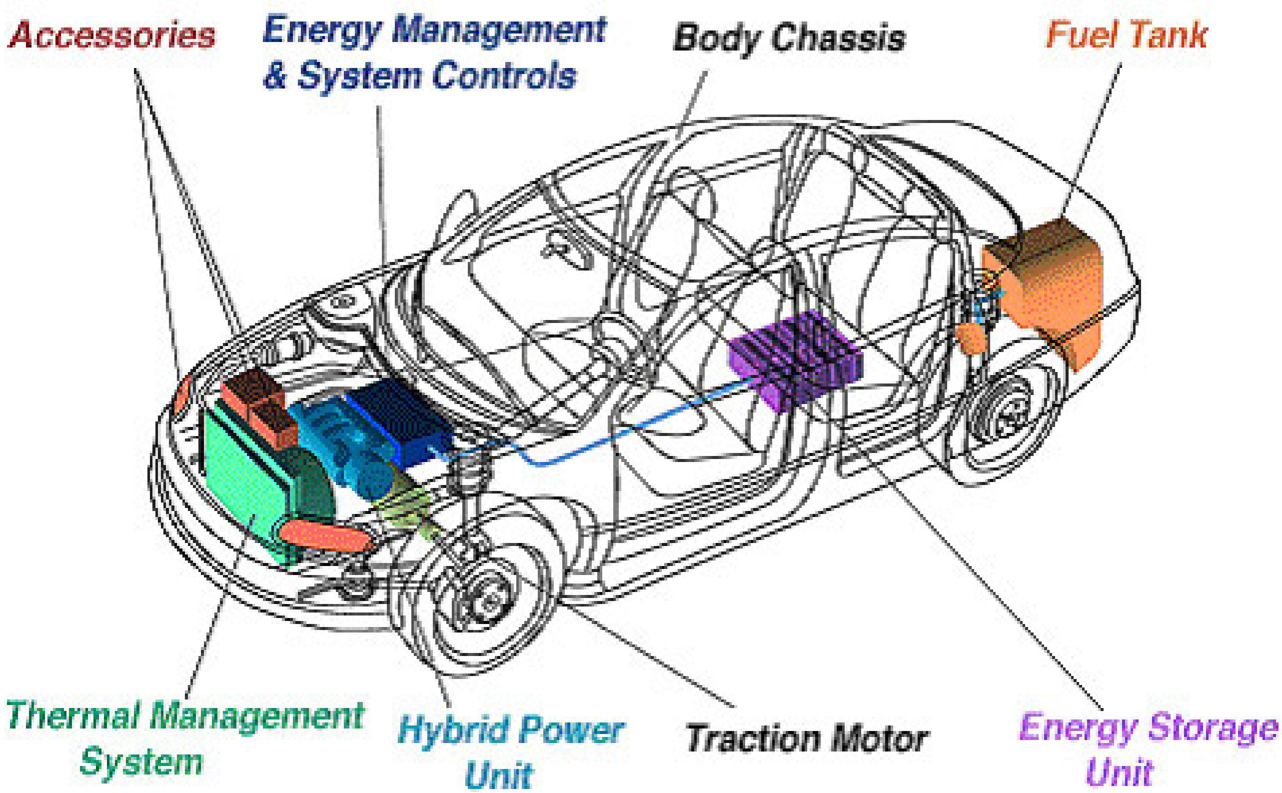
Automaker Choice. Only Toyota and Honda have so far offered hybrids for sale in the US market. Both are likely to offer more models very soon, as are most other automakers. Ford intends to enter the market with a hybrid SUV using a design similar to the Prius. GM and Daimler- Chrysler are expected to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

HEV Components

A hybrid electric vehicle (HEV) is an optimized mix of various components. View a typical hybrid configuration in the diagram below and learn more about the various HEV components by following the links below.



HEV Drivetrain Components:

- Electric traction motors/controllers
- Electric energy storage systems, such as batteries and ultracapacitors
- Hybrid power units such as spark ignition engines, compression ignition direct injection (diesel) engines, gas turbines, and fuel cells
- Fuel systems for hybrid power units
- Transmissions

To help reduce emissions and improve vehicle efficiencies, these systems and components are being improved through research and development.

- Emission control systems
- Energy management and systems control
- Thermal management of components
- Lightweight and aerodynamic body/chassis
- Low rolling resistance (including body design and tires)
- Reduction of accessory loads

HEV Motors/Controllers

Motors are the "work horses" of Hybrid Electric Vehicle (HEV) drive systems. In an HEV, an electric traction motor converts electrical energy from the energy storage unit to mechanical energy that drives the wheels of the vehicle. Unlike a traditional vehicle, where the engine must "ramp up" before full torque can be provided, an electric motor provides full torque at low speeds. This characteristic gives the vehicle excellent "off the line" acceleration.

Important characteristics of an HEV motor include good drive control and fault tolerance, as well as low noise and high efficiency. Other characteristics include flexibility in relation to voltage fluctuations and, of course, acceptable mass production costs. Front-running motor technologies for HEV applications include permanent magnet, AC induction, and switched reluctance motors.

HEV Batteries

Batteries are an essential component of HEVs. Although a few production HEVs with advanced batteries have been introduced in the market, no current battery technology has demonstrated an economically acceptable combination of power, energy efficiency, and life cycle for high-volume production vehicles.

Desirable attributes of high-power batteries for HEV applications are high-peak and pulse-specific power, high specific energy at pulse power, a high charge acceptance to maximize regenerative braking utilization, and long calendar and cycle life. Developing methods/designs to balance the packs electrically and thermally, developing accurate techniques to determine a battery's state of charge, developing abuse-tolerant batteries, and recyclability are additional technical challenges.

Lead-Acid Batteries

Lead-acid batteries can be designed to be high power and are inexpensive, safe, and reliable. A recycling infrastructure is in place for them. But low specific energy, poor cold temperature performance, and short calendar and cycle life are still impediments to their use. Advanced high-power lead-acid batteries are being developed for HEV applications.

Nickel-Cadmium Batteries

Although nickel-cadmium batteries, used in many electronic consumer products, have higher specific energy and better life cycle than lead-acid batteries, they do not deliver sufficient power and are not being considered for HEV applications.

Nickel-Metal Hydride Batteries

Nickel-metal hydride batteries, used routinely in computer and medical equipment, offer reasonable specific energy and specific power capabilities. Their components are recyclable, but a recycling structure is not yet in place. Nickel-metal hydride batteries have a much longer life cycle than lead acid batteries and are safe and abuse-tolerant. These batteries have been used successfully in production electric vehicles and recently in low-volume production HEVs. The main challenges with nickel-metal hydride batteries are their high cost, high self-discharge and heat generation at high temperatures, the need to control losses of hydrogen, and their low cell efficiency.

Lithium Ion Batteries

The lithium ion batteries are rapidly penetrating into laptop and cell-phone markets because of their high specific energy. They also have high specific power, high-energy efficiency, good high-temperature performance, and low self-discharge. Components of lithium ion batteries could also be recycled. These characteristics make lithium ion batteries suitable for HEV applications. However, to make them commercially viable for HEVs, further development is needed similar to those for the EV-design versions including improvement in calendar and cycle life, higher degree of cell and battery safety, abuse tolerance, and acceptable cost.

Lithium Polymer Batteries

Lithium polymer batteries with high specific energy, initially developed for EV applications, also have the potential to provide high specific power for HEV applications. The other key characteristics of the lithium polymer are safety and good cycle and calendar life. The battery could be commercially viable if the cost is lowered and higher specific power batteries are developed.

HEV Spark Ignition Engines

A spark ignition (SI) engine runs on an Otto cycle—most gasoline engines run on a modified Otto cycle. This cycle uses a stoichiometric air-fuel mixture, which is combined prior to entering the combustion chamber. Once in the combustion chamber, the mixture is compressed, then ignited using a spark plug (spark ignition). The SI engine is controlled by limiting the amount of air allowed into the engine. This is accomplished through the use of a throttling valve placed on the air intake (carburetor or throttle body).

Advantages

- A century of development and refinement: For the last century, the SI engine has been developed and used widely in automobiles. Continual development of this technology has produced an engine that easily meets emissions and fuel economy standards. With current computer controls and reformulated gasoline, today's engines are much more efficient and less polluting than those built 20 years ago.
- Low cost: The SI engine is the lowest cost engine because of the huge volume currently produced.

Disadvantages

The SI engine has a few weaknesses that have not been significant problems in the past, but may become problems in the future.

- Difficulty in meeting future emissions and fuel economy standards at a reasonable cost: Technology has progressed and will enable the SI engine to meet current standards, but as requirements become tougher to meet, the associated engine cost will continue to rise.
- Throttling loss lowers the efficiency: To control an SI engine, the air allowed into the engine is restricted using a throttling plate. The engine is constantly fighting to draw air past the throttle, which expends energy.

- Friction loss due to many moving parts: The SI engine is very complex and has many moving parts. The losses through bearing friction and sliding friction further reduce the efficiency of the engine.
- Limited compression ratio lowers efficiency: Because the fuel is already mixed with the air during compression, it will auto-ignite (undesirable in a gasoline engine) if the compression ratio is too high. The compression ratio of the engine is limited by the octane rating of the engine.
- Typically, 80% of the combustion energy is wasted as heat.

HEV Compression Ignition Direct Injection Diesel Engines

Progress continues to advance the compression-ignition direct-injection (CIDI) engine, (more commonly called the diesel engine), which has the highest thermal efficiency of any internal combustion engine. Challenges to improvements include a lower specific power than the gasoline engine; significant particulate matter and nitrogen oxides in the exhaust; and the noise, vibration, and smell of the engine.

Recent advancements in high-speed automotive diesel engines, which address some of these shortcomings, have made them nearly ideal candidates for HEV applications. These advancements include high-pressure direct fuel injection, low oxides of nitrogen catalysts, and sophisticated electronic controls. With a thermal efficiency upwards of 40% and well-understood maintenance, reliability, manufacturing, and operating characteristics, the high-speed CIDI engine shows great promise as a near-term hybrid power unit.

HEV Gas Turbine Engines

The gas turbine engine runs on a Brayton cycle using a continuous combustion process. In this cycle, a compressor (usually radial flow for automotive applications) raises the pressure and temperature of the inlet air. The air is then moved into the burner, where fuel is injected and combusted to raise the temperature of the air. Power is produced when the heated, high-pressure mixture is expanded and cooled through a turbine. When a turbine engine is directly coupled to a generator, it is often called a turbo generator or turbo alternator.

The power output of a turbine is controlled through the amount of fuel injected into the burner. Many turbines have adjustable vanes and/or gearing to decrease fuel consumption during partial load conditions and to improve acceleration.

Advantages

- The turbine is light and simple - The only moving part of a simple turbine is the rotor. A turbine has no reciprocating motion, and consequently runs smoother than a reciprocating engine.
- A turbine will run on a variety of fuels - Any combustible fuel that can be injected into the airstream will burn in a turbine. A turbine has this flexibility because the continuous combustion is not heavily reliant on the combustion characteristics of the fuel.
- A turbine produces low levels of emissions - Because of its multi-fuel capability, a fuel which burns completely and cleanly can be used to reduce emissions.

Disadvantages

The turbine engine has a few drawbacks, which have prevented its widespread use in automotive applications:

- Turbine engines have high manufacturing costs - Because of the complicated design, manufacturing is expensive.
- A turbine engine changes speed slowly - A gas turbine is slow to respond (relative to a reciprocating engine) to changes in throttle request.
- A gas turbine is less suitable for low-power applications - At partial throttle conditions, the efficiency of the gas turbine decreases.
- A turbine requires intercoolers, regenerators, and/or reheaters to reach efficiencies comparable to current gasoline engines - This adds significant cost and complexity to a turbine engine.

HEV Fuel Cells

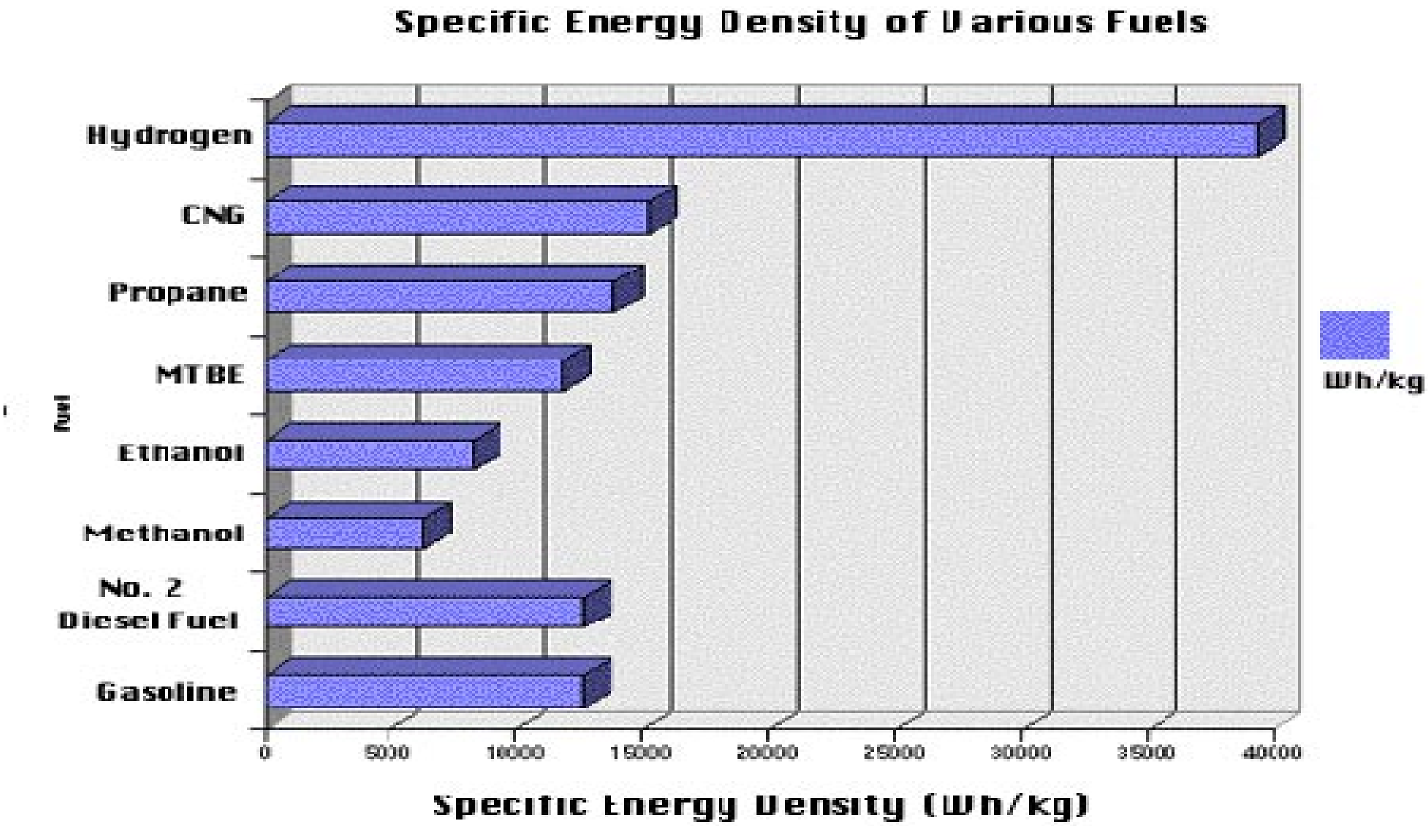
Fuel cells generate electricity through an electrochemical reaction that combines hydrogen with oxygen in ambient air. Pure hydrogen, or any fossil fuel that has been "reformed," can be used to produce hydrogen gas. Methanol is a common fuel choice. For the most part, the fuel cell's only emission is water vapor, giving it potential as the cleanest hybrid power unit alternative. Efficient, quiet, and reliable, fuel cells are predicted to demonstrate energy conversion efficiencies up to 50%; relatively high in comparison to the 20%-25% efficiency of standard SI gasoline engines.

The choice of fuel for a fuel-cell-powered HEV has important implications for required infrastructure, system accessories, efficiency, cost, and design. Although its viability has been well-proven in the space program, as well as in prototype vehicles developed by the U.S. Department of Energy (DOE) and industry partners, very high capital costs, large size, long start-up times, and immature technologies make it a longer-term enabling technology for an HEV.

HEV Fuel Systems

The two primary fuels used in automobiles today are gasoline and diesel. The infrastructure is in place to produce, refine, truck, or tank diesel and gasoline. Many of today's HEVs, and the ones that will be available in the near future, will use either gasoline or diesel to fuel the hybrid power units. However, to ensure the security of our oil supply and to address increasing environmental concerns associated with gasoline and diesel, alternative fuels are very attractive. The opportunity for fuels such as biodiesel, natural gas (CNG & LNG), ethanol, hydrogen, and propane to be used as alternative fuels for vehicles is great. Many alternative fuel vehicles are already being used effectively around the world. These fuels have the potential to be used in HEVs as well.

The following graph shows the energy density for various fuels. The graph does not take into consideration containment weight. For instance, the energy density for hydrogen and compressed natural gas is much lower than that of gasoline if the containment weight for the fuel is taken into consideration. The containment weights are not taken into consideration in the following graph due to the variability of manufacturer's containment weight estimates.



HEV Transmissions

Hybrid electric vehicles (HEVs) can use a variety of transmissions, based on the system design of the vehicle. Some transmissions are more efficient than others, however, sometimes less efficient transmissions are used for a variety of reasons. The four types of transmissions used in HEVs are:

- Continuously variable transmission
- Automated shifted manual transmission
- Manual transmission
- Traditional automatic transmission with torque converter

HEV Emission Control Systems

Automotive emissions contribute significantly to urban air quality problems. HEVs can reduce this contribution significantly through increased fuel economy, use of alternative fuels, and improved power unit and aftertreatment technology.

A well-tuned spark ignition engine produces relatively low emissions. Significant emissions occur when the vehicle is started and warming up. During this time the engine must be choked to run properly. This creates excess unburned fuel in the exhaust, which leads to hydrocarbon and carbon monoxide emissions. During normal driving, emissions are relatively low because the air-to-fuel mixture is precisely controlled, allowing the catalytic converter to effectively reduce emissions.

The diesel engine emissions are primarily nitrogen oxides (NO_x) and particulate matter (PM). NO_x is produced because the engine is operated with a lean air-to-fuel mixture. The high compression ratio of a diesel engine (required because of compression ignition) creates much higher pressure and temperature in the combustion cylinder. This lean mixture and high temperature cause the higher level of NO_x production. At high engine loads, where more fuel is injected, some of the fuel burns incompletely leading to the black smoke (PM) characteristic of a diesel engine.

The fuel cell produces water as emissions when operating on pure hydrogen. Other types of fuel cells have reformers that convert methane to hydrogen, then use the hydrogen. The reformer produces some emissions in the conversion process, but overall emission levels are low.

HEV Energy Management and System Control

A hybrid electric vehicle (HEV) has two or more sources of on-board power. The integration of the these power-producing components with the electrical energy storage components allows for many different types of HEV designs. A power control strategy is needed to control the flow of power and to maintain adequate reserves of energy in the storage devices. Although this is an added complexity not found in conventional vehicles, it allows the components to work together in an optimal manner to achieve multiple design objectives, such as high fuel economy and low emissions.

The biggest distinction between different hybrid designs is whether they are parallel or series, or a combination of the two. In a parallel design, the auxiliary power unit (APU) can mechanically drive the wheels; in a series design the APU generates electricity and doesn't directly drive the wheels. A third type combines the best aspects of both, and is sometimes called a combined or a series/parallel design. A combined design allows the APU to directly drive the wheels but also has the ability to charge the energy storage device through a generator. The combined hybrid is a subset of the parallel design since it can directly drive the wheels from the APU. The way the hardware components are connected (parallel, series, or a combination of the two) will be referred to here as the "hardware configuration" and the management of the power flow among the components will be referred to as the "control strategy" or more generally "energy management."

A secondary distinction between hybrids is charge-sustaining versus charge-depleting hardware configurations and control strategies. Charge-depleting vehicles allow their batteries to become depleted and cannot recharge them at the same rate they are being discharged. The common "range-extender" is a charge-depleting vehicle unless the APU is larger than the average power load of the vehicle over a given cycle. A charge-sustaining hybrid has an APU that is adequately sized to meet the average power load, and if operated under the expected conditions, will be able to keep adequate electrical energy storage reserves indefinitely.

Control strategies for HEVs

The flexibility in HEV design comes from the ability of the control strategy to manage how much power is flowing to or from each component. This way, the components can be integrated with a control strategy to achieve the optimal design for a given set of design constraints. There are many (often conflicting) objectives desirable for HEVs. The primary ones are to:

- Maximize fuel economy
- Minimize emissions
- Minimize propulsion system cost to keep the vehicles affordable to the consumer market
- Do all of the above while maintaining or improving on acceptable performance (acceleration, range, handling, noise, etc.)

To achieve these objectives, the hardware configuration and the power control strategy are designed together. The hardware configuration dictates to some extent what control strategies make sense, but as you can see from the following examples, there is still a wide spectrum of control strategies for each hardware configuration.

Consumer appeal made possible through control strategies

Because hybrid control strategies open up so many energy management possibilities, there is great potential for the control strategies and hardware configurations to be customized for different market groups. There is even potential for the car to adjust itself to maximize its ability to meet a driver's expected driving behavior. A few examples are listed here to give a flavor of some possibilities:

- The car could be warmed up or cooled down while it's still in the garage (based on a timer) to make the first few minutes of commute more enjoyable and energy efficient.
- For "lead-foot" drivers, the control strategy could always keep batteries as close to fully charged as possible to allow maximum power for hard accelerations and keep the APU running continuously to have full power available on demand.
- For people who drive their cars with maximum fuel economy in mind, the vehicles would use their on-board components in such a way that they would be operating in their highest efficiency regions as much of the time as possible.
- For people who normally drive long commutes, the vehicle could turn on the APU before batteries are depleted in anticipation of extra on-board power being needed.
- For those who have a short, repeatable commute, the vehicle could delay turning on the APU to allow the commuter to use only "wall charged" electric energy except when driving longer trips.

Implementing energy management and control strategies

Before a control strategy is implemented, an HEV consists simply of hardware components hooked up electrically and mechanically, with nothing telling them what to do or when to do it. The control strategy brings the components together as a system and provides the intelligence that makes the components work together. The implementation does require other connections to control the individual components, however, and the two classifications of mechanical and electrical are explained in a little more detail here.

- **Mechanical Control:** This includes mechanically controlled clutches, throttles controlled by the accelerator pedal and dials on the dashboard, and other controls activated mechanically by the driver from the car's interior.
- **Electrical Control:** With the increased use of on-board computers in today's conventional vehicles, electrical controls will most likely be the dominant means of implementing control strategies. This will be done through software programs running on microchips that then activate relays and other electromechanical systems to perform the desired functions. These computing systems will most likely have multiple data inputs measured on the current state of the vehicle (such as component temperatures, battery voltage, current, and state of charge) as well as the standard desired response requested by the driver (such as braking and acceleration).

HEV Thermal Management

Just as conventional gasoline engines require a cooling system, HEVs need proper thermal management of the power and energy storage units for optimum performance and durability. The type of thermal management system required will depend on the type of power and energy storage units selected. In many cases, waste heat from these components can be used for cabin air and other heating needs.

Batteries

The performance and life-cycle costs of electric vehicles (EV) and hybrid electric vehicles (HEV) depend on the performance and life of their battery packs. Each battery chemistry operates over a particular operating range to achieve optimum life and performance. Temperature variations from module to module in a battery pack could result in an un-balanced pack and thus reduced performance. It is important to regulate battery pack operating temperature because it affects performance (power and capacity), charge acceptance (during regenerative braking), and vehicle operating and maintenance expenses. Battery thermal management is critical for high-power battery packs used in EVs and HEVs to maintain their battery packs within the desired temperature range. To learn more go to the NREL battery thermal management Web site.

Power Units

Fuel cells offer highly efficient and fuel-flexible power systems with low to zero emissions for future HEV designs irrespective of the reformer. There are a variety of thermal issues to be addressed in the development and application of fuel cells for hybrid vehicles. For example, solid oxide fuel cells potentially offer very high efficiencies and lower cost than PEM or phosphoric acid cells, but run hotter. Isolation of this heat from the rest of the vehicle is important not only for improved efficiency, but also passenger safety. Reducing the warm-up time of fuel cells via thermal management is important to achieve quick power and minimal emissions. More standard power units such as small diesel or spark-ignition engines also need proper cooling. For more information on fuel cells go to DOE's Fuel Cell Program page.

Exhaust Systems

60% to 80% of emissions in an auto's typical driving cycle come from "cold start" emissions, that is, pollutants that are emitted before the catalytic converter is hot enough to begin catalyzing combustion products. The National Renewable Energy Laboratory has shown that its patented variable conductance insulation and phase-change heat storage material can be used to keep the catalyst hot for more than 17 hours, yet allow heat to flow during peak engine loads to prevent the converter from overheating. This would allow 95% of all auto trips to begin with a hot catalyst and little or no cold start emissions. This is particularly important with many HEVs, since their power unit may cycle on and off during a trip.

Fuel System

As emissions standards tighten and exhaust control technologies improve, the issue of evaporative emissions becomes increasingly important. Thermal management of fuel tanks is one approach to reducing these emissions.

Waste Heat Utilization

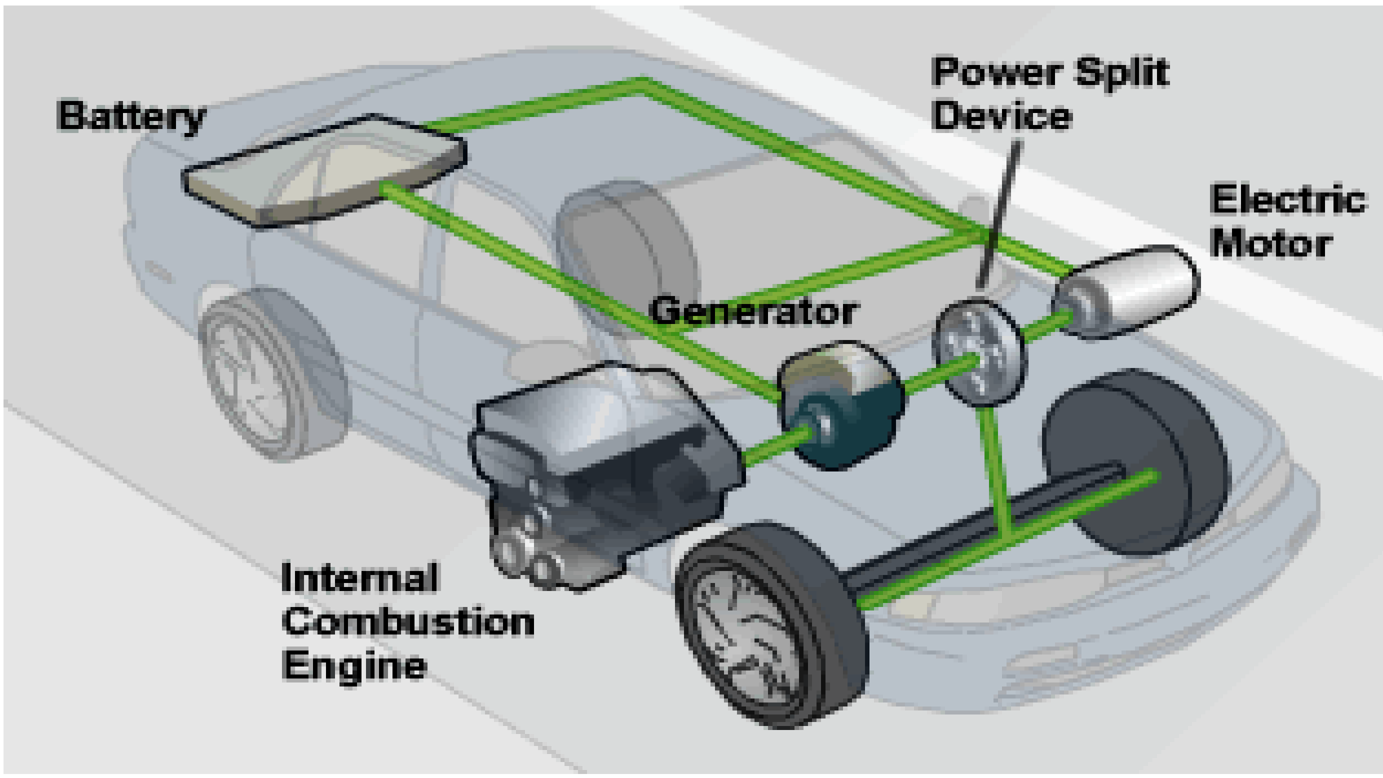
Heat recovered from any of the above sources can be used in a variety of ways. For winter driving, heat recovery from HEV sources such as the power unit exhaust, propulsion motors, batteries, and power inverter can significantly improve cabin warm-up. Because of their small power units, hybrid vehicles generally cannot supply enough heat to the cabin via the conventional coolant-to-air heat exchanger. Waste heat can also be converted into electricity via thermoelectric devices

HEV Body/Chassis

Tomorrow's HEV's will contain a mix of aluminum, steel, plastic, magnesium, and composites (typically a strong, lightweight material composed of fibers in a binding matrix, such as fiberglass). To make these materials affordable and durable, research is intensifying on vehicle manufacturing methods, structural concepts, design analysis tools, sheet-manufacturing processes, improved material strength, and recyclability. Since 1975, the weight of a typical family sedan has decreased from 4,000 pounds to 3,300 pounds. Researchers are working to reduce overall vehicle weight by yet another 40% to 2,000 pounds. To achieve this, they must reduce the mass of both the outer body and chassis by half, trim powertrain weight by 10%, and reduce the weight of interior components.

How Hybrids Work

Hybrid-electric vehicles (HEVs) combine the benefits of gasoline engines and electric motors and can be configured to obtain different objectives, such as improved fuel economy, increased power, or additional auxiliary power for electronic devices and power tools



Some of the advanced technologies typically used by hybrids include

Regenerative Braking. The electric motor applies resistance to the drivetrain causing the wheels to slow down. In return, the energy from the wheels turns the motor, which functions as a generator, converting energy normally wasted during coasting and braking into electricity, which is stored in a battery until needed by the electric motor.

Electric Motor Drive/Assist. The electric motor provides additional power to assist the engine in accelerating, passing, or hill climbing. This allows a smaller, more efficient engine to be used. In some vehicles, the motor alone provides power for low-speed driving conditions where internal combustion engines are least efficient.

Automatic Start/Shutoff. Automatically shuts off the engine when the vehicle comes to a stop and restarts it when the accelerator is pressed. This prevents wasted energy from idling.

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.

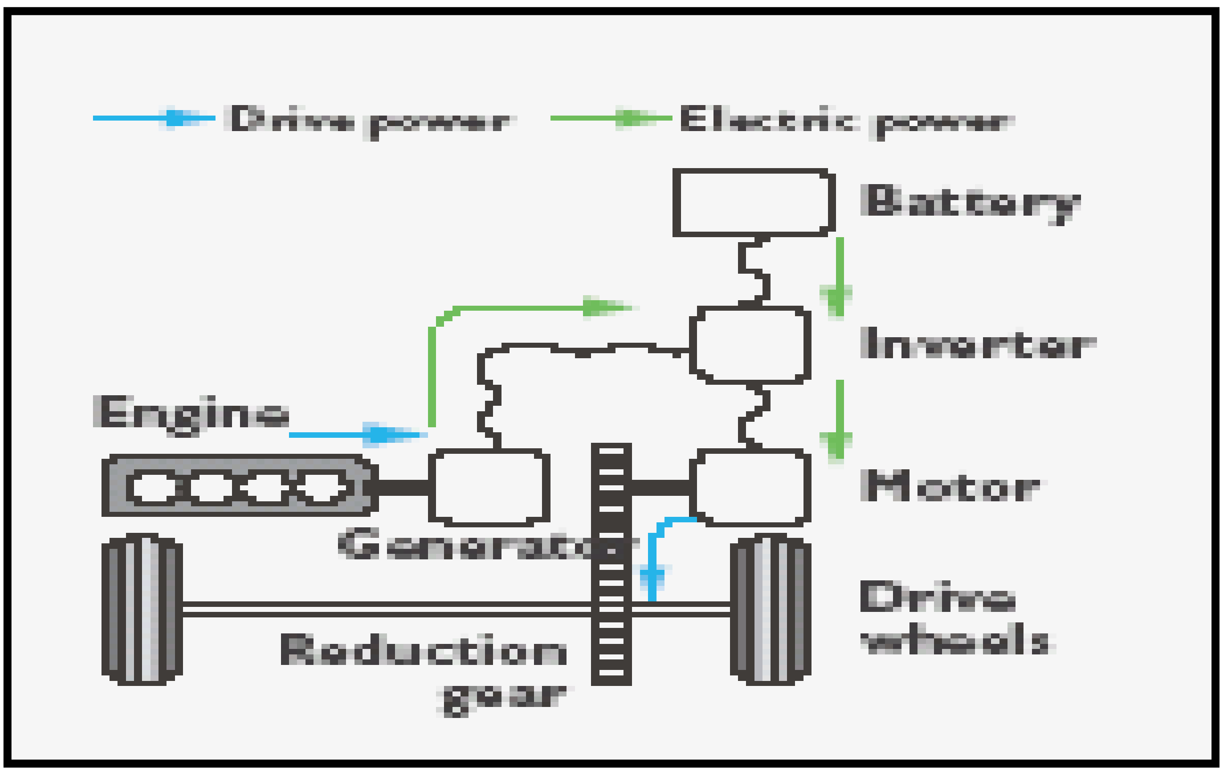
Defining Hybrids

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).

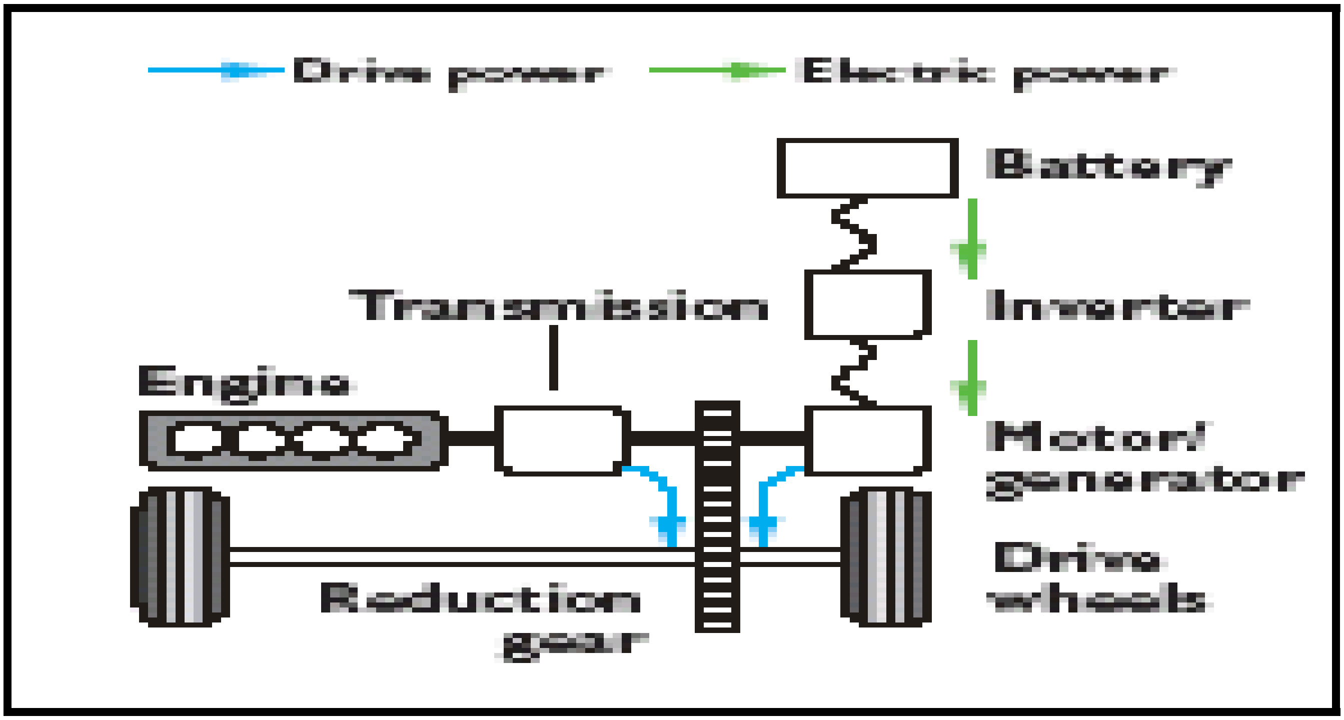
Many other hybrid variations could undoubtedly be envisioned, but the key to success lies in creating a hybrid vehicle that provides consumers, at a reasonable cost, the performance they seek along with improved fuel economy and decreased emissions. So far, only hybrid electric vehicles meet these criteria 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 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). 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. 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). 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).

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 energyconversion 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.

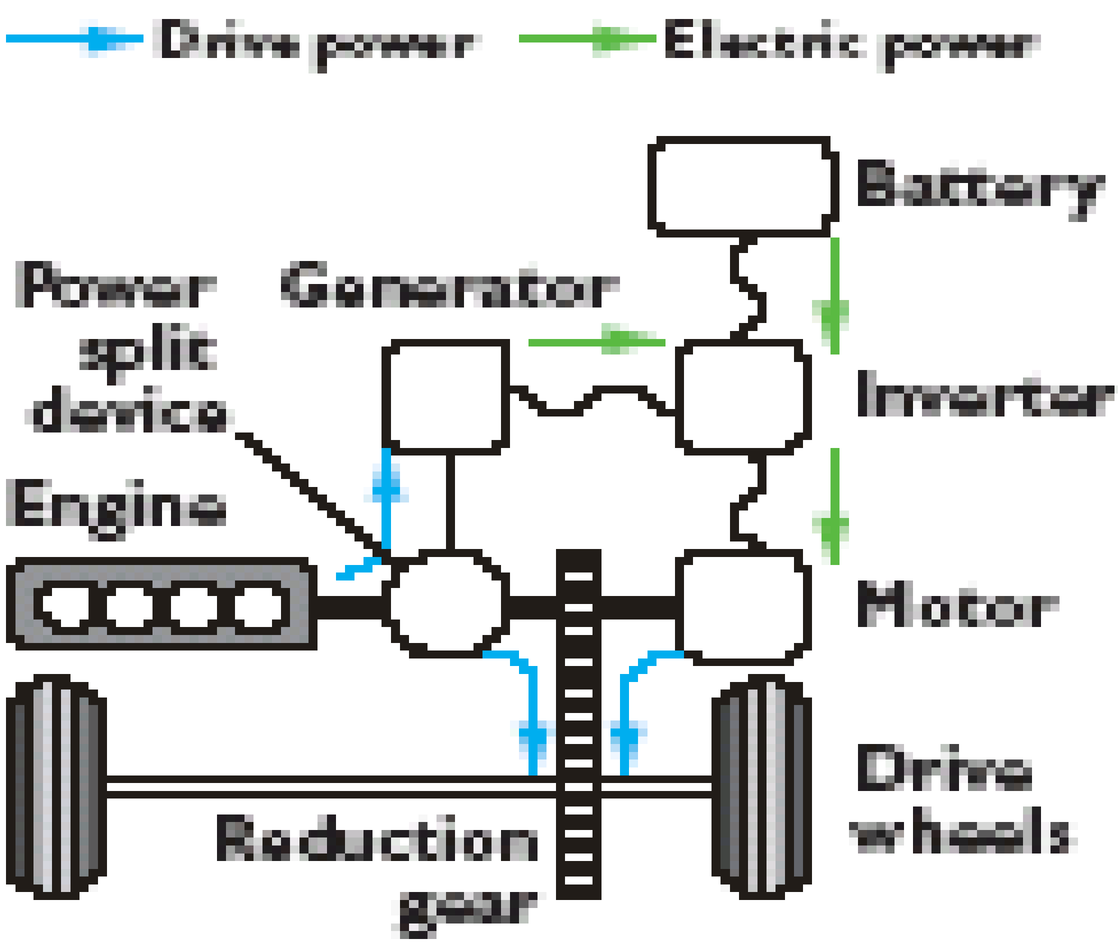


Figure 4 **Series Hybrid Electric Vehicle Drivetrain**

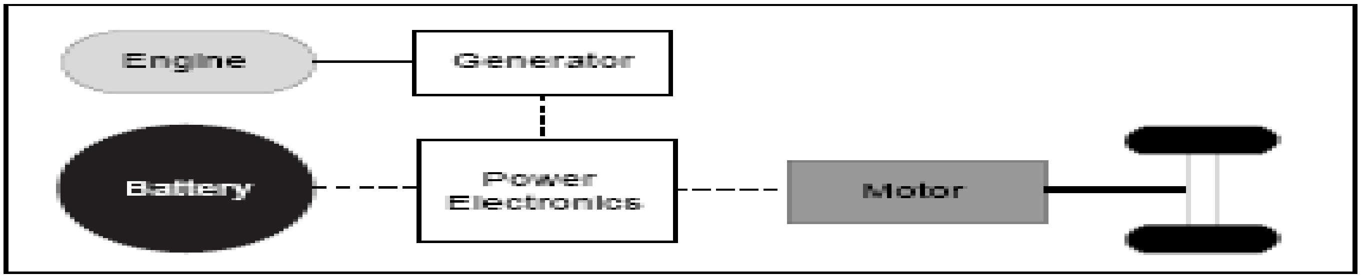


Figure 5 **Parallel Hybrid Electric Vehicle Drivetrain**

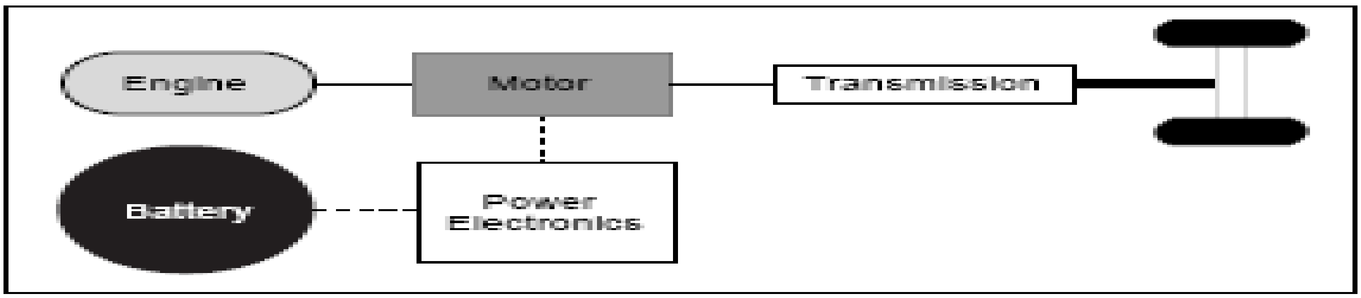


Figure 6 **Split-Parallel Hybrid Electric Vehicle Drivetrain**

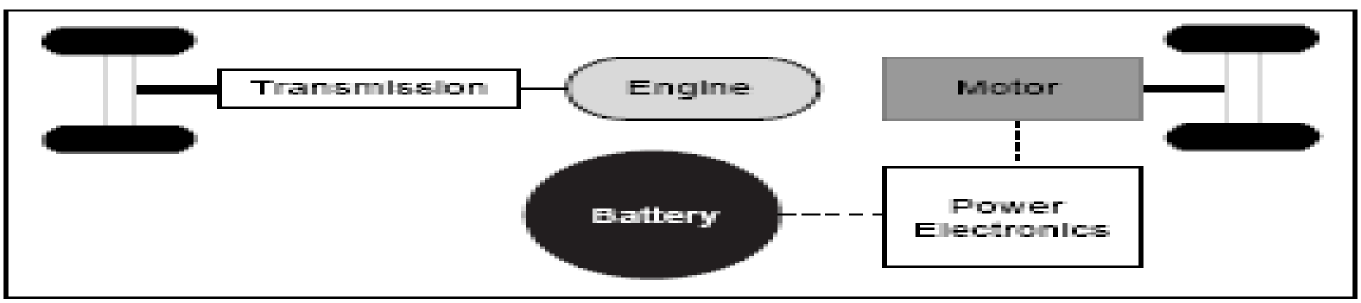
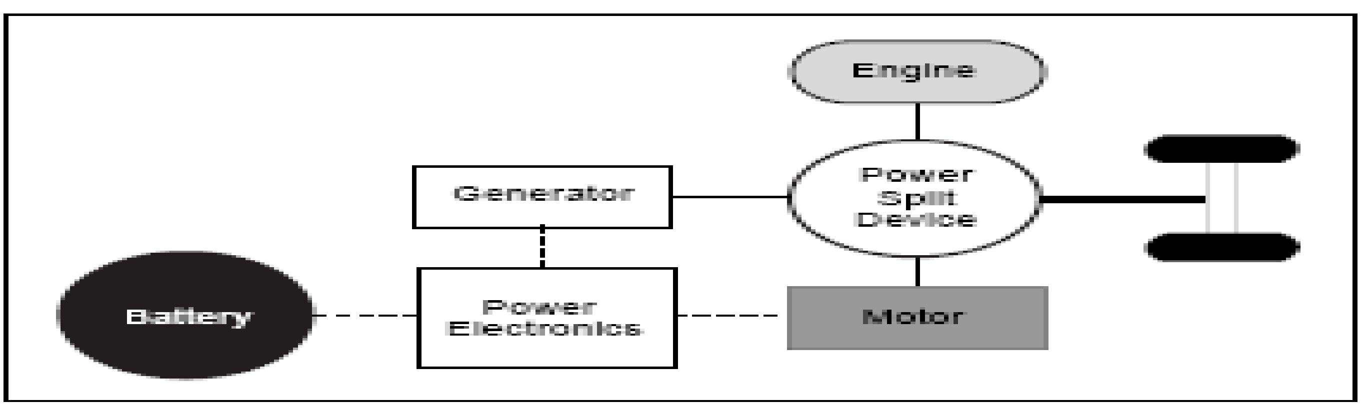


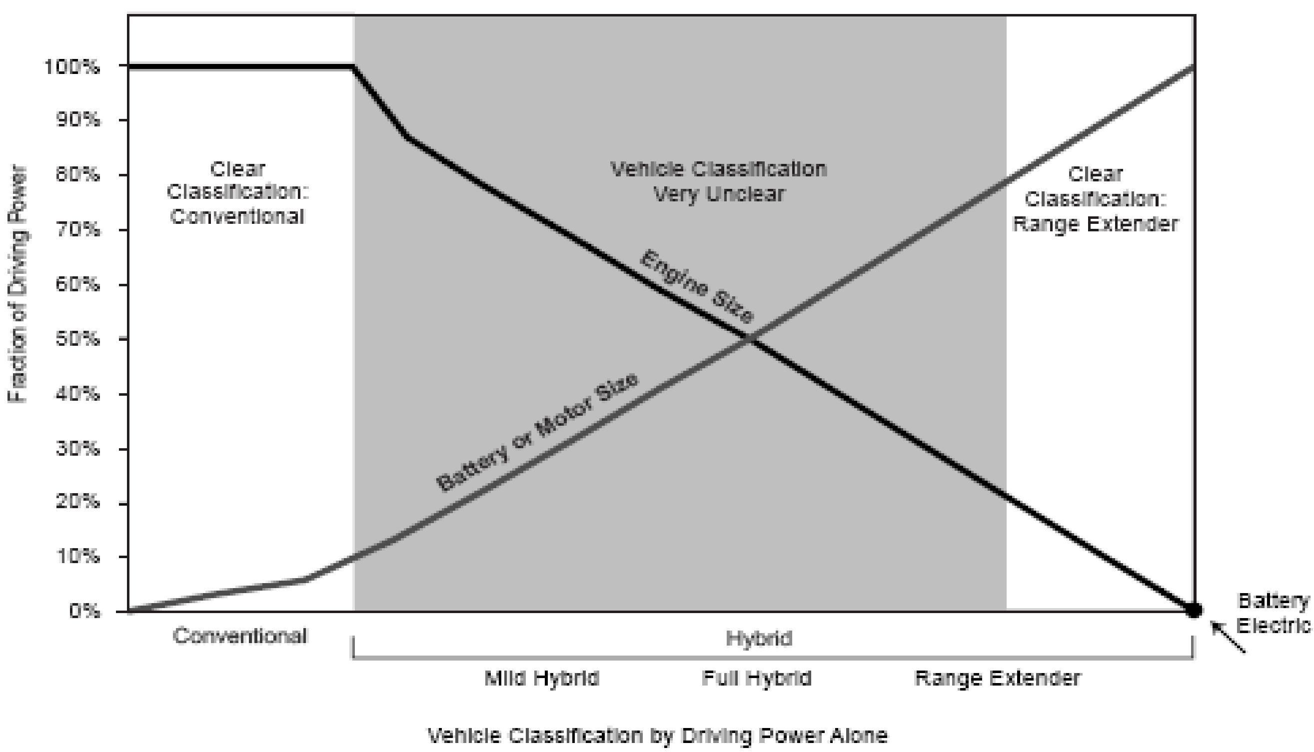
Figure 7 **Toyota Series-Parallel Hybrid Electric Vehicle Drivetrain**



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). 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 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 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 idleoff 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. 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 idleoff 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 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 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 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   lays out the links between the technologies, the hybrid classifications,

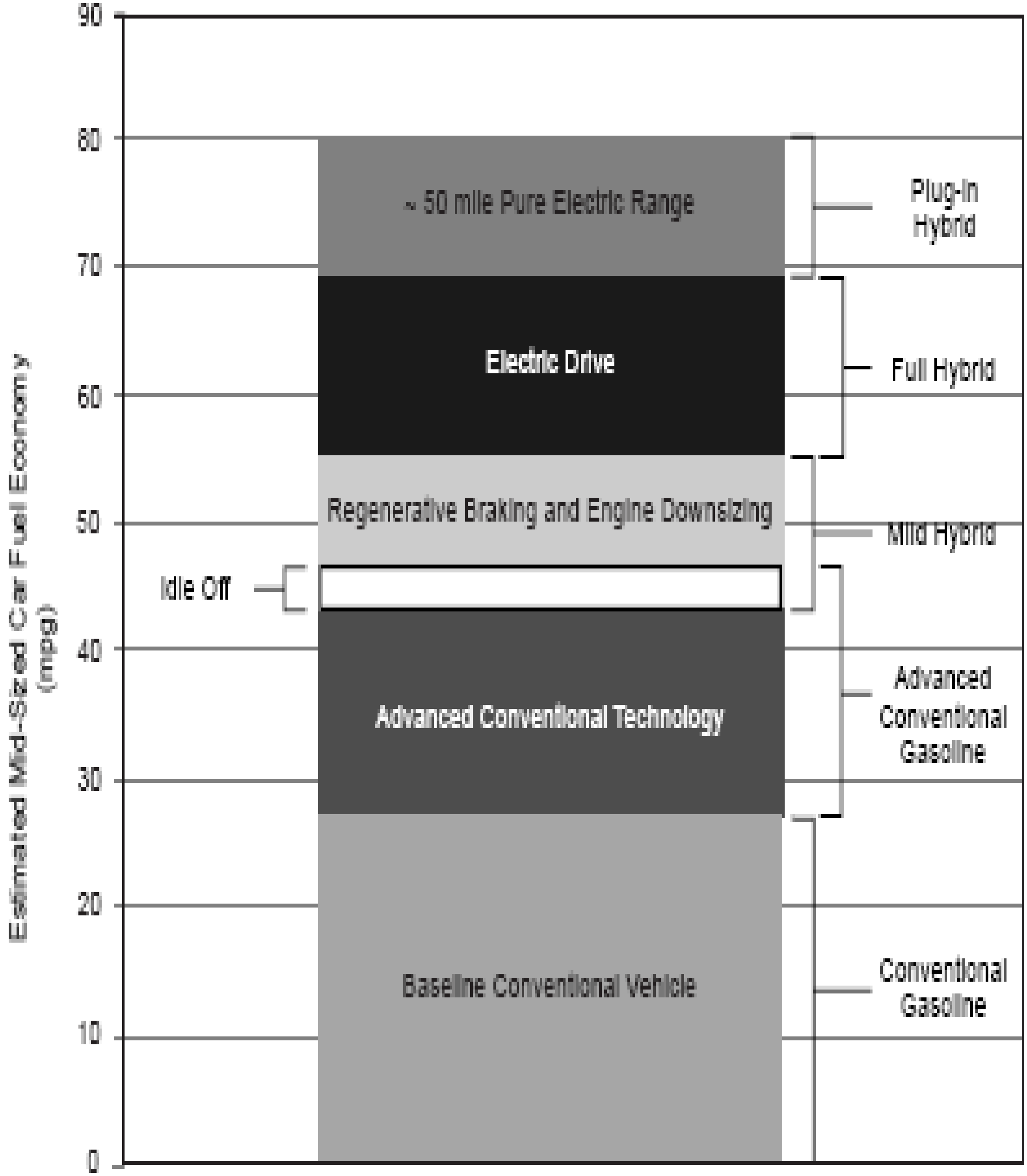
and their potential to improve fuel economy for a typical mid-size family car. The gains shown for

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.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 nonzero 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 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.

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



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 conventionalvehicles. If the canister is not fully purgedby 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

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 today1 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 determine 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 , 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 , have yet to enter the marketplace, but have already passed out of the research and development 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. 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 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 , 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.

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 Transmis-sions • 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

CONCLUSION

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.